MODELLING AS A TOOL IN INTEGRATED WATER RESOURCES MANAGEMENT

Conceptual Issues and Case Study Applications

R.E. Schulze

With contributions by M.J.C. Horan, K.B. Meier, J.C. Smithers, A. Pike, V. Taylor, T.G. Lumsden, G.P.W. Jewitt, D. Dlamini, L.A. Perks, N.L. Lecler, M.J. Summerton, S.D. Lynch and E.J. Schmidt

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School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

EXECUTIVE SUMMARY

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WRC Project K/749 "Modelling the Benefits of Integrated Catchment Management"

1. BACKGROUND

This project, a component of the Hydrological Modelling Systems Programme funded by the WRC at the School of Bioresources Engineering and Environmental Hydrology (formerly the Department of Agricultural Engineering) at the University of Natal in Pietermaritzburg, commenced in 1996 and was completed in 2002.

a) Objectives

The project objectives were

- the development and applications of a *linked agrohydrological modelling infrastructure* (i.e. model plus databases and decision support systems)
- to assess *benefits* of integrated catchment management (ICM)
- in order to address and quantify *real and contentious issues* which characterise South African catchments, often under stress, and which make their management difficult with respect to, *inter alia*,
  - the vagaries of climatic variability
  - hydrological risk management
  - multi-sectoral water demands
  - land use intensification, e.g. by afforestation and sugarcane plantations
  - land use extensification, e.g.by veld degradation
  - best management practices in irrigation or
  - future climates
- and where the benefits could imply, *inter alia*,
  - taking cogniscance of the interactions of the natural with the social, political, legal and economic environments
  - addressing impacts of land use and its change
  - pro-actively planning catchment operations with respect to optimising land and water resources
  - identifying environmentally sensitive areas within a catchment and
  - identifying areas where conflict management could be undertaken with the aid of modelling.

b) Motivation and Method

The motivation for this project was that water related issues, which often result in conflicts over allocation and use, be *managed holistically*, through *working partnerships* between researchers and stakeholders. These stakeholders may be water users, land holders, environmental interest groups, communities and government agencies, as well as NGOs. Such holistic management would require, *inter alia*, *versatile* *agrohydrological modelling tools* with process representations and configurations appropriate for southern African conditions.

The *ACRU* modelling system was to be the 'carrier' for this project because it was deemed suitable to be applied simultaneously as a

- scenario planning model
  - assessing alternative land and water uses and
  - assessing impacts, sensitivities and thresholds on catchments
- a multi-specialist model
  - providing a versatile modelling framework for further development and interlinkages to other models/modules and
- an operational model
  - to be used in management decisions.

Apart from further model development, specialist fieldwork, decision support and database development, a major methodological focus of this project was to be the application of the model in appropriate case studies.

c) Directions given . . . directions taken

It was in the course of this project that major conceptual rethinking took place in regard to ICM, which is a very far-reaching overarching concept of water management and which, in hindsight, was found to be beyond the scope of a project such as this. The focus of this report is, therefore, rather on Integrated Water Resources Management, IWRM, which is a (still wide-ranging) subset of ICM (cf. Chapter 1). Simultaneously, the late 1990s saw major paradigm shifts in the management of water resources as well as, of course, the promulgation of the National Water Act of 1998. The ushering in of this Act had major repercussions on directions taken in, and research undertaken through, this project, and many of the chapters bear testimony to that.

In light of the project's objectives, motivations, methods and new directions which evolved during the project's duration, this report of 14 chapters is presented in three broad sections:

- **Section A : Conceptual and Modelling Issues**
  This consists of six chapters covering
  - perspectives on integrated water resources management (IWRM)
  - thoughts on, and concepts, basic premises and requirements of models for IWRM
  - concepts, structure and typical applications of the *ACRU* agrohydrological modelling system
  - background to impacts of land cover and land use on hydrological responses
  - the use of detailed information in modelling and
  - a framework for hydrological risk management, with examples from southern Africa.
- **Section B : On Modelling Impacts of Land Use on Hydrological Responses**
  This section contains a further six chapters which cover
  - a forest hydrology decision support system
  - a regional study on streamflow reduction activities by different land uses
  - water use by, and water use efficiencies of, sugarcane
  - a sensitivity study on competing land uses, *viz*. afforestation and irrigation
  - compensatory forestry from riparian zone alien vegetation clearance and
  - impacts of veld degradation and rehabilitation on catchment sediment yields.
- **Section C : Looking Towards the Future**
  This section has two chapters which address
  - the application of seasonal rainfall forecasts to sugarcane yield forecasts and
  - a threshold analysis on when, and where, climate change is likely to impact on water resources in South Africa.

A number of the chapters titles and most of the chapter subheadings have been *posed as questions* to which the respective contents provide some answers. Each chapter, while linked conceptually and contextually to the others, can in essence be read as an entity. A summary of the chapter contents follows. Under the listings of each chapter's subheadings the acknowledgements and references have not been repeated each time in this Executive Summary.

2. SUMMARY OF CONTENTS

SECTION A : CONCEPTUAL AND MODELLING ISSUES

CHAPTER 1 WHAT IS INTEGRATED WATER RESOURCES MANAGEMENT? A PERSPECTIVE

R.E. Schulze

(pp 1 - 19; 4 figures; 1 table)

Abstract

The ecosystem which has been inherited from past actions is a 'damaged' one, to which Integrated Water Resources Management (IWRM) is one response. IWRM is defined and placed within the broader perspective of integrated catchment management, of which it is a subset. The major goals and strategies of IWRM are condensed into six approaches, *viz*. the systems approach, as well as the integrated, management, stakeholder, partnership and sustainability approaches. Reasons are advanced as to why the river basin is the scale on which IWRM is carried out, including that it is the scale at which attributes typical of small and large hydrological scales merge, at which anthropogenic processes shape hydrological processes, at which action and management occur, at which attempts are made to right previous wrongs and at which models become operational tools as aids in decision making. Advantages and disadvantages of the catchment as the 'ideal' unit for IWRM are assessed before discussing the range of temporal and spatial scale issues which need to be considered in IWRM. A major focus then falls on the different characteristics of developed countries and lesser developed countries (LDCs) which shape their respective needs for IWRM, highlighting problems of IWRM in LDCs. Preconditions for effective and efficient IWRM are evaluated, as are the main barriers of success of IWRM. The chapter concludes by reiterating that it remains an ambiguity that most stakeholders relate well to the concepts of IWRM, but that it cannot easily be translated into operational terms.

CHAPTER 2 ON MODELS AND MODELLING FOR INTEGRATED WATER RESOURCES MANAGEMENT : SOME THOUGHTS, BACKGROUND CONCEPTS, BASIC PREMISES AND MODEL REQUIREMENTS

R.E. Schulze

(pp 20 - 46; 8 figures; 3 tables)

Abstract

The complexity and demands of Integrated Water Resources Management, IWRM, are truly mind boggling if one considers that different natural influences dominate hydrological responses at a range of different scales, as do anthropogenic influences, and that these intersect; furthermore that IWRM follows the concepts of the DPSIR (Drivers, Pressures, States, Impacts and Responses) approach; and that with recent developments, which include the Water Services Act (1997) and the National Water Act (1998), major paradigm shifts have occurred in the management of water resources in South Africa.

All these perspectives demand that one looks (and re-looks) afresh at basic premises of models and their requirements in light of IWRM. This chapter highlights selected basic premises under four themes:

- *Hydrological process* and the *model conceptualisations* include discourses on the roles of precipitation, evaporation, soils and runoff generation mechanisms and concludes that for current and anticipated hydrological problems, models need to be physical-conceptual in structure, such that they can provide robustly ‘right answers for right reasons’ for multi-purpose outputs of water quantity and quality under unknown/unmeasured conditions.
- The *hydrological modelling system* requires that it be modular, adaptable to demand driven requests, multi-level in structure and that it must be operated by data available in direct or derived form from national data networks and spatial digital information, suitably “translated” into attributes required by models.
- The *model applications* need to be multi-scalar with the facility for spatial zooming in/out, also at scales finer than Quaternary Catchments and with hydrologically realistic subcatchment discretisation. Of paramount importance is the concept that in hydrology one can scale up realistically, but not down.
- *Responsibilities* of both *model developers and users* are discussed. Model developers need to respond to hydrological issues of the day and of the region, have to anticipate future modelling needs ahead of time, work in teams, follow strict protocols and provide service to users. Model users, on the other hand, need to comprehensively understand the model, follow user protocols conscientiously and be wary of the pitfalls of adopting new models too readily.

The chapter concludes with a reminder on the fundamental objective of modelling, uncertainties in modelling and some notes of caution in modelling.

CHAPTER 3 THE *ACRU* AGROHYDROLOGICAL MODELLING SYSTEM AS OF 2002 : BACKGROUND, CONCEPTS, STRUCTURE, OUTPUT, TYPICAL APPLICATIONS AND OPERATIONS

R..E. Schulze and J.C. Smithers

(pp 47 - 83; 14 figures)

Abstract

This chapter commences by tracing the development of the *ACRU* agrohydrological modelling system, from a distributed catchment evapotranspiration model in the mid-1970s through its various phases of enhancement, with milestone years in terms of new documentation being 1984, 1989 and 1995, to the present system, which is a multi-partnered national and international development spearheaded by funding from the Water Research Commission.

The conceptual basis of the model is outlined next. This includes discussion on the model's physical-conceptual process representation and on *ACRU* as a multi-purpose and multi-level model founded on daily multi-layered soil water budgeting procedures. The model can be operated as a lumped or distributed catchment simulator of streamflow components, with options for reservoir yield, sediment yield, irrigation demand/supply, crop yield and climate change analyses, and with a strong focus on land use impacts on hydrological responses. The model contains a dynamic input option to account for changes, either abrupt or gradual, in the catchment over time. Thereafter, the *ACRU* model's water budget is described, with emphasis on the vertical redistribution of soil water, evapotranspiration processes and runoff generation mechanisms, followed by a section on output options.

A major section of the chapter is a review of applications of the model to date, with some 150 references from the international and national refereed literature, conference proceedings, as well as research and consulting reports being cited. Examples of applications are categorised into water resources assessments (ranging from small to large catchments' to national scale assessments), design hydrology, irrigation supply and demand, crop yield and primary production modelling, land use impacts, forest hydrological impacts, groundwater modelling, hydro-economic analyses, impacts of climate change on both crop yields and hydrological responses, seasonal agrohydrological forecasting for operational purposes, applications in the service of the National Water Act of 1998, and international applications.

A section is devoted to the operation of *ACRU* as a distributed model. Modelling system components and linkages are illustrated and typical minimum input requirements are presented diagrammatically before some of the main system utilities, such as the *ACRU Menubuilder*, its *Outputbuilder* and the option for use of a stochastic daily rainfall generator are discussed.

This is followed by a section on capacity building which highlights contributions to the modelling system's development made by masters and doctoral students, and then concludes with a summary of perceived model system strengths, what the model should *not* be used for and where the current (2002 and beyond) research focus lies.

CHAPTER 4 ON LAND COVER, LAND USE AND THEIR IMPACTS ON HYDROLOGICAL RESPONSES

R.E. Schulze

(pp 84 - 97; 10 figures; 2 tables)

Abstract

Hydrologists intuitively associate different land covers and uses such as afforestation, urbanisation or irrigation with differences in the partitioning of rainfall into components of runoff such as stormflow or baseflow and with water quality determination. After defining the terms land cover and use, this chapter highlights the significance of the extents of land use changes, worldwide and in South Africa. The interplay between society and nature in land use change receives attention, with some emphasis on the difference between land use which is dependent on water vs land use which impacts on water. When ecosystems change as a result of land use alterations, they may be classified as conserved ecosystems, alternatively as utilised, replaced or completely removed ecosystems. Land use transformations may be represented as attribute changes, ecological response changes or hydrological response changes. Important generalisations regarding impacts of land use change on hydrological responses are summarised as follows: Land use change often leads to ecosystem degradation, it usually takes place slowly, its impacts are easily observable at small spatial scales but not easily recognised regionally, land use impact depends on its intensity and spatial extent, and management of the land frequently has greater impacts on hydrological responses than changes in land cover. The discussions on most of these generalisations are backed up with examples in the form of tables and diagrams. By way of conclusion, a case study on impacts of land use on hydrological responses is presented, using the Mgeni catchment in KwaZulu-Natal as the example. Maps illustrate that land use change can reduce baseline mean annual runoff (MAR) by up to 61% through agricultural intensification while increasing MAR by up to 103% in urbanised and degraded areas.

CHAPTER 5 DOES DETAIL MATTER? CASE STUDIES IN SUPPORT OF USING DATA AND INFORMATION BASES THAT ARE MORE DETAILED THAN PROVIDED BY WATER INDUSTRY 'STANDARDS'

R.E. Schulze

(pp 98 - 108; 6 figures; 5 tables)

Abstract

While pleas are made for the use of freely available standard national datasets and spatial digital information in modelling for integrated water resources management (IWRM), multi-scalar issues of upstream vs downstream hydrological conflicts often dictate that more detailed inputs may be necessary in hydrological models, especially when sensitive land use related issues are under the spotlight. Two case studies are presented to illustrate this.

In the first, from the Bivane catchment in KwaZulu-Natal, differences in detail of land use information derived from different sources are shown to be highly sensitive when used as input to models applied to upstream - downstream water management issues. In this catchment the critical land use issues were the hydrological impacts related to the extent of commercial forest plantations the area under irrigation and the number and capacity of dams supplying some of the water for irrigation. The sources of land use information were 1993 Landsat TM images and 1996 aerial photographs at scale 1 : 30 000, with the latter backed up by field checks. The aerial photos identified 69% more afforestation and six times as many farm dams, with full supply capacities three times in excess of those computed from the Landsat image, but irrigated lands were only 14% in area of those identified from the satellite image - the latter example clearly a case of misinterpretation of a land use classification system.

The second case study compared the spatial distribution of rainfall from the 1' x 1' latitude/longitude national grid of mean annual precipitation (MAP) with that derived from local physiography : rainfall relationships in three catchments on the North Coast of KwaZulu-Natal. Differences in MAP ranging from

+300 mm to -300 mm were found, i.e. $\pm$ 20% of the MAP. Detailed studies showed that these 'errors' could translate to differences in streamflows of up to 60%.

Both case studies illustrate clearly that in IWRM any errors caused by lack of appropriate detail in inputs to hydrological models could result in markedly different decisions being made.

CHAPTER 6 RISK, HAZARDS AND VULNERABILITY WITHIN A CONTEXT OF HYDROLOGICAL RISK MANAGEMENT : A CONCEPTUAL FRAMEWORK AND EXAMPLES FROM SOUTH AFRICA

R.E. Schulze

(pp 109-137; 13 figures)

Abstract

The concepts of risk, hazard and vulnerability are defined and discussed as background to focussing on the scope of hydrological risk management. Approaches to hydrological risk management are reviewed, first of risk assessment with its two major components of 'objective' hazard determination (which includes hazard identification, approaches to statistical hazard determination and the question of uncertainties related to meteorological and catchment conditions as well as to data attributes) and 'subjective' risk evaluation (which includes the perception of risk and the concept of acceptable risk). Thereafter risk mitigation and control are discussed. These are made up of hazard modification by manipulation of primary and secondary processes and vulnerability modification, for example, by forecasting and warning systems. The second part of the paper consists of South African examples of some of the components making up hydrological risk management, mainly in the form of comparative maps illustrating indicators of within-country variability, of hazard and of risk. General hydrological hazard indicators are presented first, followed by statistical hazard indicators of 'deprivation' and 'assault events in regard to droughts and floods. The question of using short data sets and of hazard modification through land use practices also receive attention. The final examples illustrate an application of vulnerability modification through seasonal forecasts of runoff and show potential hydrological impacts of climate change as a future hazard with associated risk. The paper illustrates, throughout, the amplification of the hydrological system of any climatic hazard.

SECTION B : ON MODELLING IMPACTS OF LAND USE ON HYDROLOGICAL RESPONSES

CHAPTER 7 THE *ACRUforest* DECISION SUPPORT SYSTEM TO ASSESS HYDROLOGICAL IMPACTS OF COMMERCIAL AFFORESTATION PRACTICES IN SOUTH AFRICA

R.E. Schulze, M.J. Summerton, K.B. Meier, A. Pike and S.D. Lynch

(pp 138 - 149; 10 figures)

Abstract

The recent moves towards identifying streamflow reduction activities and focussing on integrated water resources management have renewed questions on water use by commercial forest plantations in South Africa. This chapter first describes the process representations and factors such as age, genera, soil conditions, macro- and meso-climate and management practices which forest hydrological models need to account for. The *ACRUforest* decision support system is comprised of the *ACRU* model, linked with extensive daily climate and soils databases at Quaternary Catchment scale and dynamic growth algorithms for different genera, macro-climates and management practices in South Africa. A feature of this interactive package is that it prompts the user with easy-to-answer questions which are then used with *ACRUforest* to provide answers to decision makers on forest hydrological impacts. The first questions relate to the location at which impacts are to be assessed, whereupon *ACRUforest* responds with typical altitude, mean annual precipitation and soils characteristics for that Quaternary Catchment. These default values can be changed by the user to be more representative of a particular plantation/location under review. Next, simple information is required on the baseline land cover from which the conversion to afforestation is taking place, followed by questions on which genera (pines, wattle or eucalypt), thinning practices, site preparation and rotation lengths are to be considered. From this information the relevant 45 year daily climate record is interrogated for both baseline and afforestation runs for *ACRUforest* to output daily time series of runoff characteristics from which various statistics on the hydrological impacts of the afforestation are produced for the decision maker. The chapter concludes with a discussion on what can and cannot be computed by *ACRUforest*.

CHAPTER 8 PERTINENT QUESTIONS ON STREAMFLOW REDUCTIONS BY DIFFERENT LAND USES UNDER DIFFERENT CLIMATIC AND SOILS CONDITIONS : A COMPARATIVE CASE STUDY IN THE SUGARCANE BELT OF SOUTH AFRICA

R.E. Schulze and M.J.C. Horan

(pp 150 - 171; 22 figures; 3 tables)

Abstract

Following upon a definition of streamflow reduction activities (SFRAs), a major challenge to hydrologists is identified, this being the ability to objectively quantify SFRAs in regard to different crops grown on different soils over a range of climatic regimes and management practices. A case is made for Acocks' Veld Types to be used as a baseline land cover against which to assess SFRAs. The major objective of this chapter is to map and graph regional differences in SFRAs in the so-called sugarcane belt of South Africa for competing crops grown under varying soils and local as well as inter-seasonal climatic conditions. After illustrating that SFRAs cannot be established by simple regional relationships, it is shown that significant regional differences in annual streamflows, those occurring in the driest year in 10, and in baseflows occur for the competing 'crops' of sugarcane, pines and eucalypts, with these differences amplified in shallow as against deep soils. Results also show that very different spatial patterns of streamflow reductions are exhibited, depending on whether they are expressed in absolute (i.e. mm; m^3) terms or in relative (% difference) terms. The chapter concludes that no simple generalisations may be made in regard to SFRAs, which are shown to be highly location specific, conditioned by soil depth and dependent on whether or not the season is considered to be average or dry.

CHAPTER 9 IRRIGATION WATER USE BY SUGARCANE IN SOUTH AFRICA: A CASE STUDY ON WATER USE REQUIREMENTS, WATER USE EFFICIENCIES, YIELD GAINS AND WATER LOSSES

R.E. Schulze, T.G. Lumsden and M.J.C. Horan

(pp 172 - 191; 14 figures; 1 table)

Abstract

Irrigation is the major user of water in South Africa and, with around 85 000 ha of sugarcane under irrigation, any increases in the efficiency of its water use is a matter of major interest to the sugar industry and to water resources managers. In this chapter on sugarcane : irrigation water relationships net irrigation demand, water use efficiency, incremental yield through irrigation and water losses through deep percolation and stormflow from irrigated fields are evaluated for the 127 Quaternary Catchments making up the so-called sugarcane belt. Consideration is given to influences of soil depth, harvest date and inter-seasonal climatic variability on irrigation water use and losses. Net irrigation requirement is found to vary markedly between wet and dry years while the incremental yield through irrigation is of the order of 7.5 - 9.0 t/ha/100 mm irrigation. Deep percolation and stormflow from irrigated sugarcane fields range from 40 mm to over 200 mm, with both highly influenced by a season's rainfall regime. In virtually all evaluations performed, the total irrigation water use as well as losses to deep percolation decrease as the cycle of irrigation increases from 7 to 14 to 21 days - a factor of great importance in demand water management of irrigated sugarcane.

CHAPTER 10 WHICH LAND USE UTILISES MORE WATER? A COMPARATIVE SENSITIVITYSTUDY OF HYDROLOGICAL RESPONSES TO CHANGES IN AREAS UNDER AFFORESTATION AND IRRIGATION IN THE PONGOLA-BIVANE CATCHMENT

V. Taylor and R.E. Schulze

(pp 192 - 202; 6 figures; 2 tables)

Abstract

Many conflicts surrounding an equitable allocation of water to competing users in a catchment revolve around the impacts which various forms of land use have on the distribution of water in time and space. This chapter addresses conflicts between water uses by commercial afforestation and sugarcane under irrigation in the Pongola-Bivane catchment in northern KwaZulu-Natal. The *ACRU* agrohydrological model is used in this sensitivity study to illustrate that these two land uses impact streamflows very differently and that hydrological responses are highly dependent on the *climatic regime*. For a relatively 'moist' and relatively 'dry' subcatchment (SC) within the Pongola-Bivane system it is shown by simulation modelling that afforestation water use by *Eucalyptus grandis* is markedly different for the macro-climates representing those two subcatchments. Furthermore, percentage reductions in low flows are shown to be less than those of mean annual flows in the moist SC, while being higher in the dry SC. For both SCs relative impacts in dry years are higher than in median years, and those, in turn, higher than in wet years for stormflows and baseflows. Reductions in streamflows by irrigation are significantly higher in the dry compared to the wet SC. The additional water use by irrigated sugarcane per hectare is 9 - 15 times that of afforestation, and this ratio increases for both drier (vs wetter) SCs as well as for drier (vs average or wet) seasons by a factor of up to 30. The study illustrates clearly that relative water use by competing sectors within agriculture is a complex issue which cannot be resolved with conceptually simplistic models.

CHAPTER 11 CAN ADDITIONAL STREAMFLOWS FROM CLEARING OF ALIEN INVASIVE VEGETATION IN RIPARIAN ZONES BE USED TO COMPENSATE FOR AFFORESTATION ELSEWHERE? A CASE STUDY FROM THE PONGOLA-BIVANE CATCHMENT

G.P.W. Jewitt, M.J.C. Horan, K.B. Meier and R.E. Schulze

(pp 203 - 220; 9 figures; 7 tables)

Abstract

There is a growing concern regarding the extent of uncontrolled invasion and infestation of alien vegetation in South Africa, particularly along the moister riparian areas of a catchment where seed dispersion and alien tree establishment conditions are optimal. This study set out to simulate the impact of alien invasive vegetation on median annual and mean four month low flows in the Pongola-Bivane catchment to assess scenarios of compensatory forestry, i.e. granting permits for commercial afforestation elsewhere in the catchment, where the additional water used by the forest would be compensated for by the reduction in water use by the removal of alien vegetation. In order to achieve the above objectives, the 20 subcatchments making up the Pongola-Bivane were each further delineated by land use into sub-subcatchments, of which one was the riparian zone, into which streamflows from other upstream subcatchments were routed, and out of which streamflows were routed downstream. The *ACRU* model was modified to account for any subsurface flows from upslope to feed into the riparian zone as influent flows, and also to account for the percentage of alien infestation of the riparian zone as well as the density of infested aliens. Hydrological responses were simulated for scenarios of current land use, of riparian zone invasive vegetation removed and replaced by a natural vegetation of grass, and of differences in water use by different percentages and densities of alien infestation vs water use when riparian zones were cleared. The potential for compensatory commercial afforestation was then calculated per subcatchment. It was found to range from 0% to 18 - 20%. The economic feasibility of compensatory forestry in the Pongola-Bivane was established. A net benefit analysis undertaken showed clear economic benefits of compensatory forestry for different scenarios.

CHAPTER 12 HOW DO SIMULATED SEDIMENT YIELDS VARY SPATIALLY AND TEMPORALLY UNDER DIFFERENT LAND USES AND STATES OF DEGRADATION OR REHABILITATION ? A CASE STUDY FROM THE MBULUZI CATCHMENT IN SWAZILAND

D. Dlamini and R.E. Schulze

(pp 221 - 232; 8 figures; 2 tables)

Abstract

Soil erosion is a serious concern in the Mbuluzi catchment in Swaziland, especially upstream of the Mnjoli Dam. Sediments deposited in reservoirs result in the reduction of their storage capacities. Besides scouring and washing away the topsoil which leads to the loss of crop production media, soil erosion and sediment transportation may have negative impacts on the availability and management of water resources.

Owing to the unavailability of any measured records of sediment loads of the streams in the Mbuluzi catchment which to analyse and from which to make generalisations regarding the spatial extent and magnitudes of sediments, the *ACRU* agrohydrological modelling system was used to simulate sediment yield for individual events on a day-by-day basis. The simulations were for hydrologically homogeneous individual subcatchments, of which 40 were delimited in the Mbuluzi, with each subcatchment further discretised into seven dominant land use classes which were assigned critical sediment yield attributes.

Simulation results indicate that the highest sediment yields (exceeding 20 $t.ha^{-1}annum^{-1}$) are generated in the upper middle section and the north eastern part of the catchment. These areas are occupied predominantly by rural communities who practice subsistence agriculture and communal grazing. A comparison of sediment yields simulated under different land uses shows that subsistence agriculture and communal rangelands, i.e. grasslands in poor hydrological condition, produce the highest and second highest sediment yields respectively, while land under forest and rehabilitated grasslands generate the lowest sediment yields. Through an assessment of impacts on present sediment yields of different possible land use changes, it was found that allowing land to be degraded to an overgrazed condition could lead to increases in subcatchment sediment yields by a factor of up to 20 times, while employing land rehabilitation and conservation measures solely by grazing management could result in the reduction of more than 50 % of present sediment yields in certain parts of the catchment.

SECTION C : LOOKING TOWARDS THE FUTURE

CHAPTER 13 APPLYING SEASONAL RAINFALL FORECASTS TO FORECASTING SUGARCANE YIELDS USING A MODELLING APPROACH : CAN IT BENEFIT THE SUGARCANE INDUSTRY?

T.G. Lumsden, R.E. Schulze, N.L. Lecler and E.J. Schmidt

(pp 233 - 249; 11 figures; 4 tables)

Abstract

The main objective of this study involved the development and evaluation of a sugarcane yield forecasting system for the Eston Mill Supply Area in the midlands of KwaZulu-Natal using yield simulation models and seasonal rainfall forecasts. Following a verification analysis, the daily time step *ACRU*-Thompson model was selected and used to generate sugarcane yield forecasts for a number of seasons, through the application of seasonal categorical rainfall forecasts in the model. The categorical rainfall forecasts were supplied by the South African Weather Service. These rainfall forecasts first had to be translated into daily rainfall values for input into the model. The modelled sugarcane yield forecasts were then evaluated against observed yields as well as against forecasts generated by more traditional methods, these methods being represented by the so-called Simple Rainfall Model (SRM) developed and used by the sugarcane industry and Mill Group Board (MGB) estimates for the Eston mill. The skill of the statistically based categorical seasonal rainfall forecasts was found to be disappointingly poor.

When comparing the *ACRU*-Thompson cane yield forecasts to those generated by the SRM, the former was found to be more consistent in the accuracy of its predictions over the various seasons considered. When *ACRU*-Thompson cane yield forecasts were compared to MGB forecasts, it was noted that the accuracy of the MGB forecasts improved relative to those of the *ACRU*-Thompson model only at a 4.5 month lead time, but were worse for longer lead times. This lead time is relatively short and would not allow a great deal of time for changes in major planning decisions. The *ACRU*-Thompson yield forecasts would thus offer a better alternative for longer lead time planning. When comparing *ACRU*-Thompson yield forecasts to the median yield for the Eston MSA, the modelled forecasts gave a better representation of the seasonal yield for those seasons which were more strongly influenced by ENSO events. As rainfall forecasts were found to generally be poor, the benefit of using the *ACRU*-Thompson model in these seasons must relate to the use of observed rainfall up to the time of forecast.

A simple cost-benefit analysis was conducted to assess whether economic benefits could be derived from the application of the various yield forecasting systems. The analysis indicated that the *ACRU*-Thompson system could potentially give rise to greater net economic benefits when compared to traditional forecasting methods (SRM, MGB). This cost-benefit analysis centred around improvements in forecast accuracies (and thus improvements in mill operating decisions) and the cost of implementing a yield forecasting system. There are potentially many other benefits and costs associated with yield forecasting, particularly at scales other than the Mill Supply Area, e.g. at farm and national scales.

CHAPTER 14 THE POTENTIAL THREAT OF SIGNIFICANT CHANGES TO HYDROLOGICAL RESPONSES IN SOUTHERN AFRICA AS A RESULT OF CLIMATE CHANGE: A THRESHOLD ANALYSIS ON WHEN THESE COULD OCCUR, AND WHERE THE VULNERABLE AREAS ARE

R.E. Schulze and L.A. Perks

(pp 250 - 258; 4 figures)

Abstract

In climate change studies, thresholds represent magnitudes of a response variable, e.g. runoff, to a change in driving variables, e.g. precipitation and temperature, at which that response becomes significantly different to its value under present climatic conditions. Threshold analyses were carried out using the *ACRU* hydrological modelling system to simulate where and at what point in time a significant change in mean annual runoff (MAR) and mean annual recharge of soil water into the vadose zone could be expected to occur in southern Africa. 'Significant', in this study, is defined as a + or - 10% change from present mean annual values. Temperature and precipitation output for a future climate scenario represented by an effective doubling of atmospheric carbon dioxide was obtained from the 1998 version of the Hadley Centre's General Circulation Model (GCM) which excluded sulphate forcing, *viz*. the HadCM2-S GCM. The threshold analyses allowed the identification of areas where changes exceeding + or - 10% in mean annual runoff and recharge into the vadose zone could occur either sooner, or later, than in other areas, giving an indication of the potential vulnerability of regions in southern Africa to climate change.

The chapter describes the derivation, from GCMs, of precipitation and temperature changes associated with a climate change scenario represented by an effective doubling of atmospheric CO_2 concentrations, their downscaling to Quaternary Catchment scale, the methodology of applying a threshold analysis to a climate change scenario and results obtained with the HadCM2-S GCM. Results indicate for the case of a 10% decrease in MAR that this could occur in the western third of South Africa by 2015 already, and progressively later as one moves eastwards. This finding, together with results from a sensitivity study of changes in MAR to changes in individual climate change driving variables (Chapter 6), indicates that the Western Cape Province appears to be the most vulnerable region in South Africa to hydrological impacts of climate change.

3. ACKNOWLEDGEMENTS

a) Contributing authors

This project could only be undertaken with input from a number of colleagues and collaborators, but especially with the contributions of several graduate students, many of whom have subsequently already made their mark in South African hydrology. The inputs of Mark Horan (Chapters 5, 8, 9, 11), Kevin Meier (Chapters 5, 7, 11), Jeff Smithers (Chapters 3, 11), Andrew Pike (Chapters 5, 7), Valerie Taylor (Chapters 5, 10), Trevor Lumsden (Chapters 9, 13), Graham Jewitt (Chapter 11), Dennis Dlamini (Chapter 12), Lucille Perks (Chapter 14), Neil Lecler (Chapter 13), Mark Summerton (Chapter 7), Steven Lynch (Chapter 7), Erik Schmidt (Chapter 13) and Cynthia O'Mahoney (preparation of document) are acknowledged with appreciation.

b) Collaboration with external organisations

The acknowledgements at the ends of the various chapters bear testimony to the collaboration which this project enjoyed with various organisations for its successful completion.

- Thus, in chapter sequence, case studies were undertaken collaboratively with, or with co-funding from, Umgeni Water (Chapter 4), the Forest Industries Association (Chapters 4, 10), the Department of Water Affairs and Forestry, DWAF (Chapters 4, 11), the National Research Foundation (Chapters 6, 14), the United States Country Studies for Climate Change Program

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c) Project Steering Committee

The following members of the Project Steering Committee, who participated actively at meetings, are thanked for their encouragement:

Mr H. Maaren	Water Research Commission (Chair), Deceased 2002
Dr G.R. Backeberg	Water Research Commission
Mr A.H. Conley	Department of Water Affairs & Forestry
Prof P.J. Ashton	CSIR
Dr L. Randall	Umgeni Water
Prof P.W.L. Lyne	University of Natal
Dr R.M.B. Auerbach	Farmers' Support Group

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Mr H. Maaren	Water Research Commission
Prof P.J.T. Roberts	Forestry Consultant
Prof D.A. Hughes	Rhodes University
Dr A. Singels	SA Sugar Association Experiment Station

4. CAPACITY BUILDING

Research undertaken under the auspices of this WRC project resulted in PhDs being awarded to Lucille Perks and Dorothe Herpertz while Neil Lecler's doctorate is to be completed in 2004. Kevin Meier was awarded his MSc Engineering degree and Valerie Taylor (*cum laude*), Trevor Lumsden (*cum laude*), Dennis Dlamini, Mark Summerton and Jason Hallowes attained MSc degrees in Hydrology - all working on facets of research within this project. One further masters degree in Hydrology, by Andrew Pott, is pending. Important new skills were acquired by WRC funded staff engaged in the execution of this project, *viz*. Steven Lynch, Andrew Pike, Manju Maharaj and Mark Horan. Furthermore, Honours, 3rd and 2nd year students in Hydrology as well as final year Agricultural Engineering students, in classes made up of 30 - 70% students from disadvantaged backgrounds, benefited from lectures in hydrological modelling, integrated water resources management, land use impacts, GIS and hydrological risk management by staff engaged in this project.

5. RECOMMENDATIONS FOR FURTHER RESEARCH

Results from this project have brought to attention numerous issues which require further research in order to operationalise Integrated Water Resources Management and put into practice various facets of the National Water Act of 1998 at the level of Catchment Management Agencies. These include:

- *Enhancements to the ACRU model* to facilitate realistic and deterministically based daily time step simulations of critical elements of contention and potential conflict emanating from the both land and channel components of the catchment, e.g.
  - riparian zone processes
  - hillslope hydrological processes
  - land management processes
  - water quality determinants (N, P, salinity)
  - channel transmission losses and
  - irrigation routines, by imbedding the CROPWAT and WAPWAT routines, which are now industry standards;
- *Enhancements to model decision support tools* to facilitate multi-scale simulations to be undertaken anywhere in South Africa, e.g. enhancements to
  - the national hydrological soils database and decision support tool AUTOSOIL to enable soil parameters to be mapped and used to terrain unit level
  - the baseline land cover hydrological attributes
  - the National Land Cover hydrological attributes
  - the interlinked Quaternary Catchments (and finer resolution) database for South Africa, Lesotho and Swaziland and
  - rainfall and other climatic data.
- *Development of installed hydrological modelling systems* for Catchment Management Agencies, based on the enhancements discussed above, but including also information on reservoirs, return flows, inter-basin transfers, environmental flow requirements, risk management, irrigation supply and demand as well as the human reserve (and hence populating the databases with demographic data);
- *Development of near real-time to seasonal translation of climate forecasts to hydrological forecasts*, through an ensemble of 1-day to 3-, 7-, 14- and 28-day as well as 3- to 6-month forecasts of streamflow and reservoir levels for improved and pro-active operational decisions to be made; and
- *Assessing mitigation and adaption options related to climate change impacts on hydrological responses*.

To those ends it is hoped that further support from the WRC will be forthcoming.

R.E. Schulze
April 2002

Ch00ExecSumm

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CHAPTER 1

WHAT IS INTEGRATED WATER RESOURCES MANAGEMENT? A PERSPECTIVE

R.E. Schulze

School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

ABSTRACT

The ecosystem which has been inherited from past actions is a 'damaged' one, to which Integrated Water Resources Management (IWRM) is one response. IWRM is defined and placed within the broader perspective of integrated catchment management, of which it is a subset. The major goals and strategies of IWRM are condensed into six approaches, *viz*. the systems approach, as well as the integrated, management, stakeholder, partnership and sustainability approaches. Reasons are advanced as to why the river basin is the scale on which IWRM is carried out, including that it is the scale at which attributes typical of small and large hydrological scales merge, at which anthropogenic processes shape hydrological processes, at which action and management occur, at which attempts are made to right previous wrongs and at which models become operational tools as aids in decision making. Advantages and disadvantages of the catchment as the 'ideal' unit for IWRM are assessed before discussing the range of temporal and spatial scale issues which need to be considered in IWRM. A major focus then falls on the different characteristics of developed countries and lesser developed countries (LDCs) which shape their respective needs for IWRM, highlighting problems of IWRM in LDCs. Preconditions for effective and efficient IWRM are evaluated, as are the main barriers of success of IWRM. The chapter concludes by reiterating that it remains an ambiguity that most stakeholders relate well to the concepts of IWRM, but that it cannot easily be translated into operational terms.

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1.1 WHAT IS THE STATUS OF THE CATCHMENTS WE HAVE INHERITED?

Up until a few decades, indeed in cases only a few years, ago the conventional approaches in most parts of the world to water and its utilisation were essentially

- simplistic, largely because of an inheritance of ideas and practices from small populations, limited human activities and any waste produced being effectively evacuated by rivers without long term/significant damage to water quality downstream; later it was
- one of conquer, develop land and water and, when a problem was created, of migration; still later, one of
- applying technologies such as dam building or inter-catchment transfers to manage adequate supplies of water for society's and agriculture's needs; and even
- solving water quality problems by chemical treatment downstream of waste production rather than upstream at source (Falkenmark *et al*., 1999).

What we have inherited as a consequence, is a 'damaged' ecosystem (Newson *et al*., 2000), as illustrated in Figure 1.1, in which

- spontaneous regulatory functions of rivers and their catchment areas have been disturbed (e.g. through deforestation or increased erosion or dam construction), or removed (e.g. by draining of wetlands), thereby causing changes of state of the hydrological system;
- while the manner of exploiting water, and the land from which it is generated, has changed through
  - intensification of water use (e.g. by irrigation, dryland cropping, urbanisation) on the one hand, and on the other
  - destruction of traditional extensive exploitation (e.g. by marginalisation of more traditional land use systems and exploitation of marginal lands),

  both signifying impacts on human systems.

Examples of the above include that 61% of the UK's agricultural land is now drained, urban areas in England grew by 58% from 1945 -1990, that 66% of channels in England and Wales have been profoundly modified and 83% of river channels are maintained regularly (Newson *et al*., 2000).

1.2 HOW HAVE WE RESPONDED TO THIS CATCHMENT INHERITANCE?

Responses to the 'damaged' catchment ecosystem we have inherited can be through

- *reactive responses*, for example, by making recommendations for precautionary actions (e.g. Newson, 1997) or by promoting rehabilitation of clearly damaged elements of the system; alternatively, through
- *proactive responses*, in seeking to prevent the destructive causes and adopting a "least regrets" approach in water management by conserving the natural capital of the broader land/water environment through integrated water resources management, IWRM (Newson *et al*., 2000).

Turning points in contemporary thinking on IWRM, and its more enveloping umbrella concept of integrated catchment management (ICM), and giving legitimacy to both of them, were probably the six years 1987-1992 (Newson *et al*., 2000), commencing with the so-called Brundtland Report on "Our Common Future" (WCED, 1987) which gave definition to *sustainable development* as

> *"development that meets the needs of the present without compromising the ability of future generations to meet their needs"*

and followed by the Dublin Conference on Water and the Environment (ICWE, 1992) in which a key statement was

> *"since water sustains all life, effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems"*

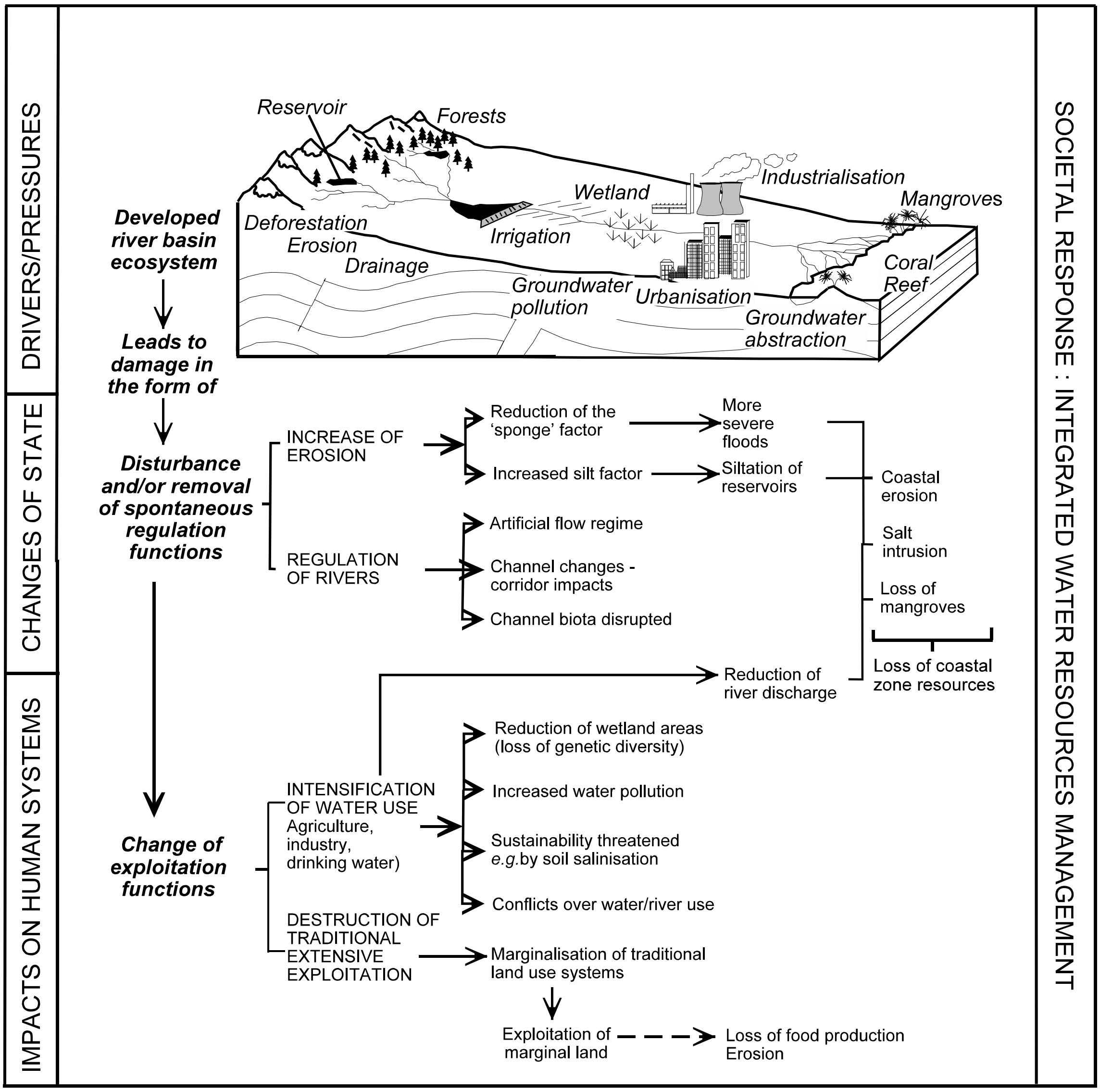

Figure 1.1 The 'damaged' catchment ecosystem, resulting in IWRM as the societal response (after Marchand and Toornstra, 1986; Newson, 1997 and with modifications by Meybeck, 2001)

and, in turn, by the 1992 UNCED Rio de Janeiro Conference (Johnson, 1993) in which Chapter 18.8 of Agenda 21 pronounced that

> *"in developing and using water resources, priority has to be given to the satisfaction of basic needs and safeguarding of ecosystems".*

Legislative responses to the above have included, for example, South Africa's new National Water Act (NWA, 1998), in which the preamble recognises

> *"the need for the integrated management of all aspects of water resources and, where appropriate, the delegation of management functions to a regional or catchment level so as to enable everyone to participate".*

By implication, the definitions and statements above have already circumscribed the spirit of IWRM. What follow are more detailed evaluations on a selection of relevant questions on IWRM, particularly when applied to catchments at the river basin scale of 10^1 - 10^5 km^2, *viz*.

- what is IWRM?
- is the river basin, indeed, the ideal unit for IWRM?
- what is the role of hydrology and hydrologists in IWRM?
- at which scale(s) should IWRM be enacted?
- what problems of IWRM occur in lesser developed countries compared with those in developed countries?
- what makes for successful IWRM? and
- what are perceived barriers to successful IWRM?

The ensuing discourse is not intended as a comprehensive overview of IWRM, as many important issues such as stakeholder participation, the "soft" and "hard" tools needed to drive effective IWRM or legislative and administrative aspects are beyond the scope of this project, and hence this chapter. It may be argued that there is no purely objective view of IWRM. This chapter, therefore, presents one perspective on IWRM, influenced to an extent by personal experiences.

1.3 WHAT IS INTEGRATED WATER RESOURCES MANAGEMENT?

a) How can IWRM be defined and what is its relationship with Integrated Catchment Management?

Of the plethora of definitions of IWRM which abound in the literature, three are given below, *viz*.

- IWRM is the co-ordinated planning and management of land, water and other environmental resources for their equitable, efficient and sustainable use (from the UK; Calder, 1998);
- IWRM is a framework for planning, organising and controlling water systems to balance all relevant views and goals of stakeholders (from the USA; Grigg, 1999); and
- IWRM is a philosophy, a process and a management strategy to achieve sustainable use of resources by all stakeholders at catchment, regional, national and international levels, while maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits (from South Africa; DWAF, 1998).

Implicitly or explicitly these definitions place IWRM beyond being simply the management of water quantity and quality, or a catchment manager's 'wish list', while simultaneously it is not as overarching and broad a socio-economic nor politico-institutional concept as ICM, which UNESCO (1993) defines as

> *"the process of formulating and implementing a course of action involving natural and human resources in a catchment, taking into account social, economic, political and institutional factors operating within the catchment and the surrounding river basins to achieve specific social objectives"*

and to which may be added the second part of DWAF's (1998) conceptualisation of ICM, *viz*.

> *". . . to achieve a sustainable balance between utilization and protection of all environmental resources in a catchment, and to grow a sustainable society through stakeholder, community and government partnerships in the management process".*

IWRM is thus a vital, albeit incomplete, subset of ICM particularly if socio-political aspects do not receive the same emphasis as biophysical factors in management scenarios (Schulze, 1999). Diagrammatically, IWRM may be placed into a context of varying levels of management complexity and levels of integration needed, as conceptualised by Ashton (2000) in Figure 1.2.

b) What approaches embody the major goals and strategies of IWRM?

Of the many approaches that have been proposed, six are viewed as embodying the major goals and strategies of IWRM (DWAF, 1996; DWAF, 1998; Calder, 1999; Schulze, 1999; Ashton, 2000; Frost, 2001; Schulze, 2001). They are as follows:

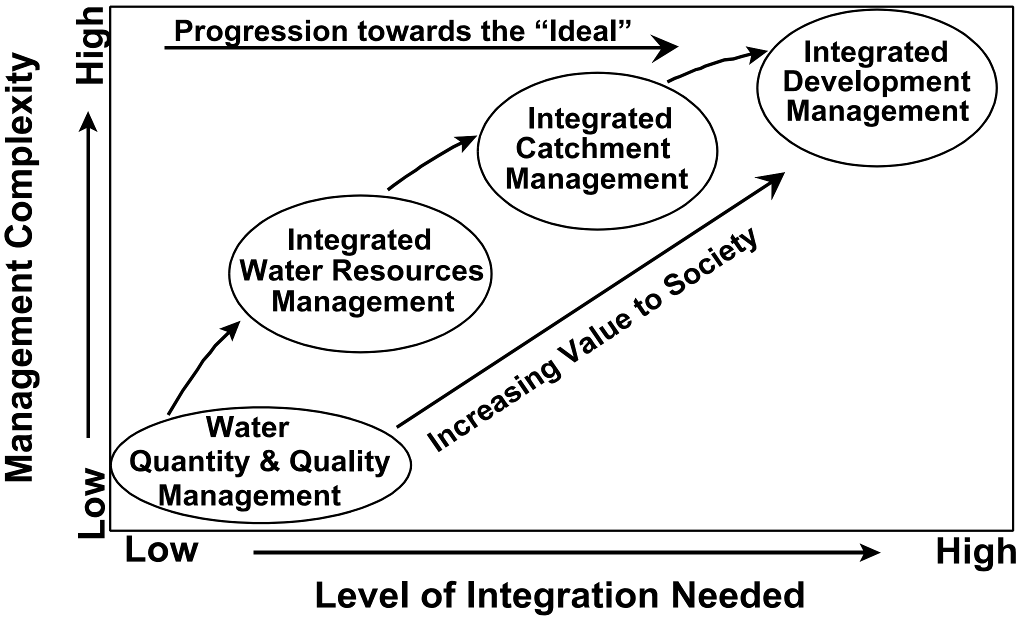

Figure 1.2 The relationship of IWRM and ICM and their value to society to the level of management complexity and level of integration needed (after Ashton, 2000)

- *A Systems Approach*, i.e.
  - recognising individual components, as well as linkages between them, and addressing the needs of both human and natural systems (DWAF, 1996)
  - recognising water and land management at *local* catchment level to be mutually dependent, then enabling and ensuring an *upward integration* of strategic water management at scales beyond those of the local catchments, i.e. scaling up from local to larger catchments
  - seeking solutions by an incrementally evolving and iterative process rather than by attaining one optimal solution
  - using a blend of 'soft system' tools focusing on the human dimension, together with 'hard system' methodologies such as models and their decision support systems (Calder, 1999; Schulze, 1999) and
  - recognising that solutions should focus on underlying causes and not merely their symptoms.
- *An Integrated Approach*
  - Integration implies 'joined-up', 'together', 'holistic' and 'with integrity' (Schulze, 1999) and, in IWRM, beyond being only "comprehensive" (DWAF, 1998)
  - with integration of the various sectors and components of
    - the biophysical system of climate, land and water, together with the
    - socio-political system of equitable allocation needs and institutional management, together with the
    - anthropogenic system of land use (and misuse) with its characteristics of hydrological intensification and extensification, together with the
    - engineered system of dams, sewage works or inter-catchment water transfers, together with the
    - aquatic system with its variable instream flow requirements

    that are considered by the stakeholders to be significant and relevant key issues of concern to the set of IWRM objectives of the area under consideration.
  - While integration is not achieved easily where social, political, administrative and natural boundaries do not coincide (which is usually the case), two types of integration are required (Jewitt and Görgens, 2000; Frost, 2001). The first is
  - *horizontal integration*, which takes place within the same hierarchical level, where that level can be at macro-scale or micro-scale, and where integration could be

- either between nations sharing a river, or
- between different water use sectors within the same river basin such as domestic vs industrial vs agricultural vs environmental, or
- between upstream vs downstream users, or
- between activities of adjacent land uses/users within a catchment,

and the second is

- *vertical integration*, where collaboration/co-ordination crosses a range of political, legislative or management sectors; alternatively of modelling systems or components of a natural system (such as river basins or aquatic ecology) which function at different vertical scales within the same sector (Figure 1.3).

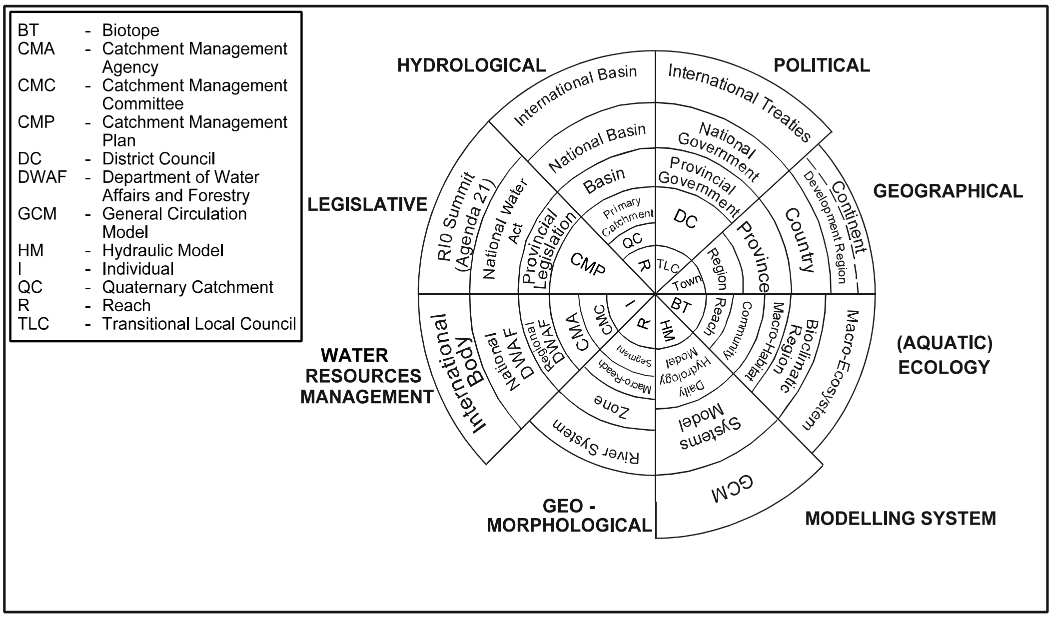

Figure 1.3 Examples of vertical and horizontal integration, taken from an IWRM approach in the Kruger National Park, South Africa (after Jewitt and Görgens, 2000; modified by Schulze, 2001)

- *A Management Approach*
  - In more generic IWRM terms management implies
    - maximising use of resources
    - minimising consequences of the above over the long term
    - even reversing the consequences of previously damaged systems by catchment rehabilitation and renaturalisation of stream/riparian zone systems
    - seeking the well-being and enhancing the quality of life of the inhabitants within the area of study and
    - seeking equitable solutions which must be fair and just to all concerned (Schulze, 1999).
  - Management must be seen to recognise the intrinsic value and importance of water and not merely its availability to satisfy economic needs.
  - In more pragmatic terms, management in IWRM includes
    - land and water to be managed together, for every land use decision becomes a water resources decision (Falkenmark *et al*., 1999)
    - water to be managed at the *lowest* appropriate level using a bottom-up, rather than a top-down, approach
    - water allocation to take account of all affected stakeholders, including the often non-vocal poor and the environment
    - that water should be recognised as an economic good and
    - that the principles of demand management be applied, with appropriate pricing policies, to encourage efficient usage of water between competing sectors such as domestic, agriculture, industry and the environment.

- *A Stakeholder Approach*
  This approach recognises the importance of the involvement of individuals, landowners and government agencies, in a participatory process where all decisions around the management and sustainable use of land and water resources are made.
- *A Partnership Approach*
  - This emphasises common objectives as well as defining the collective rules, responsibilities and accountabilities of every individual who, and every water use and administrative agency which, participates in the process of decision making on use and management of land and water resources at all levels, down to that of the village and even the individual household (DWAF, 1996; Calder, 1999).
  - It thus reflects a commitment to the principle of stewardship at all levels of management (Ashton, 2000).
- *A Balanced, Sustainable Approach*
  - With IWRM being a balanced approach, close attention needs to be given to decisions designed to achieve a sustainable blend, or compromise, between long term and viable economic development for all the catchments' dependants (local, national and international), equitable access of water resources to them and protection of resource integrity (DWAF, 1996; Calder, 1999).
  - As such, a balanced approach attempts to optimise the relationship between the capacity of available resources to provide sustainable services (e.g. water of a given quantity and quality - a basic human need) and utilisation of the resource, including consumptive water uses such as agricultural or industrial, and non-consumptive water uses such as environmental requirements, as well as waste disposal (Ashton, 2000).
  - Sustainability, it should be noted from the above, is not to be confused with zero growth (Ashton, 2000).
  - The relationship illustrated in Figure 1.4 shows that while sustainable resource utilisation requires a high level of resource management, it is also highly vulnerable to degradation.

1.4 WHY THE CATCHMENT SCALE FOR I.W.R.M.?

What sets apart the catchment, i.e. river basin scale of 10^1 - 10^5 km^2, from other hydrological scales are six characteristics.

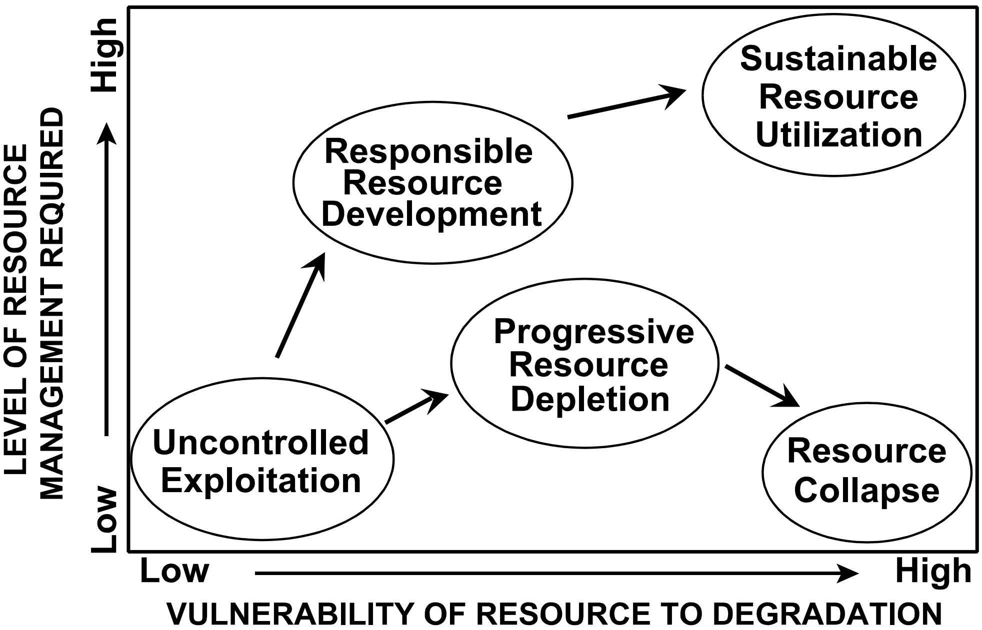

Figure 1.4 The relationship between sustainable resource utilisation in terms of the level of resource management required and the vulnerability of the resource to degradation (after Ashton, 2000)

a) First, it is the scale at which attributes typical of small and large hydrological scales merge

This is the scale at which all three of vertical, lateral and horizontal water movements attain more or less equal importance, as against the smaller hydrological scales of (say) hillslopes, where vertical and, to a degree, lateral fluxes often dominate (e.g. precipitation, infiltration, interflow), while at the larger subcontinental to global scales the horizontal movement of water and material are emphasised. Furthermore, in hydroclimatic up- and downscaling, the catchment may be viewed as the meeting point of spatial upscaling (which takes place from point hydrological measurements through experimental plot and research catchment scale process studies, which are then upscaled to try and explain what happens in a heterogeneous river basin) and climatic downscaling (from large scale synoptic situations superimposed upon regional climates both of which are, in turn, influenced by local physiographic features such as mountain ranges, and which provide the distributed climatic input variables required by catchment level hydrological models).

b) Secondly, it is that scale at which fundamental regional differences in hydrological responses attain importance

In explaining differences in hydrological responses over space and time, researchers and operators alike working at the catchment scale have to make clear distinctions about the processes by which rainfall is partitioned into different runoff components (e.g. stormflow, baseflow, snowmelt) under different climatic and/or physiographic regimes. They need to distinguish between those runoff generating processes in the river basin which vary in their dominance, for example, at high vs low altitudes, high vs low latitudes, flat vs mountainous terrain or humid vs arid catchments, in order to also dispel what Falkenmark *et al*. (1999) term ‘temperate zone imperialism’, i.e. assuming that the way in which dominant hydrological processes are represented in temperate zones may be transferred readily to other parts of the world in model algorithms.

c) Thirdly, it is the scale at which anthropogenic pressures reshape hydrological responses

The catchment is the scale at which massive manipulation of the land- and waterscapes have become evident to support a given population’s four ‘f’s, *viz.* food, fibre, fodder and fuel (Falkenmark *et al*., 1999; Schulze, 2001). Development on the catchment includes urbanisation (both formal and of the informal shack type without proper services), intensification of agriculture (and associated pesticide/herbicide problems), extensification of agriculture (into climatically marginal areas, and including deforestation and overgrazing), or mining, all of which alter water quantity, its seasonal distribution and water quality. More direct water engineering includes dam construction (and associated changes to downstream flows of water and matter), inter-basin water transfers, major groundwater abstractions, land/wetland drainage, irrigation and in-channel modifications (e.g. dredging, canalisation). Through these multiple alterations to the natural hydrological system and its states, with often several forms of alteration within a single river basin, the many individual process changes have become intermingled and/or diluted downstream through the patchwork of landscape changes. This has occurred to the extent that it often becomes difficult to isolate individual causes of hydrological change or to lay individual blame on the impacts.

d) Fourthly, it has become the scale of action and management

The catchment is the ‘action scale’ (Falkenmark *et al*., 1999) in which coping mechanisms have to be developed in regard to water issues. These are related to both natural phenomena, where impacts of floods and droughts have to be dealt with, as well as to human induced hydrological phenomena, such as pollution or the amplifications of effects of floods and droughts which, even more so, have to be coped with.

Because it is the action scale at which there is simultaneously a demand for public water supply, public sanitation, reduced flood risk, cheap hydropower or secure food supplies (e.g. through irrigation), the river basin has also become the ‘management scale’. It is at this scale that politicians make decisions on water and that policy, together with research and management, have to adapt to ensure that development of water is carried out in an environmentally sustainable manner by balancing the direct needs of people - often short term - with the indirect needs of a healthy environment - often longer term (Acreman, 2000). Because there is a continuum of water users throughout the catchment, this is the scale where upstream actions can have either positive or negative impacts on, or cause conflict with, downstream users. Furthermore, with competition between user sectors for a finite amount of water and the quest for an equitable allocation of this resource to people, environment and development, multipurpose integrated water resources management (IWRM) becomes a major objective within catchments. In essence the river basin scale is where 'real people/communities with real land use and water decisions have to operate on real catchments' (Schulze, 1999) and where the issues of stakeholder meet the issues of water policy makers.

Because this is the scale at which problems have their origin in planned human activities, but often with limited (or even erroneous) understanding of linkages between water, land and vegetation, it is also the scale at which many of these problems could be avoidable provided driving forces were correctly identified and understood (Falkenmark *et al.*, 1999) and the scale at which scientists as well as managers and policy makers appreciated more fully the interrelationships and feedbacks of the DPSIR (i.e. **D**riving forces, **P**ressures, **S**tates, **I**mpacts and **R**esponses) approach (cf. Chapter 2; Table 2.1).

e) Fifthly, it is the scale at which attempts are made to right previous wrongs

It is within river basins that concepts such as channel restoration, wetland rehabilitation and ecological integrity are being enacted. The river basin is thus the scale at which biotic/abiotic links are researched and at which controlled floods are used as a management tool to mimic more closely pristine catchment flows in order to sustain aquatic habitats (Jewitt and Görgens, 2000).

f) Sixthly, it is the scale at which hydrological models become operational tools as aids in decision-making

Hydrologists develop and/or apply models through the range of scales from point to global (Schulze, 2000). At smaller research catchment levels, insights into micro- and meso-scale understanding of processes are usually the focus, while at continental to global levels earth system scale interlinkages and feedbacks are now being understood more fully than in the past. At neither these dipolar scales are major operational decisions made, however. The catchment, on the other hand, uses hydrological simulation models to aid in design and sizing of hydraulic structures, forecasts of high or low flows, water quality implications or sediment delivery into reservoirs, often using the scenario approach to attempt to answer 'what if' questions to actual (real life) water resources planning, design and operating problems, as well as to evaluating alternative and mitigating options. It is at the catchment scale that hydrological models thus become part of the water manager's armoury of decision support tools (cf. Chapter 2).

1.5 IS THE CATCHMENT THE IDEAL UNIT FOR I.W.R.M.?

a) What are the indicators of catchment consciousness?

From both socio-economic and hydrological perspectives, a catchment represents a complexity of social, economic, jurisdictional and political relationships. These relationships are of two types (Falkenmark *et al.*, 1999), *viz*.

- *intra-catchment*, i.e. the upstream:downstream relation with conflicts between downstream countries (in the case of international rivers) and downstream users who are impacted upon by upstream activities, and
- *inter-catchment* relations, which represent local, regional, national and international levels which have to co-operate administratively.

The catchment has been promoted and advocated as a basic, appropriate and ideal spatial unit by many prominent experts and international fora (Newson *et al.*, 2000) to

- organise human activity for regional planning (Smith, 1969)
- integrate patterns and processes of both natural and social systems (Young *et al.*, 1994), but particularly to
- integrate ecosystems-based land, environment and water resources management related aspects (Agenda 21; Johnson, 1993; Falkenmark, 1997; UNECE, 1999), with catchments being in the forefront, internationally, in moving towards being operational, environmentally meaningful management units (Newson *et al.*, 2000).

Newson *et al*. (2000) list numerous indicators of 'catchment consciousness' in science, society and policy making, for example in

- *Hydrology*, with the identification of hydrological and environmental capacities and the impacts of critical land use/development on water by catchment scale research;
- *Hydraulic Engineering*, focusing on imaginative use of technology to assist in water management on a catchment basis, e.g. leakage control, control of water pollution at source, recycling;
- *Economics*, through use of resource and environmental economics to assess new water schemes, pricing of water, water as a tradeable commodity or economic demand management - all at the catchment scale;
- *Society*, through a rise in public awareness of water issues within catchments; stakeholder involvement in decision making; checks and balances on development and land use change with respect to the water environment and current hydrological capacities; and
- *New Policy Frameworks* which use the catchment as a basic unit (e.g. Agenda 21) and including integrated water resources management strategies firmly entrenched in revisions to water laws (e.g. South Africa's National Water Act of 1998), with built-in legal structures for concepts such as Catchment Management Agencies and Catchment Committees (NWA, 1998).

b) What are the advantages of the catchment as a management unit?

The above factors already make for compelling practical, socio-economic and policy-based arguments in favour of using the catchment as the spatial management unit in IWRM. Other advantages (Schulze, 1999) include the following:

- it is a topographically clearly bounded unit within which to study inputs and outputs of the water-related biophysical system, particularly if the focus is on surface water and water quality;
- it is therefore a natural 'integrator' of interdependent water issues such as water supply, flood control and water quality (sediment, chemical and biological pollution production) as well as being a natural unit for river navigation; and
- the catchment may be hierarchically subdivided into modular, relatively homogeneous and hydrologically cascading sub-units in cases when issues of strong local interest prevail, or where the catchment is physiographically or socio-economically complex/diverse, or where a sub-unit adequately addresses particular stakeholder needs.

As a visible physical domain, a catchment as a management entity intuitively 'feels right', and is a sensible unit to use for stakeholders.

c) What are the disadvantages of the catchment as a management unit?

- Even in terms of water, however, a management unit may encompass an area of more than one contiguous and topographically defined catchment, particularly where
  - inter-basin transfers of water take place, or
  - groundwater is a major component of usable water, when major aquifers may not coincide with surface water catchments (Schulze, 1999).
- Administrative units of countries, provinces or local authorities within which decision-making is generally effected, seldom follow natural catchment boundaries;
  - indeed, the river itself is often the political boundary and thus acts as a management divide rather than an integrator;
  - alternatively, the catchment may straddle a number of countries, with complex international water security issues at stake as well as complex cultural historical backgrounds, with countries possibly at different levels of development or covering major hydroclimatic regions (Schulze, 1999; Newson *et al*., 2000).
- Furthermore, neither the
  - social world of different tribes or ethnic/linguistic groupings, nor the
  - economic world of different levels of development, regional collaboration, trade, industry or capital flows straddle natural catchment boundaries.
- Major regional problems such as air pollution or potential impacts of climate change are determined by factors beyond the natural catchment.
- 'Natural' regions, e.g. of agricultural production, are often defined by climatic, physiographic or

edaphic boundaries which do not coincide with the water catchment.

d) What are the alternatives to the catchment as a management unit?

Many alternatives to the catchment, or 'water-shed', as a management unit have, therefore, been suggested. These include

- resource-sheds
- opportunity-sheds or
- econo-sheds
- community-sheds.

Despite the catchment's socio/political/economic disadvantages, the importance of water is such that the catchment remains a viable management unit.

1.6 AT WHAT SCALE(S) SHOULD I.W.R.M. BE CARRIED OUT?

a) General

- Catchment processes take place at a range of spatial and temporal scales, as do land use practices, socio-economic processes and levels of governance. The scale at which water related integrated management should take place is, therefore, not one with a straightforward answer (Frost, 2001).
- As a general statement, however, the appropriate temporal and spatial scales of operation in IWRM are those scales at which the policy makers, catchment managers and stakeholders of an IWRM plan believe that they can achieve their set(s) of objectives, depending on the problem(s) at hand (Schulze, 1999).
- This will depend on the life expectancy of a planning or management option, or the time it takes for such a plan to become operational.
- In turn, this will be defined, *inter alia*, by
  - how effectively an area can be managed
  - what level of development previously had been attained in the area of interest
  - the homogeneity of the catchment i.t.o.
    - ° biophysical resources (water, agriculture)
    - ° human resources
    - ° wealth and
    - ° ease of communication with stakeholders
  - all of which will be influenced by constraints of politics, finances and bureaucracy (Schulze, 1999).
- Within an overarching 'scale of operation' an IWRM plan will, therefore, be imbedded a hierarchy of intermediate and internal smaller space and shorter time scales, to define interim stages of implementation, or goals or milestones (Schulze, 1999).
- Each catchment manager should thus work within a logical framework of scales, which need to range up and down, because the physical and social systems dealt with in IWRM are not bounded.
- One cannot, therefore, in IWRM be too prescriptive i.t.o. ideal scale(s), minimum scale(s) or maximum scale(s) (Schulze, 1999).

b) Are there spatial scale considerations in IWRM?

- IWRM has to take cognisance of all, or some, of
  - global scale issues, e.g. water conventions, climate change, El Niño-Southern Oscillation (ENSO) scale events
  - international scale problems, e.g. international rivers
  - national issues, e.g. national water management agendas
  - catchment scale issues
  - local government scale initiatives
  - community scale issues
  - household scale problems, e.g. in poorer countries these include household food security and/or household water poverty.
- Spatial scale issues in IWRM often reflect the level of development of a country, e.g. in poorer countries or poorer regions within a country, the space scale tends to be much smaller, determined by factors such as the distance range at which one can mobilise communities, or land

availability around a village or access to local water sources (Schulze, 1999).

- The larger the spatial scale the more difficult management becomes, according to Frost's (2001) observations in rural Africa, i.t.o.
  - the range of resources available
  - the number and diversity of stakeholders, who have
    - different skills,
    - different interests,
    - different resource endowments, as well as
    - different capacities for management,
  - implying that agreement/consensus is not easy, and
  - plans of action become more complex and time-consuming.
- When focussing at too *broad a scale*,
  - it is often impossible to keep in view the 'fine grained variation' embodied in all the various processes and
  - there is a risk of overlooking local features, needs, circumstances, and/or aspirations, especially of the poor within the catchment (again from Frost, 2001; working in Africa).
- On the other hand, when focussing on too *fine* a *scale*, there is a danger of
  - losing sight of the wider context of IWRM and
  - losing sight of the overall governing processes of IWRM (Frost, 2001).

c) What are the temporal scale considerations in IWRM?

- From the aforegoing discussions on scale in IWRM it is clear that time scales in IWRM should not be viewed as static, but rather as a hierarchy of overlapping scales (Schulze, 1999).
- A number of types of time scales are identified and need to be considered in juxtaposition with one another in IWRM (Schulze, 1999). These include
  - *climate scales* at intra-seasonal, inter-seasonal and decadal (re. climate change) time frames, which 'drive'
  - *river flow scales*, which for
    - surface water issues range from high flow/drought 'cycles' related to ENSO at multiple year scales; and the inter-seasonal variability associated with that; the seasonality and concentration of streamflows within a year; intra-annual variability; the forecastability of river flows up to a season ahead; and studies on extremes such as floods; while for
    - groundwater the temporal recharge patterns and water table fluctuation are of importance
  - *ecological time scales*, which are determined by magnitudes, frequencies and durations of low and high flows as biological triggers
  - *agricultural time scales*, where for
    - crops, the intra- and inter-seasonal timeframes are important whereas for
    - forestry, inter-seasonal to decadal timeframes are of greater significance
  - *economic time scales*, ranging from longer term international to national, regional to local to shorter term individual rural subsistence household time scales
  - *political time scales*, which need to distinguish between
    - essentially stable government structures vs
    - potentially unstable government structures and
    - inter-election time scales for national to local governance structures
  - *management and planning time scales*, often of the order of 10-20 years and
  - *wealth/development level time scales*, where wealthy countries tend to have longer term planning horizons while for poorer countries they tend to be shorter (Schulze, 1999).

In summary, it needs re-emphasising that the scale at which IWRM is best initiated is the scale at which people are impacting on land and water resources. Thus, in Europe when the Rhine is impacted, large spatial scale IWRM is the order of the day while in South Africa, the mainstem Thukela River's waters *per se* are barely impacted by anthropogenic activities, but some of its individual tributaries may be severely affected, and hence effective IWRM generally takes place at smaller spatial scales with shorter time horizons.

1.7 IS I.W.R.M. IN LESSER DEVELOPED COUNTRIES (LDCs) DIFFERENT TO THAT IN DEVELOPED COUNTRIES (DCs)?

a) What are the characteristics of DCs and LDCs which shape their needs in IWRM?

These are summarised in Table 1.1.

b) How do consequent needs of IWRM therefore differ between DCs and LDCs?

Because of the high levels of expectation of IWRM in developed countries, a pro-active perspective and a generally non-life-threatening environment and infrastructure, IWRM there can focus more on quality of life and environment as well as long-term issues, which include (Schulze, 1999)

- preservation of the environment, with a focus on aquatic ecosystems
- the re-naturalisation and rehabilitation of the catchment and its receiving streams
- water quality related matters
- demand management of water and
- potential impacts of climate change on water resources.

As a consequence of poorer infrastructure in lesser developed countries, higher vulnerability to natural events and often being in survival mode, IWRM there frequently has to address more immediate issues (Schulze, 1999) such as

- creating basic water supplies (vs water of the highest quality)
- managing the water supply (vs demand management)
- poverty alleviation (vs quality of life enhancement)
- harnessing the environment (vs sustaining it)
- short term needs (vs long term perspectives)
- climate variability, both intra- and inter-seasonal (vs climate change), or
- creating an infrastructure (vs maintaining, improving it).

c) What problems regarding IWRM can thus be identified for LDCs?

- With the tendency for concepts on IWRM and ICM to emanate largely from the developed world, a re-focus is necessary on problems of IWRM in LDCs. First, certain generalities need to be stated and/or re-iterated, for example
  - that decisions on water are often made 'from a distance' in a far-away capital city
  - that poor peoples' water needs are frequently overlooked or underestimated in broader scale IWRM
  - that amongst stakeholders there are major disparities in wealth, influence with government, opportunity, skills, resource endowments and capacity for management as well as for economic performance (Frost, 2001)
  - that government project failures abound because funds have run out, or they are behind schedule, or operation and maintenance are inadequate
  - that the main need is for basic infrastructural development to provide for water security
  - that priorities pertaining to environmental issues are frequently lowered, and where considered, often focus on economic benefits such as erosion and river control.
- If pre-conditions for successful implementation of IWRM are considered, the following of Farrington's and Lobo's (1997) points pertain specifically to the LDC context:
  - application of local catchment planning methodologies that are both technically sound and participatory, building on local peoples' (vernacular, indigenous) knowledge, experience and practice
  - planning initiatives that are accessible to, and involve, local community organisations and which include appropriate capacity building and technical support
  - development of a framework of local-level collaboration amongst NGOs, CBOs (community-based organisations) and government departments with relevant government agencies.

Table 1.1 Characteristics influencing IWRM in more developed vs lesser developed countries (after Schulze, 1999)

	Developed Countries	Lesser Developed Countries
	INFRASTRUCTURE	
•	High level of infrastructural development, with infrastructure generally improving	Infrastructure often fragile and frequently in a state of retrogression
•	Infrastructure decreases vulnerability to natural disasters (e.g. floods, drought)	High vulnerability to natural disasters; heavy damage and high death toll
•	High ethos of infrastructure maintenance	Low ethos of infrastructure maintenance
•	High quality data and information bases available, well co-ordinated	Data and information bases not always readily available
	CAPACITY	
•	Scientific and administrative skills abundantly available	Limited scientific and administrative skills available
•	Expertise developed to local levels	Expertise highly centralised
•	Flexibility to adapt to technological advances	Often in survival mode; technological advances may pass by
	ECONOMY	
•	Mixed, service driven economics buffered by diversity, highly complex interactions	High dependence on land, i.e. agricultural production; at mercy of vagaries of climate
•	Economically independent and sustainable	High dependence on donor aid, NGOs
•	Multiple planning options available	Fewer options available in planning
•	Take a long term planning perspective	Take a shorter term planning perspective
•	Countries wealthy, money available for planning and IWRM	Wealth of countries limited, less scope for planning and IWRM
	SOCIO-POLITICAL	
•	Population growth low or even negative	High population growth rates and demographic pressures on land
•	Generally well informed public with good appreciation of planning	Poorer informed public, less appreciation of science/planning
•	High political empowerment of stakeholders	Stakeholders often not empowered, afraid to act or to exert pressure
•	Decision making decentralised	Decision making centralised
	ENVIRONMENTAL AWARENESS AND MANAGEMENT	
•	High level of expectation of planning and IWRM	Lower level of expectation and attainment of goals
•	Desire for aesthetic conservation	Need for basics for living

- Both Farrington and Lobo (1997) and Frost (2001) lament that government-led initiatives which emphasise physical planning at the broader scale will often not be sustainable because of the lack of necessary local ‘ownership’ and ‘buy-in’ of the stakeholders on the ground, as well as lack of cohesiveness in purpose amongst land and water users.
- A further set of IWRM problems in LDCs relate to donor community involvement (Howe and Dixon, 1993), for example,
  - lack of co-ordination between donors from different countries in the same development area
  - lack of consideration by donor/lenders of host country driven national programmes, strategies and priorities regarding land and water issues
  - leading, at times, to situations whereby developing countries often cannot formulate and implement their own water-related strategies/priorities owing to financial dependence on the international donor community
  - donor countries ‘selling’ their own modelling or dam building technologies, whether or not they are appropriate, because foreign aid is often tied to the use of donor country consultants and their expertise
  - with subsequent difficulties arising in regard to project maintenance, back-up or post-audit.
- Similar problems arise in the lack of capacity building and institutional development in the field of IWRM to render LDCs technically self-sustaining, with the continuous failure of appropriate capacity building leading to continued dependence on external assistance.

1.8 DO HYDROLOGISTS HAVE A SPECIAL ROLE TO PLAY IN I.W.R.M.?

- By its very definition the multi- and inter-disciplinary nature of IWRM implies strong input from
  - the *biophysical sciences*, e.g. soil scientists, geologists, plant physiologists, agronomists, chemists, physicists, geographers, ecologists and environmentalists
  - the *engineering sciences*, such as bioresources, civil, mechanical and electrical engineering
  - the *computational sciences*, e.g. numerical modellers, GIS experts and database managers
  - the *socio/politico/economic sciences*, including economists, demographers, health care experts, legal experts, bureaucrats, policy makers, policy implementers and
  - the *managerial sciences* amongst whose ranks would be catchment managers, science and engineering synthesisers as well as industrial and financial managers.
- Amongst all these disciplines the hydrologists have a special role to play. Where water-based objectives are a key issue and objective of catchment management, they should be at the core of management (Schulze, 1999) and because of their understanding of the inter-connectivities of the total terrestrial water cycle at catchment scale - natural, anthropogenically altered and water engineered - they
  - can quantify the inputs and outputs of the water system in time and space (by observation, data handling and simulation modelling skills), including the assessment of impacts of catchment and channel modification on resource and environment
  - take due cognisance of issues of both water quantity (identifying source areas within the catchment, seasonality, availability, probability) and water quality (physical, chemical and biological), and the impacts of present and future land management on them
  - can forecast availability and usefulness of the resource by providing information on assurance of supply
  - assess risk which may be associated with specific conditions, geographic areas, including risks of flooding and droughts in terms of magnitude, duration, frequency and location, and
  - make the information available in formats that can be used by managers in order to reduce the subjectivity of their decisions (Schulze, 1999).
- Hydrologists are already used to collaborating with other disciplines, already work at catchment scale and can act as synthesisers of biophysical aspects of water management.
- A continuing problem with hydrologists is, however, that few scientists have been trained as such (although this is changing). Because they come from diverse backgrounds, disciplines and experiences their role in IWRM is, therefore, not always well defined (Schulze, 1999).
- While the hydrologists’ role in IWRM is undoubtedly significant, true integration will only be achieved when all disciplines interact to produce truly holistic options and consequences. Hydrologists should, therefore, also become more proactive within the non-biophysical sciences

associated with IWRM.

1.9 WHAT, THEN, ARE SOME PRECONDITIONS FOR EFFECTIVE AND EFFICIENT I.W.R.M.?

If IWRM is a philosophy, a process and the act of putting those into practice, then the last two are the more difficult of the three steps. Preconditions for successful IWRM include the following (Farrington and Lobo, 1997; Ashton, 2000; Frost, 2001):

- close involvement of all stakeholders, i.e.
  - planning initiatives that are accessible to, and involve, all landowners, stakeholders and local community organisations
  - building on local peoples' indigenous knowledge, experience and practice, with
  - appropriate capacity building and technical support, and
  - placing relationships between stakeholders on trust, with long-term commitment to, and continuity of, the catchment management process;
- political support at all levels of governance
  - from national through provincial to local
  - ensuring adequate financial and infrastructural support and, in a developing country context
  - developing a framework of local level collaboration amongst NGOs, CBOs and government departments;
- the will and willingness to implement IWRM, including
  - effective co-operation of land and water management which may have to extend beyond the normal 'physical' boundaries of a single catchment
  - convergence of interests and associated checks and balances within and between the various levels of organisations involved in IWRM;
- recognition that while IWRM is a long-term process, realistic short and medium term goals need to be set and audited; and
- acceptance that each catchment is unique with respect to IWRM, thus
  - defining catchment boundaries that need to be flexible, depending on the common issues of concern to stakeholders and
  - enabling specific institutional arrangements to be adaptable for each catchment's situation.

1.10 WHAT ARE THE MAIN BARRIERS TO THE SUCCESS OF I.W.R.M.?

Despite the enthusiasm for, logical appeal of, reinforcing common messages via Agenda 21 and new water legislation and belief in whole catchment water management, initiatives have often not lived up to their expectations nor reputations (Frost, 2001). Factors inhibiting the success of IWRM, particularly in LDCs but not exclusively so, include the following (Calder, 1999; Falkenmark *et al*., 1999; Frost, 2001; Schulze, 2001):

- Sectoralism within and between the government departments and the fragmented nature of institutional structures
  - with different functions and different political goals, each with different stakeholders
  - with 'control' of a water sector often being more important than integration
  - poor inter-agency linkages, e.g. in
  - risk management vs water resources vs irrigation vs land management vs international obligations;
- Lack of clearly defined overall strategies, including
  - management objectives
  - mechanisms for delivery to enable objectives to be achieved
  - being high on rhetoric and talk at strategic level and low on action on the ground;
- Lack of research to assess the resource base w.r.t.
  - water resources availability and risk
  - the value of water i.t.o. economic production (e.g. $/m^3 water, or t/m^3 water), between water use sectors and within a water use sector (e.g. agriculture)
  - consideration of the entire hydrological cycle;
- Water being a source of conflict, not only between sectors (e.g. rural vs urban) but also within a sector (e.g. dryland vs irrigated agriculture; commercial vs subsistence agriculture); however, in

particular w.r.t. upstream/downstream users and uses. This is a special concern in IWRM because of the inherent asymmetry in the interactions (Frost, 2001), with
  - downstream users affected by *direct* upstream actions, e.g. abstractions, impoundments, flow reductions through intensification of agricultural land uses and deterioration of water quality, while
  - upstream users can only be affected by downstream users *indirectly* by political pressures on water use, legislation or compensatory payments/levies;
- Deficiencies in information, which can imply
  - insufficient spatial information
  - a lack of willingness among organisations to share data and information
  - data/information not collated, out of date or not disseminated, because it resides in obscure reports or theses and/or
  - networks of information flows being inadequate;
- Deficiencies in capacity, with regard to
  - human capacity to effect IWRM
  - capacity being too centralised in certain institutions
  - information sharing and
  - infrastructure;
- Deficiencies in land management options, including
  - how the use of land impacts on quantity and quality of water
  - how to cope with/adapt to changing hydrological conditions w.r.t. inter-annual climate variability or more permanent climate change
  - trade-offs between land use practices, within a sector and between sectors;
- Deficiencies in water management options, in regard to its storage, treatment, equitable allocation and distribution as well as best practice in implementing demand management;
- Deficiencies in stakeholder involvement, e.g.
  - it may be poorly defined, with unstructured approaches to public consultation
  - there may be conflicts between objectives of the various stakeholders
  - a lack of trust between stakeholders, both in human and scientific terms, may exist
  - an unwillingness of stakeholders to shoulder responsibility may be present
  - there may be strong pressure groups and lobbies who overpower a less vocal majority;
- Lack of willingness to integrate, for example,
  - with land users and land use agencies each still seeking to assert their primacy in relation to how the land and its associated water resource should be used (Frost, 2001)
  - political power plays within the field of water
  - power plays existing between individual disciplines involved in IWRM and their distinctive methodologies of seeking solutions (e.g. types of and approaches to modelling, ‘hard’ vs ‘soft’ tools)
  - still viewing IWRM as simply a wish-list of catchment issues to be solved instead of approaching water management from an holistic and an ‘ecological footprint’ perspective (Falkenmark *et al*., 1999) which seeks to understand catchment dynamics, catchment capacities, thresholds and consequences; and
- Lack of audit and post-audit procedures, which embrace, *inter alia*, who is going to
  - enforce and ‘police’ progress in IWRM as well as
  - critically evaluate the performance of actions during and after the process of IWRM.

1.11 CONCLUDING THOUGHTS ON INTEGRATED WATER RESOURCES MANAGEMENT

IWRM aims to find long term sustainable ways to successfully cope with the particular environmental preconditions (climate, soil, topography) in a certain region while simultaneously satisfying societal needs, by balancing different functions of water with different sectors (e.g. environmental, agricultural, industrial) and stakeholder groups, which may range from policy makers to local landowners (Falkenmark *et al*., 1999). This brief overview of selected aspects of IWRM has shown that this philosophy and process is not easily put into practice because of the many conceptual, scalar, disciplinary, development level and practical problems involved. It does, however, provide a framework within which to research and evaluate a range of policy options and offers the opportunity to assist in assessing the risks and options of environmental, social and economic policy makers by re-connecting people to water issues within their catchment through consultative processes, stakeholder participation and partnership options (Newson *et al*., 2000). It does, nevertheless, remain an ambiguity of IWRM that most people relate to it well, but cannot easily translate it into operational terms.

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CHAPTER 2

ON MODELS AND MODELLING FOR INTEGRATED WATER RESOURCES MANAGEMENT : SOME THOUGHTS, BACKGROUND CONCEPTS, BASIC PREMISES AND MODEL REQUIREMENTS

R. E. Schulze

School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

ABSTRACT

The complexity and demands of Integrated Water Resources Management, IWRM, are truly mind boggling if one considers that different natural influences dominate hydrological responses at a range of different scales, as do anthropogenic influences, and that these intersect; furthermore that IWRM follows the concepts of the DPSIR (Drivers, Pressures, States, Impacts and Responses) approach; and that with recent developments, which include the Water Services Act (1997) and the National Water Act (1998), major paradigm shifts have occurred in the management of water resources in South Africa.

All these perspectives demand that one looks (and re-looks) afresh at basic premises of models and their requirements in light of IWRM. This chapter highlights selected basic premises under four major themes:

- *Hydrological process* and the *model conceptualisations* include discourses on the roles of precipitation, evaporation, soils and runoff generation mechanisms and concludes that for current and anticipated hydrological problems, models need to be physical-conceptual in structure, such that they can provide robustly ‘right answers for right reasons’ for multi-purpose outputs of water quantity and quality under unknown/unmeasured conditions.
- The *hydrological modelling system* requires that it be modular, adaptable to demand driven requests, multi-level in structure and that it must be operated by data available in direct or derived form from national data networks and spatial digital information, suitably “translated” into attributes required by models.
- The *model applications* need to be multi-scalar with the facility for spatial zooming in/out, also at scales finer than Quaternary Catchments and with hydrologically realistic subcatchment discretisation. Of paramount importance is the concept that in hydrology one can scale up realistically, but not down.
- *Responsibilities* of both *model developers and users* are discussed. Model developers need to respond to hydrological issues of the day and of the region, have to anticipate future modelling needs ahead of time, work in teams, follow strict protocols and provide service to users. Model users, on the other hand, need to comprehensively understand the model, follow user protocols conscientiously and be wary of the pitfalls of adopting new models too readily.

The chapter concludes with a reminder on the fundamental objective of modelling, uncertainties in modelling and some notes of caution in modelling.

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2.1 WHAT MAKES DEVELOPING HYDROLOGICAL MODELS FOR APPLICATION IN INTEGRATED WATER RESOURCES MANAGEMENT (I.W.R.M.) A COMPLEX AND DEMANDING TASK?

The complexities and demands of developing models for, and applying them in, Integrated Water Resources Management (IWRM) are truly mind-boggling if one considers the following three hydrological perspectives:

a) Perspective 1 : Different natural and anthropogenic influences dominate hydrological system responses at different scales

This is illustrated schematically for natural systems in Figure 2.1 (top) by the greater dominance of

- *soil* (texture, depth, drainage) and
- *local topography* (slope, aspect, altitude gradient influences on microclimate)

as the hydrological drivers at small catchment scale (~ < 10^1 km^2), compared with

- *physiography* (i.e. the macro-landscape with its morphological and/or morphotectonic units such as mountains, plateaux or lowlands) and, in phase with that,
- *vegetation* (i.e. the broad natural land cover units and their influence on seasonally variable biomass),
- *regional climate* (e.g. precipitation in its various forms, temperature and evaporation patterns as a function of physiography, latitude and continentality), the
- *waterscape* (including channels, floodplains, wetlands, lakes and estuaries with their associated ecosystems) and, to some extent,
- *macro-climate* (synoptic scale events, or so-called 'Grosswetterlagen')

which are dominant influences at the operational catchment scale of ~ 10^1 - 10^5 km^2 (Schulze, 2001a).

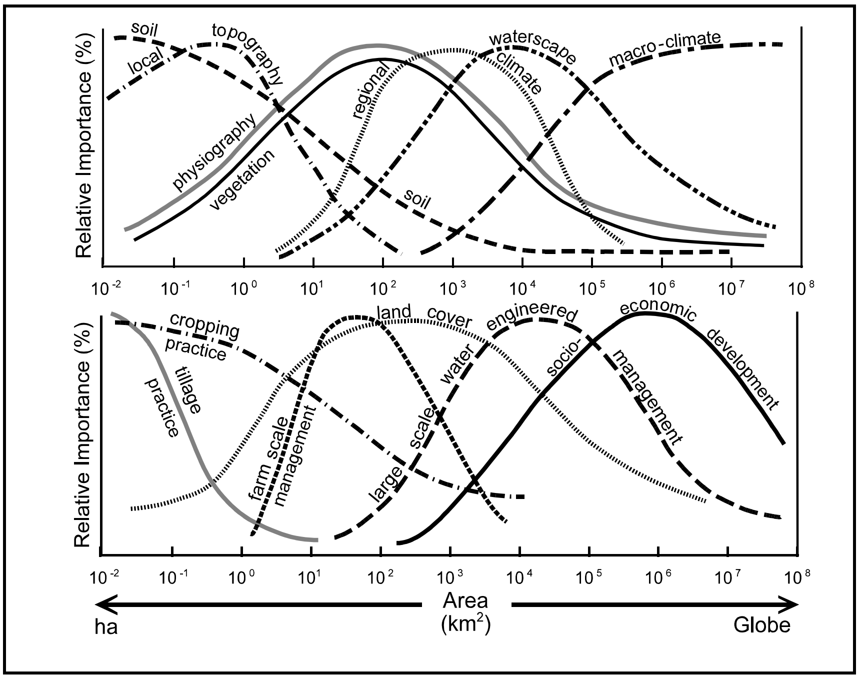

Figure 2.1 Natural heterogenieties (top) and anthropogenic influences (bottom) occur across a range of spatial scales, but dominate hydrological responses over a narrower spectrum (Schulze, 2001a)

Similarly, anthropogenic influences on the hydrological system occur at a range of scales, but again each dominates over a narrower spectrum (Figure 2.1, bottom; Schulze, 2001a). Thus, for example,

- *tillage practices* (e.g. conventional vs conservation vs minimum tillage practices, or ripping, terracing and contour banking) or
- *cropping practices* (rotation patterns, plant dates and densities) and
- *farm scale management* (e.g. individual borehole abstractions, local irrigation from farm dams up to ~ 10^5 m^3 capacity)

may have major impacts at local hydrological scale, but hardly/less so at larger catchment scale, where

- *land use and cover* (including extensification such as clearing for grazing, or intensification such as urbanisation, commercial crop/plantation agriculture) as well as
- *water engineered systems* (e.g. major reservoirs, regional scale irrigation, water diversions or inter-basin transfers) and the
- *status of socio-economic development* (e.g. developed vs lesser developed economies, predominantly subsistence vs commercial agriculture),

by themselves, or in combination, may change natural hydrological regimes (Schulze, 2001a).

b) Perspective 2 : IWRM relates closely to the DPSIR concept

If one aspect characterises IWRM at the catchment scale it is the juxtapositioning of human impacts on the natural hydrological regime, and vice versa. This may be conceptualised by the so-called DPSIR approach (Table 2.1) in which a changing river basin hydrology and its feedbacks from society is structured in terms of **D**riving forces, **P**ressures, **S**tates, **I**mpacts and **R**esponses (McCartney *et al*., 2000).

- *Driving forces* would include inter- and intra-seasonal climate variability, upon which may be superimposed anticipated changes through greenhouse gas forcing, demands of rising population, expectations of increases in food security (in developing economies) and water security and the ever increasingly dominating forces of government subsidies and legal directives as well as international market pushes and pulls which filter down into changing natural hydrological regimes.
- *Pressures*, i.e. causes of hydrological changes, include regional scale climate change of the reversible type (e.g. El Niño events and changes in their frequency and intensity) as well as of the irreversible type (e.g. global climate change with trend changes in precipitation amounts and variability), land use change through both rural to urban migrations (particularly in developing economies) and agriculture (extent and intensity), together with streamflow changes resulting from river channel manipulation (e.g. impoundments, channel modifications). These pressures have influenced the
- *State* of the hydrology, from the past states through the present and into future ones. The state implies the quantity of water a river carries and its seasonal distribution, as well as its quality in regard to suspended solids, water chemistry and the biological health of the river water. Hydrological states also include those of, for example, wetlands, constructed dams or natural lakes, as well as the level and quality of groundwater.
- *Impacts* are judged as positive or negative environmental, social and economic consequences which may arise from changes of state of the hydrological system or of ecosystems. These include the degradation of the terrestrial and aquatic ecosystems, loss of water rights, the hydrological amplification of extreme climatic events or the increased need for reliable water supplies (e.g. with urbanisation).
- *Responses* are societal reactions that attempt to affect either the driving force, or the pressures, which cause changes in the state of the hydrological system, effectively acting as a system feedback (McCartney *et al*., 2000). They can be international (e.g. statements emanating from Agenda 21 and/or the Dublin water conference), national (e.g. by implementation of integrated catchment management as a legal instrument, as in South Africa), local (e.g. through water restrictions) or institutional (e.g. by a bulk water supplier). Responses can furthermore mean new water management strategies (e.g. through levies on streamflow reducing activities, or the

Table 2.1 Changing hydrology at the river basin scale structured in terms of the DPSIR (**D**riving forces, **P**ressures, **S**tates, **I**mpacts and **R**esponses) approach (adapted from McCartney *et al.*, 2000 by Schulze, 2001a)

Driving Forces	**Pressures** (i.e. causes of hydrological changes)	**States** (of hydrology: past, present, future)	**Impacts** (+ or - results of change)	**Responses** (international, national, local institutional)
• Inter-seasonal climate variability • Greenhouse gas forcing • Rising population • Rising security expectations • State subsidies and directives • International market forces	• Regional climate change • Local land use change • Channel manipulation (dams, channel modifications) • Catchment water management • Rural-urban migration	• Rivers : quantity • Rivers : seasonality • Rivers : quality • Groundwater • Wetlands • Reservoirs • Lakes	• Degradation of ecosystems • Loss of water rights • Increased need for reliable water supply • Amplification of climatic extremes	• Agenda 21 • Johannesburg WSSD • ICM/IWRM as legal instrument • New management strategies • New research directions • Ecosystem rehabilitation • Modelling

polluter pays principle), new research directions (e.g. on impacts), putting to practice new concepts (such as ecosystem rehabilitation) or the application of hydrological simulation models for near real time operational decision making.

c) Perspective 3 : Recent paradigm shifts in water resources management imply new approaches to hydrological modelling

Historical advances in hydrological modelling have been shaped by the desired applications of the past. Equally, present and future modelling directions and advances will have to be shaped by current and anticipated information needs in the broader field of water resources. Modelling in future should, therefore, address stakeholders' *future needs and concerns* on the water related environment. Stakeholders in the water industry will have to clarify what they really want to know, while hydrologists can clarify whether they actually address those problems and what their models can produce (Schulze, 1998).

The modelling needs, as already alluded to indirectly in the discussion on the DPSIR concept, will thus be influenced, *inter alia*, by

- national political agendas
- international agreements and protocols
- water resources development goals
- user issues
- environmental issues
- regulatory goals and
- management methods.

Trends in hydrological modelling and the levels of sophistication of modelling will also reflect increasing pressures on water demands by increasing and developing populations. As a result of all the above factors, *paradigm shifts* in water resources management which started manifesting themselves in the 1990s are likely to intensify over the next decade. These include shifts/moves (Schulze, 1998) from

- concrete (literally and figuratively) to more abstract applications
- functional engineering systems to environmental issues
- harnessing the resource of water to sustaining the resource of water
- top-down political decisions to bottom-up public participation
- relatively few major water schemes to a multitude of smaller schemes
- extreme value (design) prognoses to instream flow requirements
- groundwater abstraction to groundwater recharge / contamination
- disciplinary focus (e.g. engineering) to multi-disciplinary focus
- problem solving to conflict management

- the volumes of water — to — the value of water
- prediction (magnitude) — to — forecasting (when)
- channel control/management — to — whole catchment management
- water quantity — to — water quality.

The role of hydrological modellers is to pre-empt these trends and have appropriate models (backed up by field observations) for application pro-actively (rather than re-actively) in their respective countries, each of which has different priorities.

2.2 WHAT ARE THE OBJECTIVES OF THIS CHAPTER?

It is in light of the three perspectives outlined above, that the objectives of this chapter are defined. These are to reinforce to the modelling and decision making fraternities involved in IWRM what I have summarised into 30 basic hydrological premises and resultant requirements with regard to both the hydrological model (i.e. the tool representing the hydrological system, together with its support framework) and the modeller (i.e. the model developer and user). This task is undertaken under broad but interrelated themes on hydrological process representation, the modelling system *per se*, model application, and the roles of the model developer as well as that of the user, before some conclusions are drawn on uncertainties in modelling and notes of cautions on modelling are sounded. Relevant examples will be drawn largely from own experiences in South Africa and from this project.

2.3 WHAT HYDROLOGICAL PROCESSES AND THEIR CONCEPTUALISATIONS/ REPRESENTATIONS NEED TO BE CONSIDERED IN MODELS FOR I.W.R.M.?

a) Basic Premise 1 : Precipitation is the most important driver of hydrological responses, particularly in rainfall-limited environments. Its temporal and spatial distribution therefore needs to be determined as accurately as possible, be it for individual events or for long term patterns

- The curvilinear sensitivity of runoff to rainfall from individual events to long term responses is widely documented (e.g. Schulze, 1995; 1997a; 2001a) and is a major factor in the generally low rainfall to runoff conversion in South Africa (Schulze, 2001b).
- Compounding this sensitivity is the episodic and often near random nature of individual rainfall events in space and time.
- This randomness is, however, tempered over time and long term regional/seasonal rainfall distribution patterns of magnitude and intensity emerge over South Africa, influenced by altitude *per se*, the rate of change of altitude, continentality, exposure to windward or leeward side of rainbearing winds as well as to synoptic patterns (e.g. Dent *et al*., 1989).
- Major problems persist with the physical gauge measurement of rainfall at a point, observational procedures and eventual application of rainfall records in models required by IWRM. These include
  - gauging errors through effects of eddying, turbulence, splash and evaporation which vary from event to event by up to 20%, as well as by season and region, and for which there is no systematic correction in South Africa
  - missing data through gauge malfunctioning or negligence on the part of volunteer observers (Smithers and Schulze, 2000a; cf. examples in Chapter 6 of this document)
  - imperfect techniques of infilling (patching) any missing data or data sets (Smithers and Schulze, 2000a), rendering extreme value analysis inconsistent
  - rainfall being recorded daily at 08:00, which may not correspond with actual discrete rainfall events, and which makes daily time step modelling difficult
  - data being out of phase by persistent recording of an event's rainfall either a day too early or too late (Meier, 1997; Smithers and Schulze, 2000a), which influences hydrograph generation in daily distributed modelling on operational catchments where streamflows cascade from upstream to downstream subcatchments
  - the decline in the number of stations in South Africa's rainfall monitoring network (Lynch, 2001)
  - the lack and relatively poor quality of short duration rainfall records (Smithers and Schulze, 2000b) and

- problems with the application of stochastically generated rainfall series when used in, for example, cascading river basin scale modelling (Schulze, 1995).

- Equally serious and difficult is the representation of point rainfall over a catchment, because
  - no methodological unanimity exists to date, especially in regard to preserving statistical rainfall characteristics when converting from point measurement to areal estimates, and
  - the gridded 1' x 1' latitude/longitude values of monthly and annual rainfall which are currently the best available for South Africa (Dent *et al*., 1989), and which are often used to make catchment adjustments from point station rainfall values, have been shown to be seriously in need of revision in many regions (e.g. Meier, 1997; cf. Chapter 5).

Where do we go from here when modelling for IWRM?

- At present the 80% rule probably remains in place, *viz*. spend 80% of model input time on quality controlling the rainfall input in order to attain good results.
- Through two WRC projects probably the most comprehensive quality controlled, long duration point and spatial rainfall datasets for southern Africa will be in the public domain by the beginning of 2003 (WRC Projects K5/1060 and K5/1156).
- Further developments are eagerly awaited for quality controlled operational datasets from South Africa's radar network for current (as distinct from long term historical) rainfall datasets for near real-time modelling.

b) Basic Premise 2 : Many hydrological responses are influenced significantly by the magnitude and spatio-temporal variability of the magnitude of evaporation, E. In South Africa's high atmospheric demand climate, potential evaporation, E_p , as the driving variable of all other evaporative processes, should therefore be determined as accurately as possible

- Energy driven and energy limited hydrological processes include water losses from irrigated crops, reservoirs, channels and riparian zones as well as evaporation losses from crops/trees grown under dryland conditions.
- The facts that mean annual E_p ranges from 1400-3000 mm (Figure 2.2; Schulze, 1997b, p172), that over 90% of South Africa's rainfall is lost again through various evaporative processes and that the aridity index of mean annual E_p/rainfall generally ranges from 2 - 20 is testimony to the significant role the magnitude of E_p plays in South Africa, with values of 60 - 120 mm per month even in winter. High evaporation rates are a major contributor to the low conversion rate of rainfall to runoff in this region (cf. Chapter 6).
- While errors in the estimation of E_p may not have major consequences in arid and semi-arid areas, the more humid a climate becomes the more sensitive E_p becomes in a range of hydrological responses (e.g. runoff generation; irrigation demand).
- Accurate estimates of E_p are particularly necessary when modelling a crop's irrigation water demand, with small errors in E_p resulting in major simulated changes in water demand, especially in more arid climates.

What information on E_p is available to modellers, and what of the future in respect of E_p estimates?

- The 1' x 1' gridded values of derived and verified mean monthly A-pan equivalent E_p for South Africa (Schulze, 1997b) are a significant step forward in terms of spatial resolution when compared to the pan interpolated values in general use by practitioners even to this day (for an example of potential errors in pan interpolated values, see Schulze, 1997b, p163).
- The worldwide acceptance of physically-based Penman-Monteith type equations for E_p, now already used routinely in irrigation planning in South Africa, will require revisions of the presently available maps/values of E_p provided in Schulze (1997b), especially through the use of temperature derived surrogate equations.
- To that end the 50 year series of quality controlled and verified daily values of maximum and minimum temperatures which, through a current WRC project (K5/1156), can now be generated at any point in South Africa to a resolution of 1' latitude/longitude, and which accounts also for spatio-temporal lapse rates and valley/crest differences due to cold air drainage, is seen as a major step forward in improving E_p estimations at unmeasured locations.

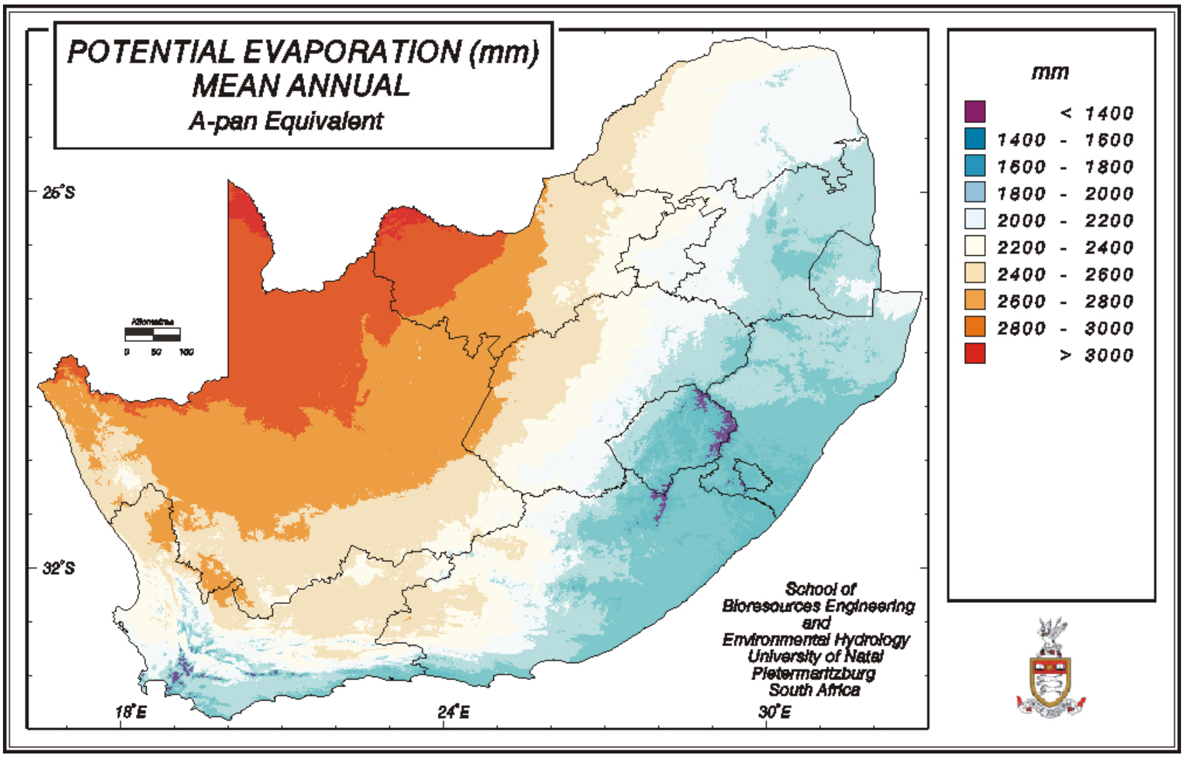

Figure 2.2 Mean annual gridded A-pan equivalent reference potential evaporation over South Africa, Lesotho and Swaziland (after Schulze, 1997b)

c) Basic Premise 3 : Similarly, total evaporation (i.e. "actual evapotranspiration") processes should be mimicked as realistically as possible in operational IWRM models

- Total evaporation, E, is made up of plant transpiration E_t, soil water evaporation E_s and the evaporation of intercepted water E_i, with potential evaporation E_p as the forcing function.
- Total evaporation is a major determinant in studies of streamflow reduction activities (SFRAs) and water use efficiency (WUE) - both key concepts of IWRM in light of the National Water Act of 1998 (NWA, 1998). Because of the severe competition for available water in South Africa, E is a key concept around which considerable IWRM controversies are likely to focus in the near future.
- To simulate total evaporation realistically for SFRAs or WUEs, models will need to
  - account for development of inter- and intra-seasonal physiologically active biomass, preferably derived from leaf area index (LAI), in a dynamic manner, which should include the "memory" from previous seasons' moisture budgets and with current season growth being energy driven (e.g. by the growing degree day concept), while stress related biomass reduction and recovery rates should be both water budget and energy constrained
  - account for curvilinear reductions of E based on plant physiological controls when E reduces to below its maximum value, either because the soil is too dry or too wet, with these reductions modified by soil textural considerations
  - account for transpiration rates determined, *inter alia*, by crop water demands which should include dynamic seasonal root development, embracing effects of root mass distribution and root colonisation, as well as by atmospheric CO_2 levels (invoked in studies of climate change impacts)
  - account for soil water evaporation rates which are influenced by both canopy shading effects of plant material and by surface litter/mulch and
  - account for plant interception determined on an event basis and modulated intra-seasonally by biomass,

  with all the above taking place in a matrix of soils with specific characteristics (see next point).

- A danger that nevertheless exists, is that models may contain detailed algorithms on E, but that not enough spatial detail exists on biomass and soils properties to do justice to the complex process representations contained in a model (Hughes, 2002).

d) Basic Premise 4 : The unsaturated soil zone acts as the regulatory medium which admits, transmits, redistributes and releases water. Being at the "heart" of the hydrological system, it has a key influence on the generation of important individual components of runoff, evaporation and irrigation water demand. Its model representation through water budgeting therefore needs to be physically and conceptually sound

- Soil is a complex hydrological medium by virtue of its variable horizonation, texture gradients and structural characteristics.
- It controls infiltration and soil water storage, facilitates transmission/redistribution of water in the vertical and lateral planes, permits preferential flowpaths through macropore activity, releases water by evaporative processes and allows capillary rise of water to take place.
- All the above should be reflected by the day-to-day as well as seasonal states of the model's soil water budget, because of its influences on runoff generation processes and evaporation.
- Hydrologically related soils properties are highly variable in space and depend, *inter alia*, on their position within the landscape, with finer textured material often translocated downslope.
- Input of critical soil parameters should facilitate the above processes to be modelled realistically in studies of IWRM, while from a spatial perspective the variability of these parameters must be available in directly mapped or derived form.
- As was the case in the previous basic premise, however, natural spatial variability of soils may be greater than we can measure or model and due cognisance has to be taken of this (Hughes, 2002).

e) Basic Premise 5 : Catchment gradients exert strong influences on evaporative processes, while together with channel slopes they are determinants of the various processes of runoff generation as well as of the dynamics of runoff concentration and its downstream attenuation

- Slope gradient is a variable used in computations of, for example,
  - catchment lag and hence peak discharge
  - interflow
  - flow routing and
  - soil loss.
- Together with slope aspect, gradient is used in computations of topographically induced variations in evaporative demand on warm vs cool slopes and (where applicable) snowmelt.
- Fine scale digital elevation models are playing an increasingly important role in obtaining slope related values rapidly. These include computations on gradient, aspect, concavity and stream flowpaths.
- More and more models which are applied especially in more detailed local conflicts surrounding IWRM will, in future, have to consider slope and aspect considerations.

f) Basic Premise 6 : The dynamics of total streamflow generation within a season, and on an event-by-event basis, is made up of contributions from individual components of runoff. The simulation of total streamflow should therefore explicitly model individual runoff components such as stormflow, interflow and baseflow

- Different components of runoff are generated by different mechanisms and derive from different sources areas within a catchment, which may be dynamic. They also display different properties and hydrological functions. Thus
  - *overland flows*, which may be generated either from connected (adjunct) impervious areas or from saturated zones of variable areas or from classical Hortonian flow when rainfall intensities exceed infiltrability, have short residence times of minutes to hours, are event-based, remove/transport sediments and other surface material (e.g. fertilizers, pesticides, industrial pollutants) and are critical in peak discharge estimation as well as in water quality determination.

  Thereagainst,
  - *subsurface stormflows* have slower response times and different water chemistries and

- *baseflows*, which are sustained by recharge from preferential zones within a catchment, have long memories, display slow decay, a different chemistry again and have a different criticality in maintaining different biological functions.

- The proportions of these runoff components vary according to topography, land use, rainfall patterns and antecedent catchment wetness.
- In modelling runoff, we need to know where in the catchment the water is coming from, how rapidly it is moving and where the remaining water is residing.
- Because of their variable residence times/lags, origins within a catchment, and associated properties of water quantity and quality, these runoff components need to be *modelled explicitly* as *distinct individual components* if certain key questions in IWRM are to be answered adequately.
- What is no longer acceptable for non-point pollution management and other critical issues in IWRM (e.g. streamflow reduction activities) is the simple empirical, or pseudo-physical, separation of runoff components from a hydrograph.

g) Basic Premise 7 : The model needs to distinguish clearly between landscape based catchment processes and channel based processes

- Within morphologically similar landscapes, hydrological processes down hillslopes tend to be *repetitive*, whether at a small catchment scale or a larger one.
- As the generator of streamflow in its many forms, catchment processes for IWRM need to be modelled hydrologically by relatively complex and not always well understood *water budgeting* procedures.
- Channel processes, on the other hand, tend to be
  - *additive* with catchment size,
  - *attenuated* by channel characteristics of slope, shape and roughness as well as by transmission losses to floodplains, banks and alluvial beds and by open water evaporation, and
  - *manipulated*, e.g. by abstractions, diversions and impoundments.
- As the recipients and transferors of water, channels and impoundments need to be modelled hydraulically with often complex, but relatively well understood, relationships and with the manipulations (e.g. abstractions, releases) accounted for by simpler procedures of *bookkeeping* rather than budgeting.
- If catchment and channel processes are not separated explicitly in models used for IWRM, scaling problems emerge in parameterisations between smaller and larger catchments.

h) Basic Premise 8 : In order to understand the fate of water, material and nutrient movement in a catchment, models need to represent explicitly hillslope hydrological processes and their interactions in the toposequence from crest through scarp, midslope to footslope and the riparian zone

- Be it impacts of fertilizer or pesticide movement, the different generation mechanisms of runoff or sediment production, or water demand by land uses in riparian vs upslope areas, these are all influenced by hillslope hydrological processes and pathways with the respective thresholds, rates, accumulations and feedbacks of the different elements making up the landscape, *viz*. the crest, scarp, midslope, footslope and riparian zone.
- The hillslope elements and their accumulative downslope interactions need to be represented in a conceptually sound manner in order to answer prognostically many of the questions which catchment managers will be posing in the near future.

i) Basic Premise 9 : Different hydrological processes dominate not only at different scales, but also according to prevailing climatic and physiographic regimes. Model process representations need to encapsulate these differences

- South Africa experiences a wide climatic range with MAPs from < 50 mm to > 3 000 mm, with low intensity winter to all year to predominantly high intensity convective summer rainfall regions coupled with high intra- and inter-seasonal variability, and physiographies ranging from steep montane to undulating hills to plains. This implies a highly variable spatio-temporal conversion of rainfall to runoff as well as a regionally and seasonally variable partitioning of runoff into overland flows, subsurface stormflows and baseflow, where the groundwater table may or may not be "connected" to the channel, depending again on season and location.

- For example, groundwater recharge may be through the soil matrix or by transmission losses, while evaporation losses may be dominated by riparian zone processes or transpiration or soil water evaporation or be influenced strongly by slope and aspect.
- By way of another example, mountain catchments' hydrology may be dominated by poorly understood precipitation:altitude gradients i.t.o. intensities, rainfall days and event magnitudes, all of which change with elevation. In addition, mountain catchments, from which many of South Africa's water resources derive, generally suffer from poor observational networks.
- Directly, or by surrogate means, all the above processes have to be encapsulated in model process representations for effective IWRM.

j) Basic Premise 10 : Variations in land management practices sometimes have larger influences on critical hydrological responses than land cover change. Models need to be able to simulate such hydrologically sensitive management practice scenarios realistically

- The identical land cover can produce significantly different hydrological responses, depending on the level of management practice. Thus, for example,
    - veld in overgrazed vs well managed condition can change stormflow responses by a factor of 2 and sediment yield by a factor of 4 or more (Schulze, 2001b); or
    - annual crops grown on fields with vs without contour banks or under conventional vs conservation tillage practices can yield vastly different magnitudes of runoff (Schulze, 2001b), in addition to changes in the partitioning of rainfall into storm- vs baseflows occurring; or
    - plantations of commercial tree species with different site preparation techniques (pitting vs ripping vs tillage) at the time of planting display different rooting, water use and runoff patterns (Moerdyk and Schulze, 1991).
- In an era where SFRAs, BMPs (best management practices) and pollution management plans are integral components of IWRM, models have to be able to simulate such differences in land use practices realistically.

k) Basic Premise 11 : To represent all the above in an operational hydrological model to be used with confidence on, for example, ungauged catchments where decisions are required in IWRM, or for extrapolation, the landscape component of the catchment ideally has to be simulated by a deterministic, conceptual-physical, process based and non-linear dynamic response model

- Such a model needs to be *conceptual* in that it conceives of a one, two or even three dimensional system in which important processes and couplings are idealised, and *physical* to the degree that the physical processes are represented explicitly through observable variables (Eagleson, 1983).
- The model should, at minimum, be functional (i.e. threshold based) in its process representation, although not necessarily always in a purely mechanistic (i.e. rate based) way (Schulze, 1998).
- Hydrological processes of relevance which take place on a catchment subjected to anthropogenic pressures, and for which a conceptual-physical model is necessary, are those
    - involving interactions of exchanges of water vapour, CO_2 and energy (condensation, precipitation, runoff, evaporation and transpiration together with its CO_2 driven feedbacks),

  modified by characteristics of
    - soil (surface infiltrability, subsurface transmissivity/redistribution of soil water and water holding capacity),
    - land cover and use (above-ground attributes related to biomass and its seasonal distribution, physiology and structure; surface attributes of soil protection by litter/mulch or of tillage practices; and below-ground attributes relating to root structure and distribution), and
    - topographic features of the landscape (altitude, slope, aspect, toposequence and topographic position).
- A conceptual-physical model's structure, which includes physically realistic initial and boundary conditions, needs to furthermore reproduce hydrological responses associated with
    - changes in land use and management practices

- changes in atmospheric CO_2 concentrations and
- changes in individual event, intra-seasonal and inter-seasonal climate, particularly of rainfall characteristics and especially of extreme events.

• The model should reproduce non-linear and scale-related catchment responses explicitly, where these are associated with
  - spatial heterogeneity in surface processes (e.g. topography, soils, rainfall, evaporation, land use)
  - non-linearities responding to
    ◦ episodic events (e.g. rainfall)
    ◦ cyclicity (e.g. seasons, evaporation)
    ◦ hillslope processes (e.g. on and below surface)
    ◦ immediate responses (e.g. surface runoff from connected impervious areas; saturated overland flow)
    ◦ rapid responses (e.g. stormflow)
    ◦ ephemerality (e.g. discontinuous flows)
    ◦ continuity (e.g. groundwater movement) and
    ◦ delayed responses (e.g. baseflow)
  - thresholds required for processes to commence, e.g.
    ◦ for surface runoff : when rainfall intensity exceeds infiltrability of the soil, or when saturated overland flow occurs from the upslope accumulations saturating a variable source area around channels; or
    ◦ for subsurface flow : by considering soil horizonation and toposequence when determining interflow, as well as considering when and whether the groundwater table is 'connected' to the channel when baseflows are determined

• Furthermore, the model should be able to account for
  - dominant processes changing with scale, including
  - identification of emerging properties, i.e. those arising from the mutual interaction of small scale properties among themselves, such as edge effects of advection leading to enhanced evaporation around irrigated fields, and
  - representing disturbance regimes, e.g. drainage of fields, gradual changes in land use intensification over time (as in agriculture and urbanisation), or in extensification (as in overgrazing impacts), or abrupt changes resulting from fires or flooding.

• While no type of model is totally devoid of some parameter adjustment, conceptual-physical models should, in theory, not require external calibration procedures to produce robustly acceptable results.

• A major advantage of such models is that, because of their high level of conceptualisation and physically based boundary conditions, they may be used with confidence in extrapolations involving 'what-if' scenarios of hitherto unmeasured land management, extreme event or climate variability change, beyond what has been observed on a given catchment. Such extrapolation cannot be undertaken with the same assurance with externally calibrated models because of the equifinality of parameter sets and their dependence on the state of the catchment during the calibration period (Beven, 2000).

l) Basic Premise 12 : For operational modelling of many elements of IWRM, simulations should be undertaken at daily time steps

• The day, and diurnality, is a *universal natural time step* (which neither the second, minute, hour, week or month are). The next natural time step up would be the season, and that displays no universality.

• Diurnality encapsulates, albeit not perfectly, many hydrologically related processes (e.g. evaporation, transpiration and many discrete rainfall events).

• Furthermore, many operational decisions are made according to daily conditions (e.g. irrigation, tillage, reservoir operations).

• There are, however, two other major reasons for promoting daily time step modelling. The first is the availability of data:
  - South Africa, for example, has daily rainfall records of over 20 years' duration for nearly 4 000, and for over 40 years' duration for over 1800 stations (Figure 2.3), while for the same durations autographically recorded data for time steps < 1 day are available for only 97 and 8 stations respectively (Smithers and Schulze, 2000a; 2000b).

- Similarly, daily values of maximum and minimum temperatures in South Africa are available for over 1300 stations and for pan evaporation from over 600 stations.
- The station networks with daily data are, thus, relatively dense (although not in all hydrologically critical areas) and have records of relatively long duration (Figure 2.3).
- Furthermore, for climate change studies daily values are now becoming available for present (1961-90) and CO_2 enhanced (2041-70) scenarios from the HadCM3 GCM.

• Secondly, daily time step models provide a vast array of potential and realistic and, in the context of the NWA and IWRM, highly relevant output which (say) monthly models do not, e.g. on
- modes of irrigation scheduling
- peak discharge
- event based sediment yields
- phosphorus/nitrate yields
- near real-time catchment states
- impacts of land management
- climate change impacts with CO_2 transpiration feedbacks
- reservoir operations
- instream flow requirements
- wetlands functions
- flow routing through channels/reservoirs
- reservoir status
- crop yields (dryland and irrigated) or
- explicit generation of stormflow, interflow and baseflow.

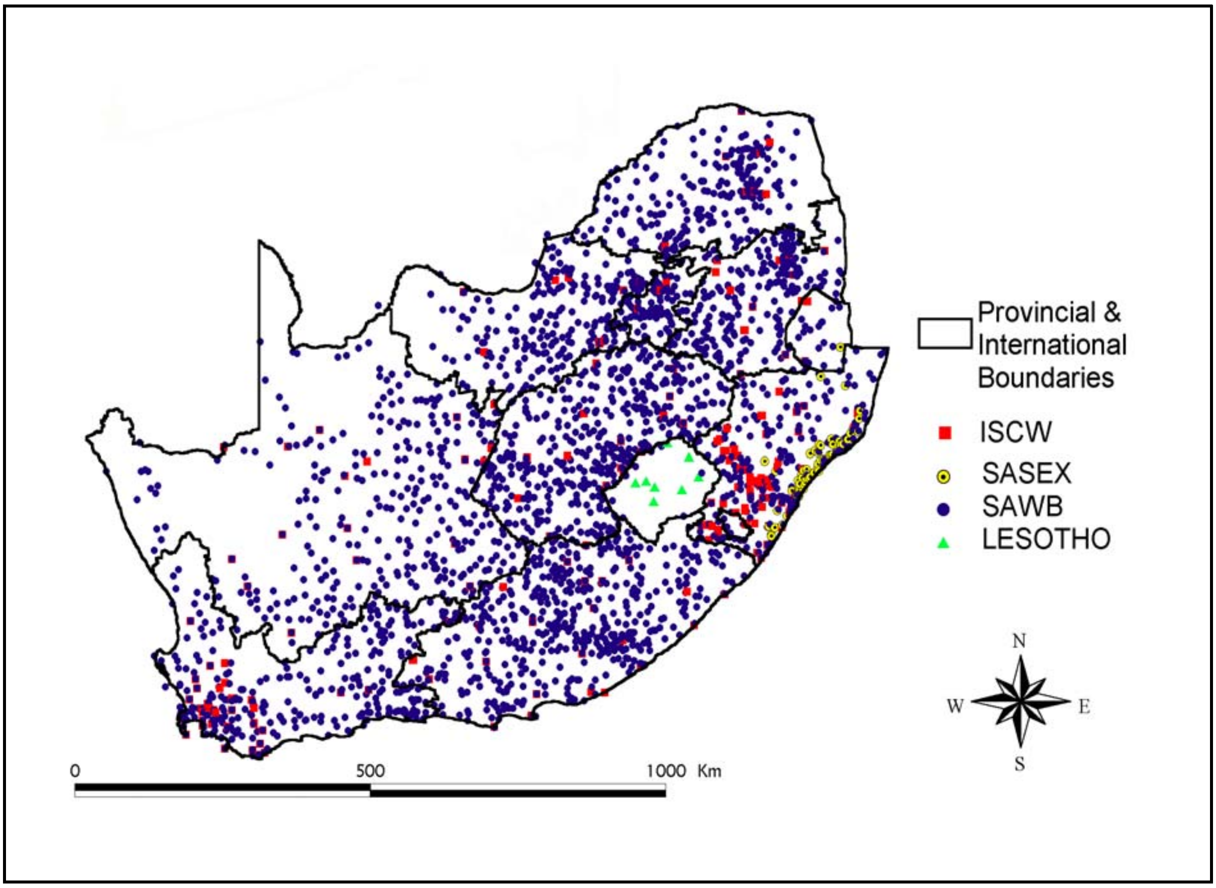

Figure 2.3 Distribution of rainfall stations with daily records > 30 years (after Smithers and Schulze, 2000a)

• There are, nevertheless, limitations to modelling at a daily time step. These include
- problems of missing data (Smithers and Schulze, 2000a)
- daily raingauges being read at 08:00 when discrete rainfall events may span more than one day or cross the 08:00 observational time and be modelled as more than one event
- the rainday spanning 08:00 to 08:00 while daily streamflow records are given from midnight to midnight (However, techniques are available to shift rainfall and streamflow into phase with one another; Smithers and Schulze, 1995)
- large areas having no rainfall stations or
- rainfall intensities not being available.

- In regard to the lack of intrinsic ‘knowledge’ on rainfall intensity from daily values at individual points there are, nevertheless, seasonal and individual event indicators which can be used in daily models to account, in some measure, for intensity.
- The advent of quality controlled daily integrated radar derived rainfall values is likely to improve distributed hydrological modelling in South Africa, with major benefits to many facets of IWRM.

2.4 WHAT NEEDS TO BE CONSIDERED IN REGARD TO MODELLING SYSTEMS FOR THEIR APPLICATION IN I.W.R.M.?

a) Basic Premise 13 : Hydrological models are but one, albeit an important, element in a broader framework of Decision Support Systems used to implement water policy through IWRM

The hydrological modelling system, consisting of the scientific model *per se*, the pre-processing of model input and the post-processing of model output, is but one element in a support framework which can aid decisions in IWRM. While no universal definitions surrounding the concepts of decision support exist, some definitions taken from Schulze *et al*. (2001) are given below to help clarify the place of the model within a broader decision support framework.

- *Decision Support* is any information, knowledge or process on social or environmental systems, which supports the development of appropriate decisions for these to have the intended desirable outcomes.
- *Decision Support Tools* are any product or methodology (but not framework) for decision support applied to a particular problem (e.g. the hydrological model).
- *A Decision Support System* (DSS) is a framework which supports the taking of appropriate decisions through the provision of information and understanding by means of tools ranging in sophistication from simple consultations through multi-process integrated mechanistic models wrapped in transparent, adaptive and flexible software interfaces. Such systems may include:
  - scientific consultations
  - scientific reports, including those from process based fieldwork to support model development,
  - maps and GIS output
  - participatory approaches
  - decision trees
  - simple logical models
  - scientific simulation models, and
  - software based integrated DSS models,

  with a distinction made between simple tools for lower level consumption and complex DSSs for higher level activities.
- The requirements and purposes of DSSs are summarised in Table 2.2.
- *Model Based Decision Support Systems*. These are of the technically most sophisticated type, which can combine GIS, models (e.g. hydrological), advanced interfaces and sophisticated scenario analysis with policy tools. Such systems are characterised by:
  - modularisation
  - transparency
  - a problem of issue focus rather than methodological focus
  - an integration of disciplines and an integration across scales
  - an ability to extrapolate through up-scaling and out-scaling
  - the incorporation of feedback processes and loops, and
  - the agility (yes, not ability!) to translate information into knowledge (i.e. present not just results, but also conclusions).

IWRM deals largely with implementing and regulating water policy. What hydrologists contribute are research and research models, which have fundamentally different requirements to policy and policy models. For this reason, hydrological research models (as tools) and the basic research which enhances such models, cannot successfully be transplanted ‘as-is’ into the policy arena. The approaches, tools, and models for policy have to be problem focused and purpose built for decision support. Fundamental differences between research and policy models are highlighted in Table 2.3.

Table 2.2 The requirements of a DSS (after Schulze *et al*., 2001)

SIMPLIFICATION	to distill complex, but good, data and science into usable models or simple rules
INTEGRATION	to integrate research results from different disciplines in a common and formal language (mathematical equations and computational algorithms)
COMMUNICATION	to 'hide' complex science from the end user and link scientists with policy advisors
FLEXIBILITY	to be flexible in the analysis of scenarios for change and policy options
INTERACTION	to be interactive, fast and easy to understand
PROVISION	to provide the end user with information they want, at the scale they need, and when they need it

Table 2.3 Attributes of research vs policy models (after Schulze *et al*., 2001)

Research Models	Policy Models
Accurate representation of processes	Adequate representation of processes
Complexity and resolution reflect processes	Complexity and resolution reflect data
Accurate representations of spatial variability	Adequate representation (existing data)
Scientifically innovative	Scientifically proven and established
Often raise more questions than answers	Provide simple, definitive answers
Interesting and worthwhile in their own right	Interesting and worthwhile only through their output
Process centered	Input/output centered
Output validatable	Outcomes validatable
As complex as necessary	As simple as possible

b) Basic Premise 14 : To lend effective support to IWRM, the hydrological model needs to be multi-purpose, but preferably 'single engined'

- In servicing the Water Services Act (WSA, 1997) and National Water Act (NWA, 1998) and accommodating the paradigm shifts in water resources management, as outlined in the introduction, it becomes very clear that we are dealing with one interrelated system with links, feedforwards and feedbacks.
- In being a decision support tool at the operational catchment scale, simultaneous answers are often required on, for example,
  - impacts of changes in land cover
  - impacts of changes in land management
  - *in situ* impacts of impoundments
  - downstream impacts of impoundments
  - inter-basin transfers and their effects
  - instream flow requirements
  - non-point source pollution, e.g. N, P
  - biological water status, e.g. *E. coli*
  - changes to dam operating rules
  - irrigation water use efficiencies
  - riparian zone changes
  - wetlands management
  - soil loss and sediment yield
  - the human reserve
  - impacts of changes in climatic means
  - impacts of changes in climatic variabilities
  - equitable water allocation to different users.
- As many of these should, ideally, be modelled within a single system in which the various modules are at a similar level of complexity and are driven by the same water budgeting procedures for the sake of compatibility between processes, feedforwards and feedbacks within the model. Hence the basic premise is made that such a model be 'single engined'!
- No single model can do complete justice to the requirements of IWRM. Many attempts have, therefore, been made recently to link models such that output of one model becomes input to another. While much depends on which models are being linked, and for what purposes, model linkage remains fraught with problems. Apart from the many practical problems such as dissimilar

model input requirements (in number and detail of parameters), model linkages seldom account for the vital feedbacks which may occur within the hydrological system and which can be conceptualised within a single model, but no easily between models (Jewitt and Görgens, 2000; Pike and Schulze, 2000).

- Certainly the more complex water budgeting elements of the landscape component of the catchment should not be linked between models; at most the bookkeeping elements (e.g. channel abstractions) can be transferred between models.

c) Basic Premise 15 : For effective operational deployment, models for IWRM are (ideally) data input lean. The model should, therefore, be multi-level in regard to input requirements and process representation. This allows alternative simple or more complex pathways to be selected in the model, depending on the level of available input or the degree of desired detail of output

- Models should be able to operate on a minimum of 'compulsory' (as against optional) input, where this input consists of either observed data or derived information.
- This is most important when models are to be set up in developing areas characterised by data scarcity.
- However, where more detailed input values are available, they should be used in alternative and more sophisticated pathways within the model in order to provide higher level output.

d) Basic Premise 16 : Models for IWRM should be able to be 'driven' by standard datasets which are freely available from national networks and by standard (usually non-hydrological) spatial digital information available at national level, suitably 'translated' (i.e. converted) into model input variables, for the models then to operate over a range of desired spatial scales

- Availability of prior information is of paramount importance in model selection for IWRM.
- Models should be able to operate with observed data or derived information from *national datasets*, if for no other reasons that these come with certain standards, national uniformity, quality control (although never enough) and therefore with general acceptance and credibility.
- This can save vast costs (timewise and financially) in data gathering for individual projects.
- Usually, however, digital spatial information used in hydrological models for IWRM (e.g. on soils or land use) has been collated by specialists who are not hydrologists, and for purposes which did not originally consider water resources planning.
- Two issues arise out of that, *viz*.
  - point data, e.g. of climatological variables, have to be converted to be spatially representative and
  - non-hydrological spatial information, e.g. of soils or land use, has to be 'translated' into hydrological model variables.
- An example of *point to spatial conversion* is the mapping over South Africa of temperature variables or potential evaporation (A-pan equivalent) to a 1' x 1' grid by regional/seasonal multivariate analysis, as outlined in Schulze (1997b), yielding levels of spatial detail well beyond what many consultants still use (cf. Figure 2.2).
- Translation into hydrological variables is illustrated for soils and land use information over South Africa.
- Soils information for hydrological models is derived from the Institute for Soil, Climate and Water's (ISCW) land type maps and tables. These were originally developed for agricultural purposes. The computer program AUTOSOILS (Pike and Schulze, 1995 and subsequent updates) can interrogate land type tables and 'translate' the information to variables required by a hydrological model. By algorithms and methodologies developed by Schulze *et al*. (1985; 1995), critical threshold values for soil water retention (e.g. at porosity, drained upper limit, lower limit) and drainage rates are determined for top- and subsoils, the soil thicknesses of which are derived from AUTOSOILS. An example of such a 'translation' is given in Figure 2.4. Information can be deduced for either the entire land type mapping unit or for individual toposequential terrain units (i.e. crest, scarp, midslope, footslope and valley bottom) making up the land type, depending on the spatial resolution required in modelling.
- In South Africa, the basis for land use information required by numerous hydrological models is the 1996 satellite derived National Land Cover image with its 31-fold land use/cover categorisation

by Thompson (1996). For each of the 31 categories certain critical above-ground, surface and below-ground attributes (required by models for the simulation of total evaporation, soil moisture, runoff and sediment production) have been assigned in a consistent methodology based on field research, the literature and experience (Schulze, 2001c). For some hydrologically critical land uses (e.g. commercial afforestation, dryland sugarcane, urban residential areas) the attributes have been assigned at a more detailed level than the Thompson categories, to allow for more detailed simulations to be undertaken (Schulze, 2001c).

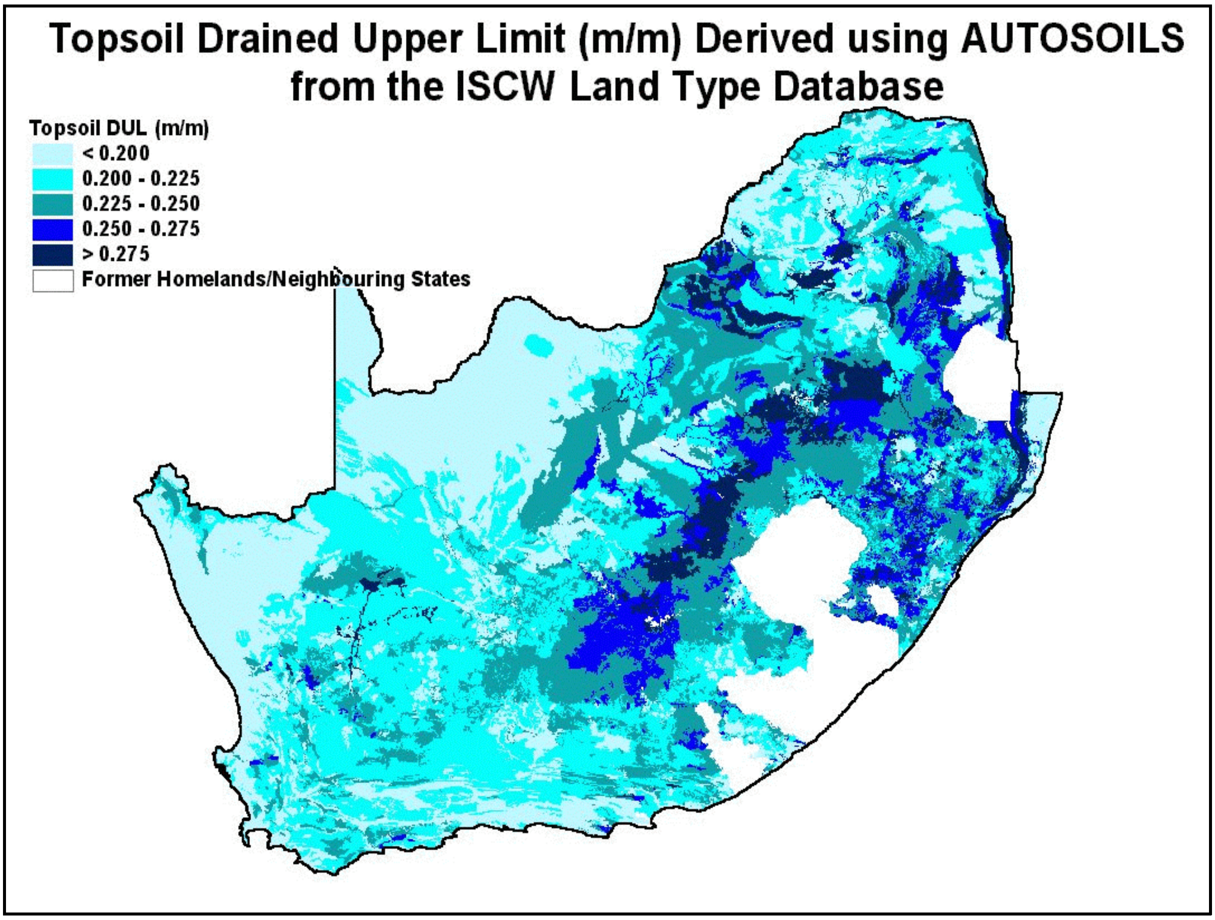

Figure 2.4 'Translation' of ISCW land type information by AUTOSOILS into a hydrological variable required by hydrological models (after Pike, 1999)

- The hydrologically translated variables of soils and land use input are not model specific and can, therefore, be used generically in many models.

e) Basic Premise 17 : Through overlays of relevant GIS coverages many problems of the hydrological uniqueness of individual catchments can now be overcome

- It is a 'geographical aphorism' to stress that every catchment is unique (Beven, 2000, p 301) and this uniqueness underlies many of the difficulties inherent in hydrological theorising and understanding.
- However, with the increasing availability of hydrologically translated variables available in the form of national GIS coverages, many of the uniquenesses of individual catchments, for which parameter transfer from 'similar' catchments was a hazardous exercise in the past, can now be expressed through physically realistic variables (with initial and boundary conditions) from the detailed spatial databases discussed above.
- This allows for the application of models to catchments other than those where observations facilitate calibration and verification, thereby greatly aiding decisions in IWRM.

2.5 WHAT ARE SOME OF THE ISSUES OF PRACTICAL APPLICATIONS OF HYDROLOGICAL MODELLING IN I.W.R.M.?

a) Basic Premise 18 : The modelling system must be applicable at the catchment scale

- In a South African context this implies applicability at Water Management Area (WMA) scale, to address issues relevant to Catchment Management Agencies (CMAs), such as the human and
- Some of the WMAs consist of a single, contiguous catchment; others are made up of multiple catchments. However, all are made up of hydrologically linked, cascading Quaternary Catchments (QCs), which constitute the smallest operational catchment level of DWAF.
- The databases of each QC will need to be populated for use in modelling with information typical of that required by operational catchment units, e.g. on climate, land use, irrigated areas and their water demands/supply, dams and their attributes, water transfers, reservoir operating rules and return flows as well as on socio-economic and demographic characteristics.

b) Basic Premise 19 : The multi-scalar issues in IWRM as well as the intra-catchment spatial variability imply that catchments may need to be dis-aggregated into smaller, more homogeneous units than the Quaternary Catchments in order to account for the non-linearities of hydrological responses within the Quaternaries and to address management conflicts for a range of spatial scales and timeframes

- Modelling for IWRM will have to address multi-scalar management conflicts arising out of
  - upslope vs downslope impacts
  - upstream vs downstream impacts, as well as
  - within vs between Water Management Area transfers.
- Practical modelling has already shown that for IWRM the QC is frequently too coarse a scale, because major critical land use categories or ecological flow requirements or proposed new reservoir development or sources of point pollution do not necessarily coincide with QCs or their flow outlets (e.g. Pike and Schulze, 2000; Taylor *et al*., 2001).
- Statistical analysis has, furthermore, shown that intra-QC variability of gridded altitude (as a determinant of rainfall and potential evaporation) and of gridded rainfall is high enough for approximately 1000 of the 1946 QCs to require subdivision into smaller units on the grounds of natural hydrological variability alone. This is illustrated in Figure 2.5 in which differences in gridded 1' x 1' altitude values between the 90th and 10th percentiles are shown per QC, indicating which QCs may need to be discretised further when based solely on the influence which altitude has on hydrological drivers.
- There are many methods of discretising catchments into relatively homogeneous units for modelling purposes (cf. Schulze, 1998; Krause, 2001), including
  - *raster discretisation* into fixed, equal sided cells to be modelled individually and then linked; a method which assures high parameter homogeneity of individual cells
  - *delineation into subcatchments by topographic watershed boundaries*, such as subdivision of QCs into smaller units according to natural hydrological criteria (e.g. dominant land uses, soils, physiography, climate) or water resources management criteria (e.g. gauging stations, IFR sites, dam sites, abstraction points; Figure 2.6); these are then hydrologically interlinked, with outflows of upstream becoming inflows into downstream subcatchments; however, each subcatchment may still display relatively high intra-catchment heterogeneity of relevant parameters and dominant processes may, therefore, be integrated and still misrepresented hydrologically
  - *land use classified subcatchments*, where each catchment is divided into pre-selected land use classes (each with assumed homogeneous hydrological responses) by area, for rapid application when impacts of present or anticipated future land use scenarios are evaluated by the model (Figure 2.6)
  - *hydrologically homogeneous response units*, created by GIS overlays of relevant hydrological variables (e.g. slope, soils, land use) and where subdivision of these highly homogeneous units can be effected at different spatial resolutions of basic data according to their local criticality, but where the spatial scattering of individual units are not connected in any hydrologically logical manner, and
  - *discretisation by similar runoff generation processes* which delineate, for example, areas dominated by (say) Hortonian overland flow, saturated overland flow, interflow, or

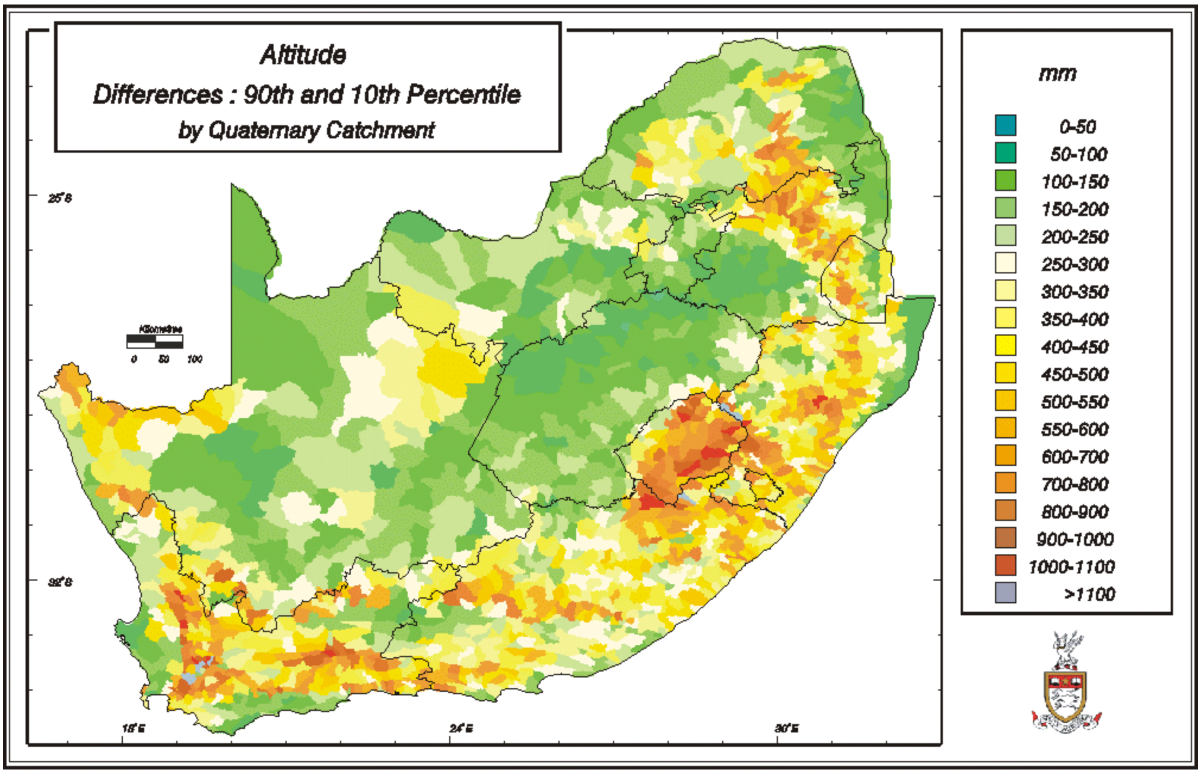

Figure 2.5 Differences between the 90th and 10th percentiles of gridded altitudes per Quaternary Catchment in South Africa, Lesotho and Swaziland

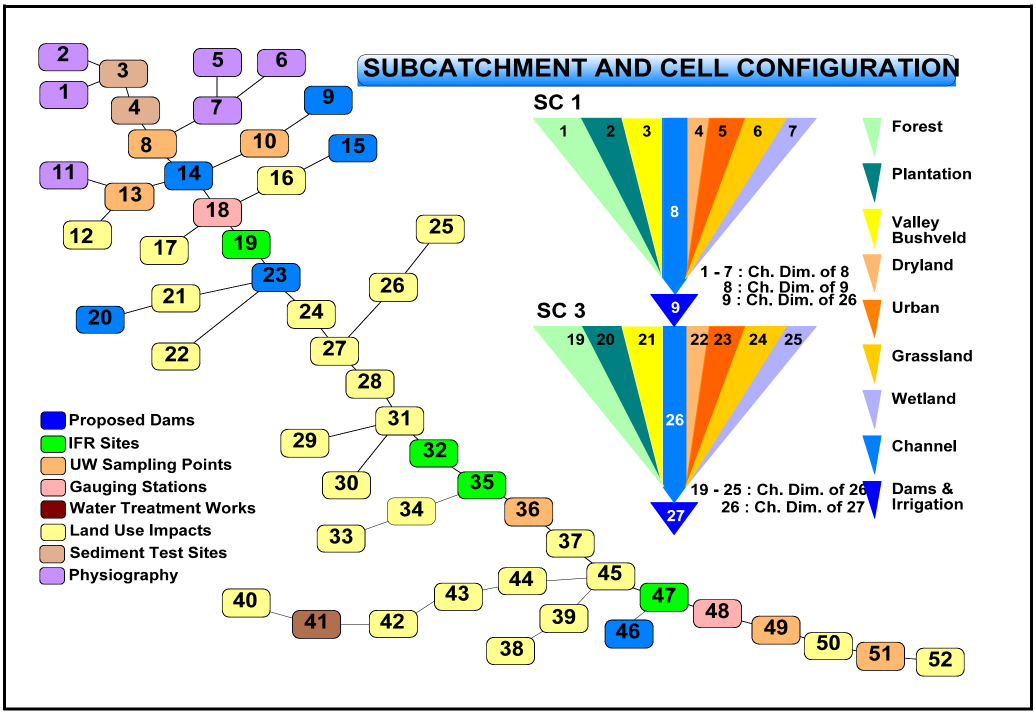

Figure 2.6 An example from the Mkomazi catchment of subcatchment discretisation by watershed boundaries and with further subdelimitation of land use classification (after Taylor *et al.*, 2001)

preferential recharge zones; alternatively, using toposequentially derived terrain units in which water cascades downslope (at, near or below the surface) from crest to scarp (if present) to midslope, the footslope zone to the riparian (or variable source area) zone.

- Several of these methods of discretisation facilitate modellers to 'zoom in' or 'zoom out' according to the level of detail required for solution to a particular problem.

c) Basic Premise 20 : In hydrology one can readily scale up, but not scale down

- Scaling up, or aggregating, implies that from (say) daily models one can sum daily output to monthly totals; or from a detailed land use discretisation one can derive broader generalisations of land use; alternatively, one can derive a 'whole catchment' average of soil properties from soil characteristics of individual hillslope elements (i.e. terrain units). An example of the latter is illustrated in Figure 2.7, which shows differences in simulated soil moisture content for terrain units 1 (crest), 4 (footslope) and 5 (valley bottom) of a single soil mapping unit (*viz.* land type Ac207) at Cedara in KwaZulu-Natal.

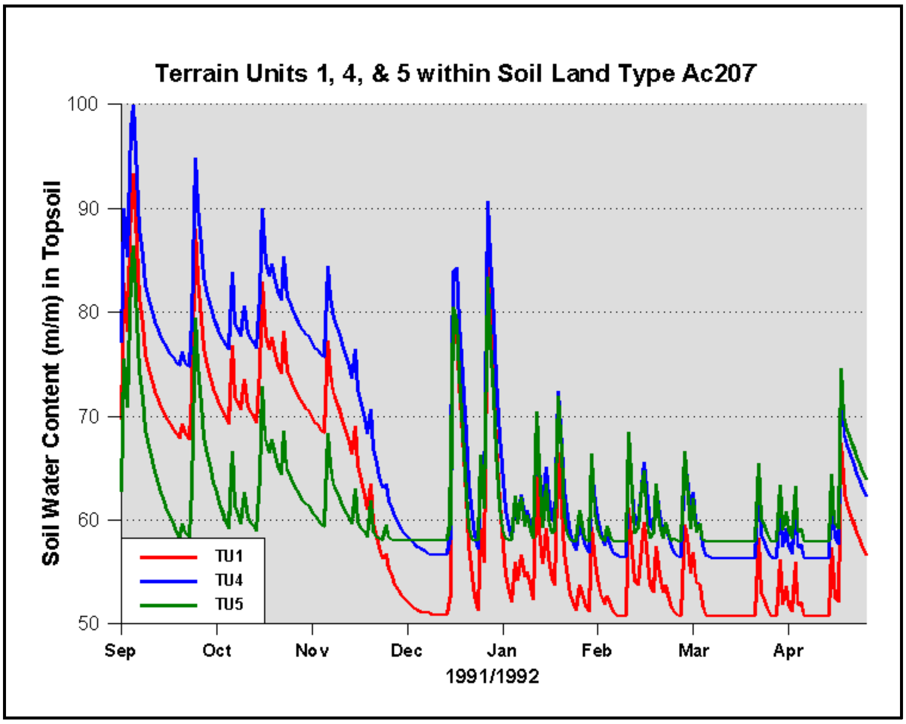

Figure 2.7 An example of terrain unit differences in soil water content within a single land type (after Pike, 1999)

- The opposite, *viz.* scaling down, is however either physically not possible (e.g. obtaining finer critical land use detail from a coarse spatial resolution is not possible), or remains highly synthetic even though results may be satisfactory (e.g. deriving daily values from a monthly time step model).
- With the high processing speeds of contemporary computers it is, therefore, usually advisable when configuring catchments for modelling in IWRM to utilise the finest resolution in time and space that is practically possible, for this will facilitate addressing issues of conflict at the scales at which they matter, be they upslope vs downslope within the same catchment or valley, or the immediate upstream vs downstream or at the more regional scale.
- Again, the ability to 'zoom in' and 'zoom out' will become a very necessary modelling tool in IWRM.

2.6 WHAT SPECIAL RESPONSIBILITIES ARE CARRIED BY MODEL DEVELOPERS AND MODEL USERS, AND WHAT PROTOCOLS DO THEY NEED TO FOLLOW, WHEN MODELLING FOR I.W.R.M.?

With hydrological modelling for IWRM goes a huge responsibility, as the hydraulic/hydrological decisions made on the basis of model output are usually very expensive and structures, once built, are essentially non-reversible with life spans of decades. Both model developers and users carry considerable responsibility. What follows below is a very much abridged summary from Schulze (1998).

a) Basic Premise 21 : Model developers need to respond to hydrological and water resources issues within the hydro-environment in which they are operating

- The model developer (MD) provides a 'tool for the trade' for practitioners and, therefore, has to render the model
  - effective
  - robust
  - relatively easy to use
  - credible to use and
  - accessible to use.
- As such, the model developer has to be
  - *demand driven* by user and decision maker needs (re. what is needed in IWRM, how it is needed, what user priorities are), but equally has to be
  - *curiosity driven* in order to add to the scientific knowledge base (as distinct from only the technological and/or operational knowledge bases).
- In a South African context this implies servicing the needs of the NWA (1998) and the Water Services Act (1997) by providing a scientifically well founded modelling framework to answer questions on, for example,
  - SFRAs
  - IFRs
  - impacts of riparian clearance
  - risk management
  - rural water supplies or
  - water conflict management

  at both the national scale as well as at the 'immediate' scale of upstream vs downstream impacts.

b) Basic Premise 22 : Model developers have to anticipate relevant modelling needs ahead of water-related crises and legislation

- Equally important to responding to current regional needs is that MDs should anticipate what will become issues several years ahead of legislators and regulators, and be proactive (rather than merely reactive) in their model development and conceptualisation.
- In a southern African context this might imply *now* emphasising more research and model development on, for example,
  - near real-time hydrology on a country-wide scale
  - hydrological forecasts in an ensemble 1 day to 1 season ahead of time
  - hydro-economic issues
  - linking hillslope hydrological processes to operational decision making on water quality/contaminant flow issues of the future
  - more physically based land use driven salt, nutrient and sediment yield algorithms off the catchment and in the channel
  - ecohydrological interactions and bio-indicators
  - water use efficiencies of different crops in different regions and different landscape elements within the catchment
  - impacts of veld degradation and rehabilitation
  - indicators of the biological health of rivers, e.g. *E. coli*
  - impacts of potential changes in climate means, persistencies and variabilities or
  - continuous modelling of floods.

c) Basic Premise 23 : Model developers have to follow protocols on conceptual/ethical issues as well as on pragmatic model structure issues

- The MD, who has to synthesise generalities and algorithms from a maze of specialist knowledge and information in the literature, needs to have a high level of conceptualisation of the hydrological system, as well as of the individual and collective processes, interlinkages and feedbacks making up the system. It is for this reason the MDs should, ideally, have considerable experience in hydrological fieldwork.

- It is vital that each representation of individual processes with a model used in IWRM be at a *comparable level of complexity*, because in hydrology the 'weakest link in the chain' concept holds, i.e. the model is as good as its weakest process representations and not as good as its most complex routines.
- For these reasons alone the indiscriminate 'mixing and matching' of routines from models of different complexity or levels of conceptualisation violates a fundamental rule of model development.
- Model developers should guard against over-parameterisation (as distinct from the model's containing as many variables, with physically defined upper and lower bounds, as is deemed necessary).
- As clearly as MDs tend to state the strengths of their respective models, they should identify and document equally clearly
  - under which conditions the model (or module thereof) is valid and not valid, hence identify its possible applications and non-applications
  - all assumptions made and their limitations
  - which parameters/variables are more sensitive than others and
  - where to derive accurate model inputs.
- In regard to developing pragmatic modelling systems
  - sound programming standards, conventions and procedures have to be laid down and adhered to (cf. Clark *et al*., 2001) and
  - user-friendly code has to be sprinkled with liberal comments, for
  - invariably source code will have to be shared with others when model refinement/enhancement takes place. Furthermore,
  - modularisation is vital for ease of future model development (e.g. Clark *et al*., 2001).
- In regard to model user friendliness the MD should include the following:
  - *pre-processing utilities*, i.e. model-associated software to
    - facilitate easy access to data/parameter/variable input, such as links to national databases and GIS coverages on, for example,
    - soils or land use, together with 'translation' algorithms into model useable variables, to
    - pre-processed climatic information, or to a
    - model menubuilder linked to 'help' facilities;
  - suggested *default values* for certain parameters and variables, derived from the collective knowledge from the literature, modelling experiences of the MD and previous users, with defaults given because users do not always have the appropriate background in hydrology, nor a modelling background, to select appropriate parameters, and
  - *post-processing utilities* for production of appropriate statistical summaries of output, as well as tables, graphs, reports or maps.

d) Basic Premise 24 : The era of the one person, ad hoc funded model developer has long passed. To be cost effective and relevant for IWRM, demand driven modelling by teams made up of diverse specialists should be undertaken with sustained financial support

- The comprehensive, integrated models required to help solve present and future hydrological problems contain the collective experience and wisdom of many years from many scientific and technological disciplines.
- Because of its interdisciplinary nature which requires a range of specialist skills, the task of developing new modelling systems has, generally, become too big and complex for any one individual to undertake.
- Comprehensive modelling efforts should, therefore, be undertaken by teams with a range of specialist skills.
- Unless long-term financial backing is provided, models do not attain enough momentum to become credible among users; furthermore, the important functions of institutional memory, continuity of model development and back-up of the system are lost. Interest is then lost by users and the whole development will have become a very expensive (often wasteful) exercise.

e) ***Basic Premise 25 : Operational modelling systems should be comprehensively documented by model developers and be supported by specialist user consultants***

- For the user, the model documentation is 'the model', as it reflects on its capabilities. For many models adequate documentation is conspicuous by its absence and for the standard practitioner, scientific papers in specialist journals or conference proceedings are not adequate substitutes for systematic formal model documentation.
- Documentation should consist of more than merely a recipe type user manual. It should include documentation on the background, concepts and theory underlying the model, with all equations given and assumptions outlined. Detailed specifications on what user manuals of hydrological models should ideally contain are given by Schulze (1998).
- For purposes of credibility, general acceptance and continuity, MDs and funders of modelling systems must ensure not only software support, but also 'people-ware' support by way of accredited user consultants who
    - know the model, its coding, its capabilities and limitations intimately
    - provide assistance to users, either on-line or personally on a one-on-one basis
    - provide users with information on model changes, the latest updates, the latest user experiences and 'tricks of the trade' and
    - organise and present public and one-on-one model courses.

f) ***Basic Premise 26 : Hydrological modelling should be viewed as a specialist operation and not a managerial function. Model users should, therefore, be trained what to do and what not to do when modelling, and to take their responsibilities very seriously***

- An appropriate model becomes a valuable tool only when it is applied correctly and responsibly by users.
- The major responsibility of the user is to *comprehensively understand the model*. That includes
    - working within the model's goals, objectives, capabilities and representation of the hydrological system
    - understanding its structure and internal options
    - its assumptions and limitations, especially in regard to scales of space and time
    - its potential for use, as well as abuse and non-use for specific problems and
    - its minimum and optional input requirements.
- What the user should *avoid* is taking a *'black box view'* of the model, e.g. by
    - attempting short-cuts
    - not studying the manual very carefully and
    - not understanding the underlying theory behind the various concepts, options or pathways in the model.

  Such a 'black box' view eventually backfires on the user.
- Users tend to want model answers quickly, often
    - without a thorough field knowledge of the catchment, which has to be obtained in order to gain a feel for the catchment
    - without applying the 80% rule, i.e. *thoroughly checking* model input parameters, especially the sensitive input data (rainfall), as well as checking the absolute control against which model output, usually streamflow, is being history-matched (cf. Figure 2.8)
    - without going through the *steps, guidelines and protocols* (often laid down clearly in user manuals, and for good reason, as they are based on many previous users' experiences and follies) to ensure the final answers are hydrologically valid
    - without always applying *'hydrologic logic'* to model output, i.e. checking that output is intuitively correct, or
    - without *interpreting the results carefully* before disseminating them to clients.
- Users do not do their cause any good by applying the 'more haste less speed' principle.
- A significant number of the problems identified above may be traced back to many present-day model users coming from the era of external calibration in modelling, where adjusting parameters until output complies with preconceived levels of goodness-of-fit mistakingly implies good modelling practice, when in reality the final set of calibrated parameters does not always reflect hydrological reality (the equifinality principle).
- With modelling being a specialist operation, it is a myth to believe that every manager should be able to operate comprehensive modelling systems on their PCs to obtain quick answers to

complex questions of IWRM. They can, at most, run pre-packaged scenarios provided by specialist modellers or spreadsheet type models.

- Important, therefore, is the model user's responsibility to stay in touch with the MD - to feed back problems, results and interpretations, to suggest improvements and obtain the latest model updates, if for no other reason than as a validation of accredited model usage.

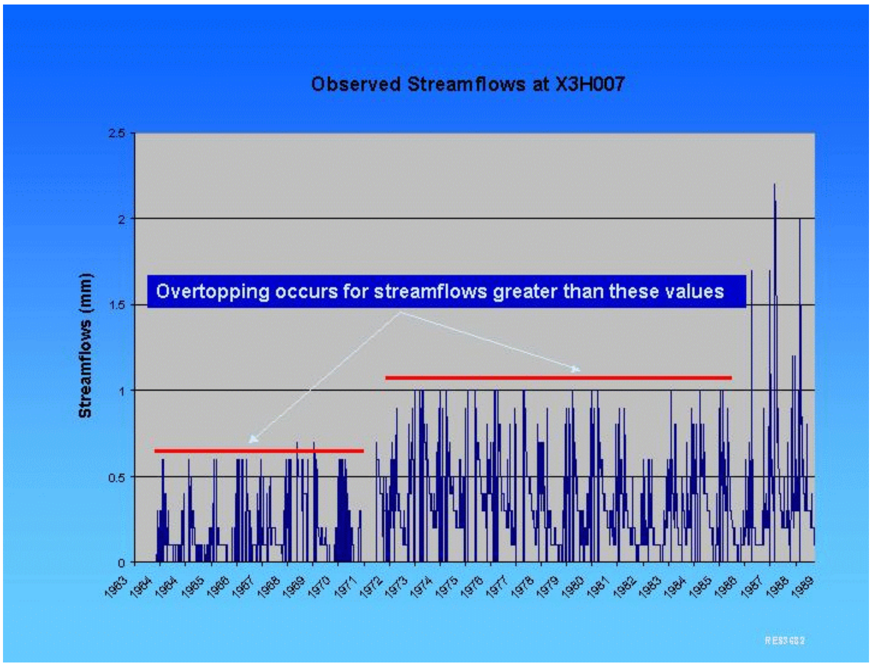

Figure 2.8 An example of inadequately quality controlled streamflow information against which model output is verified (after Pike and Schulze, 2000)

g) *Basic Premise 27 : The adoption by users of 'new' models from overseas for the 'new' paradigms in IWRM in South Africa is beset with pitfalls. Modifying existing credible modelling systems appears a viable and cost-effective alternative*

- There are compelling arguments for adopting new models : they may be customised for specific processes or regions, address new areas of relevance and concern, have attractive pre- and post-processing modules or be slickly marketed by donor organisations (Schulze, 1998).
- Experience of adopting new models in South Africa has, however, not always been positive. It takes a long time for users/institutions to accept new models, sustained user support is not always forthcoming, sponsoring donor organisations come and go without long-term commitment, coding errors found are not easily fixed, process representation may not be applicable to local conditions/responses and the often detailed data demands of such models may be difficult to meet.
- Several millions of Rand have been spent in the past decade in South Africa on testing/rejecting new overseas models.
- A viable and cost-effective (i.t.o. time and money) alternative may be the selection of a limited number of established and credible modelling systems with inherently sound process representations and modelling protocols, around which a pool of local expertise already exists, and to then modify, adapt, enhance or develop the system further, in collaboration with the broader user community, and build expert and decision support around that framework.
- It should be noted that wrapping flashy pre- and post-processing modules around inherently weakly conceptualised models does not constitute an advancement in modelling, nor a new version of the model.

2.7 WHAT CONCLUSIONS MAY BE DRAWN FROM THE ABOVE DISCUSSIONS?

a) Basic Premise 28 : We need reminding that the fundamental objective of modelling revolves around understanding the hydrological system to manage water resources sustainably. This management is, however, of an already 'damaged' ecosystem

- As a consequence of the historical approach to water resources management, which was initially one of 'conquer and develop', later to build dams and transfer water and more recently to solve many water quality problems by chemical treatment rather than at source (Falkenmark *et al*., 1999), we have *inherited a 'damaged' ecosystem* (Newson *et al*., 2000), which has been illustrated and elaborated upon in Chapter 1. In summary, however, it shows spontaneous regulatory functions of rivers and their catchment areas having been disturbed or removed (i.e. changes of state) through human activities (i.e. drivers and pressures). The manner of exploiting water and land has changed through intensification of water use as well as by the destruction of traditional extensive exploitation (impacts). To complete the DPSIR approach, which was alluded to in the introduction, the response to this damaged ecosystem is IWRM, in which modelling plays a central role.
- To this end the *fundamental objective of modelling* has to be brought into perspective again, it being to gain an understanding of the hydrological system in order to provide reliable information on managing water resources in a sustained manner to increase human welfare and protect the environment (Schulze, 1998).
- This fundamental objective of modelling is also at the core of IWRM.

b) Basic Premise 29 : Hydrological modelling remains an imperfect science because many uncertainties abound. Appropriate models for IWRM nevertheless have to be chosen according to pre-determined criteria

- A single true, or perfect, hydrological model does not exist and is, indeed, an unreachable goal for 'we have neither the model structures nor the data to identify that complex, unique, single realisation that is the real catchment' (Beven, 2000, p 304). Many uncertainties in hydrological models therefore exist. These are elaborated upon in Chapter 6, but are summarised below.
- Conceptually, uncertainty has four sources (Suter, 1993), *viz*.
  - *stochasticity*, i.e. the inherent unknowable randomness (e.g. of rainfall)
  - *ignorance*, i.e. the imperfect or incomplete knowledge of things potentially knowable (e.g. short records; poor hydrological networks)
  - *human errors*, including poor quality control of model input and
  - *scaling*, both up and down.
- Hydrologically, uncertainties may also be classed into three major categories (Chapter 6), *viz*.
  - *Uncertainties in inherent components of the system*: In this regard further uncertainties arise when future scenarios are considered. Two are important:
    - *Climate drivers*. These uncertainties revolve mainly around rainfall - its amount, seasonal timing, duration, intensity, persistence and its spatial distribution. Should modelling revolve around future climate scenarios, all those attributes are postulated to change on an event and seasonal basis, and any changes in probabilities cause amplified responses in runoff.
    - *Catchment conditions*. Runoff responses to individual rainfall events are heavily dependent on the catchment's soil water status. Catchments are not stationary, neither in terms of antecedent wetness, nor in terms of runoff intensifying or reducing land use changes over time, nor in regard to channel manipulations over time (e.g. dam construction, water diversions/transfers). Again, for future scenarios a number of questions arise: How are land cover management strategies going to change? Where? And how do model parameters change to accommodate the above? (Beven, 2000).
  - *Uncertainties in the data sets used in modelling*: Associated with these are, for example,
    - *data length* : are short data sets statistically representative of the long term?
    - *data quality*: stemming from the inherent inaccuracies in rainfall and runoff measurements, the incidence of missing data, inadequate instrument design and maintenance (e.g. control runoff gauging stations being overtopped during floodings at certain threshold stage heights, thereby invalidating their data for

verification purposes, as illustrated in Figure 2.8)
    - *data network density*, including regional representativeness of stations and conversion of point to spatial data and
    - *data availability* from official and other sources.
  - *Uncertainties resulting from the model's conceptualisation of processes*: These include the detail of process representation and parameterisation of land use and soil input, which contain point uncertainties and some spatial randomness which are usually not considered in modelling.
- Despite all these uncertainties, and the fact that no single model can be validated as 'the best' representation of the catchment's processes, models can be evaluated by well documented criteria (e.g. Schulze, 1998; Beven, 2000) and rejected, either as individual models or as whole classes of models. The surviving ones can then be re-evaluated, or ranked, or classed for suitability to specific tasks within IWRM.
- The model selection criteria (Schulze, 1998; Beven, 2000) include the following:
  - is the model readily available in the public domain?
  - is it supported by good documentation and user consultants?
  - does the model output those variables typically/specifically required by IWRM?
  - are the assumptions made by the model likely to be limiting (e.g. its time step, process conceptualisation) for the task at hand or the catchment under consideration?
  - can the model inputs be provided within time/cost constraints?
  - has the model been evaluated i.t.o. sensitivity to input and is sensitive input available in enough detail?

c) Basic Premise 30 : Modelling is not the panacea to all problems in IWRM. Some notes of caution on hydrological modelling therefore need to be sounded

- Models cannot substitute, or compensate, for a lack of hydrological knowledge, or the understanding of the hydrological system.
- Models also cannot create new facts or data. In hydrology these can only emanate from, and be confirmed by, observation, experimentation and measurement.
- Models can, at most, create information and can only anticipate the possibility that conditions, as simulated, will indeed occur.
- Models, no matter how sound their structure, cannot yield meaningful results when no satisfactory input data are available, for 'one cannot create something out of nothing'.
- Model output should never be compared against that from another model when assessing its accuracy, because other models may have different structures, timesteps and objectives. A model's performance can only be judged against appropriate, valid observations.

2.8 ACKNOWLEDGEMENTS

The experiences gained in modelling, and shared in this chapter, are those of many colleagues in our modelling team. I wish to acknowledge with sincere thanks their support and loyalty over many years in a major team effort in modelling. The helpful suggestions by reviewer Professor Denis Hughes, of Rhodes University, are also acknowledged gratefully.

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CHAPTER 3

THE *ACRU* AGROHYDROLOGICAL MODELLING SYSTEM AS OF 2002 : BACKGROUND, CONCEPTS, STRUCTURE, OUTPUT, TYPICAL APPLICATIONS AND OPERATIONS

R.E. Schulze and J.C. Smithers

School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

ABSTRACT

This chapter commences by tracing the development of the *ACRU* agrohydrological modelling system, from a distributed catchment evapotranspiration model in the mid-1970s through its various phases of enhancement, with milestone years in terms of new documentation being 1984, 1989 and 1995, to the present system, which is a multi-partnered national and international development spearheaded by funding from the Water Research Commission.

The conceptual basis of the model is outlined next. This includes discussion on the model's physical-conceptual process representation and on *ACRU* as a multi-purpose and multi-level model founded on daily multi-layered soil water budgeting procedures. The model can be operated as a lumped or distributed catchment simulator of streamflow components, with options for reservoir yield, sediment yield, irrigation demand/supply, crop yield and climate change analyses, with a strong focus on land use impacts on hydrological responses. The model contains a dynamic input option to account for changes, either abrupt or gradual, in the catchment over time. Thereafter, the *ACRU* model's water budget is described, with emphasis on the vertical redistribution of soil water, evapotranspiration processes and runoff generation mechanisms, followed by a section on output options from the model.

A major section of the chapter is a review of applications of the model to date, with some 150 references from the international and national refereed literature, conference proceedings, as well as research and consulting reports being cited. Examples of applications are categorised into water resources assessments (ranging from small to large catchments' to national scale assessments), design hydrology, irrigation supply and demand, crop yield and primary production modelling, land use impacts, forest hydrological impacts, groundwater modelling, hydro-economic analyses, impacts of climate change on both crop yields and hydrological responses, seasonal agrohydrological forecasting for operational purposes, applications in the service of the National Water Act of 1998, and international applications.

A section is devoted to the operation of *ACRU* as a distributed model. Modelling system components and linkages are illustrated and typical minimum input requirements are presented diagrammatically before some of the main system utilities, such as the *ACRU Menubuilder*, its *Outputbuilder* and the option for use of a stochastic daily rainfall generator are discussed.

This is followed by a section on capacity building which highlights contributions to the modelling system's development made by masters and doctoral students, and then concludes with a summary of perceived model system strengths, what the model should *not* be used for and where the current (2002 and beyond) research focus lies.

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3.1 WHAT DOES THIS CHAPTER SET OUT TO REVIEW?

The objective of this chapter is to review

- the historical development of the *ACRU* agrohydrological modelling system,
- its concepts, philosophies and general structure,
- the operation of the model's water budgeting processes,
- typical simulated output options,
- the range of applications to which the model has been applied,
- how the model operates as a distributed model,
- how the components of the modelling system are linked,
- the model's typical minimum data and information requirements to operate,
- the utilities which come with the model,
- the contributions made by masters and doctoral students in the model's development, and, by way of conclusion,
- thoughts on the *ACRU* modelling system, highlighting its perceived advantages, under which circumstances not to use the model and where future development is being focussed.

This review updates and supercedes those of Schulze (1995) and Smithers and Schulze (1995) and is inclusive of developments and applications up to 2002.

3.2 HOW DID THE *ACRU* MODEL COME ABOUT? . . . WHAT IS ITS PRESENT STATUS?

The *ACRU* model has its *hydrological* origins in a distributed catchment evapotranspiration based study carried out in the Natal Drakensberg in the early 1970s (Schulze, 1975). Although the acronym *ACRU* now represents a generic model name, it was initially derived from the ***A**gricultural **C**atchments **R**esearch **U**nit* within the erstwhile Department of Agricultural Engineering, now School of Bioresources Engineering and Environmental Hydrology, at the University of Natal in Pietermaritzburg, South Africa. The *agro*hydrological component of *ACRU* first came to the fore during research on an agrohydrological and agroclimatological atlas for Natal (Schulze, 1983a). Since then the model has developed, through co-operation with many colleagues and graduate students, and with funding provided primarily from the Water Research Commission (WRC), to its present status. Other partners in the development of *ACRU* have been the forest industry, the SA Sugar Association's Experiment Station, the University of Natal Research Fund, the National Research Foundation, US Country Studies for Climate Change Programme, the European Union, the Department of Water Affairs & Forestry, Universities of the Free State and Stellenbosch in South Africa, Universities of Bonn and Jena in Germany, of Cornell and Florida in the USA, the Department for International Development of the UK, Environmentek of the CSIR and Water Management Area Consultants (WMAC).

User documentation on *ACRU* was first published in 1984 (Schulze, 1984) and updated in 1989 (Schulze, 1989a; 1989b; Schulze, George, Lynch and Angus, 1990). A series of papers and reports applying continually updated and more sophisticated versions of the model has been published in the international and southern African literature, the major papers on developmental aspects being an overview by Schulze (1986), a paper on its application as a dynamic simulator of afforestation effects on runoff (Schulze and George, 1987a), a synthesis on its status as of 1988 by Schulze (1988a) and an unpublished report to the WRC in 1992 on new development to the model up to that time, mainly in regard to flow routing, wetlands, shallow groundwater routines, a forest Decision Support System and model linkage to a Geographic Information System (GIS). There are two major current references to the *ACRU* model. The 552 page *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System,* under the editorship of Schulze (1995) and also popularly referred to as *ACRU Theory*, contains background, concepts and theory in 24 chapters. Accompanying this text is the 371 page *ACRU User Manual Version 3.00* by Smithers and Schulze (1995), which includes operating instructions, input requirements and information, interpretation and graded exercises. Both the *ACRU Theory* and *User Manual* are now available on line at www.beeh.unp.ac.za/acru, through which medium they are currently also updated. A restructured version of the *ACRU* system using an object-oriented design methodology has been described in detail by, for example, Lynch and Kiker (2001) and Clark, Kiker and Schulze (2001).

Other than in southern Africa (South Africa, Botswana, Namibia, Lesotho, Malawi and Swaziland), the model has been presented via courses, lectures or symposium presentations in Australia, Austria, Benin, Canada, Chile, Costa Rica, Czech Republic, France, Germany, Hungary, Japan, Kenya, Morocco, Nepal, Netherlands, Portugal, Spain, Sweden, Switzerland, Tanzania, the UK and the USA. The model has been verified widely on data from South Africa, Swaziland, Zimbabwe, Germany and the USA. Schulze (1995) in his Chapter 22, presents 11 verification studies on various components of *ACRU*, both of outputs and internal state variables; other output verifications are included in Herpertz, 1994; New and Schulze, 1996; Schulze, Pike, Lecler, Esprey, Howe and Zammit, 1996; Kienzle, Lorentz and Schulze, 1997; Jewitt and Schulze, 1999; Taylor, Schulze, Jewitt and Pike, 1999; Lumsden, Schulze, Lecler and Schmidt, 1999; Pike and Schulze, 2000 and Dlamini, 2001; Gush, Scott, Jewitt, Schulze, Hallowes and Görgens, 2001). *ACRU* has also been used extensively as an aid to decision making in South Africa and by 2001 the model had been applied internationally in hydrological design, the simulation of water resources and research in Botswana, Chile, Germany, Lesotho, Mozambique, Namibia, Swaziland, the USA and Zimbabwe.

3.3 ON WHAT CONCEPTS IS THE *ACRU* MODEL BASED?

Fundamental concepts, basic premises and requirements around which sound operational models should be developed, if they are to be used as decision aids at a time of major paradigm shifts in water resources, have been discussed in detail in Chapter 1 and elsewhere by Schulze (1998a; 1998b; 2000a; 2001a). The *ACRU* agrohydrological modelling system (Schulze, 1995) complies with many of those premises and principles and is centred around the following aims (Figures 3.1 and 3.2):

- It is a *physical conceptual* model, i.e. it is conceptual in that it conceives of a system in which important processes and couplings are idealised, and physical to the degree that physical processes are represented explicitly (Eagleson, 1983).
- *ACRU* is not a parameter fitting or optimising model. Variables (rather than optimised parameters values) are, as a rule, estimated from physically based characteristics of the catchment.
- It is a *multi-purpose* model which integrates the various water budgeting and runoff production components of the terrestrial hydrological system. It can be applied as a versatile model for design hydrology, crop yield modelling, reservoir yield simulation, ecological requirements, irrigation water demand/supply, water resources assessment, planning optimum water resource utilisation/allocation, conflict management in water resources, climate change impacts and land use impacts - in each case with associated risk analyses.
- The model uses *daily time steps* and thus daily climate input data, thereby making optimal use of available data (Schulze, 2001a). Certain more cyclic, conservative and less sensitive variables, (e.g. temperature, reference potential evaporation), for which values may have to be input at monthly level (if daily values are not available) are transformed internally in *ACRU* to daily values by Fourier Analysis. More sensitive intra-daily information (e.g. of rainfall distribution) is obtained by synthetic disaggregation of daily values into shorter duration time steps within the model.
- The *ACRU* model revolves around daily *multi-layer soil water budgeting* and the model has been developed essentially into a versatile total evaporation model (Figure 3.2). It has, therefore, been structured to be highly sensitive to climate and to land cover, land use and management changes on the soil water and runoff regimes, and its water budget is responsive to supplementary watering by irrigation, to changes in tillage practices, enhanced atmospheric CO_2 concentrations or to the onset and degree of plant stress.
- *ACRU* has been designed as a *multi-level* model, with either multiple options or alternative pathways (or a hierarchy of pathways) available in many of its routines, depending on the level of input data available, or the detail of output required. Thus, for example, reference potential evaporation, interception losses, values of soil water retention constants, maximum (i.e. 'potential') as well as total evaporation ('actual evapotranspiration'), leaf area index, components of peak discharge estimation, hydrograph routing, reservoir storage : area relationships or the length of phenological periods in crop growth, may all be estimated by different methods according to the level of input data at hand or the relative accuracy of simulation required.
- *ACRU* can operate as a *point* model, as a *lumped* small catchments model, on large catchments or at national scale. In areas of complex land uses and soils, over large catchments or at national scale *ACRU* operates as a *distributed* cell-type model. In distributed mode individual subcatchments which ideally should not exceed 50 km^2, but which are often at the level of Quaternary or sub-Quaternary (Quinery) Catchments in South Africa, are identified. Once discretised into subcatchments, flows can take place from 'exterior' through 'interior' cells according to a predetermined scheme, with each subcatchment able to generate individually

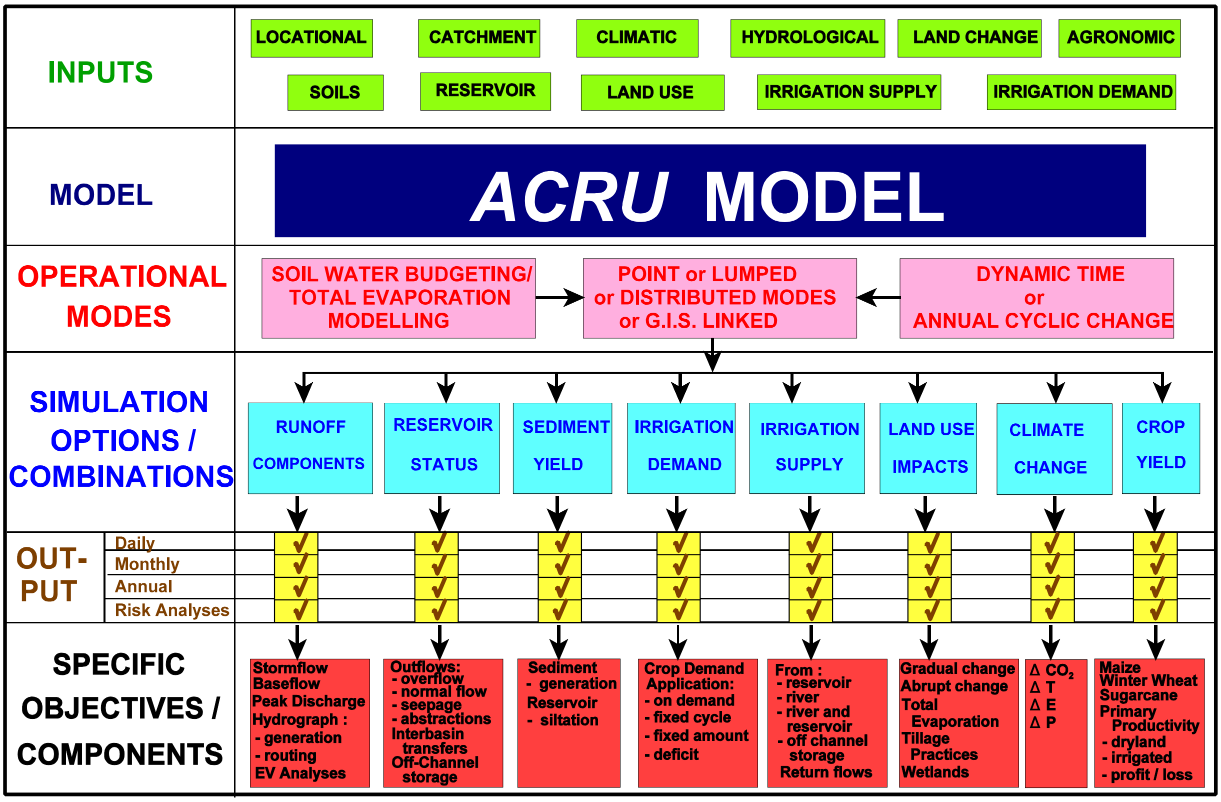

Figure 3.1 The *ACRU* agrohydrological modelling system : Concepts (after Schulze, 1995)

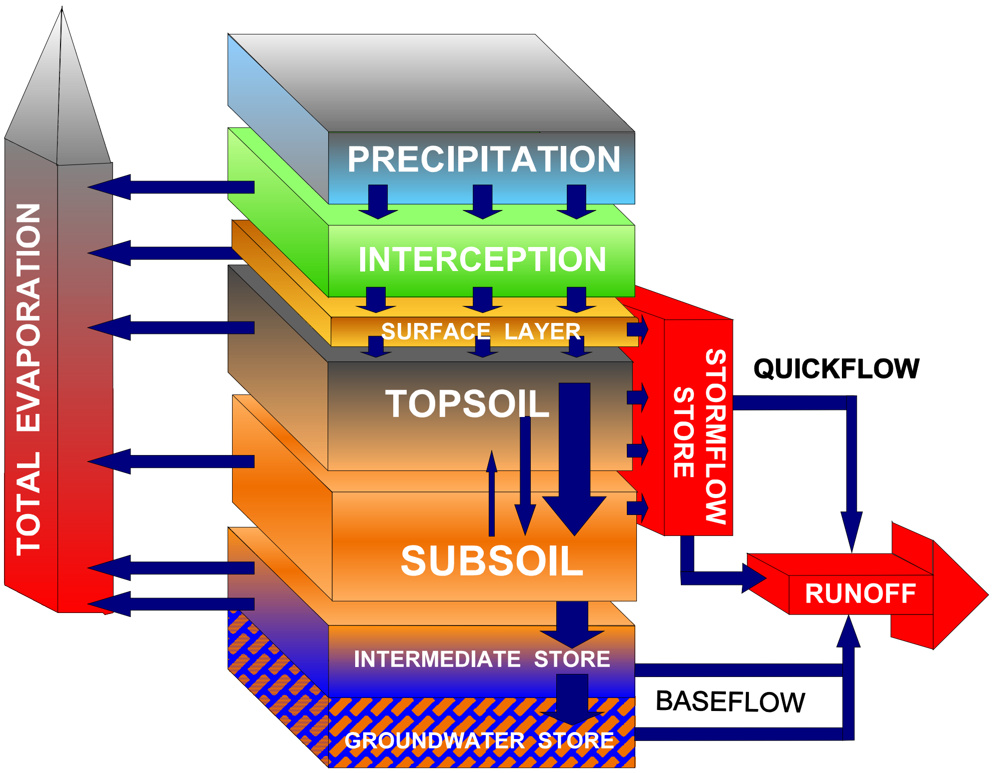

Figure 3.2 The *ACRU* agrohydrological modelling system : General structure (after Schulze, 1995)

requested outputs which may be different to those of other subcatchments or with different levels of input/information.

- The model includes a *dynamic input option* to facilitate modelling the hydrological response to climate or land use or management changes in a time series, be they long term/gradual changes (e.g. forest growth, urbanisation, expansion of an irrigation project or climate trends), or abrupt changes (e.g. clearfelling, fire impacts, construction of a dam, development of an irrigation project, or introduction of new land management strategies such as tillage practices), or changes of an intra-annual nature (e.g. crops with non-annual cycles, such as sugarcane). A dynamic input file is then accessed each year, with the new variable inputs to be used from that year onwards, e.g. water use coefficients, root mass distributions, planting dates or soils properties (e.g. for new tillage practices).
- *ACRU* operates in conjunction with the interactive *ACRU Menubuilder* and *Outputbuilder* and the associated *ACRU Input Utilities*. The latter are suites of software programs to aid in the preparation of input data and information. The *ACRU Menubuilder* prompts the user with unambiguous questions, leading the user into inputing, for example, complex distributed catchment information easily. The *Menubuilder* contains alternative decision paths with preprogrammed *Decision Support* values. Furthermore, the *Menubuilder* includes a *HELP* facility, built-in *default values* as well as warning and error messages. The *Outbuilder* allows the user to select, from a predefined list, which variables are to be stored during a simulation for subsequent output and analysis.
- The *ACRU Output Utilities* enable the user to print out, and to analyse, any observed as well as simulated results. The types of analyses include frequency analysis, extreme value analysis and comparative statistics in order to determine the goodness of fit between simulated and observed data.

3.4 HOW DO THE *ACRU* MODEL'S WATER BUDGETING PROCESSES OPERATE?

Multi-layer soil water budgeting by partitioning and redistribution of soil water is depicted in Figure 3.2 That rainfall and/or irrigation application not abstracted as interception or as stormflow (either rapid response or delayed), first enters through the surface layer and 'resides' in the topsoil horizon. When the topsoil is 'filled' to beyond its drained upper limit (field capacity), the 'excess' water percolates into the subsoil horizon(s) as saturated drainage at a rate dependent on respective horizon soil textural characteristics, wetness and other drainage related properties. Should the soil water content of the bottom subsoil horizon of the plant root zone exceed the drained upper limit, saturated vertical drainage/recharge into the intermediate and eventually groundwater stores occurs, from which baseflow may be generated. Unsaturated soil water redistribution, both upwards and downwards, also occurs but at a rate considerably slower than the water movement under saturated conditions, and is dependent, *inter alia*, on the relative wetnesses of adjacent soil horizons in the root zone.

Evaporation takes place from previously intercepted water as well as simultaneously from the various soil horizons, either separately as soil water evaporation (from the topsoil horizon only) and as plant transpiration (from all horizons in the root zone), or combined, as total evaporation (i.e. 'actual evapotranspiration'). Evaporative demand from the plant is estimated, *inter alia*, according to atmospheric demand (through a reference potential evaporation, E_r) and the plant's stage of growth. The roots absorb soil water in proportion to the distributions of root mass density of the respective horizons, except when conditions of low soil water content prevail, in which case the relatively wetter horizons provide higher proportions of soil water to the plant in order to obviate plant stress as long as possible.

It is vital in land use and crop yield modelling to determine at which point in the depletion of the plant available water reservoir any plant stress actually sets in, since stress implies a soil water content below the optimum for evaporation, hence the necessity to irrigate (if irrigation is applied). It also implies a reduction in crop yield. In modelling terms, this problem may be expressed as the critical soil water content, ψ_l^{cr}, at which total evaporation, E, is reduced to below the vegetation's maximum evaporation, E_m (formerly termed 'potential evapotranspiration'). Experimental evidence points to E equalling E_m until a certain fraction, f_s (Figure 3.3), of maximum (profile) available soil water to the plant, *PAW*, is depleted. Maximum available water to the plant is the difference in soil water content between that at the soil's drained upper limit, *DUL*, and its lower limit, *PWP* (Figure 3.3). Research results show that the critical soil water fraction at which stress commences varies according to atmospheric demand, E_r , and the critical leaf water potential of the respective vegetation, the latter being an index of the resilience of the vegetation to stress situations. The implications of stress setting in at such different levels of soil water content are significant in terms of total crop evaporation, crop production modelling and irrigation scheduling. Total evaporation also reduces when the soil is too wet, as a result of annoxia, with a linear decline assumed when soil water content is above *DUL*, but below saturation, indicated by *PO* in Figure 3.3.

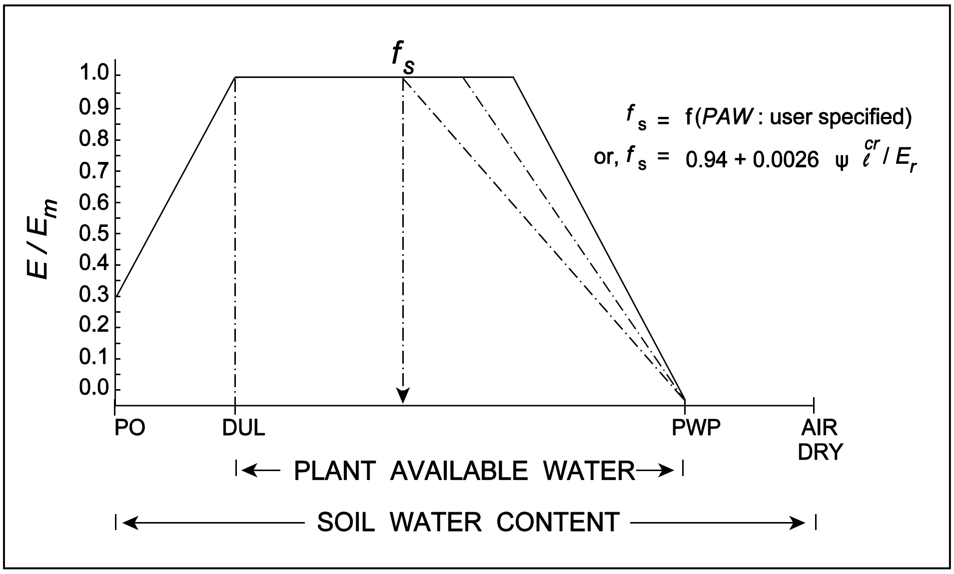

Figure 3.3 Interrelationships used in *ACRU* between soil water content and the ratio of $E : E_m$ (after Schulze, 1995)

The generation of stormflow in *ACRU* is based on the premise that, after initial abstractions (through interception, depression storage and that infiltration which occurs before runoff commences), the runoff produced is a function of the magnitude of the rainfall and the soil water deficit from a critical response depth of the soil, D_{sc}(m). The soil water deficit which is antecedent to a rainfall event is simulated by *ACRU*'s multi-layer soil water budgeting routines on a daily basis. The critical response depth has been found to depend, *inter alia*, on the dominant runoff-producing mechanism. This depth is, therefore, generally shallow in more arid areas characterised by eutrophic (i.e. poorly leached and drained) soils and high intensity storms which would produce predominantly surface runoff, while it is generally deeper in high rainfall areas with dystrophic (highly leached, well-drained) soils where interflow and 'push-through' runoff generating mechanisms predominate (Figure 3.4). Not all the stormflow generated by a rainfall event responds at the catchment outlet on the same day; stormflow is therefore separated into quickflow (i.e. same day response) and delayed stormflow (Figure 3.2), with the 'lag' (which may be conceptualised as a surrogate for simulating interflow) dependent, *inter alia*, on soil properties, catchment size, slope and the drainage density.

Baseflow in *ACRU* is modelled explicitly, with the baseflow contribution deriving from soil water which has percolated out of the base of the subsoil horizon (hence the importance of soil depth and the saturation redistribution fraction) into a baseflow store. The baseflow store is assumed to be 'connected' to the stream's channel system and releases water into the stream through an input decay coefficient which is then varied within the model according to the previous day's ground water store. The stormflow contribution on a given day plus its baseflow, constitute the catchment's total runoff for the day, with both assumed to discharge directly into the stream's channel system.

When riparian zone processes are simulated (for example, when assessing influences of alien invasive infestation in the riparian zone and effects of its clearance), it is assumed that the baseflow contributions from their contributing areas within a catchment, are routed to a defined riparian zone subcatchment as subsurface flows, as illustrated schematically in Figure 3.5. These subsurface flows fill the riparian zone's soil profile from the bottom upwards, thereby increasing the soil water availability to deeper rooted plants. Should the total soil profile become saturated right to the soil surface, any excess water is added to the stormflow contribution. In the riparian zone the main channel has a maximum capacity and when that is exceeded, water spills onto the riparian zone, wetting it from the top downwards.

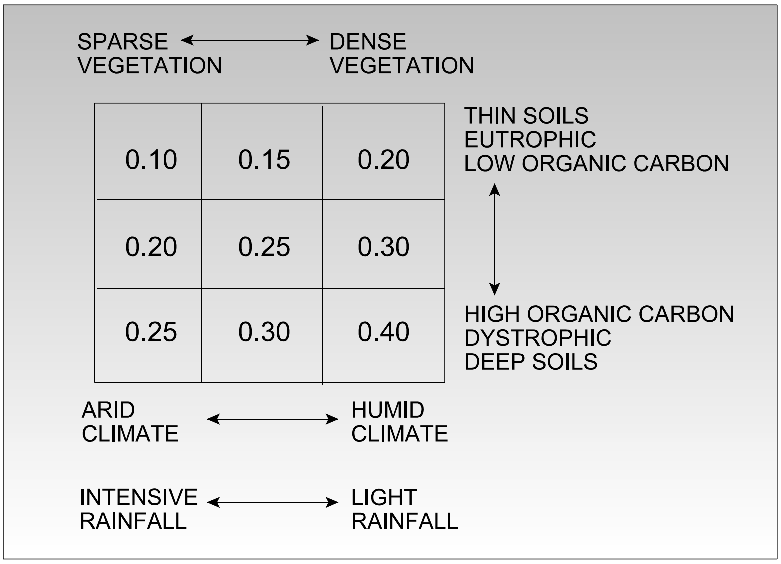

Figure 3.4 Suggested default values of the critical stormflow response soil depth, D_{sc}(m), according to climatic, vegetation and soils characteristics (after Schulze, 1995)

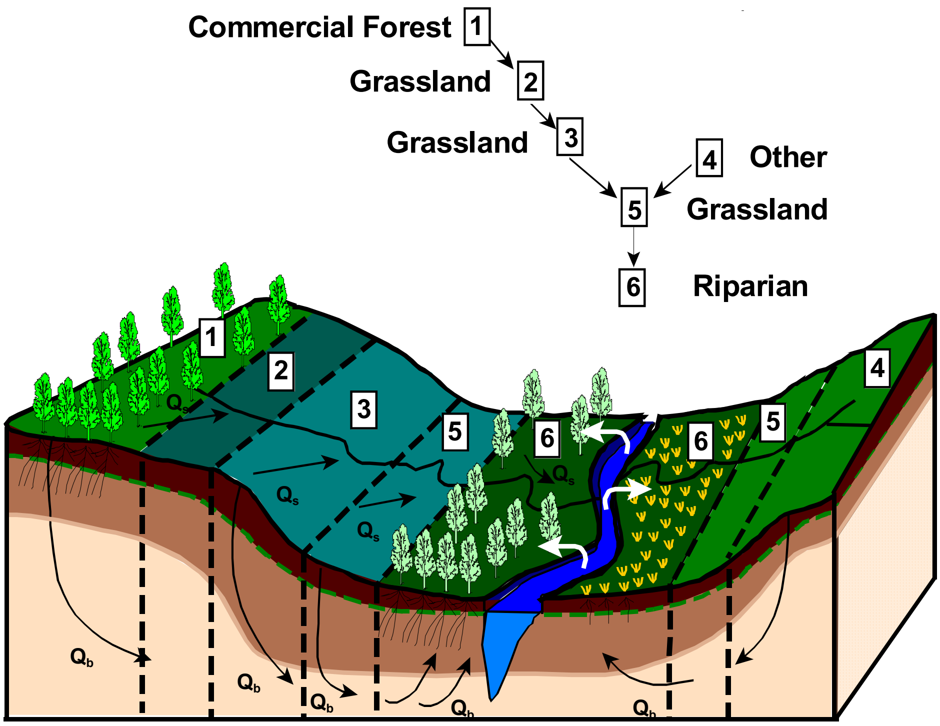

Figure 3.5 Schematic representation of riparian zone processes in *ACRU* (after Meier *et al*., 1997; Schulze, 2000b)

3.5 WHAT OUTPUT CAN BE GENERATED BY *ACRU*?

The 'heart' of the *ACRU* model is a daily multi-layer soil water budget, and hence the model simulates the components of the hydrological cycle affecting this soil water budget, including :

- canopy interception of rainfall by vegetation
- net rainfall reaching the ground surface
- infiltration of net rainfall into the soil
- total evaporation (transpiration as well as soil water evaporation) from the various horizons of the soil profile to root depth
- suppression of soil water evaporation by litter or mulch
- the redistribution of soil water in the soil profile, both saturated and unsaturated, and
- percolation of soil water into the intermediate/groundwater zone.

The model can output any of the above components. In the output routines the user may select which components to output from a predefined list of variables. Thus for example, output on a daily basis, or summations as monthly or annual totals of the daily values, may be made of:

- gross rainfall, i.e. the input daily rainfall, adjusted (if necessary) for systematic differences between station and catchment representative rainfall
- canopy interception
- effective rainfall
- reference potential evaporation, i.e. the input E_r , adjusted (if necessary) for differences between station and catchment representative E_r
- maximum evaporation, i.e. 'potential evapotranspiration', from the vegetation under conditions of freely available soil water
- total evaporation, i.e. 'actual evapotranspiration', in the form of transpiration and soil water evaporation from top- and subsoil horizons respectively
- soil water content of top- and subsoil layers, also in relation to the horizons' drained upper limits and
- drainage from the various soil zones to the next lower zone.

From the soil water budget, the model is capable of outputing simulated elements of streamflow on a daily time step, or as monthly or annual totals of daily values. These include :

- stormflow depth (or volume)
- baseflow depth (or volume)
- total runoff
- accumulated streamflow from all upstream catchments when simulating distributed, multiple subcatchments and
- peak discharge (including hydrograph routing when simulating distributed multiple subcatchments).

The components of the water budget are integrated with modules embedded within the *ACRU* system to enable modelling of:

- effects of land use change and alien vegetation clearance on the riparian zone (Figure 3.5)
- reservoir yield analysis (overflow, reservoir status, abstractions, transfers; including routing of flows through reservoirs; using processes of the reservoir water budget as conceptualised schematically in Figure 3.6)
- sediment yield analysis (daily, monthly, annual; reservoir sedimentation)
- irrigation water demand (for different crops, application efficiencies, modes of scheduling; with processes as illustrated schematically in Figure 3.7)
- irrigation water supply (from streams, reservoirs and combinations thereof; alternatively, pumped off-channel reservoir storage; with processes as illustrated schematically in Figure 3.8)
- wetlands hydrological responses (based on processes as illustrated schematically in Figure 3.9)
- effects of abstractions from the stream (e.g. for domestic purposes) on catchment water yield
- fluctuations of shallow groundwater under certain conditions
- hydrological impacts of afforestation
- effects of other land cover, land use and management (e.g. tillage) changes (gradual or abrupt)
- seasonal crop yields (maize, sugarcane, winter wheat - either dryland or irrigated, as well as for non-crop specific net above ground primary production) and
- the effects of enhanced atmospheric CO_2 levels on transpiration suppression and hence on crop yield and water resources.

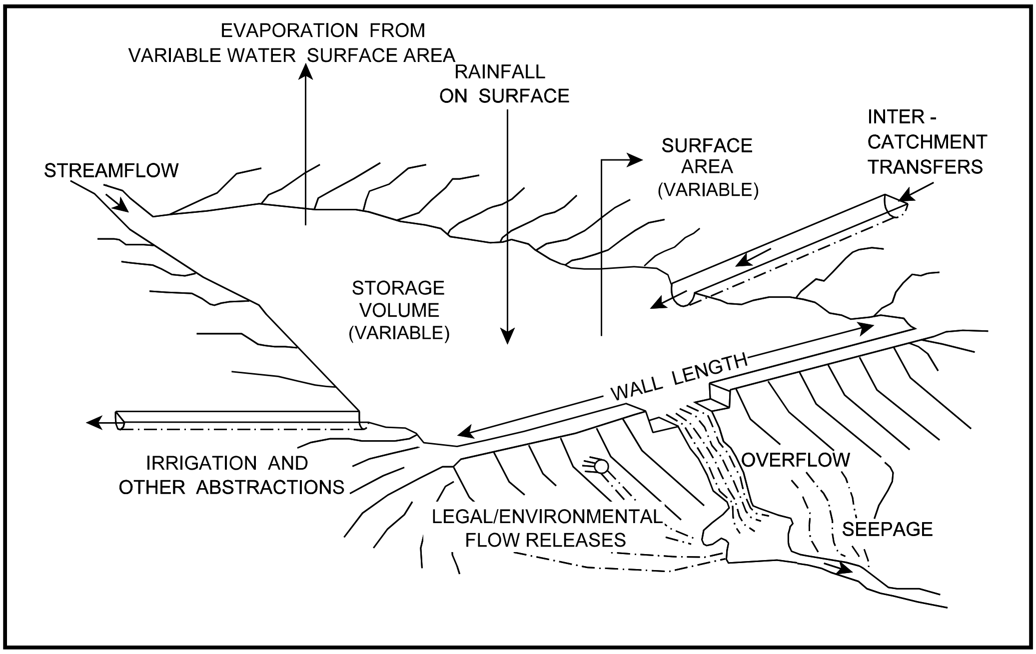

Figure 3.6 Schematic depiction of the reservoir water budget in *ACRU* (after Schulze, 1995)

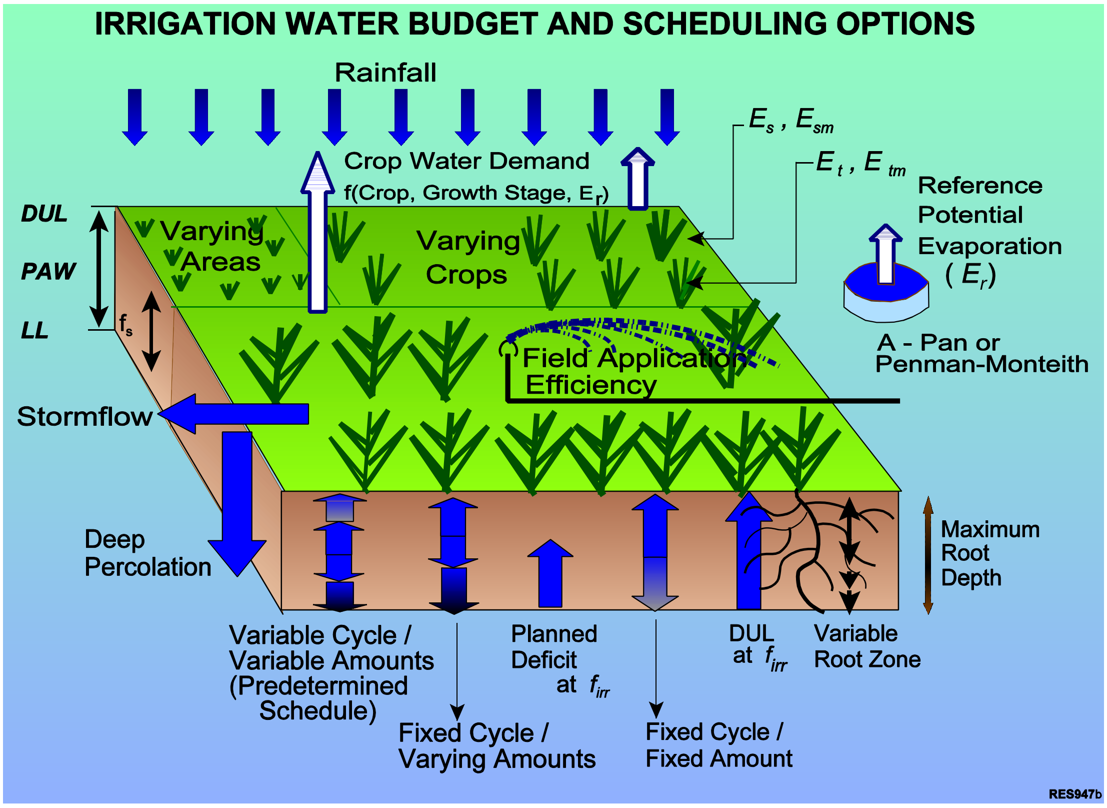

Figure 3.7 Schematic of irrigation water demand and scheduling options available in *ACRU* (after Schulze, 1995 and updates)

3.6 WHAT HAS THE *ACRU* MODEL TYPICALLY BEEN APPLIED FOR?

Since the mid-1980s the *ACRU* model has been used extensively to provide assessments to a range of water resources related problems associated with the modules listed above. A number of references are cited in the following subsections, which refer to the various capabilities of *ACRU*. The integrating nature of the model is highlighted by the appearance of the same reference under a number of the subheadings.

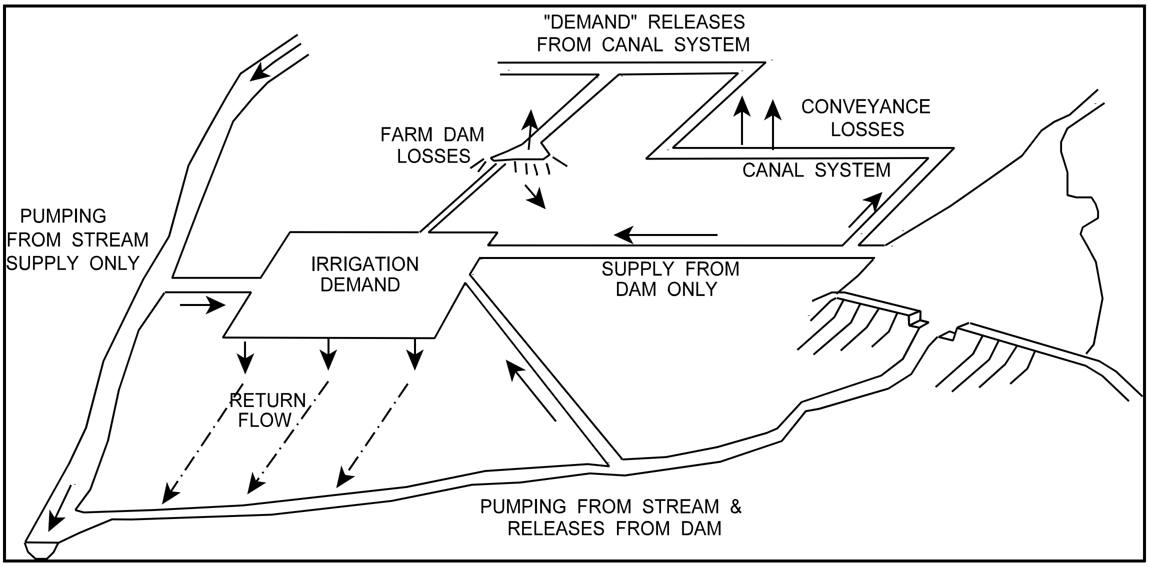

Figure 3.8 Schematic of irrigation water supply options available in *ACRU* (after Schulze, 1995)

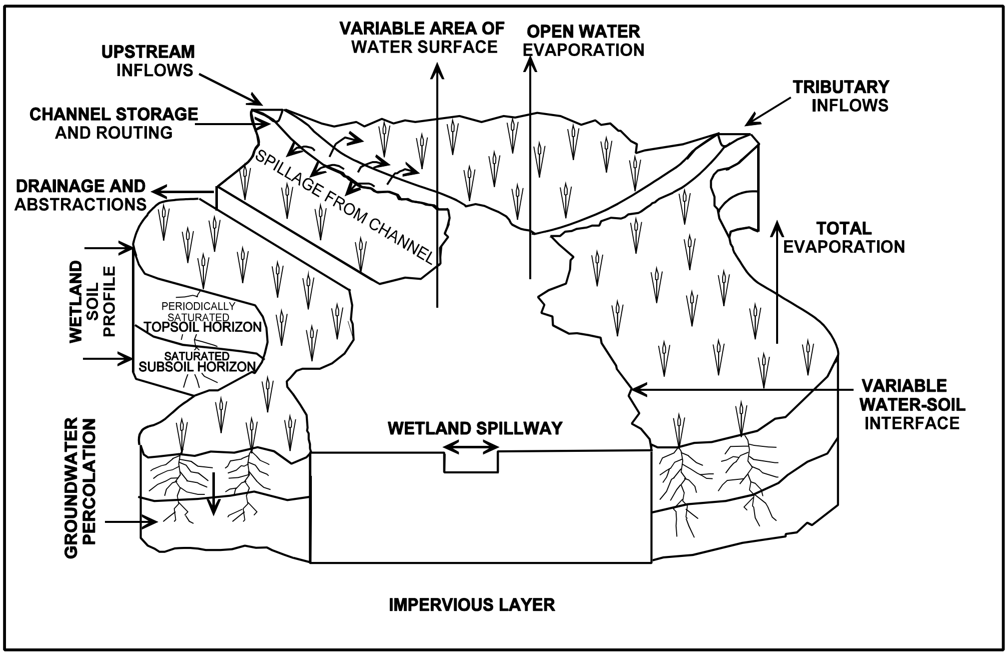

Figure 3.9 Concepts, processes and assumptions involved in the *ACRU* wetlands module (after Schulze *et al*., 1987; with modifications by Schulze, 2001d)

a) Water resources assessments

It is the multi-purpose structure and versatility of the *ACRU* system, in integrating land use sensitive and daily time step catchment hydrological processes with channel hydraulics in a (usually) semi-distributed hydrologically cascading (upstream to downstream) system, with facilities to simulate reservoir yield, sediment yield, wetlands processes, irrigation water demand/supply, crop yield and climate change feedbacks, that has made this widely verified model an ever increasingly applied tool in a range of water resources assessments in South Africa and elsewhere. While ensuing sections review more specific applications, five general types of water resources assessments may be identified, *viz*.

- general water resources assessments on catchments of 10 to ~1000 km^2
- specialised evaluations on off-channel storage
- water resources assessments associated with rural development
- comprehensive basin studies with *ACRU* as an installed hydrological modelling system and
- national scale studies.

First, general water resources assessments on catchments of 10 to ~ 1000 km^2 have been carried out on the Mhlatuze (Dunsmore, Angus and Schulze, 1990), in the Bushman's Nek (Smithers and Schulze, 1990), Cathkin Park (Lecler and Schulze, 1991), Babangibone (Schulze and Donkin, 1992) and Alpine Trout areas (Pike, Schulze, Thorpe and Horan, 1997), the Little Tugela/Sterkspruit system (Schulze, 1988b; Schulze and Jewitt, 1990a), the WJM dam catchment in the Western Cape (Schulze, Cluer, Hohls and Kunz, 1991), the Bröl tributary of the Rhine in Germany (Herpertz, 1994), as well as in the Franklin area (Schulze and Pike, 1995a; Pike and Schulze, 1996) and at the proposed Braamhoek/Bedford hydro-electric power scheme (Smithers, Schulze, Chetty and Royappen, 1998).

More specialised feasibility studies on off-channel storage schemes, which include input on the number and capacity of pumps as well as upper and lower thresholds of main channel flows outside which no pumping should take place, have also been undertaken with *ACRU* in KwaZulu-Natal (New, Lecler and Schulze, 1993) and in the Free State (Lorentz and Lecler, 1994).

More specific, and particularly post-1994, were simulations of water resources assessments often focussing on reservoir yield analyses (cf. Figure 3.6) associated with rural development and community requirements. Projects on which the *ACRU* model was applied included ones in East Pondoland (Schulze and George, 1986), Cwaka in Zululand (Schmidt and Schulze, 1986), Nkwalishane in Swaziland (Furniss and Schulze, 1990a; Schulze and Moerdyk, 1991a; 1991b), the Sikoto Dam catchment (Schulze and Pike, 1995b), the Esidumbini Dam catchment (Schulze and Pike, 1995c), the Biyela area (Schulze and Pike, 1995d) and the Nadi catchment (Schulze, Horan and Perks, 1997).

Thirdly, a need for comprehensive basin studies requiring output from a distributed daily model has seen the *ACRU* system be configured and applied, often with specific emphasis on particular local catchment problems, as an 'installed hydrological model' which, once up and running, can be applied many times over in follow-up studies. For example, the 4 354 km^2 Mgeni catchment has had a focus on land use impacts on water quantity and quality (sediment yield, phosphorus, *E. coli*) and multi-reservoir operational problems (Tarboton and Schulze, 1990; 1991; 1992; Kienzle and Schulze, 1995a; 1995b; 1995c; Kienzle *et al.*, 1997). The main foci on the 5 789 km^2 Pongola-Bivane catchment, on the other hand, have been upstream-downstream water availability conflicts between afforestation and irrigation, scale issues, hydro-economics of compensatory afforestation following clearance of alien riparian vegetation and the impact of Paris Dam on assured water to irrigators and aquatic habitats (Schulze, Pike, Lecler, Esprey, Howe and Zammit, 1996; Schulze, Taylor, Matthews and Hughes, 1997; Taylor, 1997; Schulze, Horan, Shange, Ndlela and Perks, 1998; Horan, Jewitt, Meier, Pike and Schulze, 2000; Jewitt, Horan, Meier and Schulze, 2000). The studies on the Sabie catchment of 6 260 km^2 contributed to the integrated catchment management initiatives of the Kruger National Park Rivers Research Programme with concentration initially on sediment yield (Pike, Schulze, Lorentz, Ballim, Taylor and Howe, 1997), later on assessment for environmental flows (Pike and Schulze, 2000) and simulation of the floods of 2000 (Smithers, Schulze, Pike and Jewitt, 2001). An overall water resources assessment of the Mdloti, Tongati and Mhlali catchments on the rapidly developing North Coast of KwaZulu-Natal was undertaken by Schulze, Pike and Meier (1996), with emphasis later on scale issues in basin studies (Meier, 1997; Schulze, 2001b). Through an EU funded project the Mkomazi, Mbuluzi in Swaziland and Mufure in Zimbabwe have been under the spotlight of integrated water resources systems studies (Staudenrausch, Flügel, Ranchin, Herlin, Rodolfi, Clark, Schulze, King, Tevera and Matondo, 1999). Foci on the 4 383 km^2 Mkomazi catchment have been impacts of a proposed large dam, allocation of water and impacts of development on environmental flows (Taylor *et al*., 1999; Taylor, 2001; Taylor, Schulze and Horan, 2001; Taylor, Jewitt and Schulze, 2001). In Swaziland's Mbuluzi catchment, on the other hand, studies have concentrated on effects of veld degradation and rehabilitation, as well as international water obligations to downstream Mozambique (Dlamini, 2001; Dlamini, Schulze and Matondo, 2001) while the *ACRU* system has been used on Zimbabwe's Mufure catchment for water allocation studies and infilling of missing hydrological data (Makoni, 2000; Makoni, Kjeldsen and Rosbjerg, 2001). Another large catchment to have been configured as an installed modelling system has been the 30 000 km^2 Thukela, on which studies to data have focussed on sediment yield, impacts of inter-basin transfers and of proposed major dams (Jewitt, Taylor, Hallowes and Horan, 1999; Taylor, Schulze, Jewitt, Pike and Horan, 2001).

Fourthly, at the national scale of South Africa, Lesotho and Swaziland, which covers 1 946 interlinked Quaternary Catchments over an area of 1 267 681 km^2, a spatial hydroclimatic database has been developed (Meier and Schulze, 1995; Meier, 1997; Perks, 2001) which is continually being enhanced and has been used, *inter alia*, in studies of overall hydrology in the *South African Atlas of Agrohydrology and -Climatology* (Schulze, 1997a), impacts of irrigation and afforestation (Meier, 1997; Gush, Scott, Jewitt, Schulze, Hallowes and Görgens, 2001), hydrological risk management (Schulze, 2001b) and impacts of climate change on hydrological responses (Schulze and Perks, 2000; Perks, 2001).

b) Design hydrology

Verified stormflows simulated by the *ACRU* model from research catchments in the USA, representing a range of climates and catchment areas, were used in the development of SCS design flood estimation techniques for southern Africa by Schulze (1982), Dunsmore, Schulze and Schmidt (1986) and Schmidt and Schulze (1987a). In the latter study, the *ACRU* model was used to integrate risk analysis with simulated soil water changes antecedent to design events, and was also used to estimate design streamflow by considering the joint association between rainfall and antecedent soil moisture conditions. The culmination of this work was the PC-based *SCS-SA* design manual for practitioners published by Schulze, Schmidt and Smithers in 1993, and currently under revision with more up-to-date databases. A series of background papers associated with this design hydrology approach appeared in the scientific literature (e.g. Schmidt and Schulze, 1984; Schmidt, Schulze and Dunsmore, 1986; Haan and Schulze, 1987; Schmidt and Schulze, 1987b; 1987c; 1989). A plea for an *ACRU*-type continuous modelling approach to estimating design runoff as a consequence of the non-stationarity of catchment responses over time, made by Schulze (1989c), is being followed up in a current WRC project (Smithers and Schulze, 2001).

Other applications of the design hydrology capability of *ACRU* have been design flood estimations upstream of Midmar Dam associated with the Mooi-Mgeni water transfer scheme (Smithers, Kienzle and Schulze, 1995; Smithers, Schulze and Kienzle, 1997), mapping indices of hydrological risk (Schulze, 2000b; Schulze, 2001c; Schulze, Meigh and Horan, 2001) and simulations of the February 2000 floods in the Sabie catchment (Smithers *et al*., 2001).

The lagging and attenuation of floods through river reaches and reservoirs is important in the estimation of peak discharge from a catchment consisting of numerous linked and hydrologically cascading subcatchments. The hydrograph routing routines developed and verified by Smithers and Caldecott (1993), have been used by Tarboton and Schulze (1992) in the hydrological modelling of the Mgeni River system and Smithers *et al*. (2001) on the Sabie system.

c) Irrigation water demand and supply

One of the *ACRU* model's strengths is the integration of water demand and supply on a catchment scale. The basic processes involved are illustrated schematically in Figures 3.7 and 3.8. This integration has been used extensively in reconciling and optimising irrigation water demand and supply. Crop water requirements for irrigation planning in southern Africa were determined by Dent (1988) and Dent, Schulze and Angus (1988) using the *ACRU* model. The sensitivity of crop water requirements to estimates of reference potential evaporation was investigated by Lecler, Kunz and Schulze (1993). Crop water requirements have been integrated with catchment water yield (e.g. Dent, 1988; Schulze, 1988b; Lecler, Kiker and Schulze, 1994) while the effects of different irrigation strategies have been studied, *inter alia*, by Furniss, Dent and Schulze (1988), Furniss and Schulze (1989), Lecler and Schulze (1994) and Schulze, Lumsden and Horan (2001).

The optimum utilisation of the limited water resource for irrigation planning and irrigation project water supply/demand, often linked with crop yield analyses, has been investigated in many areas in South Africa, Swaziland and Namibia by Schulze and George (1987b; 1987c; 1987d), Furniss *et al.* (1988), Furniss and Schulze (1989), Schulze and Hughes (1989), Dunsmore and Schulze (1990), New *et al*. (1993), Schulze (1983) and Lecler and Schulze (1994). Schulze and George (1987b) include an economic analysis in assessing the implications of deficit irrigation in Namibia while the paper by Lecler, Schulze, Mottram, De Jager and Bennie (1993) compares *ACRU* with other models used at that time in South Africa as an irrigation management tool. The water use efficiency of irrigated sugarcane in relation to regional climates, inter-annual variability, soil properties and modes of irrigation scheduling, as well as the yield increment from irrigation and deep percolation/stormflow losses from irrigated fields have been evaluated in depth for the sugarcane belt of South Africa by Schulze, Lumsden, Horan and Maharaj (1999) and Schulze, Lumsden and Horan (2001).

At larger (i.e. > 1 000 km^2) catchment scale irrigation supply/demand and their impacts on downstream flows impacts have been an integral part of studies on the Pongola (Schulze *et al*., 1996; 1997; 1998), the Mgeni (Kienzle *et al*., 1997), Sabie (Pike and Schulze, 2000), Mkomazi (Taylor, Schulze and Horan, 2001) and the Mbuluzi in Swaziland (Dlamini *et al*., 2001). Economic, risk and environment issues surrounding the allocation of irrigation water supply when it becomes scarce has been the subject of intensive studies in the Little Thukela catchment by Grové (1997), Grové, Bender and Oosthuizen (1998), Grové and Oosthuizen (1998) and Oosthuizen and Grové (2001).

At national scale, irrigation water demand has been mapped on a month-by-month basis in the *South African Atlas of Agrohydrology and -Climatology* (Schulze, 1997a).

d) Crop yield and primary production modelling

The *ACRU* model has options to simulate seasonal yields of

- maize (with the original *ACRU* maize model refined by Domleo, 1990),
- winter wheat (Domleo, 1990),
- sugarcane (using the Thompson, 1976; 1977 concepts; refined by Lumsden, Schulze, Lecler and Schmidt, 1999), as well as
- primary production (Schulze, 1984).

Schulze (1985a; 1986; 1989b) has reviewed *ACRU* 's crop yield output with particular reference to risk analysis and irrigation, while Furniss and Schulze (1989; 1990b) used the maize yield simulation option to investigate crop yield in relation to soil properties and optimum irrigation applications at diverse locations in South Africa and Swaziland. The maize yield model has been used to assess dryland and irrigated yields for development projects in the Eastern Cape (Schulze and George,1987e) and to derive optimum planting dates (Schulze and Moerdyk, 1991c). Schulze (1992) also used the maize yield option to examine likely shifts in maize production regions as a consequence of elevated levels of atmospheric CO_2 while Schulze (2000b) and Perks (2001) further investigated effects of acclimation to enhanced CO_2 levels on potential maize yields and economic consequences thereof. A version of the CERES suite of crop growth models has been linked to the *ACRU* model to form a tool which can simulate crop growth and hydrological events at regional scale. This hybrid model was used by Schulze, Kiker and Kunz (1993; 1995; 1996) and by Downing, Kiker and Schulze (1996) to simulate possible changes in maize production as a consequence of likely global climate change and associated CO_2 fertilisation. Countrywide maize and sugarcane yields and inter-annual yield variabilities using the *ACRU* modules are evaluated in the *South African Atlas of Agrohydrology and -Climatology* (Schulze, 1997a).

The *ACRU*-Thompson sugarcane yield model has been improved (Lumsden, Schulze, Lecler and Schmidt, 1999) to facilitate simulation at multi-harvesting dates using degree-day driven biomass development (Hughes, 1992) and with these improvements, has been shown to outperform both more complex as well as more traditional sugar industry based yield prediction models at mill supply area (Lumsden, Lecler and Schulze, 1998; Lumsden *et al*., 1999) The *ACRU*-Thompson cane yield model has been applied at national scale for simulation of mean yields and inter-annual variability of yield by Schulze (1997a) while Lumsden *et al*. (1999; 2001) have applied it for seasonal yield forecasting at Eston sugar mill in KwaZulu-Natal.

The *ACRU* model was used to simulate primary production over southern Africa by Schulze, Angus, Lynch and Furniss (1990) as part of a State food strategy and production initiative. This application was subsequently expanded to include the spatial distribution of inter-annual variability of primary production (Schulze and Lynch, 1992), with that work revisited at higher spatial resolution in Schulze and Lynch (1994) over KwaZulu-Natal and countrywide in the *South Africa Atlas of Agrohydrology and -Climatology* (Schulze, 1997a). The *ACRU* model of primary production was used to successfully simulate herbage yield and veld carrying capacity at three locations in South Africa (Schulze, 1994).

e) Assessments of impacts of land use and land use change on hydrological responses

The *ACRU* model's conceptual representations render it particularly suitable to simulating hydrological responses to land use and management impacts and changes thereof. Important background papers in that regard include those by Schulze in 1987, 2000a and 2001a. Impacts of land use on both water quantity and quality (selected determinants) can be simulated with *ACRU*. Examples of these studies, which exclude specific afforestation related impacts which are reviewed separately, fall under four broad subheadings, *viz*.

- general land use impact studies
- impacts of sugarcane
- land use impacts on water quality and
- impacts in the riparian zone.

General land use impact studies include ones in Pondoland (Schulze and George, 1986a), on the Mgeni catchment (Tarboton and Schulze, 1990 on farm dams; 1993 on urban impacts; Kienzle and Schulze, 1995b; 1995c; Kienzle *et al*., 1997; Schulze, 2000a), on the Pongola catchment (Schulze *et al*., 1996; 1997; 1998a; 1998b), in the Umzinto area (Smithers and Schulze, 1996) and the Lenjane catchment (Schulze, Pike, Horan and Hughes, 1997).

A focus on impacts of sugarcane, including those of different management practices, on hydrological responses commenced with studies by Haywood and Schulze (1990; 1991) and was followed by the research by Smithers and Schulze (1996) as well as by Smithers, Mathews and Schulze (1996), which was then synthesised by Schmidt, Smithers, Schulze and Mathews (1998) - with many of the above papers based on analyses of results of flows and sediment yields from the La Mercy research catchments. Schulze, Lumsden, Horan and Maharaj (1999) followed this up by regional analyses of hydrological responses from sugarcane fields for the so-called South African sugarcane belt.
Of the studies on land use impacts on water quality, the most comprehensively verified studies have been those on the Mgeni (sediment, phosphorus and *E. coli* yields; Kienzle *et al*., 1997; Schulze, 2000a) and of sediment yield from sugarcane under different management regimes (Smithers *et al*., 1996; Schmidt *et al*., 1999) Simulations of sediment yield have, furthermore, been carried out on the Upper Molen catchment, where natural vegetation has been cleared (Schulze and Horan, 1998), on the Mbuluzi catchment in Swaziland, on which impact studies of veld degradation and rehabilitation have been conducted (Dlamini *et al*., 2001) and at national scale in a study of irrigation factors in hydrological risk management (Schulze, 2001c).

Hydrological responses from the riparian zone are particularly sensitive to land use changes and, following a series of modifications to the *ACRU* model to account for these, studies have been undertaken by Meier, Brodie, Schulze, Smithers and Mnguni (1997), by Horan *et al*. (2000), by Jewitt *et al*. (2000) and by Gillham and Hayes (2001).

f) Forest hydrological impacts

With the impacts of commercial plantation afforestation to exotic tree species in South Africa under the spotlight as a streamflow reduction activity for the past 50 years, the *ACRU* model, by virtue of its physical-conceptual structure, has frequently been applied to provide answers to a range of forest hydrological questions. Extensive verification studies on forest hydrological impacts on streamflows have been carried out by Schulze and George (1986b; 1987a), Jewitt and Schulze (1993; 1999) and Gush *et al*. (2001) while results from fieldwork on forest hydrological processes in support of algorithms developed for *ACRU* have been presented by Jewitt (1991), Jewitt and Schulze (1991; 1993), Moerdyk and Schulze (1991), Summerton and Schulze (1995) and Summerton (1996).

Impacts of afforestation on groundwater levels was the focus of studies by Kienzle and Schulze (1992a; 1992b; 1995d) while assessments of timber yield via *ACRU* were made by Leenhardt and Schulze (1993) and Schulze, Pike, Howe and Maharaj (1997). Most emphasis has, however, been placed on impacts of commercial afforestation on downstream streamflows and the impacts of site preparation techniques on both the potential for afforestation, as well as on alterations in the partitioning of rainfall into stormflows vs recharge. Examples of such studies include those by Schulze (1985b) at Highflats, Schulze and George (1986b; 1987a) at Cathedral Peak, Tarboton and Schulze (1990; 1992; 1993) in the Mgeni catchment, Schulze and Stewart (1990) in the northeast Cape, Schulze (1990a) as well as Schulze and Jewitt (1990b) at Himeville, Jewitt and Schulze (1992a; 1992b; 1992c) in Qwa Qwa, at False Bay and at Louwsburg respectively, Lorentz and Schulze (1992) at Matikulu, Kienzle and Schulze (1994; 1995b) in the Mgeni catchment, Schulze and Pike (1995a) around Franklin, Schulze, Pike and Fourie (1996) in the Nyambathi catchment and Schulze *et al*. (1996; 1997; 1998) in the Pongola catchment. To distinguish between different hydrological impacts induced by genera, age and site preparation, decision support systems relating to forest hydrological inputs to *ACRU* were developed by Jewitt (1991) and published in Jewitt and Schulze (1991) as well as in Schulze, Jewitt and Leenhardt (1995), with updates which included dynamic age-related LAI driven biomass indicators, regionalisation and impacts of thinning practices having been reported by Summerton (1996), Meier (1997), Schulze, Summerton, Meier, Pike and Lynch (1997) and by Schulze, Summerton and Jewitt (1998). Mapping impacts of afforestation on streamflows on a nationwide basis has been performed at Quaternary Catchment scale by Meier (1997; published in Schulze, 2001d) and Gush *et al*. (2001).

g) Assessment of hydrological impacts of wetlands

A wetland module for the *ACRU* model was initially developed by Schulze, Chapman, Angus and Schmidt (1987) and used to assess the potential hydrological impacts of proposed reservoirs upstream of wetlands in East Griqualand. A schematic depiction of concepts, processes and assumptions involved is given in Figure 3.9. Smithers (1991) further refined and verified the model against observed data from the Ntabamhlope wetland, while the Hydrology Honours class did the same in 1999 for the Mvoti vlei. The model has been applied by Smithers and Schulze (1993) to investigate the influence of wetlands on streamflow regulation and flood attenuation, and by Schulze and Pike (1995a) in East Griqualand as well as by Schulze, Pike, Horan and Hughes (1997) in northern KwaZulu-Natal in studies of afforestation impacts on wetlands responses.

h) Groundwater modelling

The use of *ACRU*'s shallow groundwater module to simulate likely long term consequences of afforestation on fluctuations in groundwater was demonstrated and verified for deep sandy soils in northeastern KwaZulu-Natal by Kienzle and Schulze (1992b). The techniques developed were subsequently applied at six sites in Mozambique (Kienzle and Schulze, 1995d). *ACRU* was used as the hydrological simulator of recharge from the soil to groundwater in national scale studies by Lynch, Reynders and Schulze (1994; 1995; 1997), who applied the DRASTIC equation to map groundwater vulnerability to pollution over South Africa using a GIS approach, as well as being applied by Schulze (1997a) in the *South African Atlas of Agrohydrology and -Climatology* and by Lorentz, Hughes and Schulze (2000). Long term groundwater fluctuations were simulated successfully in the Romwe research catchment in Zimbabwe, with Butterworth, Schulze, Simmonds, Moriarty and Mugabe (1999) making some important conceptual improvements to *ACRU*'s groundwater routines to account for groundwater tables being either connected or disconnected from the stream channel.

i) Hydro-economic analyses

With water becoming a tradeable commodity and the value of water being realised, in terms of monetary value per m^3 used, yield (tonnage) per m^3 of water utilised and allocation to competing crops under irrigation, the *ACRU* model is being used more and more frequently in hydro-economic analyses. One of the first such studies was on economic implications of deficit irrigation in Namibia (Schulze and George, 1987b). More recent work by Pott, Creemers, Schulze and Kiker (1999) has linked economics to various agricultural water uses in the Mvoti catchment, while Lumsden, Schulze Lecler and Schmidt (1999; 2000) have undertaken benefit : cost analysis of forecasting sugarcane yield with the *ACRU*-Thompson model at the scale of a sugar mill supply area. Numerous studies have assessed the economics of alien riparian vegetation clearance in relation to water gains and/or compensatory forestry elsewhere in the catchment, e.g. Horan *et al*. (2000) and Jewitt *et al*. (2000) in the Pongola and Gillham and Hayes (2001) in the Mgeni catchment.

ACRU has also been used to analyse the effects of stochastic water supply and demand on the economic efficiency of irrigation farming in the Little Thukela catchment with the view to determining the optimal mix of crops under irrigation (Grové, Bender and Oosthuizen, 1998), particularly when the allocatable water resource is sparse and crops are competing for water (Grové and Oosthuizen, 1998). These studies comprised components of a comprehensive study by Grové (1997) and Oosthuizen and Grové (2001) on the optimal management of variable water availability at farm and regional scales when taking cognisance of risk and environmental issues.

j) Assessment of potential impacts of global climate change on crop production and hydrological responses

A number of studies utilising the *ACRU* model have been conducted to assess the potential impact of elevated CO_2 and temperature levels and possible resultant changes in precipitation and potential evaporation on crop and runoff production in southern Africa. Papers of a general and/or strategic nature in which *ACRU* is applied as a tool for climate change impacts include those by Schulze and Kunz (1994), Schulze (1997b) and Schulze, Meigh and Horan (2001). Likely shifts in maize production regions in southern Africa as a consequence of global climate change were simulated using the *ACRU* model by Schulze (1991b; 1992). This work was greatly improved when the hybrid *ACRU*/CERES model was used subsequently by Schulze, Kiker and Kunz (1993; 1995; 1996; Downing, Kiker and Schulze, 1996) to simulate possible changes in maize production under different management scenarios over southern Africa. Uncertainty and economic considerations of potential shifts in maize production are contained in Schulze (2000b), based on work by Perks (2001), while an analysis of C : N ratio changes was published by Kunz, Scholes and Schulze (1995). In regard to possible hydrological responses to climate change Schulze (1990b; 1991a; 2000a; 2000b) presents applications of *ACRU* to scenarios of design stormflow production as well as potential water yield changes. Kunz and Schulze (1993) and Schulze (2000b) used *ACRU* to assess the sensitivity of runoff production in southern Africa to climate change and also used the model to ascertain critical climate thresholds of the hydrological system to change. New and Schulze (1996) assess implications of climate change for erosion in the southwestern Cape. The most comprehensive overviews of climate change on a range of hydrological responses are, however, provided by Schulze and Perks (2000) and Perks (2001).

k) Agrohydrological forecasting

The high inter-annual variability of South Africa's climate, the effects of which are amplified in the hydrological system (Schulze, 2001c), render seasonal forecasts of crop yields and streamflows vital for a range of operational decisions (e.g. Lumsden *et al*., 1999). Seasonal categorical rainfall forecasts at regional scale, appropriately downscaled spatially and temporally for application with the *ACRU* model, have been used successfully to forecast sugarcane yields (Lumsden *et al*., 1999; 2000; Lumsden, Lecler, Schulze, Schmidt, Bartman and Landman, 1999) and maize yields (Lecler, Schulze and Pike, 1996). Because of complexities in partitioning rainfall into stormflows and baseflows, and its dependence on antecedent conditions, seasonal forecasts of streamflows are much more difficult to perform, given present levels of seasonal forecast accuracy, than forecasts of crop yields. However, Lecler *et al*. (1996), Lecler and Schulze (1997) and Lecler, Pike and Schulze (1998) have demonstrated the feasibility of seasonal streamflow forecasts on the Pongola, while at national level, albeit with less success, runoff forecast skill has been evaluated by Schulze, Hallowes, Lynch, Perks and Horan (1998) and Hallowes, Schulze and Lynch (1999).

l) Simulations with ACRU in the service of the National Water Act of 1998

A change in water supply priorities since 1994 and promulgation of the National Water Act of 1998 (NWA, 1998) have ushered in a series of new simulation opportunities for daily hydrological models in Integrated Water Resources Management. These include streamflow reduction activities, rural water supplies, environmental flow computations, risk analysis, reservoir operating rules for the human and ecological reserves and impacts of alien riparian vegetation clearance ('Working for Water' programme). In this context the *ACRU* system has been applied to RDP related rural water supply schemes (Schulze and Pike, 1995b; 1995c; 1995d), water allocation analysis (Taylor, Schulze and Horan, 2001), environmental flow analysis (Taylor, Jewitt and Schulze, 2001), streamflow reduction activity evaluations (Schulze *et al*., 1999; Schulze, Horan and Schmidt, 2000), reservoir operating rules (Butler, Smithers, Jewitt and Clark, 2001) and for alien riparian clearance impact assessment (Meier *et al*., 1997; Horan *et al*., 2000; Jewitt *et al*., 2000; Gillham and Hayes, 2001).

m) International applications of ACRU

ACRU is increasingly being applied internationally. Examples include irrigation demand analysis in Namibia (Schulze, 1983b), hydrological design in Botswana (Schulze and Tarboton, 1989), reservoir sizing in Swaziland (Furniss and Schulze, 1990a; Schulze and Moerdyk, 1991a; 1991b), afforestation impacts in Mozambique (Kienzle and Schulze, 1995d), regional water resources assessments in Germany (Herpertz, 1994, on the Bröl), Swaziland (Dlamini, 2001; Dlamini *et al*., 2001 on the Mbuluzi) and Zimbabwe (Makoni, 2000; Makoni *et al*., 2001 on the Mufure) as well as groundwater level simulations in Zimbabwe (Butterworth *et al*., 1999), with Staudenrausch *et al*. (1999) reporting on an international research programme in southern Africa for which *ACRU* was the selected IWRM model.

n) Other applications of ACRU

ACRU has, in recent years, been applied to diverse other agrohydrologically related problems, *inter alia*, assessing

- potential impacts of cloud seeding on streamflow production (Howard and Görgens, 1993)
- water quality under urban conditions (Schmitz, De Villiers and Schulze, 1993)
- hydrological effects of a wildfire in a forest plantation (Scott, Schulze and Kunz, 1991)
- soil forming factors (Donkin and Schulze, 1990)
- the palaeo-rainfall history over South Africa by relating wetting cycles to percentage finer of the soil in granitic parent material (Partridge, Demenocal, Lorentz, Paiker and Vogel, 1997) and
- sediment yield using contributing area techniques (Howe and Lorentz, 1995).

Furthermore, the model has been used in the adjustments of stormflow responses to antecedent soil moisture conditions in the PC based SCS-SA package, now in standard use by practitioners in southern Africa, on design hydrographs from small catchments (Schmidt and Schulze, 1987a; Schulze, Schmidt and Smithers, 1993).

3.7 HOW DOES *ACRU* OPERATE AS A DISTRIBUTED MODEL?

Being a daily time step model, *ACRU* does not, in most of its standard routines, account for the temporal variability within individual storm events. However, the distributed version of the *ACRU* model has the ability to take account of the spatial variability not only of rainfall, but also of land uses and soils to provide a more accurate representation of where, within the catchments, the hydrological responses are occurring and with what magnitude.

a) Catchment discretisation

Characteristics, advantages and disadvantages and methods of catchment discretisation are given in Schulze (1998a) and Schulze (2001a). *ACRU* generally makes use of a 'cell' type discretisation to subdivide the catchment, where each cell may be regarded as a subcatchment. Cell boundaries are defined from large scale orthophotos or topographical maps. In southern Africa the current standard subcatchment is the DWAF Quaternary Catchment (QC), of which 1 946 have been delineated within the borders of South Africa, Lesotho and Swaziland. Generally, the more complex a region is physiographically or developmentally, the finer the spatial resolution of QCs. The QCs may, nevertheless, be too diverse physiographically and climatically to act as a basic and relatively homogeneous hydrological unit (cf. Schulze, 2001a; in this Report, Chapter 2) and may therefore require further discretisation into Quinery level catchments.

Criteria considered in the finer delineation of QCs are classed as either

- *natural*, e.g. based on
  - rainfall range
  - altitude range (and associated temperature/evaporation change)
  - breaks in terrain morphometry, e.g. an escarpment
  - natural vegetation zones, e.g. Acocks' (1988) Veld Types or Low and Rebello's (1996) vegetation zones
  - soil groups with similar hydrological response properties or
  - major tributaries joining a mainstem river; or
- *anthropogenic* in origin, e.g. based on present and/or future
  - land uses with different hydrological responses
  - inflow or outflow points, on a reservoir
  - water abstraction or return flow points
  - monitoring sites, such as
    - streamflow gauging weirs
    - water quality monitoring sites
    - instream flow requirement locations on a stream, or the
    - raingauge network.

The level of subcatchment discretisation is highly dependent on the particular purpose for which the model is being put to use and remains subjective up to a point. Two illustrations of subcatchment discretisation, described in more detail in Chapters 2 and 11 of this Report, are presented below (Figures 3.10 and 3.11). These two figures show that in cell-type distributed models such as *ACRU*, the catchment is depicted as an assembly of interconnected, i.e. cascading, units of area, each considered a lumped (averaged) representation of that area.

Two types of cells can be identified from Figures 3.10 and 3.11, *viz*. exterior and interior cells. An exterior cell has a portion of its boundary as a common boundary with the main catchment and the outflow from an exterior cell is assumed to be independent of that of all the other cells. An interior cell has one or more upstream cells (i.e. subcatchments), and the outflow from an interior cell may include contributions from upstream cells.

b) *Inter-subcatchment streamflows*

The lumped model's soil water budgeting routine is performed assuming a point scale with all units expressed in mm. Stormflow and baseflow, which together make up streamflow, are thus also expressed in mm. In order to direct outflow to downstream cells, the streamflow depth calculated by the model is converted to a volume (m^3) to account for the different areas of each subcatchment.

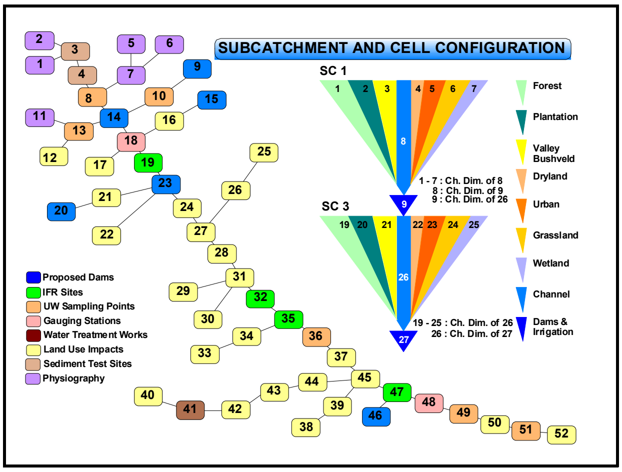

Figure 3.10 An example from the Mkomazi catchment of subcatchment discretisation by watershed boundaries and with further subdelimitation by land use classification (after Taylor *et al*., 2001)

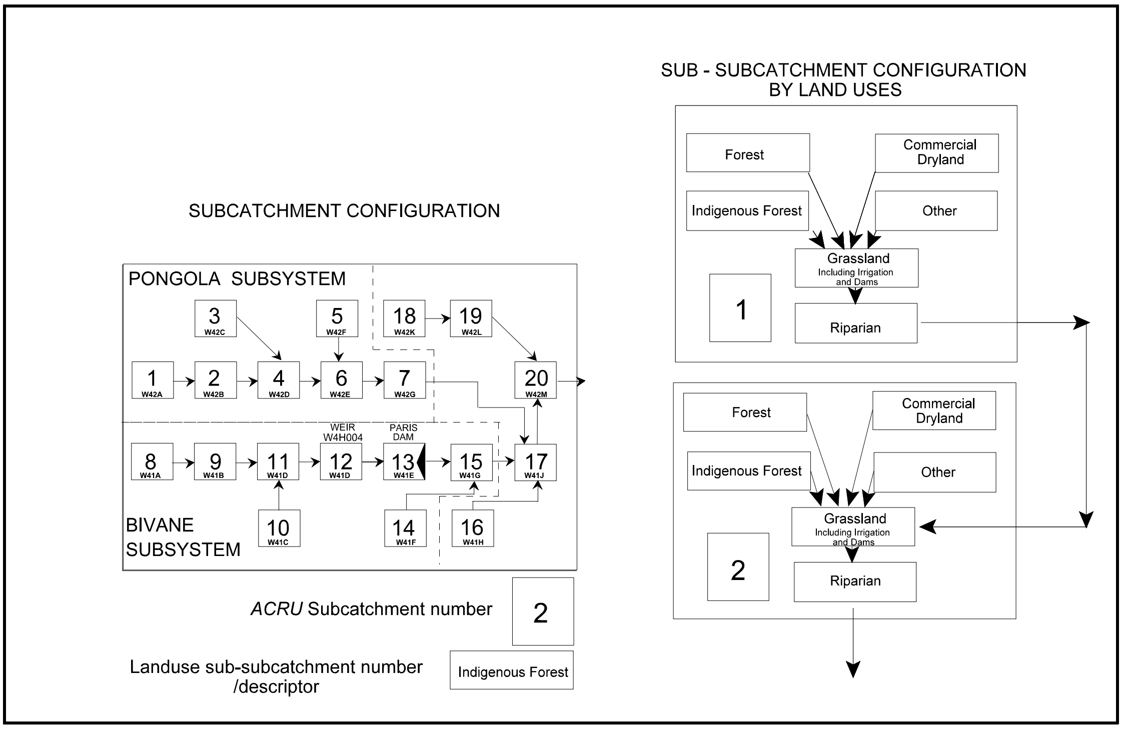

Figure 3.11 Subcatchment configuration : Pongola-Bivane study area (after Schulze *et al*., 1998)

c) Other features of ACRU as a distributed model

A feature of the *ACRU* distributed model is that each subcatchment, while nested within other up- and downstream subcatchments in transmitting water, also operates as a unique, individual catchment.

- Therefore, individually requested input information pathways can be used on different subcatchments and individual and different output can be requested for each subcatchment. Thus, for example, one could request crop yield and sediment yield together with a risk analysis of only monthly streamflow from Cell 1, whilst requesting an irrigation requirement analysis, reservoir yield risk analysis and daily water budget printout from the next subcatchment.
- In, for example, a series of complex multi-irrigated subcatchments, irrigation water from the river may all have been abstracted by upstream users, requiring downstream irrigation users to request water releases from an upstream reservoir as draft - a ‘fact’ which the simulation only ‘finds out’ after having cascaded through a number of subcatchments downstream. For such cases, a so-called ‘loopback’ option can be operated in *ACRU*, by which complex transfers of water (other than natural streamflow) between subcatchments are accounted for.

3.8 HOW ARE THE COMPONENTS OF THE *ACRU* MODELLING SYSTEM LINKED?

The *ACRU* modelling system is made up of a number of discrete, but interlinked components. As shown in Figure 3.12, the *ACRU* model requires both an input menu file and a file containing hydrometeorological data, and may contain an optional dynamic file.

3.9 WHAT ARE TYPICAL MINIMUM DATA AND INFORMATION REQUIREMENTS TO OPERATE *ACRU*?

ACRU has been designed as a *multi-level* model, with either multiple options or alternative pathways (or a hierarchy of pathways) available in many of its routines, depending on the level of available input

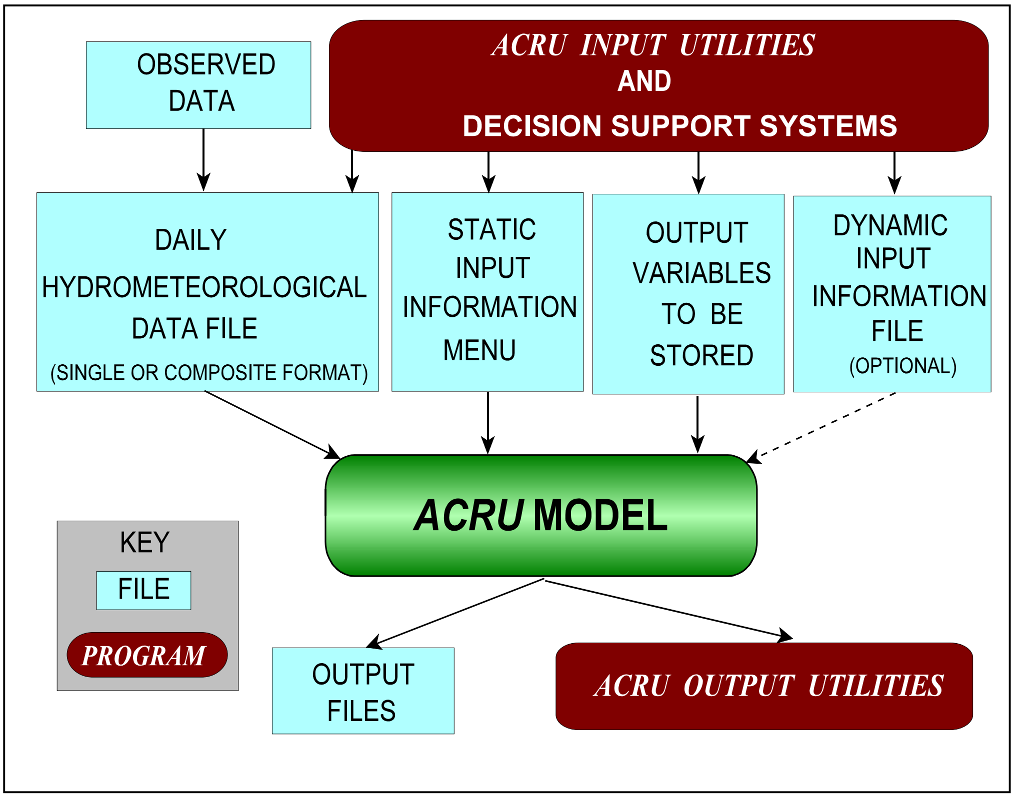

Figure 3.12 Components and linkages of the *ACRU* modelling system (after Schulze, 1995)

data/information or the type and detail of output required. The minimum data and information required to run the model is, therefore, not unique and depends on the options chosen and on the availability of data/information to a particular user. Typical minimum data and information requirements which are compulsory input into the model and which are readily obtainable for southern Africa, are summarised schematically in Figure 3.13. The optional inputs to the model, which are required to simulate specific processes (e.g. peak discharge or sediment yield), are also included in Figure 3.13.

3.10 WHAT UTILITIES COME WITH THE *ACRU* SYSTEM?

Deterministic hydrological models, particularly when operating in distributed mode, require detailed soils, land use and climatic information and the collection and inputing of this information can be both time consuming and laborious. It is to this end that a suite of software programs, the *ACRU Utilities*, has been developed to aid users in preparing input information for, and output information from, the *ACRU* agrohydrological simulation model. A schematic overview of the way in which the *Utilities* link with the *ACRU* model is given in Figure 3.14 and brief descriptions of just a few of key individual programs making up the *Utilities* follow. Details on the other *Utilities* are found in the *ACRU* User Manual (Smithers and Schulze, 1995).

a) The ACRU Menubuilder

The *ACRU Menubuilder* is an interactive, user friendly program of over 250 subroutines which prompts the user with questions for information, also guides (with internal help and error checking facilities) the user through the various options available and facilitates rapid information input through a MENU file (Figure 3.13). It contains preprogrammed *Decision Support tools*. Technical details on the *Menubuilder* are given in Chapter 5 of the *ACRU* User Manual (Smithers and Schulze, 1995).

Information is input into the *Menubuilder* in a sequential mode, dealing with individual processes one at a time. A feature of the *Menubuilder*, which can assist in editing a previously created MENU, is the facility to

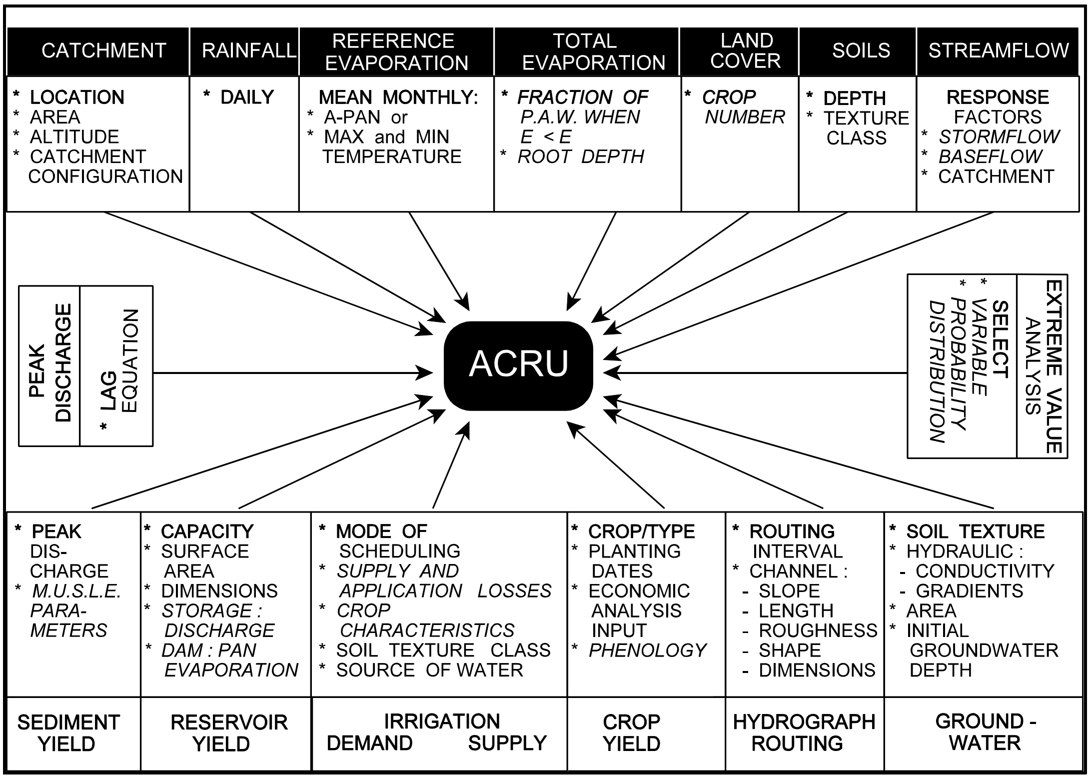

Figure 3.13 Schematic of the *ACRU Utilities*' linkages with the *ACRU* model (after Schulze, 1995)

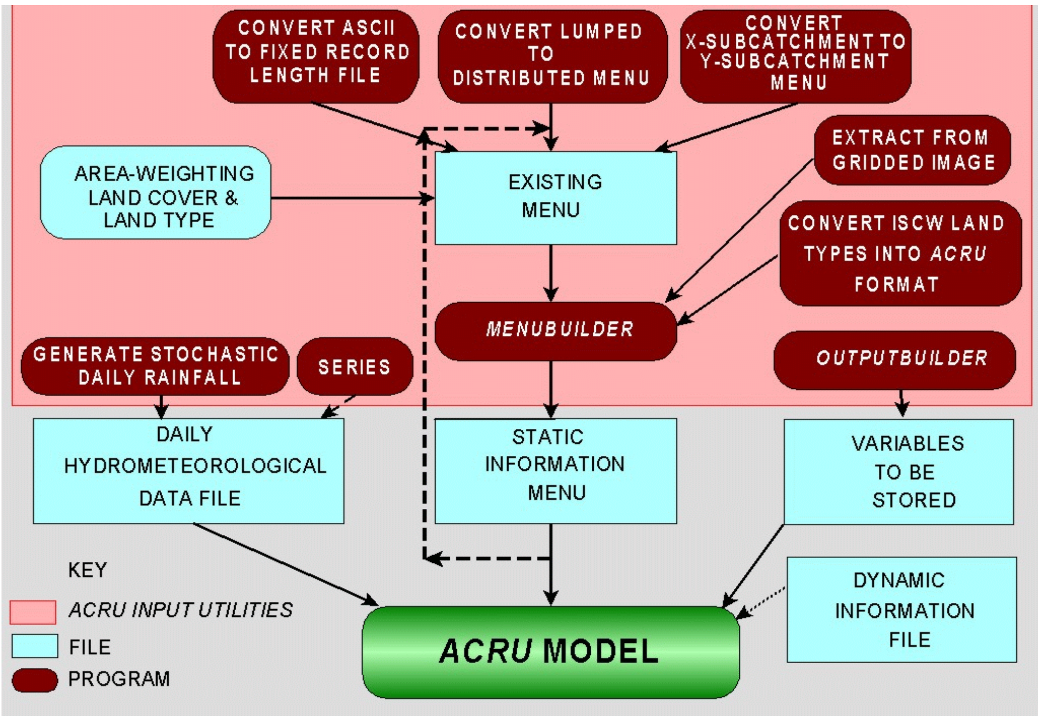

Figure 3.14 Schematic diagram of the *ACRU Utilities'* linkages with the *ACRU* modelling system as of 2001 (after Schulze, 1995)

proceed to any selected section of the MENU, and skip over previously input information. In addition, the user can end the session at any time and all information will be written to the user selected output MENU file name.

ACRU caters for several levels of information availability. Detailed information is often not available and the user can then resort to the 'experience' that has built into *ACRU* and the *Menubuilder* through *Decision Support* tools by way of default values and pre-programmed information.

The two areas where this facility is particularly useful are in inputing soils and land use information. In each case, if catchment information is limited or considered 'inadequate', the user can select from a range of classes of input and the program assigns realistic default values to the variables.

b) The ACRU Outputbuilder

As illustrated in Figure 3.14, the *ACRU* model requires an input file containing details on which variables to store during a simulation, for which output and analysis at the completion of the simulation are then required. Users may select to store only those variables relevant to their problem. The *Outputbuilder* lists all the variables available for storage during the simulation (with descriptions of the variables) and the user may click on either a subset of all the variables or the entire set for graphical or statistical analysis.

c) Generation of stochastic time series of daily rainfall

Often, for planning purposes, a stochastic time series of daily rainfall values is used in preference to historical data, which may be difficult to obtain or which may contain missing data. A routine may be called to generate a stochastic time series of daily rainfall, for any one of over 3 000 station locations in South Africa, based on an original study by Zucchini and Adamson (1984), and subsequent updates of that research. The user inputs latitude and longitude co-ordinates for the location of interest, and then selects any one of the 10 computer selected rainfall stations closest to the location and appearing on screen, before selecting any length of record desirable. The generated daily rainfall series can be automatically formatted to an *ACRU* format, ready for use; alternatively the user can request that the stochastic series be output in any one of a number of other formats.

d) Extraction of gridded images

The School of Bioresources Engineering and Environmental Hydrology at the University of Natal has developed gridded images of altitudes, median monthly rainfall, mean monthly A-pan equivalent evaporation, monthly means of daily solar radiation and of relative humidity as well as monthly means of daily maximum and minimum temperatures, at a resolution of one minute by one minute (1' x 1') of a degree latitude/longitude covering southern Africa (Schulze, 1997a). A routine is included which will extract values from the gridded image for a rectangular catchment boundary which the user has to specify.

3.11 ADVANCING THE MODEL BY DEGREES : A REVIEW OF CAPACITY BUILDING THROUGH *ACRU* MODEL DEVELOPMENT BY POST-GRADUATE RESEARCH

If the reference list of this chapter on the structure and applications of the *ACRU* modelling system has been consulted as the review has unfolded up to this point, it will have been noted that a number of the single authors' contributions have been by way of higher degrees (i.e. MSc, MScEng, PhD), awarded mainly through the University of Natal, but also at other South African universities as well as overseas universities (e.g. Cambridge, Bonn, Cornell). These references to theses already bear testimony to *ACRU* probably being the mostly intensively researched hydrological model of ones to have been developed to date in southern Africa. The research masters and doctoral documents already mentioned are, however, only a fraction of the ones where students have contributed to *ACRU*'s development. Listed below, by broad themes, are those students who we know to have obtained higher degrees (40 masters, 8 PhDs), or who are currently registered (7 masters, 3 PhDs), through their research contributing in a major or minor way, either through component/process development and/or enhancement, or through verification, and/or application, to the status of the *ACRU* agrohydrological modelling system as of 2002.

- In *runoff generation*, contributions have come from Hope (1980), Arnold (1981), Dunsmore (1985), Schultz (1985) and Angus (1988) in regard to stormflow simulation, while Schmidt (1982) and

Weddepohl (1988) researched elements of peak discharge estimation in *ACRU*. Caldecott (1989) developed and tested its flow routing modules while Royappen (current) has worked on parameter estimation of runoff components and Chetty (current) is using *ACRU* for research into design hydrology.

- Many enhancements to *process representations* have built on Schulze's (1975) original conceptualisations. Thus Seed (1987) and Schäfer (1991) researched facets of rainfall as the driver of the hydrological cycle, Everett (1990) as well as Buitendag (1990) and Sewell (1993) contributed to improved modelling of the redistribution of soil water, while Pike's (1992) research was on aspects of soil characterisation through spatial analysis. Topping's (1993) research was on initial abstractions, Moerdyk's (1991) on site preparation impacts, Hughes' (1997) on baseflow recession and Howe's (1999) on modelling variable source areas of sediments. New insights were gained by Scott (1994) into modelling effects of forest fires (i.e. hydrophobia) on hydrograph shape and more recently process-based snowmelt routines have been added to *ACRU* by Herpertz (2001) for the model's application in higher latitudes. *ACRU*'s wetland routines owe their origin largely to research by Chapman (1990), followed by that undertaken by Donkin (1997).
- Research with *ACRU* into aspects of *irrigation* initially focussed on the work of Dent (1989), who studied crop water requirements, and that of Furniss (1989) on effective water utilisation, with a resurgence of research into irrigation through studies on hydro-economic aspects by Grové (1997), on deficit irrigation by Lecler (current) and links to CROPWAT and SAPWAT by Meikle (current).
- An emphasis on *land use impacts* modelling using *ACRU* prompted research on responses to tillage practices by Buitendag (1990) and Sewell (1993), sugarcane by Haywood (1991) and afforestation practices by Jewitt (1992), Summerton (1996) and Gush (2002).
- The *crop yield* modules in *ACRU* are based on research undertaken by Domleo (1990) for maize and winter wheat and by Hughes (1992) on sugarcane.
- Water quality research towards higher degrees includes studies on impacts of feedlots on the Mgeni system by De Wet (1993) and of herbicides by Seed (1992), while Howe (1999) developed initial modules on modelling variable source areas of sediments using *ACRU*, as already mentioned. In as yet incomplete research, Teweldebran (current) is developing salinity routines for *ACRU*.
- *Climate change* impacts on agrohydrological responses have been at the core of *ACRU*-based research and model enhancement by Kunz (1994), Lowe (1997), New (1999) and Perks (2001).
- *Hydrological forecasting* has been the theme for postgraduate research with *ACRU* by Lumsden (2001) on sugarcane yield forecasts and by Hallowes (current) on streamflow forecasting using climate forecasts.
- *ACRU*'s dependence on *spatial databases* has led to the research by Kunz (1994), Meier (1997) and Perks (2001), while Chapman (current) is researching surrogate methods of estimating climatic variables where they are not being measured, in an update of the research by Clemence (1986).
- Aspects of *ecohydrology* have been researched by Kiker (1998), who worked on vegetation dynamics, Taylor (2001) on the environmental reserve and Butler (2002) on an operating rules framework for environmental flows.
- Finally, recent emphasis on *Integrated Water Resources Management* and upstream-downstream conflict management has prompted the whole catchment/installed modelling system approaches researched by Herpertz (1994) on the Bröl catchment in Germany, Taylor (1997) on the Pongola catchment, Makoni (2000) on the Mufure in Zimbabwe, Taylor (2001) on the Mkomazi, Dlamini (2001) on the Mbuluzi in Swaziland as well as on the Thukela (current) and Hayes (current) on the Blyde River catchment.

3.12 CONCLUDING THOUGHTS ON THE *ACRU* MODELLING SYSTEM : WHY TO USE; WHEN NOT TO USE; WHERE DOES THE FUTURE LIE?

a) *Perceived advantages and strengths of the ACRU agrohydrological modelling system*

From the basic premises on modelling for IWRM (outlined in Chapter 2), as well as from the description of the model's structure and its varied applications, *ACRU*'s perceived modelling strengths are its

- physical-conceptual process representation, mimicked at a
- daily time step resolution, its
- multi-purposeness, which includes the
  - landscape
  - riparian and
  - channel phases

of the natural hydrological system, on to which are juxtaposed routines to simulate
- land use/management influences on water and sediment flows
- reservoir performance
- irrigation demand/supply and/or
- crop yields,

all combined into a single system,

- thus making it an *agrohydrological* rather than only a *hydrological* model; furthermore, it contains
- multi-level input facilities which are determined, *inter alia*, by data availability, the
- ability to model in distributed cell-type mode,
- dynamic input options and extensive
- pre- and post-processing facilities,
- all together making it a modelling *system* rather than only a *model*.
- Further major perceived strengths are the *ACRU* model's comprehensive documentation. Both the *ACRU* Theory and the *ACRU* User Manual are now continually updated via the *ACRU* home page at www.beeh.unp.ac.za/acru and are downloadable
- the model's continual enhancement and refinement, driven by user needs, in particular through requirements from the National Water Act of 1998 and, with that, the advent of Catchment Management Agencies
- the availability of a dedicated *ACRU* User Consultant and
- model support from other WRC projects on databases and decision support.

b) What not to use the ACRU model for

In Chapter 2 the point is stressed that model developers should document clearly for what purposes *not* to use their model. In the case of *ACRU*

- the model should ideally not be used to simulate catchment hydrology on areas less than 1-2 km^2 because of the type of stormflow and baseflow equations used, nor should spatial units exceed 50 km^3 (ideally)
- the model does not yet, in its present state, simulate
  - channel transmission losses
  - aquifer related processes
  - subsurface tile drainage
  - rate functions of infiltration and soil water redistribution
  - 2-dimensional hillslope hydrological processes
  - vegetation dynamics explicitly
  - snowmelt processes or
  - salinity processes.
- Furthermore, it should be stressed that while *ACRU* is a *modelling system* (i.e. a model with pre-processors, decision support tools and post-processors), it is *not a systems model*.

c) Where to . . . the future?

Research on the model is currently (2002) focussing on

- reservoir operating rules
- environmental flows
- further refinements to land management strategies
- snowmelt (through a partnership with the University of Jena, Germany)
- nitrate and phosphate modelling (through partnership with the University of Florida, USA)
- salinity modelling
- sediment routing
- transmission losses and
- adding socio-economic and demographic components to the model.

In regard to model support, attention is at this point in time focussed on

- enhancing the functionality of the *Menubuilder* and *Outputbuilder*
- migrating to a Windows operating system and

- revision and new developments on national scale data and information systems (rainfall, temperature, land use, soils).

All of the above will render the *ACRU* model more versatile and easier to use in IWRM.

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CHAPTER 4

ON LAND COVER, LAND USE AND THEIR IMPACTS ON HYDROLOGICAL RESPONSES

R.E. Schulze

School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

ABSTRACT

Hydrologists intuitively associate different land covers and uses such as afforestation, urbanisation or irrigation with differences in the partitioning of rainfall into components of runoff such as stormflow or baseflow and with water quality determination. After defining the terms land cover and use, this chapter highlights the significance of the extents of land use changes, worldwide and in South Africa. The interplay between society and nature in land use change receives attention, with some emphasis on the difference between land use which is dependent on water vs land use which impacts on water. When ecosystems change as a result of land use alterations, they may be classified as conserved ecosystems, alternatively as utilised, replaced or completely removed ecosystems. Land use transformations may be represented as attribute changes, ecological response changes or hydrological response changes. Important generalisations regarding impacts of land use change on hydrological responses are summarised as follows: Land use change often leads to ecosystem degradation, it usually takes place slowly, its impacts are easily observable at small spatial scales but not easily recognised regionally, land use impact depends on its intensity and spatial extent, and management of the land frequently has greater impacts on hydrological responses than changes in land cover. The discussions on most of these generalisations are backed up with examples in the form of tables and diagrams. By way of conclusion, a case study on impacts of land use on hydrological responses is presented, using the Mgeni catchment in KwaZulu-Natal as the example. Maps illustrate that land use change can reduce baseline mean annual runoff (MAR) by up to 61% through agricultural intensification while increasing MAR by up to 103% in urbanised and degraded areas.

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4.1 THE LAND SURFACE : HYDROLOGY CONNECTION

The land surface is the locus of most human activities. It is where we live, grow our food and harvest our fresh water. Exchanges of energy, mass and momentum between the atmosphere and hydrosphere take place at the land surface. These exchanges are complex functions of the many processes that occur over a range of temporal and spatial scales. Many details have to be considered at the land surface, with processes often occurring in non-linear relationships. However, any attempt at understanding all these details can only be realised through the simplified algorithms which we use to represent, for example, the land cover and land use components in agrohydrological models.

This chapter sets out to discuss some background to the impacts which the land cover and use components of the land surface can have on hydrological responses. It does so by first highlighting what responses hydrologists intuitively associate with different land uses, then defining the differences between land cover and land use, giving examples of the extent of land cover/use changes that have occurred, explaining the interplay between society and nature and land use change from a hydrological perspective, how ecosystems which have been changed by land uses are classified and how land use transformations are represented as ecological and/or hydrological changes of state. Thereafter, important general findings regarding impacts of land use change are discussed before concluding with a case study on impacts of land use in the Mgeni catchment in KwaZulu-Natal, South Africa.

The ideas and concepts expounded in this chapter find direct application in Chapters 5, 6, 7, 8, 9, 10, 11, 12 of this report.

4.2 WHAT RESPONSES DO HYDROLOGISTS INTUITIVELY ASSOCIATE WITH DIFFERENT LAND USES?

Many of the conflicts arising out of the quest for an equitable allocation of water between competing sectors within an individual catchment (e.g. agricultural vs environmental vs industrial sectors), and even allocations within a single sector (in agriculture, e.g. irrigated vs dryland production, or grazing vs afforestation), stem from the impacts different land uses have on indicators of both water quality and quantity.

Hydrologists intuitively associate certain mechanisms of water utilization and runoff generation with different land uses. Some examples follow:

- *Commercial plantation afforestation*, for example, allows less water to enter the soil profile through increased canopy and litter interception. That water which does enter the soil, does so at higher infiltration rates than it would for most other crops. Added to that, more water is evapotranspired through the enhanced wet canopy evaporation of a forest than from short crops, more is extracted from the soil profile by deeper rooting systems, the higher aerodynamic roughness of the canopy enhances the evaporation process, as does, in the case of evergreen forest species, photosynthetic activity throughout the year. The result of this particular disposition of rainfall over forests is that stormflows as well as recharge to groundwater are reduced which, in combination with one another and the increased evaporative losses, alters the daily, seasonal and thus total generation of streamflows (cf. Chapters 8, 10). In addition, with forest growth cycles in South Africa of 10 - 30 years, these effects change dynamically over time in a sigmoidal manner (cf. Chapter 7). Furthermore, primarily because of their deeper rooting systems, the impacts that forest plantations have on streamflows can change with their position within the landscape, with greater impacts on streamflow generation in the wetter riparian areas (cf. Chapter 11).
- *Human settlements*, on the other hand, are characterised by rapid hydrograph responses to rainfall, with higher stormflows and higher peak discharges, the latter associated with shorter lag times. These responses are linked to high proportions of impermeable surfaces which may be adjunct, i.e. connected, to receiving streams, by efficient stormwater discharge systems, or disjunct from the stream, i.e. unconnected. The high wash-off from the impermeable areas, exacerbated by localised production of industrial pollutants, also implies a frequent deterioration of water quality from urban areas.
- *Irrigation*, in turn, impacts streamflows by very different mechanisms. Flows of water are reduced by direct abstractions from run-of-river or from reservoirs. Immediate downstream influences may

thus be very marked and quite pulsar (episodic), dependent on the mode of irrigation scheduling, which in itself affects water use and its efficiency (cf. Chapter 9). Further downstream, however, the impacts of abstractions may become attenuated. The impacts of irrigation on streamflows may also be highly seasonal and tend to be amplified in relatively drier areas as well as in drier years (cf. Chapter 10). Irrigated areas experience evaporation at constant near 'potential' rates, with the result that if surrounding areas are relatively soil water stressed, additional advective activity can enhance evaporative losses at the edge of irrigated fields. Irrigated lands, with their higher soil moisture contents, can experience increased water losses through additional stormflows and deep percolation (cf. Chapter 9) and, because irrigated crops tend to be heavily fertilised, these losses can cause a deterioration of downstream chemical water quality, often lagged by several years.

- *Agricultural practices* such as ploughing change the soil's bulk density and hence water holding capacity, thereby reducing stormflows. Furthermore, tillage practices increase the soil surface roughness, which enhances infiltrability. Compared to untilled lands, these factors alter the partitioning of rainfall into stormflow and baseflow components. The effects of both bulk density and surface roughness changes diminish as the growing season progresses after initial tillage, but are re-introduced with each mechanical disturbance of the soil. Additionally, the construction of contour banks retards stormflows and causes them to partially re-infiltrate again, while practices such as conservation tillage, where crop residue/mulch is left on the field after harvest, enhance infiltrability and reduce evaporative losses from the soil surface.
- *Grazing*, on the other hand, if poorly managed as a consequence of degradation through overstocking, results in biomass denudation and soil surface exposure as well as soil compaction, all of which enhance stormflows as well as soil losses (cf. Chapters 6, 12), while well managed grazing increases infiltrability, reduces stormflows, encourages recharge and, additionally, offers a near-closed canopy which breaks the erosive potential of raindrops (cf. Chapters 6, 12).
- *Reservoirs* (dams) are associated with high evaporative losses on the one hand, but on the other may be used to control downstream outflows and attenuate flood hydrographs. While their facility to store water for domestic, industrial and agricultural allocations and to control floods are major positive functions of dams, the altered downstream flows frequently do not meet ecological requirements and controlled releases may be required.
- *Riparian vegetation*, particularly if it consists of infestations of alien plants, is often associated with reductions in streamflows emanating from enhanced extraction of influent subsurface flows towards a stream (Chapter 11). Reductions in flows are dependent on the physiological characteristics of the alien growth (e.g. evaporative demand, stomatal conductance, root characteristics, photosynthetic cycle), the proportion of the riparian zone infested and the density of infestation (Chapter 11).

The above are all examples of influences of land cover and land use on water quantity and water quality, often resulting in altered partitioning of rainfall into different components of runoff. Before continuing, however, it is important to distinguish between what is understood by the terms *land cover* and *land use*.

4.3 WHAT DO WE UNDERSTAND BY THE TERMS LAND COVER AND LAND USE?

Land cover (Figure 4.1) refers to the biophysical state of the earth's surface and immediate subsurface in terms of broad categories such as cropland, natural or man-made forest, grassland, settlements, water bodies or mining (Turner, Moss and Skole, 1993; Turner, Skole, Sanderson, Fischer, Fresco and Leemans, 1995). These broad land cover categories can be changed by natural forcing such as long-term climate changes or climatic persistence (for example, consecutive years of drought), or by naturally occurring episodic events such as fire, volcanic activity or flooding. Overwhelmingly, however, land cover has been changed to a *land use* by human actions through land cover conversion, or alternatively land cover modification, primarily for purposes of agricultural production and settlement (Turner *et al*., 1995).

In agricultural hydrology the term land use distinguishes between *land utilisation* (for example, by specific crops and their different seasonal evaporative demands) and *land treatment* (Schulze, Schmidt and Smithers, 1993). Under land treatment, a further categorisation for hydrological modelling purposes needs to be made between direct *mechanical practices* such as conservation structures (contours, terraces), which usually intervene in horizontal water flows, and the more indirect *management practices* such as

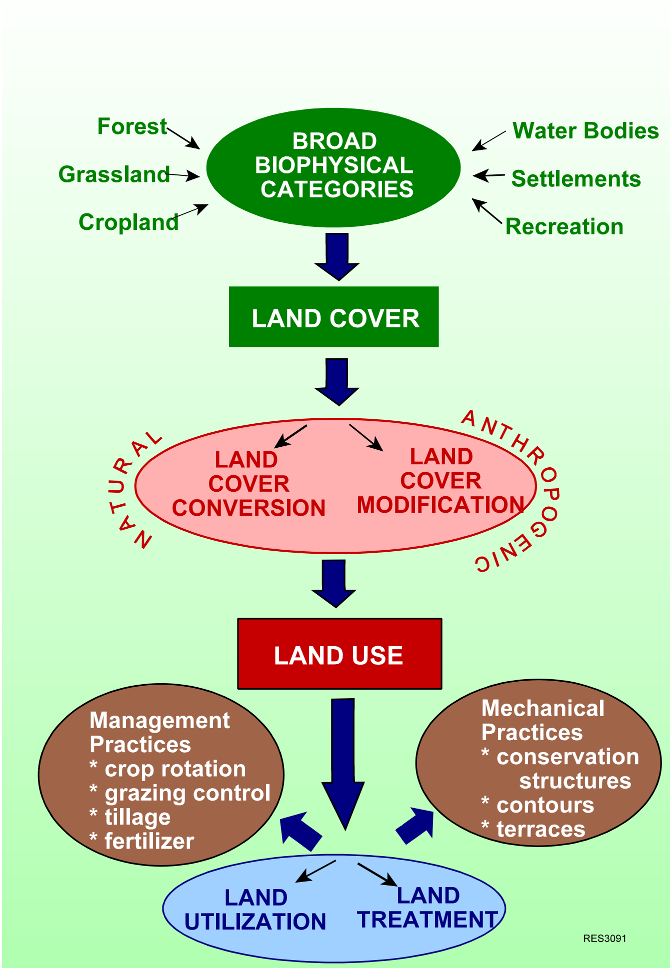

Figure 4.1 The relationship between land cover and land use (after Schulze, 2000)

grazing control or crop rotation or intensification of production, where these become the drivers for changes in hydrological states of water quantity and quality through, for example, different modes of tillage practices which change water quantities, or the application of fertilizers and herbicides which change the state of water quality (Figure 4.1). These practices often alter the vertical fluxes of water.

4.4 HOW SIGNIFICANT ARE THE EXTENTS OF LAND USE CHANGE, WORLDWIDE AND IN SOUTHERN AFRICA?

Land cover conversion and modification have taken on vast proportions. Thus, for example, Meyer and Turner (1992) cite that worldwide, conversion to cropland has now replaced 14.3 million km^2 of natural vegetation, while the net loss of natural wetlands is 1.9 x 10^6 km^2 and natural closed forests have been reduced by 7.2 x 10^6 km^2. Irrigated areas now make up 2 x 10^6 km^2 of the earth's land surface of approximately 130 x 10^6 km^2 (Richards, 1990), while urban areas cover about 4 x 10^6 km^2 (Douglas, 1994). Turner, Moss and Skole (1993) report that some 40% of the earth's original land cover has been extensively modified or converted for production or habitation purposes and that only one quarter of the earth's land surface is, today, under near-natural conditions.

By socio-politico-economically driven production and consumption dynamics the South African landscape of 1.193 million km^2 has, for example, seen natural land cover conversion of over 37 600 km^2 to maize, some 14 900 km^2 to commercial timber plantations, 12 950 km^2 to wheat and 4 120 km^2 to sugarcane, while over 14 300 km^2 are under irrigation (Schulze, 1997).

Historically, in the 'old world', especially in temperate climates, land use change has been going on for centuries and in the UK 70% of the land is now under agriculture and grazing, 10% is urbanised, 10% derelict land and mines while only 10% remains in woodland (DOE-UK, 1993). In 'newer world' countries overall levels of urbanisation and agriculture may be proportionately lower, but other hydrologically sensitive land uses become important, with concentrations in certain regions. Thus, in the case of South Africa (Table 4.1), plantation forests are expected to impact on hydrological responses in Mpumalanga province, with urban areas are most likely to influence runoff patterns in Gauteng, rainfed cultivation in the Free State, irrigation in the Western Cape and degraded areas as well as reservoirs in KwaZulu-Natal province.

Table 4.1 Percentages of selected hydrologically important land uses in certain provinces of South Africa (Schulze, 2001, based on Thompson's National Land Cover images from 1996 satellite imagery)

Land Use Category	Country or Province, with Area in km^2						
	RSA, Lesotho, Swaziland 1 267 681 km^2	Mpumalanga Province 78 238 km^2	Northern Cape 362 393 km^2	Gauteng Province 18 610 km^2	Free State 129 833 km^2	KwaZulu-Natal 92 285 km^2	Western Cape 129 578 km^2
Plantation Forest	1.47	9.19	0.01	1.29	0.16	6.75	0.83
Urban	1.29	1.95	0.16	19.30	0.80	1.57	0.83
Cultivated- Rainfed	10.87	15.80	0.28	19.14	28.34	15.83	13.53
Irrigated	1.23	1.74	0.46	0.92	0.53	1.47	3.52
Severely Degraded	4.79	2.11	0.88	0.13	0.68	7.97	2.76
Wetlands	0.48	0.13	0.81	0.40	0.89	0.83	0.18
Grassland	21.30	40.70	12.00	42.30	50.80	39.20	0.94
Reservoirs	0.38	0.51	0.18	0.47	0.63	1.11	0.50
Other[1]	58.19	27.87	85.22	16.05	17.17	25.27	76.19

1) Other will be mostly vegetation still in a relatively near-natural state

4.5 WHAT IS THE INTERPLAY BETWEEN SOCIETY AND NATURE IN LAND USE CHANGE, AND WHAT IS ITS HYDROLOGICAL SIGNIFICANCE?

Societal requirements for food, water, energy or hazard prevention have to be satisfied by the natural resources of water, biomass, energy and minerals (Falkenmark, Andersson, Carstensson and Sundblad, 1999; Figure 4.2). Through society's needs, the natural landscape is, therefore, manipulated for purposes of livelihood in both physical terms (e.g. land conversion) and chemical terms (e.g. waste and pollutant production). This, in turn, has environmental side effects (e.g. air, water, land and ecosystems degradation; Figure 4.2) with reactive responses (both passive - usually in the developing world, and active - more characteristic of developed countries) which can feed back into the landscape again, and into changed water requirements.

The interactions illustrated in Figure 4.2 manifest themselves in land use activities and land management decisions which impact on water resources at the river basin scale. Falkenmark *et al*. (1999) distinguish between two types of land use activities that have a fundamental bearing on the hydrological cycle, *viz*.

- *land use which is dependent on water*, i.e. where water poses limitations on societal production from land, e.g. when there is too little water or too much water - both of which are limitations/disturbances caused by nature; and
- *land use which is impacting on water*, i.e. when flows of water change through altered partitioning of precipitation into evaporation and runoff components as a consequence of disturbances created by societies (e.g. urbanisation, afforestation, overgrazing, tillage practices), or when flows of matter are altered by new land management scenarios (e.g. enhanced sediment or nutrient production). In either case, every land management decision becomes a water resources decision (Falkenmark *et al*., 1999).

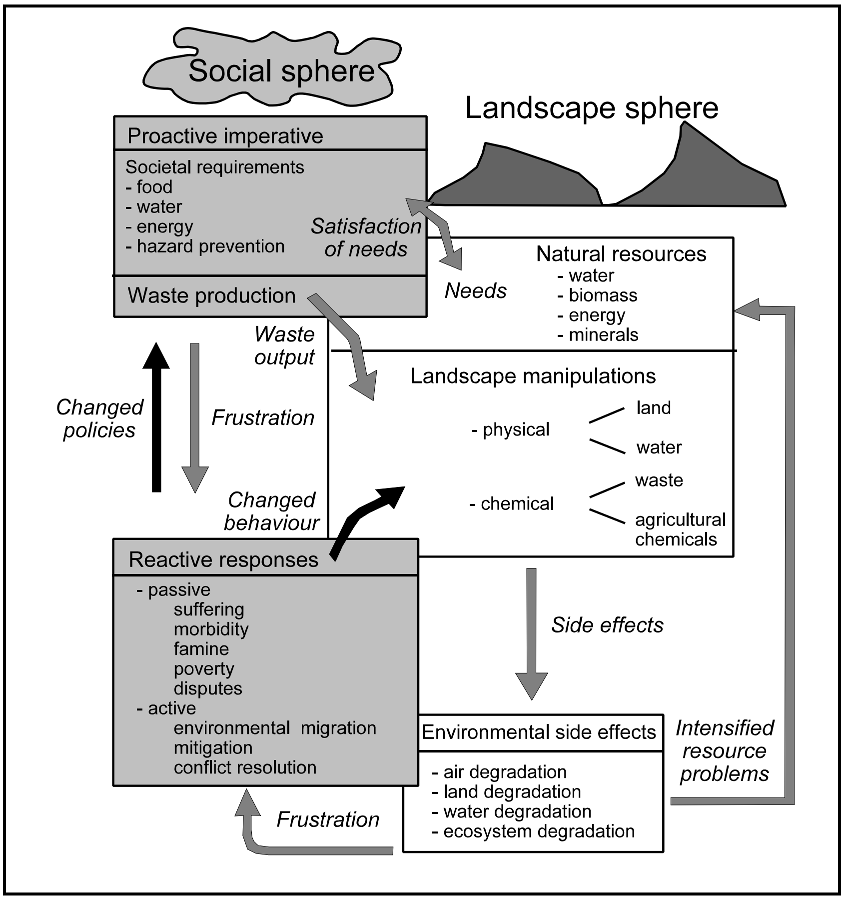

Figure 4.2 Human activities in the landscape as produced by the interplay between the social and landscape spheres (after Falkenmark *et al*., 1999)

4.6 HOW ARE ECOSYSTEMS CLASSIFIED WHICH HAVE BEEN CHANGED BY LAND USES?

There are different degrees of alteration of natural ecosystems states through land use changes. Hobbs and Hopkins (1990) have categorised these, with a hierarchy of impacts on water resources added by the author. They are as follows:

- *Conserved ecosystems*, i.e. where no deliberate modifications to the natural landscape have been made, either by design (e.g. wilderness/conservation areas; unutilised government owned land; catchments reserved for water production) or by default (e.g. environments too harsh for habitation) and hydrological responses do not alter from baseline responses;
- *Utilised ecosystems*, i.e. where indigenous ecosystems have been exploited (e.g. by non-plantation forestry; pastoralism; recreation), again with zero to negligible hydrological impacts;
- *Replaced ecosystems*, i.e. where intensively managed systems have removed native ecosystems and replaced them with simpler, less biodiverse systems geared towards agricultural, horticultural and exotic forestry production, and where hydrological consequences as a result of a different partitioning rainfall into evapotranspiration and the various components of runoff, and thus total runoff generated and its seasonality, as well as changes in water quality, can range from minor to major; and
- *Completely removed ecosystems*, i.e. where native ecosystems have been destroyed, with each land use entailing a suite of deliberate and/or inadvertent impacts of varying severity on natural responses (e.g. urban and industrial development, mining, transport), with major local hydrological repercussions with respect to peakedness of flows and chemical pollution of waters.

4.7 HOW ARE LAND USE TRANSFORMATIONS REPRESENTED AS ECOLOGICAL AND/OR HYDROLOGICAL CHANGES OF STATE?

In a manner akin to that of ecologists who view a land use transformation as a change in 'ecosystem state' (i.t.o. structure, composition and/or function), so to hydrologists changes in land use also represent hydrological response transformations (Schulze, 2001). These may be represented as follows:

- *Land Surface Attribute Changes* : These include intra- and inter-seasonal changes in
  - *above ground attributes*, such as biomass indices and aerodynamic roughness, from which may be derived changes in canopy and litter interception losses, in consumptive water use by plants and in shading of the soil, thereby partitioning evaporation of water from the soil surface and from plant tissue (transpiration) differently (Schulze, 1995; 2001);
  - *ground/surface level attributes*, such as the extent of compaction or of imperviousness, surface crusting and sealing, surface roughness, surface cover by litter/mulch or conservation structures, all of which alter pathways of water entry into the soil, consequently runoff/erosion from the surface and also alter pathways of streamflow generation into their respective stormflow and baseflow components; and
  - *below surface attributes*, such as bulk density of the soil as a result of various types of tillage practice, and hence soil water transmissivity, as well as root mass distribution which influences extraction patterns of soil water from the different horizons of the soil (Schulze, 1995; Schulze, 2001).
- *Ecological Response Changes* : In this case changes in the ecosystem state are expressed in terms of decline and recovery over time (Hobbs, 2000; Figure 4.3) as
  - rapid and permanent changes of state, e.g. following urbanisation or permanent clearance for agriculture
  - gradual degradation, e.g. from overgrazing
  - sudden disturbance, but with full recovery, e.g. following a fire, or shifting agriculture
  - sudden disturbance, but with only partial recovery, e.g. urbanisation followed by a re-greening of the urban landscape
  - recovery following cessation of stress, e.g. rehabilitation of rangeland following removal of cattle, and
  - recovery following deliberate action, e.g. ecosystem restoration or wetland rehabilitation.
- *Hydrological Response Changes* : From a catchment's perspective, the above changes of ecosystem states and the associated attribute changes are accompanied by changes in flows of water and/or sediments and/or nutrients. The hydrological flows may be manifested as
  - increases in total flows, e.g. following urbanisation
  - decreases in total flows, e.g. following afforestation
  - changes in seasonality of flows, e.g. after dam construction
  - changes in peakedness/responses of flows, e.g. higher peaks and shorter lag times following a fire or urbanisation

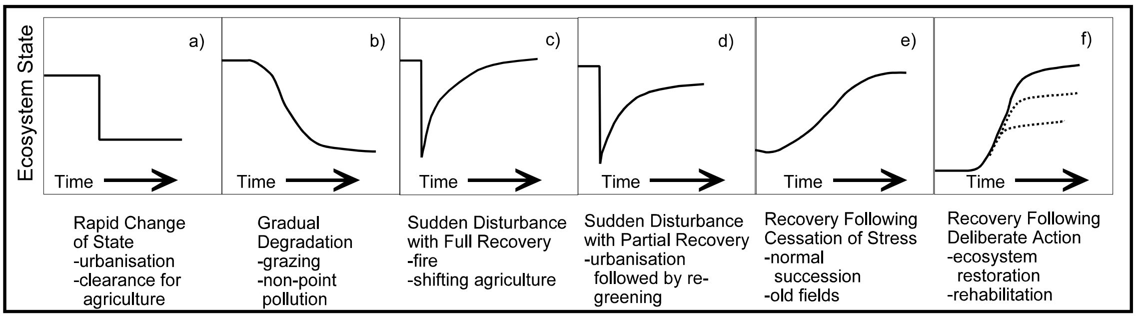

Figure 4.3 Changes in ecosystem states as a result of land use changes (modified by Schulze, 2001; after Hobbs, 2000)

- changes in the partitioning of flows, into baseflow and/or stormflow, e.g. after agricultural conservation structures are put in place, or
- re-naturalisation of flows, after rehabilitation (Schulze, 2001).

4.8 WHAT, THEN, ARE IMPORTANT GENERAL FINDINGS REGARDING IMPACTS OF LAND USE CHANGE ON HYDROLOGICAL RESPONSES?

The potential impact of land use on hydrological responses is beyond dispute. In considering land use impacts on hydrological responses, however, six important general findings are highlighted :

a) Land use change often leads to ecosystem degradation

This view is held strongly by ecologists (e.g. Hobbs, 2000). However, the feedbacks to hydrology (and to society) may be either negative, as in the example by Batchelor (1995) on population pressure/drought in a subsistence agricultural setting (Figure 4.4, top), or positive, as in Batchelor's (1995) example of the effects of community gardens in the same agricultural setting (Figure 4.4, bottom).

b) Land use change, while usually taking place slowly over time, nevertheless has to be accounted for in simulations, ideally in a dynamic manner as a temporal change

In a regional context, land use change usually takes place slowly and in a largely piecemeal fashion as and when individual farmers respond to market forces and/or legislation (Acreman and Adams, 1998; Robinson, Boardman, Evans, Heppell, Packman and Leeks, 2000) or as cities expand. A case in point is the gradual agricultural intensification of the 349.2 km^2 Lion's River catchment in KwaZulu-Natal, where from a series of aerial photographs over time, the expansion of commercial afforestation and irrigated agriculture was as given in Table 4.2.

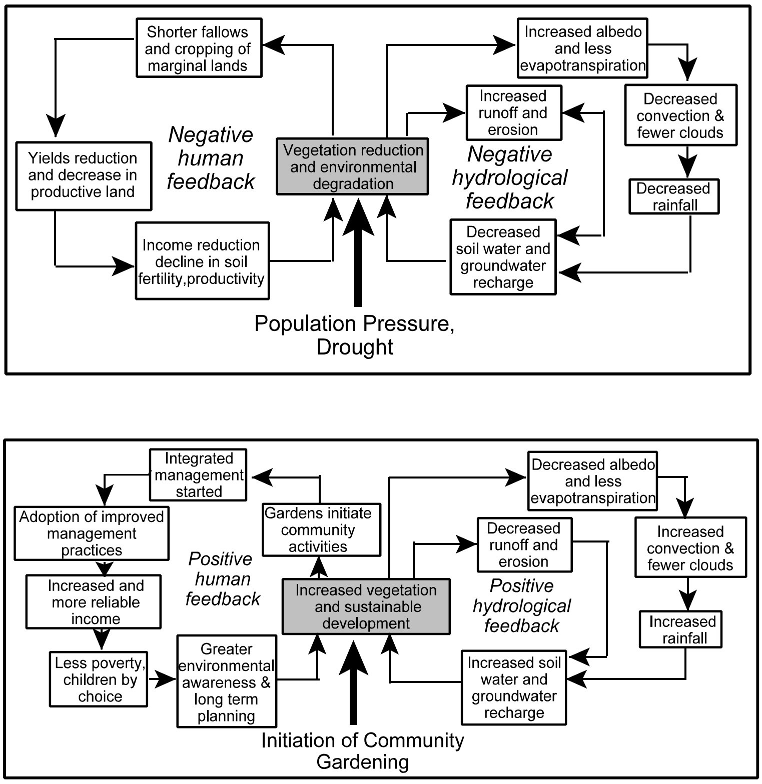

Figure 4.4 Negative (top) and positive (bottom) hydro-societal feedbacks to changes in land use (after Batchelor, 1995)

The significance of these land use changes in hydrological simulations with the *ACRU* model (Schulze, 1995) were that if the relatively extensive land use of 1959 was used in a 31 year simulation (1959 - 1990), the model over-estimated accumulated observed streamflows by 17%, if the relatively intensive land use of 1990 was used, the model under-estimated observations by 32%, while if dynamic land use change over time was incorporated, the model was within 8% of accumulated observed flows (Tarboton and Cluer, 1991).

Table 4.2 Percentages of major land uses over time in the Lion's River catchment, KwaZulu-Natal (after Tarboton and Cluer, 1991)

Year	% Commercial Afforestation	% Irrigated Agriculture	% Veld and Dryland Crops	% Other
1959	10.7	1.4	87.7	0.2
1967	16.5	4.8	77.4	1.3
1978	18.0	11.2	68.5	1.3
1990	21.7	13.2	62.3	2.8

c) Land transformation impacts are easily measured at small scale, but are often not easily distinguishable regionally

At point, plot or small catchment scale, process studies often provide unequivocal evidence of direct hydrological effects of a particular land use. However, at progressively larger catchment scales these impacts are often difficult to detect because they become attenuated when viewed together with other stable land uses and/or their effect is diluted downstream (e.g. Acreman and Adams, 1998; Schulze, Horan, Shange, Ndlela, and Perks, 1998; Robinson *et al*., 2000). This is well illustrated in Figure 4.5 for median annual and dry season flows in the Pongola-Bivane catchment of 4 721 km^2 upstream of Subcatchment 17. Individual subcatchments display highly variable proportions of plantation afforestation (the figures in brackets) and, consequently, of local impacts, but the accumulated flows become attenuated and impacts are diluted/smoothed as flows accumulate and cascade downstream.

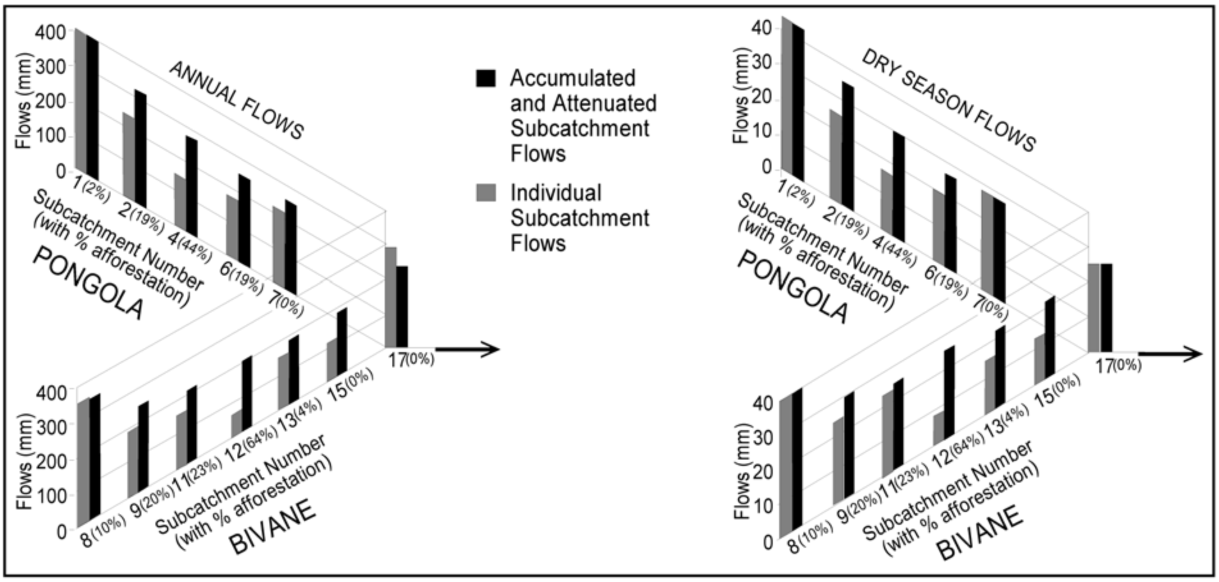

Figure 4.5 Impacts of varying percentages of plantation afforestation per subcatchment (% afforestation in brackets) on median annual and dry season streamflows in the Pongola-Bivane catchment, and its attenuation downstream by flow accumulations (after Schulze *et al*., 1998)

d) Some land use impacts display considerable lag

Impacts, particularly those reacting through the groundwater system, such as nitrate pollution or effects of plantation afforestation on low flows, may only manifest themselves several years later. Such potential impacts require careful and pro-active consideration.

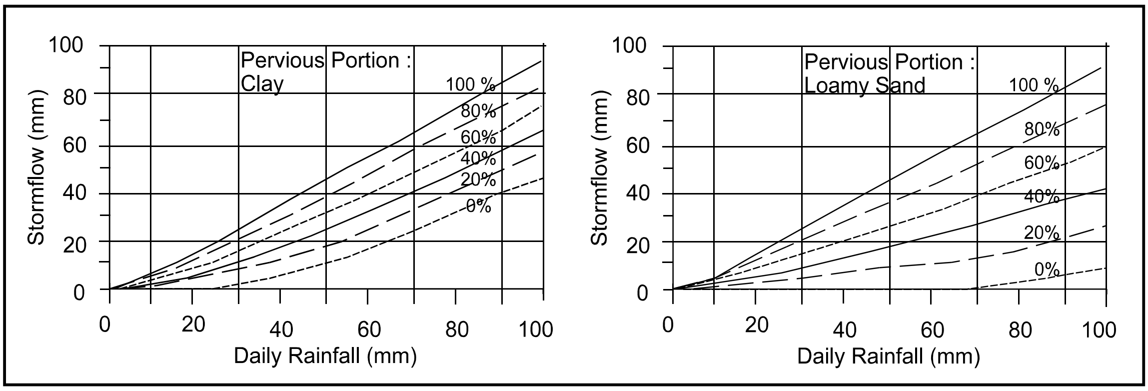

Figure 4.6 Conversion of daily rainfalls to stormflows by the SCS model (Schulze *et al*., 1993) for different percentages of imperviousness on two different soil textures, assuming pervious areas to be well grassed and the impervious portion to be connected to stormwater drainage (after Schulze, 2001)

e) The impact of land use often depends on its intensity

The intensity of urbanisation on stormflows is a case in point (Figure 4.6), as would be the application of artificial fertilizer on agricultural land.

f) Land use management often has more significant hydrological effects than land cover change

Hydrologists and water legislators tend to place great emphasis on changes of land cover and its hydrological effects. It is often, however, the management practice (e.g. rangeland with controlled grazing vs overgrazed, depth and type of tillage, rate and amount of fertilizer application) and/or mechanical practice (e.g. presence or absence of terraces, contours and other conservation structures) that alters the conversion rate of precipitation into hydrological responses (e.g. stormflow, recharge, sedimentation, nitrate leaching) to a far greater degree than, say changing from crop A to crop B (e.g. Moerdyk and Schulze, 1991; Schulze, 2001). This is illustrated in Figure 4.7, which shows that for maize grown on an A/B category soil (typically a sandy clay loam), a 60 mm daily rainfall would produce 8 mm stormflow when conservation tillage and structures are in place vs 13 mm when grown in straight rows. In the case of sugarcane the impact of conservation structures is even more marked.

4.9 IN CONCLUSION : A CASE STUDY ON IMPACTS OF LAND USE ON HYDROLOGICAL RESPONSES

To conclude this chapter an example of the potential influences of land use on hydrological responses from a catchment is presented.

The 4 079 km^2 Mgeni catchment in KwaZulu-Natal is highly modified, with six baseline land cover types, represented by Acocks' (1988) Veld Types, having been replaced by 21 classes of land use and cover representing present conditions (Figure 4.8, top vs bottom). After extensive verification studies of the *ACRU* model in the Mgeni catchment on seven catchments which displayed a range of combinations of land uses, soils and climatic conditions (Kienzle, Lorentz and Schulze, 1997), the influence of land uses on hydrological responses was assessed on the 137 interlinked subcatchments making up the Mgeni system in three analyses.

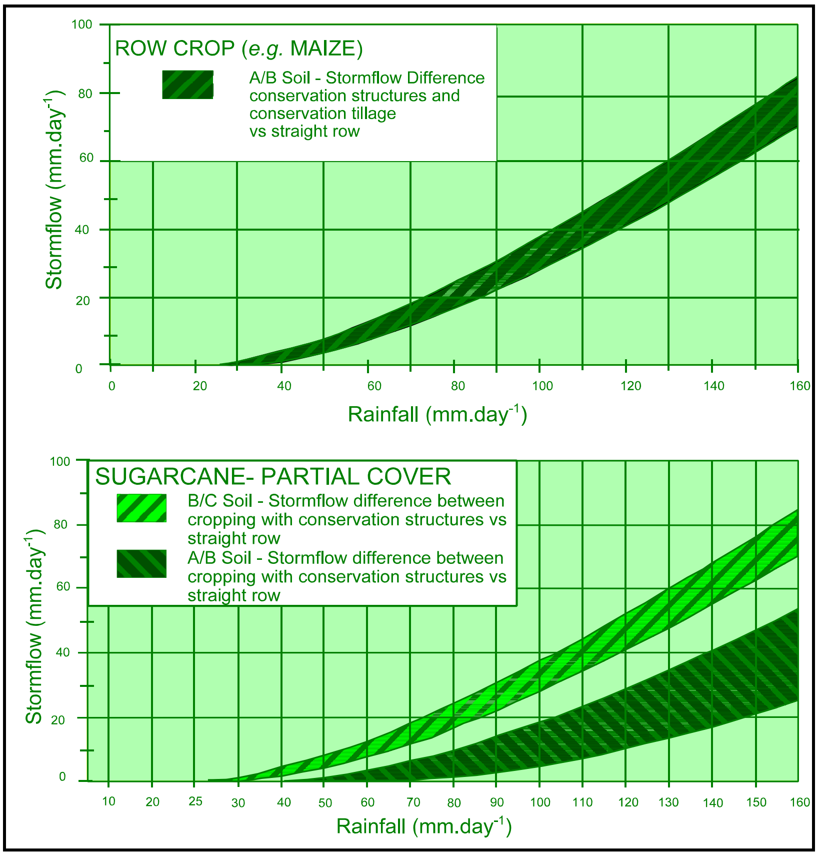

Figure 4.7 Impacts of conservation practices on stormflow : rainfall relationships for maize and sugarcane using the SCS-SA model (Schulze *et al*., 1993; Schulze, 2001)

In a first assessment the runoff coefficient, i.e. the mean annual runoff (MAR) expressed as a percentage of the mean annual precipitation (MAP), was plotted against MAP for the 137 subcatchments. In Figure 4.9 the plot for baseline land covers shows an expected high correlation between the runoff coefficient and MAP, while the runoff coefficient for present land covers displays no association whatsoever with MAP, illustrating clearly the disruption to the natural rainfall : runoff conversion as a result of land cover modification and land use intensification. In a second assessment, the percentage changes in median annual streamflows resulting from the modifications and conversions of baseline land covers were mapped. Figure 4.10 (top) illustrates that MAR reductions of up to 61% can occur, mainly in areas of intensive sugarcane and exotic forest plantations, while gains in MAR of up to 103% were simulated in areas which were urbanised or had dense rural populations where, additionally, overstocking and associated land degradation were prevalent.

Changed hydrological responses to land use are not confined to streamflow changes, however, and a third assessment (Figure 4.10, bottom) illustrates the spatial patterns of the biological status of the receiving streams of the Mgeni system in a map of simulated mean annual concentrations of the pathogen *Escherichia coli* (*E. coli*). In developing and verifying the model to simulate the fate of *E. coli* in a catchment, two land use variables were identified as major driving forces, namely, livestock density and the number of humans living in close proximity (< 250 m) to streams and under conditions of poor sanitation (Kienzle *et al*., 1997). The map shows simulated *E. coli* concentrations to range from under 250 (lowest, 30) to over 10 000 (highest, 18 200) counts per 100 ml, with areas of highest concentrations associated with informal settlements, cattle feedlots and areas of high general stocking rates.

This case study illustrates clearly the importance that needs to be attached to land use influences in IWRM.

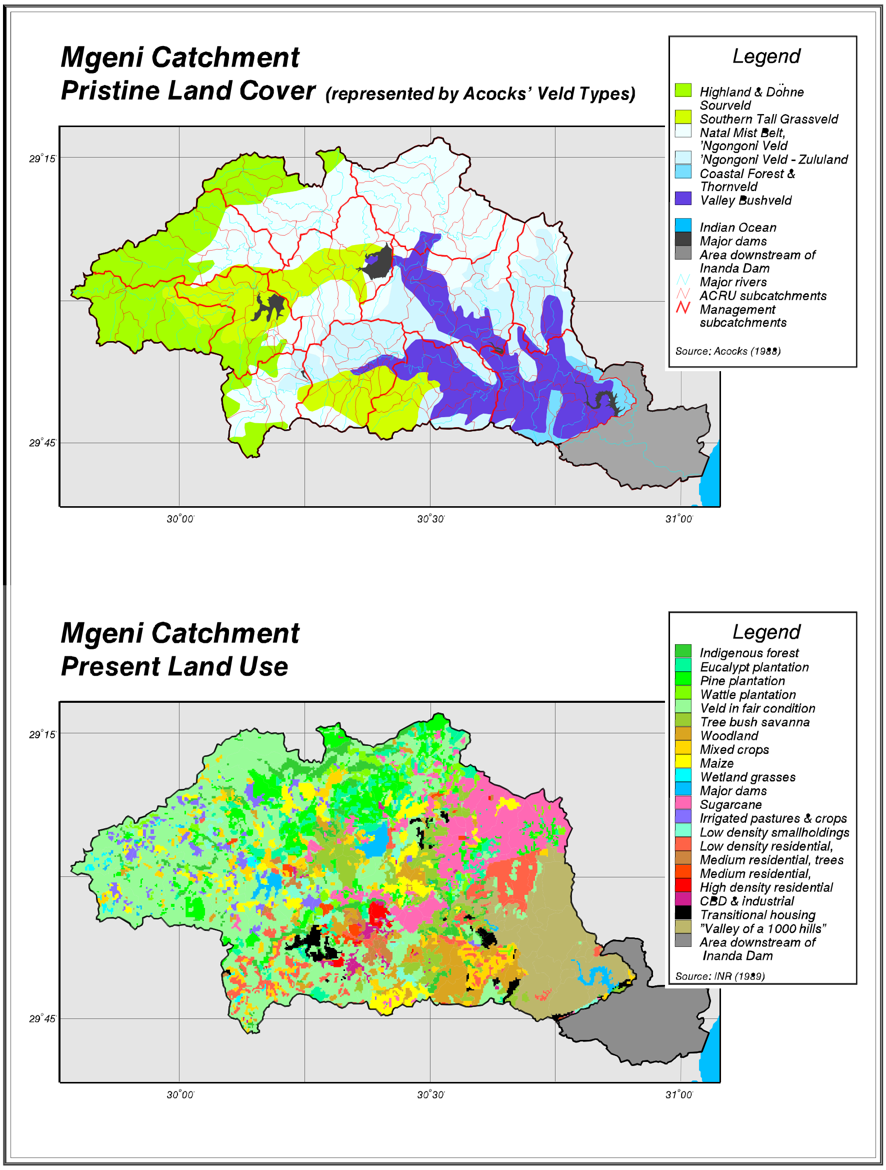

Figure 4.8 Distribution of baseline ('pristine' on the map) land cover (top) and present land use (bottom) in the Mgeni catchment (after Kienzle *et al*., 1997)

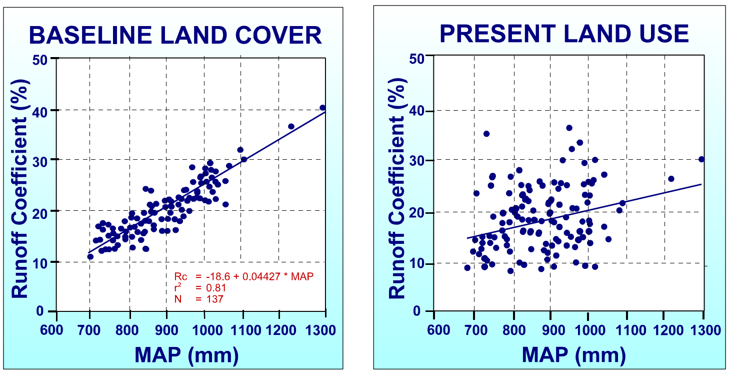

Figure 4.9 Associations between the runoff coefficient and MAP (mm) for 137 subcatchments of the Mgeni river system for (a) baseline and (b) present land uses (after Schulze, 2000)

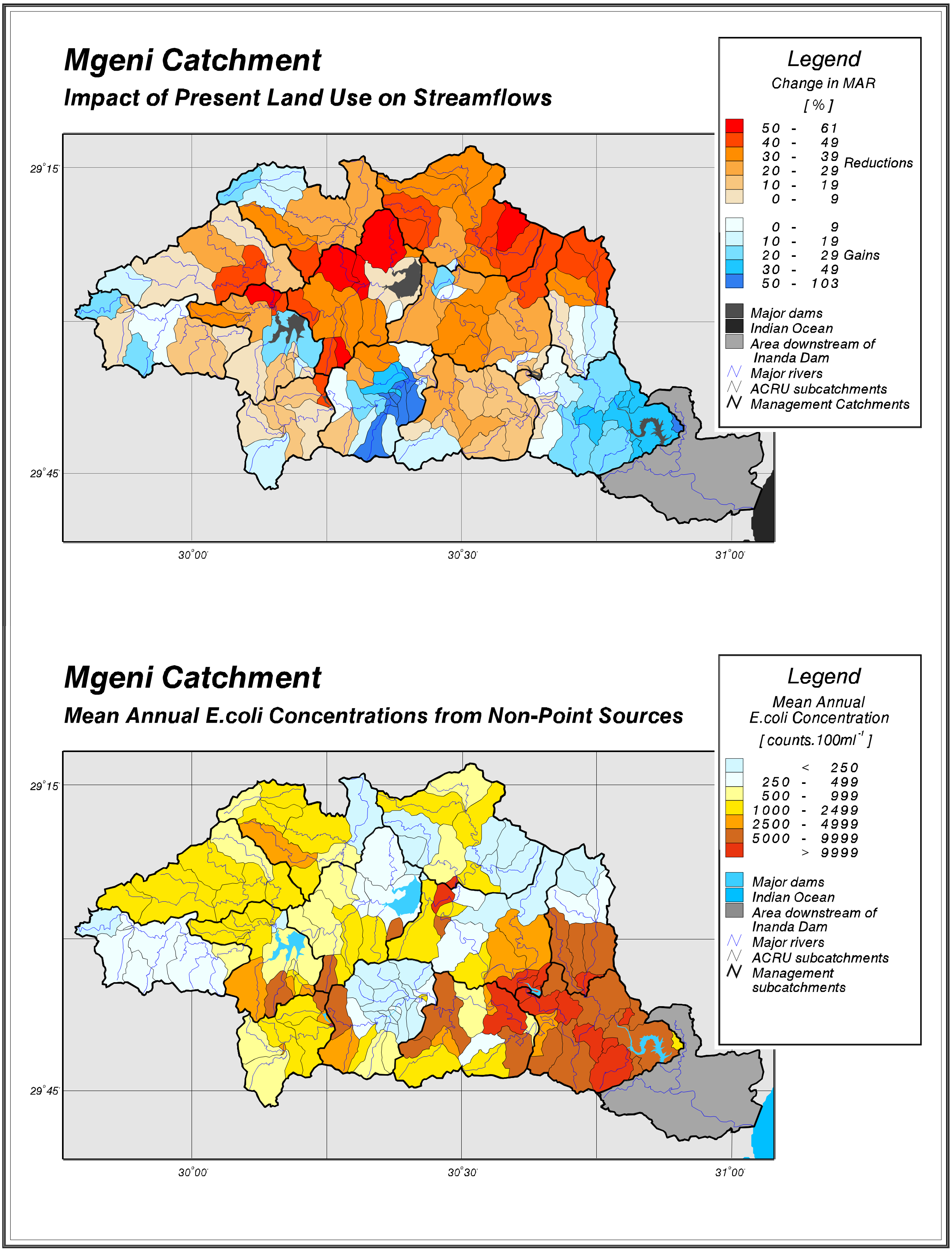

Figure 4.10 Percentage changes in MAR as a result of conversion from baseline land cover to present land use (top) and variations in mean annual concentrations of *E. coli* from present land use in the Mgeni catchment (after Kienzle *et al*., 1997)

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CHAPTER 5

DOES DETAIL MATTER? CASE STUDIES IN SUPPORT OF USING DATA AND INFORMATION BASES THAT ARE MORE DETAILED THAN PROVIDED BY WATER INDUSTRY 'STANDARDS'

R.E. Schulze[1], V. Taylor[1], M.J.C. Horan[1], K.B. Meier[2] and A. Pike[1]

[1] School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

[2] Now: Land Resources International, Pietermaritzburg, South Africa

ABSTRACT

While pleas are made for the use of freely available standard national datasets and spatial digital information in modelling for integrated water resources management (IWRM), multi-scalar issues of upstream vs downstream hydrological conflicts often dictate that more detailed inputs may be necessary in hydrological models, especially when sensitive land use related issues are under the spotlight. Two case studies are presented to illustrate this.

In the first, from the Bivane catchment in KwaZulu-Natal, differences in detail of land use information derived from different sources are shown to be highly sensitive when used as input to models applied to upstream - downstream water management issues. In this catchment the critical land use issues were the hydrological impacts related to the extent of commercial forest plantations the area under irrigation and the number and capacity of dams supplying some of the water for irrigation. The sources of land use information were 1993 Landsat TM images and 1996 aerial photographs at scale 1 : 30 000, with the latter backed up by field checks. The aerial photos identified 69% more afforestation and six times as many farm dams, with full supply capacities three times in excess of those computed from the Landsat image, but irrigated lands were only 14% in area of those identified from the satellite image - the latter example clearly a case of misinterpretation of a land use classification system.

The second case study compared the spatial distribution of rainfall from the 1' x 1' latitude/longitude national grid of mean annual precipitation (MAP) with that derived from local physiography : rainfall relationships in three catchments on the North Coast of KwaZulu-Natal. Differences in MAP ranging from +300 mm to -300 mm were found, i.e. $\pm$ 20% of the MAP. Detailed studies showed that these 'errors' could translate to differences in streamflows of up to 60%.

Both case studies illustrate clearly that in IWRM any errors caused by lack of appropriate detail in inputs to hydrological models could result in markedly different decisions being made.

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5.1 DOES DETAIL MATTER? SOME INITIAL THOUGHTS

In Chapter 2 of this Report, which reviews models and modelling, a plea was made that models used in Integrated Water Resources Management (IWRM) be 'driven' by standard datasets which are freely available from national networks and by standard spatial digital information available at national scale (Chapter 2, Basic Premise 16). Arguments advanced included that these come with certain standards, uniformity, quality control, general acceptance and credibility. South African examples of water industry standards include use of

- Quaternary Catchments (QCs) as spatial hydrological units
- the 1' x 1' latitude/longitude gridded values of mean annual precipitation (MAP) and median monthly rainfall which were derived by Dent, Lynch and Schulze (1989)
- the 1996 LANDSAT determined national land cover image with its 31 categories of land cover/use as classified by Thompson (1996)
- daily rainfall data sets from the (now) South African Weather Service and
- soil information from the Institute for Soil, Climate and Water (ISCW) land type maps and accompanying memoirs.

In the same chapter, however, the statement was made that multi-scaler issues in IWRM as well as the intra-catchment spatial variability within QCs imply that these may need dis-aggregation in smaller, more homogeneous hydrological units to account for non-linearities of hydrological responses and to address management conflicts for a range of scales (Chapter 2, Basic Premise 19).

In this chapter it is argued that using detail beyond that derived from national 'standard' databases is necessary in areas where hydrologically sensitive land use issues are under the spotlight or where ostensibly 'homogeneous' regions in fact display considerable hydrological heterogeneity.

Two case studies are provided in support of this thesis.

5.2 CASE STUDY 1 : CAN DIFFERENCES IN DETAIL OF LAND USES DERIVED FROM DIFFERENT SOURCES BE CRITICAL IN OBTAINING REALISTIC ANSWERS FROM HYDROLOGICAL SIMULATIONS? EXAMPLES FROM THE BIVANE CATCHMENT

The Bivane catchment of 1 261 km^2 in KwaZulu-Natal is part of the Pongola-Bivane system described in Chapters 10 and 11. This case study evaluates possible errors which may be introduced in areal estimates of critical land uses when these are derived using commonly available sources of information. The evaluation arose out of problems of classification and interpretation from 1993 Landsat TM images (LS) of land uses for hydrological purposes (cf. Figure 5.1, middle). Several problems were identified in the Pongola-Bivane system by Schulze, Pike, Lecler, Esprey, Howe and Zammit (1996) in regard to actual areas under afforestation, crops and irrigation. Further points of concern were the accuracy of information from Landsat images on the number of farm dams which supply much of the irrigated crops with water, and their derived storage capacities.

In a re-assessment of critical land uses, 1:30 000 aerial photographs (APs) flown in 1996, backed up with extensive field verification, were used as a second source of information (Schulze, Taylor, Matthews and Hughes, 1997). Not only could revised areas of critical land uses be established, but a distinction could be made between the main genera in commercial plantations, *viz*. eucalypts, pines and wattle, which are known to exhibit different water use characteristics under different climatic and management conditions (Summerton, 1996). Several new hydrologically important land cover/use categories could also be isolated which had either not at all, or incorrectly, been identified from satellite imagery. Examples of 'new' categories in the Pongola-Bivane catchment are riparian alien vegetation, exotic tree clumps (as distinct from formal plantations), wetlands and certain types of irrigated land.

a) Differences in land cover and land use derived from Landsat imagery and aerial photographs : General observations

Following upon analyses of land covers and land uses from both the AP and the LS images, the respective land use categories from the two sources were regrouped in order to render the two classifications

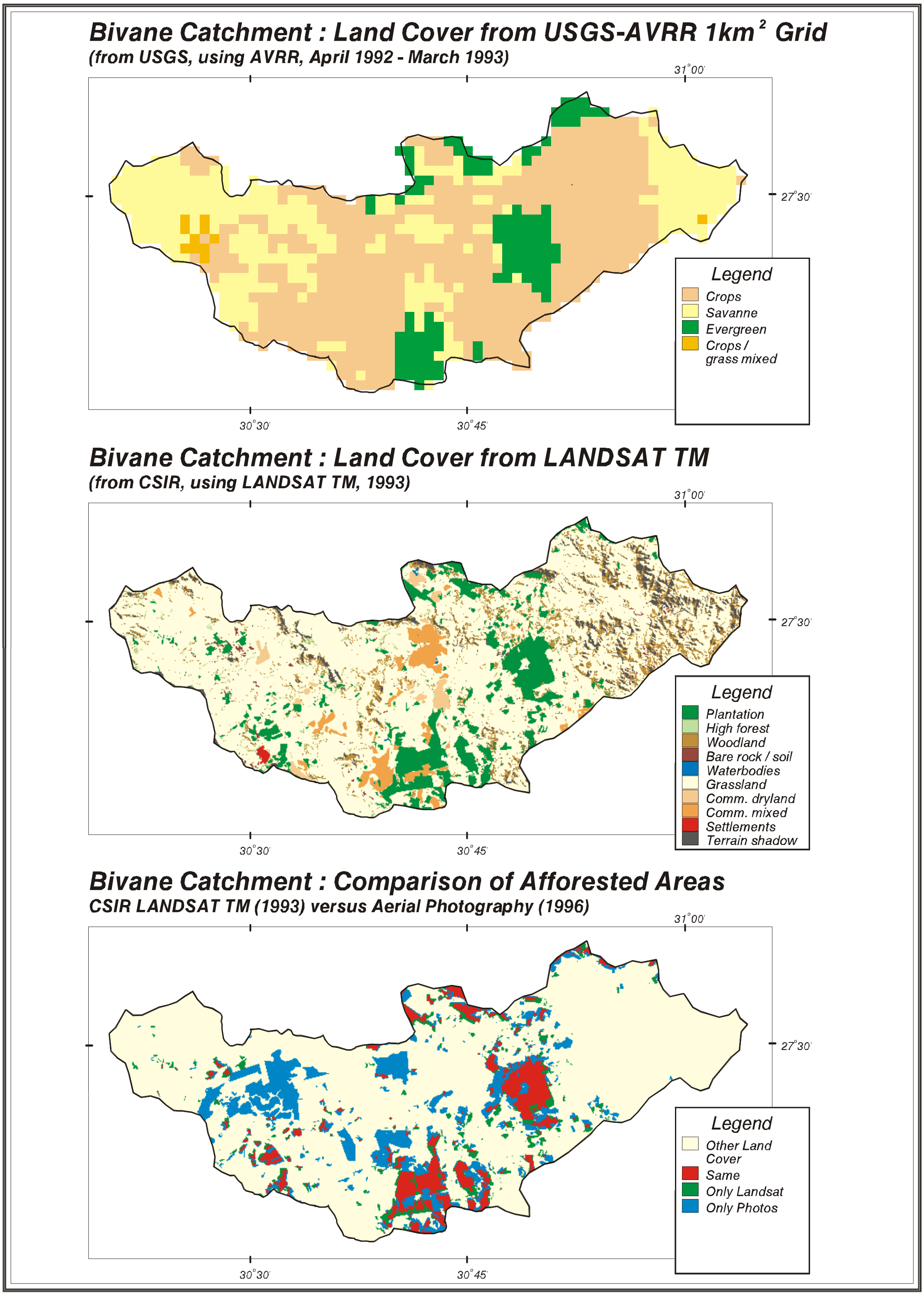

Figure 5.1 Land cover in the Bivane catchment at different spatial resolutions (top and middle) and differences in afforested areas identified by Landsat TM and aerial photographs (after Schulze *et al.*, 1997; Schulze, 2000)

compatible with one another and more directly comparable in hydrological response terms (Table 5.1). The percentages of land covers/uses for each of the six subcatchments (Subcatchments 8-13) making up the Bivane river upstream of Paris dam, at the outlet of Subcatchment 13, could then be compared (Table 5.2).

Table 5.1 Comparable land cover and land use groupings from aerial photographs and Landsat TM within the Bivane catchment (after Schulze *et al*., 1997)

Category		Groupings	
		Aerial Photographs	Landsat TM
1.	Forest	Eucalypts, wattle, pines, exotics (sparse, medium and dense)	Eucalypts, pines
2.	Indigenous Forest	Indigenous forest	High forest
3.	Commercial Dryland	Maize, soya, subsistence cultivation	Commercial dryland
4.	Other	Wetland (in SC 8); Settlement (in SC 13)	Settlement (in SC 9)
5.	Grassland	Acocks' Veld Types #63, #64	Veld Types #63, #64, woodland, bare rock/soil
6.	Riparian	Riparian	Veld (riparian not identified)
7.	Irrigation	Centre pivots, pasture, potatoes	Commercial mixed, irrigation
8.	Dams	Dams	Water bodies

Table 5.2 Comparison of percentages of land cover/land use from aerial photographs (AP) and Landsat TM (LS) within the Bivane catchment (after Schulze *et al*., 1996; 1997)

Subcatchment Number and Area (km^2)	Percentages of															
	Forest		Indigenous Forest		Commercial Dryland		Other		Grassland		Riparian		Dams		Irrigation	
	AP	LS	AP	LS	AP	LS	AP	LS	AP	LS	AP	LS	AP	LS	AP	LS
8 (183)	10.4	4.8	1.1	2.0	4.5	1.0	2.2*	0.0	79.5	91.7	1.3	0.0	0.2	0.0	0.8	0.5
9 (305)	20.4	5.5	0.0	2.5	11.5	1.4	0.0	0.6**	65.8	83.3	1.5	0.0	0.2	0.0	0.7	6.7
10 (219)	33.7	22.7	0.2	1.2	13.2	2.9	0.0	0.0	51.6	64.5	0.6	0.0	0.3	0.0	0.4	8.7
11 (212)	22.9	18.6	0.0	0.4	6.7	1.5	0.0	0.0	68.4	78.5	1.0	0.0	0.3	0.7	0.7	0.3
12 (32)	64.5	53.5	0.0	0.1	3.2	0.0	0.0	0.0	31.2	46.4	1.0	0.0	0.1	0.0	0.0	0.0
13 (310)	4.2	2.9	0.0	0.1	5.7	0.0	2.0**	0.0	87.1	96.3	1.0	0.0	0.0	0.0	0.0	0.7

* Wetland ** Settlement

Significant differences are evident from perusal of Table 5.2, one need only compare percentages of forest, commercial dryland or irrigation. It is important to note that while some land uses only cover relatively small areas, they may exert an inordinate influence on hydrological responses, e.g. wetlands, riparian areas or settlements, and their identification may be crucial in understanding or modelling the streamflows from sensitive catchments.

b) Comparison of afforested areas

The major differences between the LS and AP derived areas under commercial afforestation shown in Table 5.2 need re-emphasis, in particular the nearly 4-fold under-estimation by LS in Subcatchment (SC) 9 and a more than doubling of area under exotic forest in SC 8 when APs are used. Overall, if the commonly used satellite imagery areas are taken as the base, the Landsat TM would have under-estimated commercial afforestation by 69%; alternatively, if the field-checked APs are used as a base, the under-estimate by LS is still 41%. In Chapter 10 it has been shown that in a catchment such as the

Pongola-Bivane, errors of this magnitude in land use can introduce significant changes in base- and stormflows as well as in total streamflows from different macro-climates or in wet vs dry years.

Spatially the differences in identified commercial afforestation by LS vs AP techniques are shown in Figure 5.1 (bottom), in which the red shading indicates LS and AP both identifying plantations, while the blue shading shows areas identified as forest plantations by the APs, but not by the LS images. It may well be argued that because of the 3-year time gap between the LS and AP images, *viz*. 1993 vs 1996, some areas may have been afforested only after 1993. The vast discrepancies in both Figure 5.1 and Table 5.2 do suggest, however, that large areas of already existing afforestation in the upper Bivane were interpreted as being other land uses with the techniques used in LS analysis.

Of interest rather than of scientific usefulness at this more detailed level of assessing land use impacts is the USGS - AVRR 1 km^2 grid of land cover (Figure 5.1, top), which is freely available for the entire world.

c) Comparison of farm dam attributes

Farm dams are hydrologically important in that they often supply water for irrigation. Abstractions can change considerably the water resource available to downstream users. Losses by evaporation from the water surface can also be significant. Table 5.3 and Figure 5.2 illustrate major differences in the number of farm dams and their attributes when comparing values derived from the APs to values from LS and other sources. In Figure 5.2 reference to the Department of Water Affairs and Forestry implies their official database on registered dams over 50 000 m^3 capacity.

The AP survey identified 5.9 times as many farm dams, with a water surface area at full capacity 5.3 times greater and an estimated full supply capacity (using methods outlined in Smithers and Schulze, 1995) that was 3.0 times more than the figures derived from LS and other sources in Schulze *et al*. (1996).

Table 5.3 Comparison of number of farm dams and their attributes in the Bivane catchment from aerial photographs and Landsat TM (after Schulze *et al*., 1996; 1997)

Source	No. of Farm Dams	Surface Area (ha)	Full Supply Capacity (m^3)
Aerial Photos	59	208	4 285 000
Landsat TM	10	39	1 435 000

d) Comparison of irrigated areas

In applying any remotely sensed information for a classification of land uses there are problems of *identification* on the one hand (e.g. being or not being able to identify, say, riparian alien vegetation) and problems of *interpretation* on the other (i.e. is one labelling an identified land cover incorrectly for, say, hydrological modelling purposes).

In the case of the irrigated areas in the Pongola-Bivane catchment, an initial land use survey by Schulze *et al*. (1996) in which Landsat TM images were used without ground checking, included the ‘commercial mixed’ land use category as being under irrigation (Table 5.1). This was clearly an error of interpretation.

The 9-fold over-estimation of irrigated area in SC 9 and the 22-fold over-estimate in SC 10 (Table 5.4) clearly illustrate the need for careful verification of both the identification and interpretation of land use categories from satellite images, especially when highly sensitive land uses such as irrigated areas are under the spotlight.

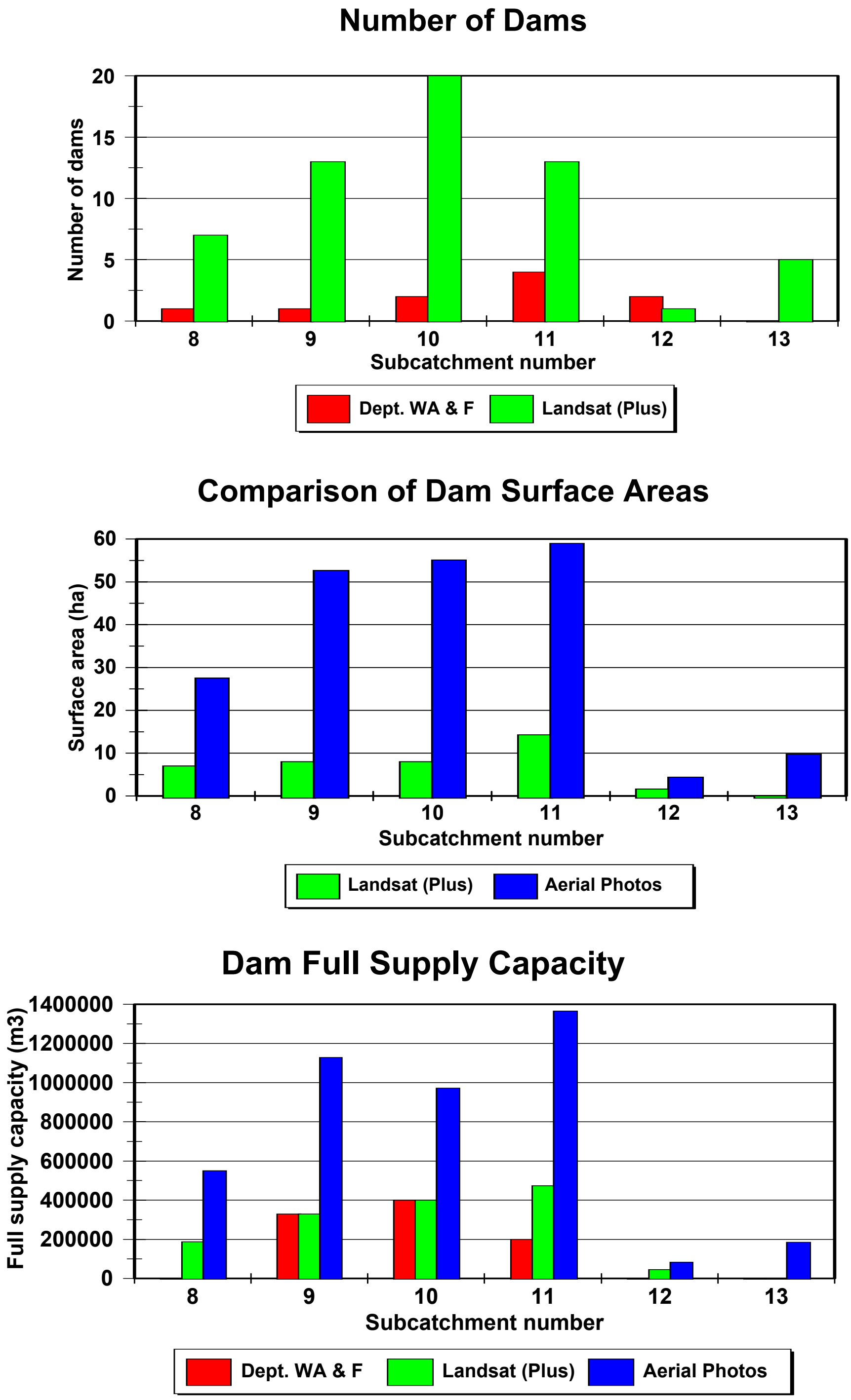

Figure 5.2 Comparisons, per subcatchment, of numbers of farm dams (top), their surface areas (ha) at full capacity (middle) and estimates of their full supply capacities (m^3) from aerial photos and Landsat TM images plus other information (after Schulze *et al*., 1997)

In this particular study in the Pongola-Bivane catchment there is, fortuitously, an element of self-cancellation of errors in having originally (i.e. in Schulze *et al*., 1996) under-estimated the extent of afforestation while over-estimating the extent of irrigation when streamflows were estimated. However, this is not always the case.

Table 5.4 Comparison of areas under irrigation in the Bivane catchment from aerial photographs and Landsat TM (after Schulze *et al*., 1996; 1997)

Subcatchment	Estimate of Hectares under Irrigation	
	Aerial Photos	Landsat TM
8	150	97
9	223	2052
10	92	1911
11	142	59
12	0	0
13	0	202

e) What can be concluded from this case study?

This case study has illustrated clearly the necessity, when land use is a critical issue in hydrological responses, of detailed analyses of land uses, including field verification, in order not to be subject to major possible mis-interpretations and mis-representations of land uses which, when used in models, could influence simulated flows significantly and, hence also, decisions which may affect downstream water users.

5.3 CASE STUDY 2 : WHAT IS GAINED BY DERIVING AND APPLYING LOCAL RATHER THAN NATIONAL RAINFALL : PHYSIOGRAPHY RELATIONSHIPS IN HYDROLOGICAL SIMULATIONS? EXAMPLES FROM THE KWAZULU-NATAL NORTH COAST

a) The 1' x 1' rainfall grid values

The high sensitivity of runoff to changes in rainfall is well documented (e.g. Schulze, 1995, Chapter 3; Schulze, 2000). In order to obtain spatially weighted Quaternary Catchment (QC) rainfall values (e.g. annual or monthly) for the adjustment of daily rainfalls from a 'driver' station representing that QC in models such as *ACRU*, the 1' x 1' latitude/longitude grid values of rainfall derived by Dent, Lynch and Schulze (1989) are commonly used.

While currently the best available, these gridded values were generated with equations from 34 large regions in South Africa using data only up to the mid-1980s, but above all they did not use a common (concurrent) rainfall base period in their derivations. In certain areas these gridded values are, therefore, not as accurate as desired and may not always reflect local physiographic influences on rainfall.

This was found to be the case in a water resources study undertaken by Schulze, Pike and Meier in 1996 in the catchments of the Mdloti, Tongati and Mhlali rivers (Figure 5.3) on the North Coast of KwaZulu-Natal province.

b) Deriving an alternative to the 1' x 1' rainfall grid values

Using a 200 m resolution grid of altitude values rather than the ~ 1.6 km x 1.6 km point values of altitude from the standard 1' x 1' grid, Meier (1997) identified those variables which were most likely to affect areal changes in MAP over the North Coast study area and then developed a regression equation to create a gridded rainfall surface. He eventually used concurrent and quality controlled records from 35 rainfall stations to derive the following equation:

$$\text{MAP} = -162.8\ \text{Lat} + 754.5\ \text{Long} + 0.987\ \text{D}^2 + 0.759\ \text{A} - 0.012\ \text{AD} - 27\,364 \quad (n = 35;\ r^2 = 0.74;\ \text{worst residual} = 6.9\%)$$

where

MAP = mean annual precipitation (mm)
Lat = latitude, derived using Gauss' conformal projection (m from equator)
Long = longitude (m from central meridian 31° E)
A = altitude (m)
D = distance from the sea (m).

This equation was then used to plot MAP at a 200 m resolution with methods akin to those described in Dent *et al*. (1989) and Schulze, Pike and Meier (1996).

c) What do results show?

Upon interpretation of Figures 5.3 to 5.6 three points require highlighting:

- First, Figure 5.4 shows that the trends from 1' x 1' gridded values of MAP do not correspond, with any clarity, with either high or low altitude areas or distance from sea when compared with Figure 5.3, while trends which are evident in Figure 5.5 do.
- Secondly, Figure 5.6 shows that the MAP from the 1' x 1' grid (resampled to a 200 grid scale) differs from that derived by regression equation for the local area by up to 300 mm, both in under-estimates and over-estimates. This translates to percentage differences of MAP up to 20% and more. These differences (Hughes, 2002) could be attributed as much to scale differences (1' x 1' vs 200 m grid) as to the quality of the regression model (based on regional vs local regressions).
- In rainfall : runoff simulations such rainfall differences are expected to produce runoff differences in the order of 40 - 60% (Schulze, 2000), thus confirming that in physiographically complex areas much stands to be gained by deriving and applying local rainfall : physiography relationships.

This last point is illustrated clearly in Table 5.5 from results of *ACRU* model simulations in Quaternary Catchments U30A and U30E along the North Coast of KwaZulu-Natal, where in the case of U30A the median annual streamflow is 45% higher when using the more detailed locally derived rainfall equations for driver station adjustments of daily rainfall, and 37% for 1 : 10 low flows, while in U30E median annual and 1 : 10 year low streamflows are simulated to be respectively 27% and 50% lower.

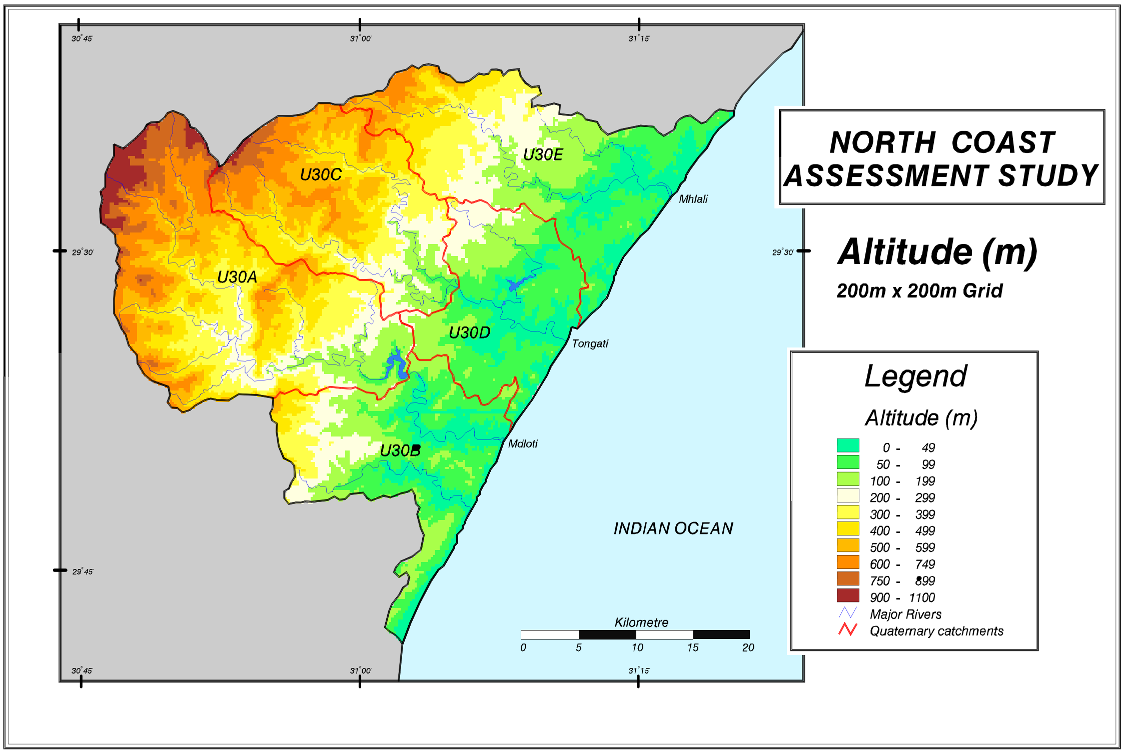

Figure 5.3 North Coast water resources study : Altitude, Quaternary Catchment boundaries and major stream networks (after Schulze *et al*., 1996)

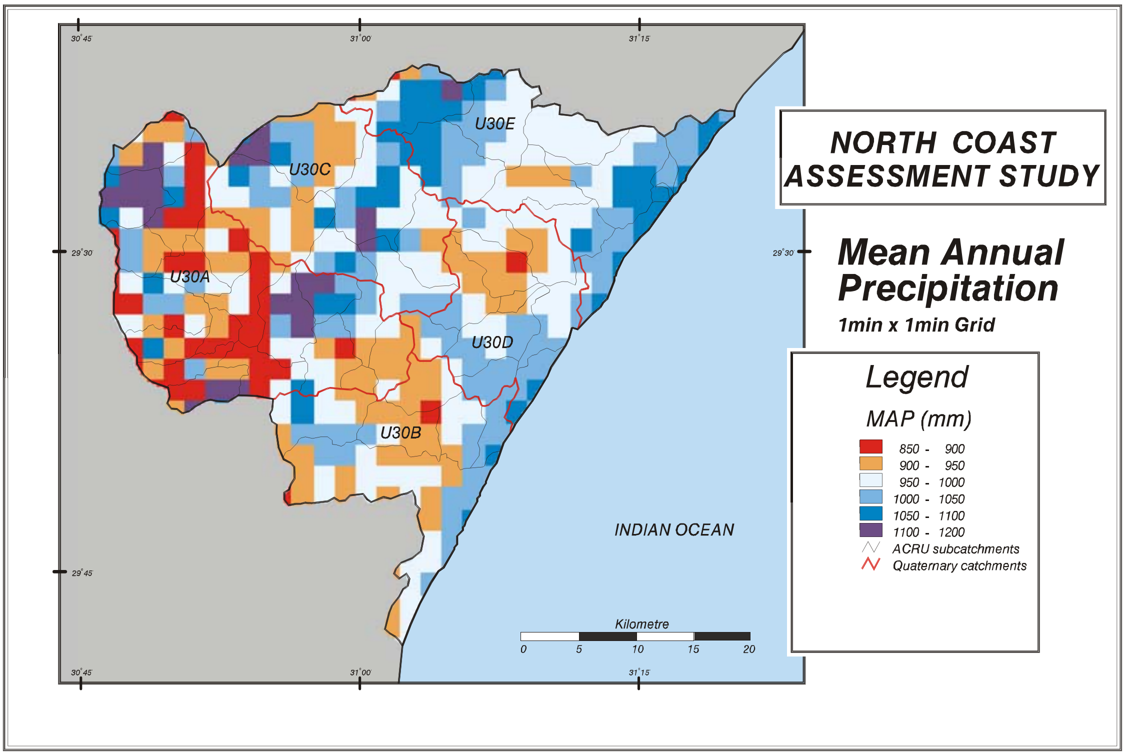

Figure 5.4 North Coast water resources study : MAP from the 1' x 1' grid (after Dent *et al*., 1989)

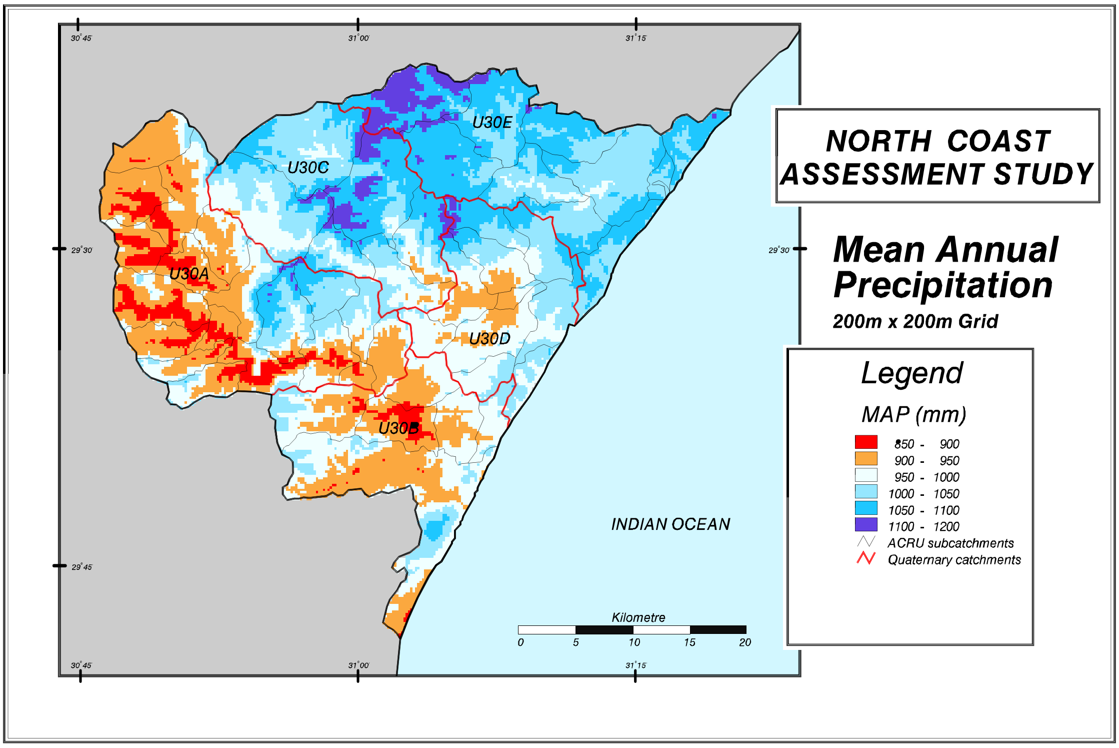

Figure 5.5 North Coast water resources study : MAP from a local equation on a 200 m grid (after Schulze *et al*., 1996)

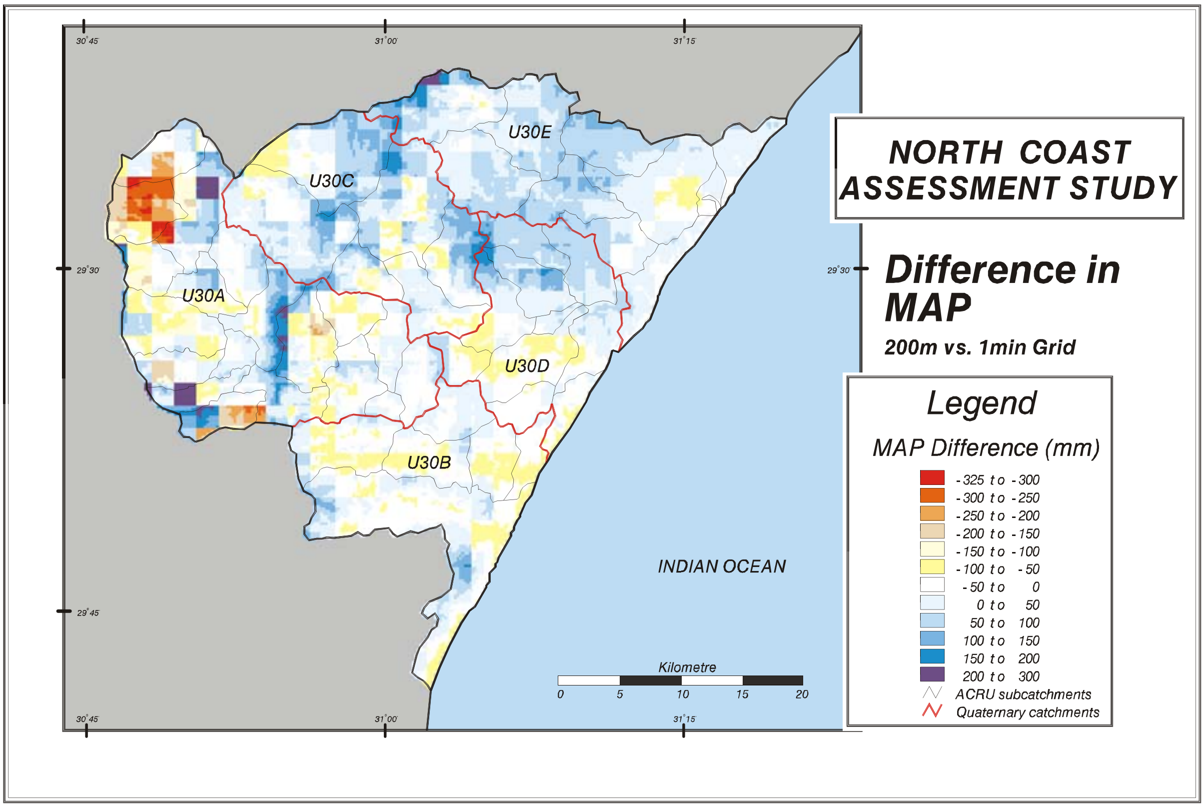

Figure 5.6 North Coast water resources study : Differences in MAP between the 1' x 1' grid and the local equation on a 200 m grid (after Schulze *et al*., 1996)

5.4 WHAT CONCLUSIONS MAY BE DRAWN, AND RECOMMENDATIONS MADE, FROM THESE TWO CASE STUDIES?

First, both case studies illustrate clearly that in IWRM errors caused by a lack of appropriate detail in inputs to hydrological models could result in significantly different decisions being made when the output of the models is used to aid in, say, the design and operation of hydraulic structures. Conflicts over water utilisation and allocation, it should be remembered, are *not* always at national or Primary Catchment scale, not even always at Quaternary Catchment level, but often at scales finer than that.

Table 5.5 Differences in median monthly and annual and 1 : 10 year low monthly and annual streamflows in two Quaternary Catchments as a result of using rainfalls adjusted by the 1' x 1' gridded values vs those from a local equation (after Meier, 1997)

		Median Streamflow (mm/month)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
U30A Median	1'x1' Rainfall Local Equation	17.0 26.0	19.0 22.5	20.0 29.6	12.5 17.5	12.5 16.0	8.0 12.5	6.5 9.0	7.5 9.0	7.0 8.5	8.0 11.5	12.5 15.5	18.0 23.5	190 275
U30A 1:10 low	1'x1' Rainfall Local Equation	5.2 9.8	4.2 8.3	5.3 8.0	3.8 5.9	2.2 4.1	1.7 3.2	1.4 2.3	1.9 2.1	1.9 2.1	2.7 3.6	4.4 5.6	7.4 6.8	75 103
U30E Median	1'x1' Rainfall Local Equation	13.6 10.0	16.0 12.0	16.0 12.2	11.8 9.5	9.4 8.7	7.4 6.4	6.2 5.0	7.2 4.0	9.6 3.8	8.1 5.2	9.3 6.2	13.3 5.5	178 130
U30E 1:10 low	1'x1' Rainfall Local Equation	3.4 2.5	2.5 1.9	3.7 1.8	2.9 1.4	2.0 0.9	1.5 0.6	1.3 0.5	1.4 0.6	2.0 1.0	2.8 1.7	2.9 1.9	4.8 2.0	62 31

Since, in hydrology, one can readily scale up, i.e. synthesise and aggregate from finer resolution to coarser resolution (cf. Chapter 2), but not scale down from coarse to finer resolutions without considerable loss of information (e.g. Schulze, 2000), it is recommended that basic information for use in hydrological models should be stored at the finest resolution available for most effective application in IWRM, which often operates through a range of scales within the same region.

5.5 ACKNOWLEDGEMENTS

In addition to the Water Research Commission, the research which provided information to the first of the two case studies was supported by the Forest Industries Association and the Department of Water Affairs and Forestry, while the research underpinning the second case study was supported by Umgeni Water.

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CHAPTER 6

RISK, HAZARDS AND VULNERABILITY WITHIN A CONTEXT OF HYDROLOGICAL RISK MANAGEMENT : A CONCEPTUAL FRAMEWORK AND EXAMPLES FROM SOUTH AFRICA

R.E. Schulze

School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

ABSTRACT

The concepts of risk, hazard and vulnerability are defined and discussed as background to focussing on the scope of hydrological risk management. Approaches to hydrological risk management are reviewed, first of risk assessment with its two major components of 'objective' hazard determination (which includes hazard identification, approaches to statistical hazard determination and the question of uncertainties related to meteorological and catchment conditions as well as to data attributes) and 'subjective' risk evaluation (which includes the perception of risk and the concept of acceptable risk). Thereafter risk mitigation and control are discussed. These are made up of hazard modification by manipulation of primary and secondary processes and vulnerability modification, for example, by forecasting and warning systems. The second part of the paper consists of South African examples of some of the components making up hydrological risk management, mainly in the form of comparative maps illustrating indicators of within-country variability, of hazard and of risk. General hydrological hazard indicators are presented first, followed by statistical hazard indicators of 'deprivation' and 'assault' events in regard to droughts and floods. The question of using short data sets and of hazard modification through land use practices also receive attention. The final examples illustrate an application of vulnerability modification through seasonal forecasts of runoff and show potential hydrological impacts of climate change as a future hazard with associated risk. The paper illustrates, throughout, the amplification of the hydrological system of any climatic hazard.

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6.1 WHAT ARE COMMON PERCEPTIONS OF RISK?

In discussion with hydrological colleagues on what the term *risk* implies to them, typical answers include that it encompasses the concepts of

- predictability (that a hydrological event will occur)
- probability (how often it will occur within a given time frame) and
- forecastability (when a hydrological event will occur); it is also about
- hazards (of extreme rains, floods or droughts) and
- vulnerability (which sectors or areas suffer more than others) and includes
- exceeding critical thresholds
- variability from year to year
- sensitivity (of a hydrological response to a given trigger) and
- magnitude (how severe the hazard will be); furthermore, it embraces
- concern for a changing future, and how hydrological responses may change with future climates or land uses, as well as
- assessment (of damage, from both objective and subjective perspectives)
- avoidance (by structural and non-structural means) and
- adaptability; as well as being about
- preparedness for a hazard; with all these attributes surrounded by a great deal of
- uncertainty, not only on *how* uncertain a risk determination is statistically, but also *why* we are unsure of the answers from our calculations.

Equally important are assertions that hydrological risk can be exacerbated by human actions, both through intensification of land use as well as extensification and land degradation, and that risk extends to aspects of both water quantity and water quality.

6.2 WHAT ARE THE OBJECTIVES OF THIS ASSESSMENT?

From an Integrated Water Resources Management (IWRM) perspective the answers given above beg questions on what is involved in managing hydrological risk, what types of hydrological hazard catchment managers face in South Africa and whether one can identify areas of greater or lesser potential vulnerability. This chapter therefore sets out to evaluate

- what risk is, viewed in relation to the concepts of hazard and vulnerability,
- what uncertainties are encountered in establishing risk
- what hydrological risk management involves and
- what indicators of hydrological hazards can be regionalised in South Africa, through mapping of
    - general hydrological hazard indicators (precipitation, an aridity index and conversion ratios of rainfall to runoff)
    - indicators of hydrological amplifications of climatic fluctuations
    - indicators of potential vulnerability to flooding
    - uncertainties induced by short data sets
    - impacts of grazing management on sediment yields
    - vulnerability modification through seasonal forecasting of runoff and the
    - sensitivity to drivers of potential climate change.

6.3 RISK, HAZARD AND VULNERABILITY : WHAT ARE THE BASIC CONCEPTS?

a) Risk : What is understood by it?

Risk, in layman's terms, is the 'chance of disaster'. More formally

> *Risk is a quantitative measure of a defined hazard, which combines the probability or frequency of occurrence of the damaging event (i.e. the hazard) and the magnitude of the consequences (i.e. expected losses) of the occurrence* (Fairman, Mead and Williams, 1998).

Imbedded within this definition is the term *hazard*, and implied in the phrase 'consequences of the occurrence' is the concept of *vulnerability* to the hazard. These two terms are therefore described next, before re-visiting broader issues of risk.

b) Hazard : What is meant by the term?

A hazard is commonly described as the 'potential to do harm'. Defined more rigorously (Zhou, 1995; Smith, 1996; Fairman *et al*., 1998; Downing, Oltshoorn and Tol, 1999),

> *A hazard is a naturally occurring, or human induced, physical process or event or situation, that in particular circumstances has the potential to create damage or loss. It has a magnitude, an intensity, a duration, has a probability of occurrence and takes place within a specified location.*

The above definition serves to highlight the concept that a physical process only then becomes a hazard when it threatens to create some sort of loss (such as loss of life or damage to property) within the human environment (Smith, 1996). This is, therefore, essentially an anthropocentric view of the concept of hazard and does not take into account the effect that an extreme natural event can have on an uninhabited area (Suter, 1993). The assessment of losses and the determination of the detrimental effects on future overall sustainability in uninhabited areas are extremely difficult to undertake and they generally fall under the concept of ecological risk assessment (Suter, 1993). In this chapter the magnitude of a hazard is thus determined by the extent to which the physical event can disrupt the human environment, i.e. a hazard is the combination of both the *active physical exposure* to a natural process and the *passive vulnerability* of the human system with which it is interacting (Plate, 2002).

The physical exposure is essentially the damage-causing potential of the natural process and is a function of both its intensity and duration. The natural process becomes a hazard when it produces an event that exceeds

- *thresholds*, i.e. the critical limits (bounds) that the environment can normally tolerate before a negative impact is produced on a system or activity (Downing *et al*., 1999). In the case of rainfall, too much produces a flood hazard and too little a drought hazard. In Figure 6.1 the shaded area represents the tolerance limits of the variation about the average, within which a resource such as water can be used beneficially for social and economic activities within the human environment (Plate, 2002). The magnitude by which an event exceeds a given threshold determines the damage-causing potential of such an event. The term
- *intensity* refers to the severity, or damage-causing, potential, of a natural process. For example, rainfall at 20 $mm.h^{-1}$ is generally less damaging than 100 $mm.h^{-1}$ over the same time period. The hazard intensity is determined by the peak deviation beyond the threshold (vertical scale in Figure 6.1). Thirdly,
- *duration*, the other variable determining the damage-causing potential of an event, implies exposure to an event, and the longer the exposure the greater the damage-causing potential (Zhou, 1995; Smith, 1996; Plate, 2002). Hazard duration is determined by the length of time the threshold is exceeded (horizontal scale in Figure 6.1).

The response to a hazard (Zhou, 1995), as discussed in more detail later, is either by

- *adaptation*, i.e. the long-term arrangement of human activity to take account of natural events (e.g. becoming more dependent on groundwater than on more erratic surface water resources in arid zones), or
- *adjustment*, i.e. the intentional response to cope with a hazard (e.g. only constructing buildings beyond a demarcated 1:50 year flood line).

c) Vulnerability : What does that imply?

Vulnerability implies the need for protection. From an anthropogenic viewpoint

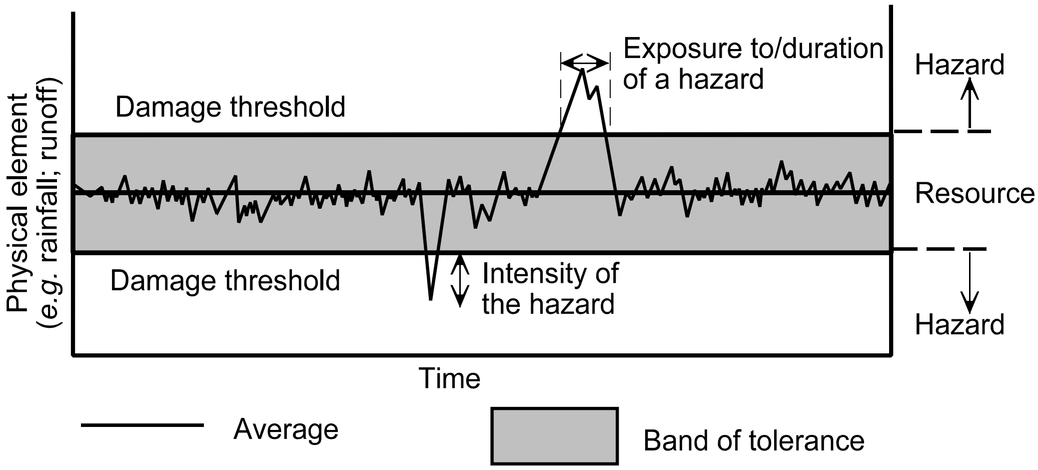

Figure 6.1 The magnitude of environmental hazard expressed as a function of the variability of a physical element within the limits of tolerance (modified after Smith, 1996)

> *Vulnerability is the characteristic of a person, or group, or component, of a natural system in terms of its capacity to resist and/or recover from, and/or anticipate and/or cope with, the impacts of an adverse event* (adapted from Downing *et al*., 1999).

Vogel (1998) describes vulnerability in terms of the resilience and susceptibility of a system, including its physical and social dimensions, while Plate (2002) adds the reliability of the system (e.g. water supply from a dam) to its attributes.

- *Resilience* (Vogel, 1998) is the capacity of a system (e.g. a dam) to absorb (e.g. a flood) and recover from a hazardous event (e.g. a drought). Resilience, therefore, implies that there are thresholds of vulnerability.
- *Reliability*, on the other hand, is the probability that the system, or a component of a system, will perform its intended function for a specified period of time (e.g. what is the probability that the dam will be able to supply water to a city over the next 50 years?).

In terms of vulnerability, systems may be subjected to

- *assault events* (e.g. heavy rainfall; flood peak; pollution levels above a certain concentration), in which case the vulnerability threshold is determined by the system absorption and redirection capacities (e.g. a heavy rainfall saturating a soil and the soil then draining the excess water rapidly enough, or a dam filling to capacity and the spillway coping adequately with the flood discharge). Systems may, according to Smith (1996), also be subjected to
- *deprivation events* (e.g. drought, soil erosion from agricultural land or leaching of fertilizers out of the soil), in which case the thresholds of vulnerability are determined by the retention and replacement capacities of the system (e.g. the buffer of deeper soil depth to storing moisture for a plant during a drought, or the rate of weathering to replace soil lost by erosion).

Vulnerability, therefore, invariably embraces an

- *external dimension* (Vogel, 1998), i.e. the threat of an event, that may increasingly predispose people to risk (e.g. climate change and its impacts on water resources), as well as an
- *internal dimension*, i.e. the internal capacity to withstand or respond to an event, such as the defenselessness to cope with a hazard (e.g. poor people living on a floodplain) or the lack of means to cope with the aftermath of damaging loss.

Individuals or societies may thus face the same potential risk, but are not equally vulnerable because they may face different consequences to the same hazard.

d) *Risk revisited*

If risk is the probability of a specific hazard's occurring and the loss caused by that hazard in regard to the level of vulnerability of the affected people or places, then several possibilities exist that give rise to risk increasing over time (Smith, 1996). These are illustrated in Figure 6.2:

- *Case A* represents a scenario where the tolerance and the variability remain constant, but there is a change over time in the mean value. In this particular case the frequency of extreme events at one end of the scale increases, as would be the case of a decrease in rainfall associated with climate change, or a decrease in runoff associated with upstream afforestation.
- *Case B* shows a scenario in which both the mean and the band of tolerance remain constant, but the variability increases. In this particular case the frequency of damage producing events increases at both ends of the scale. Climate change could again be a cause, as it is postulated that with climate change variability is likely to increase (e.g. Schulze and Perks, 2000).
- *Case C* shows that the physical variable, e.g. runoff, does not change, but the band of tolerance narrows, i.e. the vulnerability of the human system increases (e.g. because of increased water demands on a river from people living directly in the floodplain). In this particular scenario the frequency of damage-causing events increases at both ends of the scale (e.g. too little water during dry periods; vulnerability to flood damage during high flows).
- *Case D* illustrates a sudden change in both the variability and tolerance of a system as a step function. An example would be the downstream impact following construction of a major dam, with controlled releases after dam closure changing downstream flow characteristics completely.

In viewing risk as including a human component, in addition to a probabilistic one, three tiers of risk have been identified by Zhou (1995), *viz*.

- a *lower band of risk*, which is acceptable to the affected people and where, for example, the benefits of doing nothing, or little, outweigh the disadvantages of carrying an unacceptable cost burden,
- a *middle band of risk*, where decisions have to be made which trade off the costs of reducing the risk vs the benefits of the risk reduction, and
- an *upper band of risk*, where doing nothing is completely unacceptable, irrespective of cost.

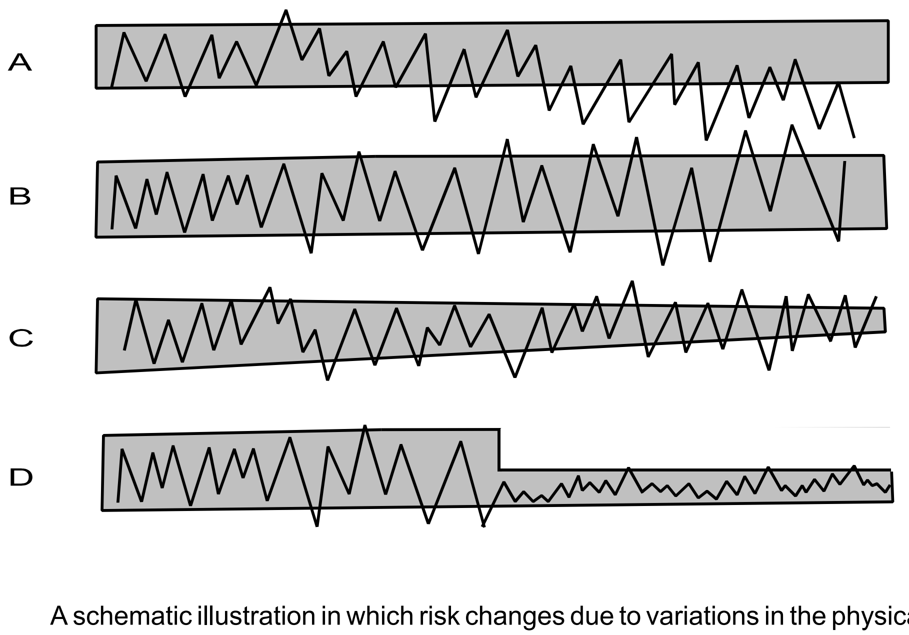

Figure 6.2 A schematic illustration in which risk changes due to variations in the physical system and the socio-economic system. In cases A to C risk increases over time, in case D it may increase or decrease (cases A to C after Smith, 1996; case D added by the author)

Each of these three tiers of risk is related to a balancing of benefits vs costs. This is usually done through risk management, which on the one hand has to be regulated by professional standards and legal measures while on the other hand it contains a large element of subjectivity.

6.4 HYDROLOGICAL RISK MANAGEMENT : WHAT ARE THE BASIC CONCEPTS?

To the person in the street, risk management is the process that attempts to reduce risk both in the short and long term by enabling choices to be made on the best course of action under a given range of situations. More scientifically in Integrated Water Resources Management, but still in generic terms

> *Risk management provides a formalised framework within which decision makers (and stakeholders . . . author's addition) can compare the harm caused by risks with the benefits associated with the risk, in order to choose appropriate risk reduction measures* (Fairman *et al*., 1998).

In regard to a generic policy of risk management Gilard (2002) has identified three interrelated components, *viz*.

- *risk prediction and forecasting*, which would include the scientific basis of risk identification and estimation
- *risk prevention*, which would include control actions and alternatives through structural means (e.g. building levees) and non-structural ones (e.g. changing land use practices),

with these two 'legs' of policy largely influenced by the

- *risk culture*, which will vary between different societies and their levels of economic development, as well as with the individual within a society, in what is acceptable or not in terms of risk (Figure 6.3).

From Plate's (2002) more engineering oriented hydrological perspective,

> *Risk management is a methodology for giving rational consideration to all the factors affecting the safety or operation of large hydraulic structures (e.g. dams) or systems of structures (e.g. a city's stormwater system or a region's multi-reservoir water supply/demand system).*

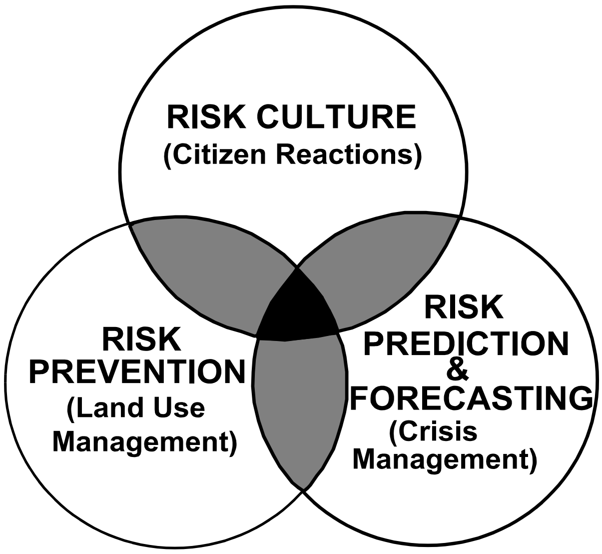

Figure 6.3 Components of a risk management policy (adapted from Gilard, 2002)

There are numerous models of risk management. One (Figure 6.4) is that the risk management process is conceptualised as a sequence of actions, including a series of methodologies, to be employed in obtaining a solution to minimise risk (Plate, 2002). These actions fall under the two broad themes of, first,

- *risk assessment* which, in a socio-politico-economic context would include both
    - determination of hazards, in the form of 'objective' scientific quantifications, and
    - risk evaluation, which covers the fields of more subjective risk perception as well as of acceptable risk; and secondly
- *risk mitigation and control*, under which would fall the
    - modification of hazards, as well as coping with risk through the
    - modification of vulnerability.

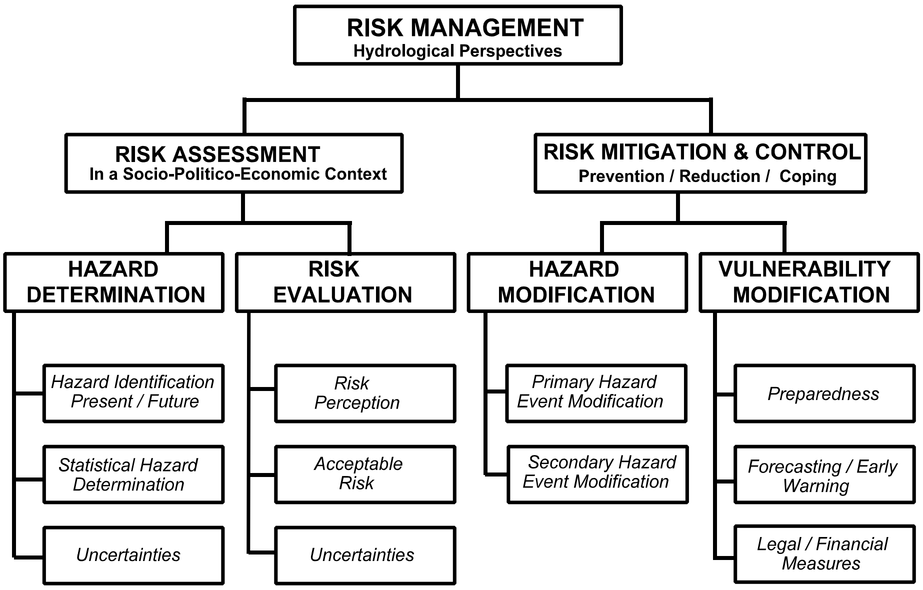

Figure 6.4 A schematic overview of approaches to risk management, developed from multiple sources

A second model of risk management, followed for example by the Dutch government's programme of environmental management (Fairman *et al*., 1998) is to distinguish between an

- *effects oriented* approach, i.e. assessing the effects, or responses, of (say) a flood in terms of damage/disruption, or a drought with its attendant food security issues, and a
- *source oriented* approach, which would study (say) the causal mechanism of a flood or drought, or the value of flood/drought forecasting.

These two models of risk management essentially cover the same ground. This chapter will follow mainly the first model (Figure 6.4) in its conceptual approach, and will focus on risk assessment issues next.

6.5 THE RISK ASSESSMENT COMPONENT OF HYDROLOGICAL RISK MANAGEMENT : WHAT ARE SOME MAJOR THRUSTS?

a) Some definitions and descriptions of risk assessment

In engineering hydrology, risk assessment requires that, for example, the consequences of structural failure (e.g. of a dam) or functional failure (e.g. of sustained water supply to urban or irrigation areas) can be quantified (Plate, 2002) in

- *monetary* terms, i.e. the damage costs of all objects (e.g. to the surrounding environment, or direct loss of property) affected by (say) an extreme hydrological event and in
- *vulnerability* terms (e.g. to the probability of loss of life).

From a more generic perspective, however, risk assessment may be expressed as follows (author's expansion of various definitions):

> *Risk assessment is the process of assigning magnitudes and probabilities to the adverse effects of natural catastrophes or human activities using rigorous, formal and consistent forms of measurement and testing; alternatively of deterministic or statistical models, to quantify the relationship between the initiating event (e.g. rainfall) and the responding effects (e.g. a flood and its associated damage) and, while acknowledging the inherent uncertainties involved, providing a quantitative basis for prioritising and comparing hazards and risks in accordance with what the people at risk perceive and judge as being acceptable or tolerable to them by their value systems.*

Such an assessment thus includes a subjective evaluation (cf. Figure 6.4) of what the risks mean in practice to those affected, and that depends heavily on how a risk is perceived. By implication, therefore, risk assessment is not always without controversy, for apart from the interpretation of results which are often surrounded by uncertainties of data adequacy (i.t.o. length, quantity and quality thereof), the socio-politico-economic context of the affected parties becomes a focus point in the evaluation of risk.

Risk assessment has defined end points (Suter, 1993) and these should

- *satisfy societal value judgements*, whereby the public and decision makers give an object at risk (e.g. a housing development on a floodplain, or a wetland, or a naturally functioning riparian zone) a value, either in monetary or societal terms, on the understanding that values are not constant over time nor over the socio-economic spectrum;
- be *environmentally relevant*, i.e. what damage the hazard would have on the ecosystem (e.g. an aquatic habitat or a wetland);
- have an *unambiguous operational definition* at a spatio-temperal scale, i.e. the endpoint must be defined quantitatively in regard to
    - magnitude (e.g. a flood peak of 'x' m^3/s),
    - duration (e.g. inundating for longer than 'y' days),
    - frequency (e.g. every 'z' years) and
    - area affected (e.g. for a catchment of 'a' km^2); and
- be *quantifiable*, i.e. be measurable in the field or simulated by a model with specified statistical confidence (e.g. at the 0.01 level).

Two major thrusts in risk assessment are the more objective hazard determination and the more subjective risk evaluation, of which the first only is alluded to in this chapter.

b) 'Objective' hazard determination

Objective hazard determination is central to the risk management framework and within the hydrological context, it is rooted in the traditional engineering approach which results from safety studies for the installation of hydraulic structures, the failure of which could cause large scale disaster with potential threat to human life. Objective hazard determination is usually undertaken at the initial stages of, especially, large water related construction projects.

Smith (1996) and Plate (2002) both identify two distinct steps in such a scientific hazard quantification, *viz*.

- the identification of hazard events likely to result in damage (e.g. to a hydraulic structure) or loss (e.g. of life, if the structure fails; or of system efficiency, as in the case of irrigation or urban water supply in a drought); and
- the calculation of risk, i.e. the estimation of the probability of the hazardous events' occurring.

To this has to be added an important third step, *viz*. that of

- assessing the level of uncertainty in a so-called ‘objective’ hazard determination.

The first and third steps are elaborated upon below.

In this section on hazard identification, the calculation of risk and issues surrounding uncertainty are discussed. A next section on risk assessment then focuses on an evaluation of the consequences of the derived risk, i.e. how the loss or damage created by such an event is perceived, and the extent to which such a loss is acceptable or not.

▱ *Hazard identification*

In this first step, those hazards that are a threat to the performance or the failure of a system are identified. These vary from system to system, and for the one it may be the threat of a drought of severity or duration exceeding a certain recurrence interval for which the capacity of a dam was designed, while for another it may be an extreme flood peak which, if exceeded, could be a threat to the breaching of a dam and consequent loss of life downstream and for a third it may be the threat of reduced low flows for downstream riparian users or the aquatic habitat or for diluting contaminants in a stream. In hazard identification it is usual to ask what is at risk, who is at risk and where (spatially) a system is at risk. It is thus important to identify

- the *economic value* of a structure/system at risk,
- its *strategic value* and
- its *environmental value*.

As important as it is to identify hazards under current conditions (e.g. of present climatic norms or of current land use on a catchment), it is to identify potential new hazards. Two such are the potential for

- *climate change*, with possible changes in rainfall magnitude, variability, intensity or persistence of wet/dry, wet/wet, dry/wet or dry/dry day sequences as well as changes in temperatures and evaporation rates and transpiration feedbacks associated with enhanced atmospheric CO_2 - with all these then related to changes in hydrological responses (Schulze and Perks, 2000); and the
- *potential for land use change* in a catchment, which could result in future changes to mean water yield, as well as to the magnitudes of extreme events, to low flows or to sediment yields.

▱ *Statistical hazard determination : Approach*

Risk (R), as defined earlier, is a function of probability (P) and loss (L). Hence, it can be measured as a factor of the two by

$$R = P \times L.$$

Once a causal hazard event (e.g. rainfall of a given magnitude) or the responding hazard (e.g. the resultant flood peak) has been defined within a population data set (e.g. an annual maximum or partial duration series), the probability of that event’s occurring with a year is calculated by any one of a number of standard extreme value distributions (e.g. log normal, Gumbel, log Pearson III, L-moments). Results at a given location can be presented by identifying the probability of recurrence of an event (e.g. the 1 in x-year rainfall) of a given magnitude (e.g. equals 120 mm) at that location. Maps can then be prepared by applying various interpolative techniques directly to point data or by developing regression equations using physical/climatological variables to point data first and then mapping results (e.g. Smithers and Schulze, 2000).

Numerous factors can render results from such a statistical hazard determination by extreme event analysis, which is purported to be ‘objective’, uncertain. These uncertainties are discussed below.

▱ *Statistical hazard determination : The question of uncertainty*

The element of uncertainty plays a central role in objective risk based decision making and the risk manager needs a clear appreciation of it (Suter, 1993). It remains a paradox in water resources, for example, that while risk predictions are made with great statistical rigour, there remain many uncertainties about the exactness of values they produce, i.e. they may be precise, but are they accurate (Zhou, 1995)? Uncertainty can thus be used as a 'shield' behind which to hide and to defend ones answers, or as a 'sword' with which to attack a certain risk decision (Zhou, 1995).

In evaluating sources of uncertainty in water resources one can distinguish between conceptual and more practical issues. Conceptually, uncertainty in risk assessment has three sources (Suter, 1993). These are, first,

- *stochasticity*, i.e. the inherent unknowable randomness of, for example, occurrences of episodic events within the terrestrial hydrological cycle. This is so mainly because its major driver, *viz*. rainfall, is not deterministic. The uncertainty problem with randomness is that while it can be described, it cannot be reduced! Secondly,
- *ignorance*, which implies an imperfect, or incomplete, knowledge of things that are potentially knowable. In hydrology this source of uncertainty includes
    - practical constraints, such as not having records at individual stations that are long enough, nor an adequate network density within a study area and
    - incomplete understanding of system dynamics, i.e. the analytical uncertainty in estimating the credibility of a predicted value because of either input error or model structure uncertainty in converting rainfall to runoff,

  and, thirdly
- *human errors*, which include mistakes made in the execution of risk assessment mainly through poor quality assurance, e.g. data recording errors or model input errors.

Many of the examples of uncertainties from a conceptual perspective re-appear, though from a different viewpoint, in the evaluation of uncertainties from a practical perspective. This can be illustrated using a water resources structure such as a dam as an example (Figure 6.5). Such an hydraulic structure is subjected to a load from one direction, this being determined from hydrological inputs which are derived either from data or a model, and to a resistance from the other direction, which is specified by the structure's capacity and design.

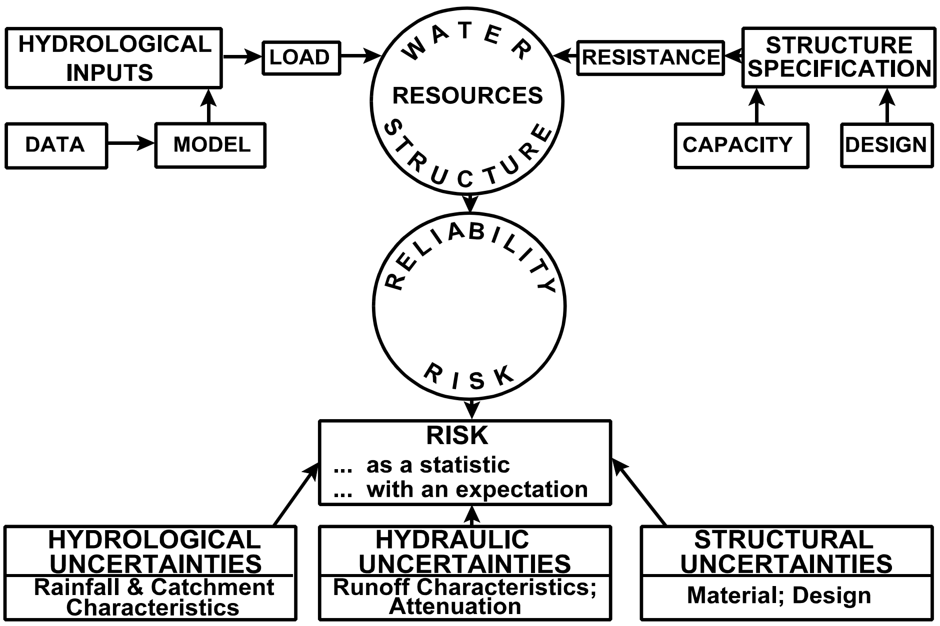

Figure 6.5 Schematic of uncertainties in scientific risk determination of a water resources structure (original idea : Plate, 2002)

In assessing the reliability of the structure (i.e. the dam) to perform its function (e.g. supply a city with water) and the risk of the structure's failing, again three sources of uncertainties are identified (Zhou, 1995).

- *Structural uncertainties* cover the safety aspects of, say, the wall or spillway and reflect their design and the material used.
- *Hydraulic uncertainties* derive from the determination of flow capacities and attenuation of the water flowing in from upstream through channels and dams, and are dependent, *inter alia*, on a channel's roughness coefficient, channel shape and gradient.
- *Hydrological uncertainties* may be categorised into three types, *viz*.
    - uncertainties in the inherent components of the hydrological system
    - uncertainties in the data sets used in modelling and thirdly
    - uncertainties in the modelling component *per se*.

In regard to uncertainties in inherent components of the hydrological system, two are important, *viz*. meteorological conditions and catchment conditions.

- *Meteorological conditions*
  These revolve around a hazardous event's rainfall, i.e. its amount, its seasonal timing, duration, intensity and its spatial distribution over a catchment. Each event may be considered unique. An important assumption made is that of the stationarity of the time series of hazardous rainfall events, i.e. one is assuming a homogeneous sample of a stationary population of such events which, while displaying natural variability, show no increasing or decreasing trend in magnitude over time (Plate, 2002). Already many time series display outliers of individual or a series of events, often made up of events derived from different meteorological conditions to the ones which usually make up the expected population of events. Such a dual population may be accounted for statistically by applying a two-component extreme value distribution (e.g. Pegram and Adamson, 1988). Uncertainty is exacerbated by the fact that any changes in probabilities do not cause a linear change in extremes, with any small changes resulting in large changes in the number and magnitude of extreme events. This begs the question of the possibly significant influence which greenhouse gas induced climate change is likely to have on hazardous rainfall events, which are predicted to change in magnitude, intensity, frequency and variability (e.g. Schulze, 1997a).
- *Catchment conditions*
  A hazardous runoff event is a response to a rainfall event from a catchment in a given state at that point in time. Again a conventional assumption is that of stationarity of catchment conditions, but in hazard determination derived from a time series of runoff events this assumption is largely invalid because of hydraulic changes over time (e.g. construction of dams or other river works), hydrological changes over time (e.g. of the runoff intensifying or reducing as a result of land use changes taking place) and catchment status changes (manifesting themselves in the dryness or wetness of the catchment just antecedent to each rainfall event, the significance of which was demonstrated, for example, by Dunsmore, Schulze and Schmidt, 1986). The net result is the considerable uncertainty which results from the combination of interactions between meteorological and catchment conditions, and with each hazardous rainfall:runoff event one is attempting to determine an objective estimation of risk from the occurrence of what is essentially a unique, non-replicated event (Suter, 1993).

With respect to uncertainties in the hydrometeorological data sets used in 'objective' hazard determination, these abound (and are unlikely to diminish) and include those associated with

- *data length* - with short record lengths (e.g. 20 years) all too frequently used as the basis to extrapolate to low probability events (e.g. 1:100 year frequencies) when one is uncertain of the statistical representativeness of the small population data set which cannot be validated with even the most sophisticated statistical techniques;
- *data quality* - comprising of uncertainties because of the inherent accuracy of measurement (e.g. both rainfall and streamflow gauges are accurate to $\pm$ 5-15% on an event basis), the incidence of missing data (particularly of crucial events, often because of instrument failure during the event; cf. Schulze, 1989; Kienzle, Lorentz and Schulze, 1997), inadequate instrument design (e.g. runoff gauging sites overtopping when river stage exceeds a certain threshold height; cf. Chapter 2), the undercatch of a standard raingauge (because of enhanced windfields around the orifice of the gauge) or inconsistencies in instrument calibration (e.g. of stage height:flow volume relationships which change over time or after extreme events at a runoff gauging site);
- *data network density* - to estimate a regionally representative value, especially when converting

from point to areal values; and

- *data availability* - from official and other sources, and including the most up-to-date processed data (so that one does not use old records, which include the same errors as used by others before) with new techniques and expect improved answers.

Because of such uncertainties in the hydrometeorological datasets, hazards are not always identified and/or the ostensibly objective risk determination may be highly biased.

Thirdly, there exist uncertainties in the modelling component per se. Again, two components are considered briefly.

- *Statistical analysis of hazard events*
  These are uncertainties inherent in having to choose one or several of the many different extreme value distributions which are available for extreme value analysis of hazardous events. Furthermore, an EVD may be institutionally prescribed (as in the case of the log Pearson III in the USA) or the best fit EVD may vary regionally (e.g. as shown by Smithers and Schulze, 2000 for short duration design rainfalls in South Africa). It needs to be re-iterated, however, that despite the considerable recent advances made in statistical, stochastic and regional approaches to extreme value analysis (for examples of their use in South Africa, see Smithers and Schulze, 2000), such sophisticated methods cannot solve nor overcome the problems of using short and suspect quality data sets. The result is uncertainty in numerical terms with high error bands around the estimate, and sometimes even questionable significance of the error bands themselves (Plate, 2002).
- *Simulation modelling of hazard events*
  In hydrology the use of simulation models to estimate probabilities of rare runoff events has been promoted because rainfall data sets are usually longer than runoff data, their network is denser and the data are considered more stationary than those of runoff (e.g. Schulze, 1989). When these longer rainfall data sets are used as input into short time step physical-conceptual models which can account for catchment land use and channel/reservoir modifications over time (e.g. *ACRU* model; Schulze, 1995) the conversion of rainfall to runoff can then account realistically for the individual event antecedent wet conditions and for the other non-stationary catchment conditions (e.g. changes in land use or hydraulic structures over time) to determine the magnitudes of floods of a given recurrence interval (e.g. Dunsmore *et al.*, 1986; Schmidt and Schulze, 1988; Schulze, 1989).

Despite the apparent attractiveness of such a rainfall:runoff modelling approach to objective risk determination one needs, nevertheless, to be highly aware of the uncertainties which remain in the climatic input to such models, especially of extreme rainfall events. There are other model inputs such as the parameterisations of land use and soils which contain point and spatial uncertainties, as well as the model's structure and how that conceptualises and executes the various interacting hydrological process representations when rainfall is transformed to runoff.

c) 'Subjective' risk evaluation

This second leg of risk assessment is often separated from the more 'scientific' determination of a hazard because there is a growing acceptance that subjective judgement and values form an integral part of any risk assessment (Fairman *et al*., 1998). By Plate's (2002) definition,

> *Risk evaluation is the examination of what the risk assessment actually means in practice, including the public perception of the risk and the influence that this will have on the acceptability of risk and risk decisions.*

A discussion on two key phrases in this definition, *viz*. the perception of risk and its acceptability, now follows. This section is concluded by a short consideration of uncertainties in subjective risk assessment.

◻ *Perception of risk*

Perceived risk is unique to the individual or community that is undertaking a specific activity (Smith, 1996; Plate, 2002). Subjectively determined risk is based on the experiences of the community, or the individual, and may well be different to the objectively determined risk. Perceived risk can be divided into two main components, *viz*. involuntary risk and voluntary risk.

- *Involuntary risk* is risk that is not willingly undertaken by communities or individuals. It is usually associated with events of rare catastrophic potential and the person or community exposed does not know the risk involved, or alternatively, perceives it as uncontrollable.
- *Voluntary risk* is risk more willingly accepted by a person or community through their own actions. This type of risk is associated with less catastrophic events that occur more frequently.

Perceived risk is often skewed in favour of the consequences of an event rather than is probability. The risk equation R = P x L hence becomes

$$R = P \times L^m$$

where m is a factor > 1 and represents the weighting that a community or individual places on the loss caused by an event (Whyte and Burton, 1982). In objective analysis an event that occurs often may have the same level of risk as a rare event that causes large loss of life. However, the perceived risk would tend to favour the event that causes a large loss of life.

As already stated, risk perception is influenced by past experiences, but also by many other factors such as present attitudes, personality, values and future expectations. The major influence on risk perception is, however, past experience, as those with direct personal knowledge of previous events have a more accurate perception of the likelihood and magnitude of future events (e.g. Schulze, 1987; Suter, 1993). When direct knowledge, or experience, with disaster is lacking, individuals learn about hazards from many indirect sources such as the media. Risk perception of a group may be strongly influenced by social and cultural factors.

Risk perception can be influenced through the so-called ‘locus of control’ (Smith, 1996), which classifies people according to the extent that they believe a hazardous event is dependent on fate (i.e. external control) or its consequences lie within their own responsibility (i.e. internal control). There are three basic types of risk perception that hazard perceivers tend to adopt in order to reduce stress associated with uncertainty (Smith, 1996):

- *Determinate Perception*
  A person who, or group which, exercises determinate perception accepts that hazards exist, but seeks to place extreme events in an ordered manner following some sort of cycle, or pattern (e.g. the El Niño is going to recur every four years). This does not take into account the random nature associated with most hazard threats.
- *Dissonant Perception*
  This does not recognise the possible threat of the hazard and is, hence, a form of threat denial. Dissonant perception can take on several forms. In many cases the hazard has not been experienced in the past and therefore its threat is not perceived (e.g. inexperienced farmers not making contingencies for a severe drought; see Schulze, 1987). In other cases past hazardous events may be viewed as anomalies that are unlikely to be repeated and, therefore, the threat tends to be denied.
- *Probabilistic Perception*
  This acknowledges that disasters will occur as part of the natural system and accepts that many events are random. In some cases, however, the acceptance of risk is often combined with the need to transfer the responsibility of dealing with the hazard event to a higher authority, i.e. ‘an act of God’. The probabilistic view has sometimes led to a fatalistic attitude whereby the individual feels no personal responsibility to hazard response and will avoid expenditure on risk reduction.

All three categories of risk perception produce a jaded perspective of the actual risk involved. This can lead to an increase in the vulnerability of certain communities or individuals when the risk perception is less than the actual risk threat.

There is currently a paradigm shift occurring, whereby hazardous events are no longer perceived as ‘acts of God’ that are uncontrolled and unlikely to happen. Extreme events are now being viewed as part of the natural system that are likely to occur at some undetermined stage in the future (Fairman *et al*., 1998). This view is being adopted by the scientific community, which is beginning to find causal links between extreme events and natural phenomena, for example, the teleconnection between the sign of the Southern Oscillation Index and the high likelihood of either a drier than average rainfall season (El Niño in southern Africa) or a wetter than average season (La Niña). Acceptance of increased causal understanding of extreme events is filtering through to government decision makers and the educated public and is changing their risk perception and level of preparedness. The state of readiness by government and certain agricultural sectors for potentially coping with the forecasted 1997/98 El Niño over South Africa is a good example. Extreme events are thus no longer only seen as certainties that will happen at some stage, but that the consequences of such events can be reduced, averted or even avoided through proper risk management (cf. later sections).

▱ *Acceptable risk*

From the aforegoing section it already becomes clear that there is a growing realisation that there are divergent value judgements of different interested parties and individuals in regard to risk perception, and that these also change over time. For example, risk is perceived most strongly immediately before and after an event. However, memory of the event fades over time (e.g. after a drought is broken). How much risk can a group or individual therefore tolerate? Or, in other words,

- what is an acceptable level of risk?
- to whom is a certain level of risk acceptable and to whom not?
- what would be considered a negligible level of risk, below which it would no longer be sensible to reduce the risk?
- what is the maximum risk that is acceptable, i.e. the level which should not be exceeded? and
- how safe is safe enough?

Finding a definition of acceptable risk is not an easy task, but it includes the following (Plate, 2002):

> *Acceptable risk is the intuitive weight the public gives to the impact of a natural disaster. The definition includes asking about the probability of loss of life from the disaster.*

A number of characteristics of acceptable risk arise out of the definition. These include the following:

- Acceptable risk is dependent on vulnerability, i.e. on the number of people affected. Hence Vrijling, van Hengel and Houben (1995) express it as an exponential index

  $$V_{ij} = 10^{-3}n^2$$

  in which V is the vulnerability, i is the event, j is the location where the event strikes and n is the number of potential casualties, e.g. death. Thus, for 20 potential deaths $V_{ij} = 0.4$ and for 50 it would be 2.5.
- What may be an acceptable risk to engineers is not necessarily an acceptable risk according to public perception (Plate, 2002).
- Risk acceptance operates on the ALARP principle, i.e. 'As Low As Reasonably Practical' (Fairman *et al*., 1998). It therefore compares the level of risk (e.g. a structure designed to safely withstand a 1:100 year flood vs a 1:20 year flood) with the costs imposed in trying to reduce the risk (e.g. what would the additional costs be of designing for the 1:100 year flood vs the 1:20 year flood).

According to Zhou (1995) there are three approaches to determining acceptable risk:

- *Professional judgement*: This is by no means objective, and is often a 'best guess', because it will depend largely on the professional's perspective, training and competence and could also vary between one client and the next. Scientists do not necessarily make good professional judgements because they are often too cautious in their statements (e.g. giving values of probabilities of occurrence, but tempering them with confidence bands) whereas bureaucrats prefer more definitive answers.
- *Formal analyses*: These often use strong prescriptive decision rules, according to highly formalised

and relatively inflexible procedures and in their calculations of best decisions would include quantifications of probabilities and their uncertainty levels, pros and cons of alternatives, sensitivity analyses and cost-risk-benefit analysis.

- *Bootstrapping*: In this approach historical precedent guides decision making on the premise that society achieves a reasonable balance between risks and benefits only through experience over time.

□ ***Some concluding thoughts on 'subjective' risk evaluation***

The above sections have alluded to potential loss of human life on several occasions. At the end of the day two major uncertainties in regard to loss of life remain. First, is the question on the number of lives at risk should a structure fail (e.g. dam breaching) or a system perform inadequately (e.g. supply of water to an irrigation project be curtailed every year). Secondly, what value is attached to a human life? This will differ from country to country and while no-one specifies the value of a human life explicitly, from the literature used in this study it ranges from between approximately US$ 200 000 and US$ 6 000 000, varying significantly between countries and levels of economic development.

6.6 THE RISK MITIGATION AND CONTROL COMPONENT OF HYDROLOGICAL RISK MANAGEMENT : WHAT ARE THE MAJOR CONCEPTS?

a) What is risk mitigation?

Risk mitigation and control constitute the second major component of risk management (Figure 6.4). Natural hazards cannot be avoided, neither can risk be totally eliminated, but society and individuals must learn to cope with the hazards and reduce their vulnerability to them. By definition (own, adapted from several sources)

> *Risk mitigation considers setting up alternative measures to reduce the impacts of a hazard by minimizing its destructive and disruptive effects, thereby lessening the scale of the disaster. It attempts to find practical and workable strategies and solutions for minimising risk at scales ranging from international to national to local.*

In evaluating alternatives, optimisation approaches may be implemented in developed countries. They may not be a workable solution in developing countries, where the alternatives nevertheless have to satisfy criteria of safety vs cost and one has to ask 'how much can be prevented for how little'. An important component of risk mitigation is the process by which decisions are made in risk/disaster management, and this process will be based not only on technical criteria, but also on intuition and political priorities (Plate, 2002).

Two main mitigation strategies can be followed (Smith, 1996), *viz*.

- *hazard modification*, i.e. modifying the physical processes that create or constitute the hazard, involving some degree of direct confrontation; and
- *vulnerability modification*, i.e. reducing the impact of the event by rendering the human environment less vulnerable to, and more prepared for, the event.

b) Hazard modification

Hazard modification is a form of pre-disaster planning which may be viewed from two perspectives.

□ ***By manipulating primary processes***

Physical event modification aims at reducing the damage potential associated with a particular hazard by some degree of physical control over the primary processes of the event involved. Theoretically, through forms of environmental control, the causes of a hazard could be suppressed (Smith, 1996) by diffusing the releases of energy or materials over a greater area and/or period of time (e.g. the stimulation of cumulus clouds to reduce rainfall intensity and increase rainfall duration). However, with the current state of technology the suppression of natural events such as those causing large scale flood events is not yet possible or, alternatively, produces uncertain results. The use of such a strategy is, therefore, still very limited.

▫ *By manipulating secondary processes*

Event modification can also be achieved via a strategy of manipulating the secondary processes that cause a hazard, rather than attempting to attack the root cause. In the case of floods, for example, instead of trying to manipulate the rainfall event, the runoff generation processes could be manipulated using land phase management, building conservation structures such as contour banks and terraces, or by ensuring that river channels are cleared or canalised for more efficient dispersal of flood waters. Hazard resistance is another form of event modification which involves the construction of defensive engineering structures such as flood control dams (which are purposely kept empty before the flood) or levees. Other methods include the setting of building codes and retrofitting older structures (Plate, 2002).

c) Vulnerability modification

Vulnerability modification is a more intricate process that involves the interaction of several different interrelated factors that need to act in tandem in order to reduce the impact of a hazard event. Vulnerability modification is concerned with human reactions toward a potential hazard and involves, *inter alia*, the changing of human attitudes and behaviour. Hazard loss reduction may be achieved through the implementation of several different measures which include

- community preparedness programmes,
- forecasting and warning systems and
- legal and financial measures

which ideally should be linked into one interrelated programme.

▫ *Preparedness*

Preparedness is defined as those pre-arranged emergency measures which are to be taken to minimise the loss of life and property damage following the onset of a hazard. Preparedness programmes involve the detailed planning and testing of prompt and efficient responses by both individuals and groups to hazards that have either been forecasted or have occurred. Preparedness programmes focus on public education and awareness, evacuation plans, the provision of medical and food aid as well as shelter for evacuees. Long term preparedness programmes have been implemented successfully in many developed countries. Authoritarian political and under-resourced financial frameworks in many of the less developed countries have limited the development of good preparedness programmes there (Smith, 1996).

▫ *Forecasting and warning systems*

Forecasting and warning systems have become increasingly important in recent decades. This can be attributed to the scientific advances in information and communications technology, such as satellites, which have improved forecast accuracy and increased the efficiency of warning systems. However, in some cases warnings are based on predictions only, as the processes or hazards are not yet sufficiently understood to provide forecasts.

The fundamental differences between forecasts and predictions are vital to remember.

- *Predictions* are based on statistical theory, which uses the historical records to estimate the probability of occurrence of events. Predictions are, therefore, based on average probabilities (e.g. a 1:10 year rainfall event does not imply an occurrence of once in 10 years, but rather of 10 times in 100 years) and give no indication of when (i.e. in which season or year) a particular event may occur (a 1:10 year event may recur in successive years).
- *Forecasts*, on the other hand, tend to focus on individual events where the physical processes or statistical interlinkages are relatively well understood (Smith, 1996) to the extent that, depending on the nature of the event being forecast, it is possible to provide information about its timing, location and magnitude. Forecasts are thus able to reduce sources of uncertainty and hence

diminish risk.

In hydrology and water resources, forecasting is used to modify the *a priori* probability distribution of future time series of hydrological information (e.g. of rainfall, runoff or level of dams) and demands (e.g. irrigation, urban/domestic) based on the concept of the 'now' state (e.g. present flow in a stream or level of a dam or current water demands) and projected future states (e.g. a season ahead). Forecasting is undertaken to enhance the operational reliability of a water resources system in regard to (say) environmental flow releases, irrigation demands, inflows to dams or groundwater recharge. Figure 6.6 illustrates the potential benefits of reducing uncertainty in a reservoir operation through forecasting.

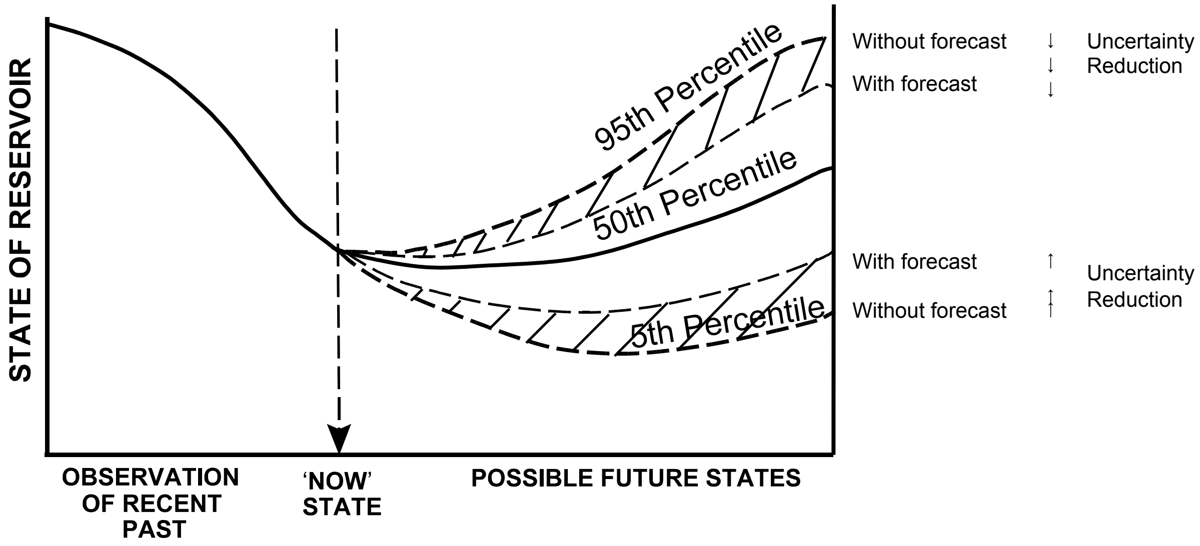

Figure 6.6 Schematic illustration of the reduction of uncertainty in a reservoir operation through application of forecasting techniques

Key questions on forecasting as a vulnerability modifying tool revolve around

- the *skill* of the forecast (i.e. is the decision made with the aid of a forecast better than simply assuming median or persistence trends?)
- the *accuracy* of the forecast (i.e. how well it compares with what was observed, in hindsight)
- the *lead time* of the forecast (i.e. how far ahead can the forecast be made)
- the *deterioration of its reliability* as time progresses (e.g. Lumsden *et al*., 1999)
- the *benefits* of the forecasts with current forecast skill and accuracy (e.g. Hallowes, Schulze and Lynch, 1999) and comparing current forecast skills with results from
- *perfect forecast accuracy* (Lumsden *et al*., 1999).

□ ***Legal and financial measures***

Legal and financial measures are designed to either avoid the settlement of individuals or communities into areas of high risk, or to provide aid that is able to accelerate the recovery of affected communities. Legal measures involve land use planning that is designed to prevent the participation in certain activities in high risk areas, i.e. they are a form of non-structural control (Smith, 1996).

6.7 EXAMPLES OF HAZARD DETERMINATION AND RISK MITIGATION FROM SOUTH AFRICA

a) What approaches and spatial databases were used?

This section illustrates some of the concepts of risk, hazard and vulnerability within a context of hydrological risk management as described above, using examples from South Africa, defined here as the contiguous area of 1 267 681 km^2 made up of the nine provinces of the Republic of South Africa plus the landlocked

Kingdoms of Lesotho and Swaziland. The country/regional scale is chosen to identify regions of similar hydrological hazard levels and thereby to distinguish between areas of higher and lower potential hydrological risk. Such a comparative view is important from the perspective that risk management is a national/regional responsibility and that at this scale an analysis may assist in identifying target areas for potential priority attention. Many of the hazard/risk indices presented by way of maps are in the form of ratios, rather than as absolute values, to highlight sensitive areas on a relative scale. Throughout, where a hydrological model has been used, it has been the *ACRU* model (Schulze, 1995).

For the production of maps at the scale of South Africa, as shown in this chapter, quality controlled daily rainfall for the concurrent 44 year period 1950-93 was input for each of the 1946 Quaternary Catchments (QCs) which have been delineated for the RSA, Lesotho and Swaziland. For each QC other climatic parameters (e.g. monthly means of daily maximum and minimum temperatures; monthly means of A-pan equivalent reference potential evaporation; all converted to daily values by Fourier Analysis within the *ACRU* model) were also input, as were hydrological soil parameters. For purposes of producing comparative hydrological hazard maps, land cover was assumed to be grassland in fair hydrological condition, i.e. 50-75% cover (Schulze, Schmidt and Smithers, 1993).

b) Examples of general hydrological hazard indicators

To set the scene, Figure 6.7 (top) shows mean annual precipitation (MAP, mm), which characterises the long term quantity of available water to a region, to display a general westward decrease, with relatively low MAP - a first indication of a largely semi-arid climate and potentially high risk natural environment for IWRM. A simple aridity index, expressed as the ratio of mean annual potential evaporation to MAP (Figure 6.7, middle) emphasises the hazard of hydrological semi-aridity, because it amplifies the effects of a low MAP when that is evaluated in association with the region's high atmospheric demand. The aridity index is an already high 2 - 3 where MAP > 600 mm, increasing to > 10 and even > 20 in the drier west. A consequence largely of the high aridity index is that the conversion ratios of rainfall to runoff over most of South Africa are exceptionally low (Figure 6.7, bottom) with, overall, only 9% of rainfall manifesting itself as runoff. These low runoff ratios, simulated with the *ACRU* model (Schulze, 1995), result in a high hydrological vulnerability over much of the region.

c) Examples of a 'deprivation' event, of hydrological uncertainty and of sensitivity to changes in a variable : The 1982/3 El Niño event over South Africa

The 1982/3 El Niño was one of the most severe experienced over South Africa. The manner in which such an event impacts on different hydrological responses is illustrated in Figure 6.8. Observed rainfall and simulated runoff and recharge into the groundwater zone through the soil profile are all expressed as ratios of their respective long term (1950-93) median values. For much of the region the El Niño season's rainfall was 60 - 75% of the median, however, with sizeable areas receiving within the range of expected rainfalls (i.e .75 - 125%) while some others received only 20 - 60% of the norm (Figure 6.8, top). The corresponding runoff responses display much more complex patterns spatially and in the range of ratios. Much of the region yielded only 20 - 60% of the long term runoff (Figure 6.8, middle), with considerable areas generating < 20% of the expected runoffs. This shows clearly once more the intensifying effects of the hydrological cycle on rainfall perturbations, as well as the dependence of hydrological responses not only on total rainfall amounts, but also on individual events, rainfall sequences and antecedent catchment wetness conditions, i.e. on the hydrological uncertainty created by meteorological and catchment conditions.

Some hydrological processes and responses display higher sensitivities, and thus higher potential vulnerabilities, than others. This is illustrated by the recharge to groundwater during this El Niño season, which was impacted even more severely than runoff (Figure 6.8, bottom). Generally only 0 - 20% of the expected recharge was simulated to take place, the reason being that a higher threshold has to be reached for recharge to commence than for stormflow to start occurring.

d) Example of an 'assault' event as an indicator of potential vulnerability and stochasticity by quantitatively defined endpoints in regard to depth, duration, frequency and area affected

Episodic flood generating events display considerable stochasticity (i.e. unknowable randomness). As an

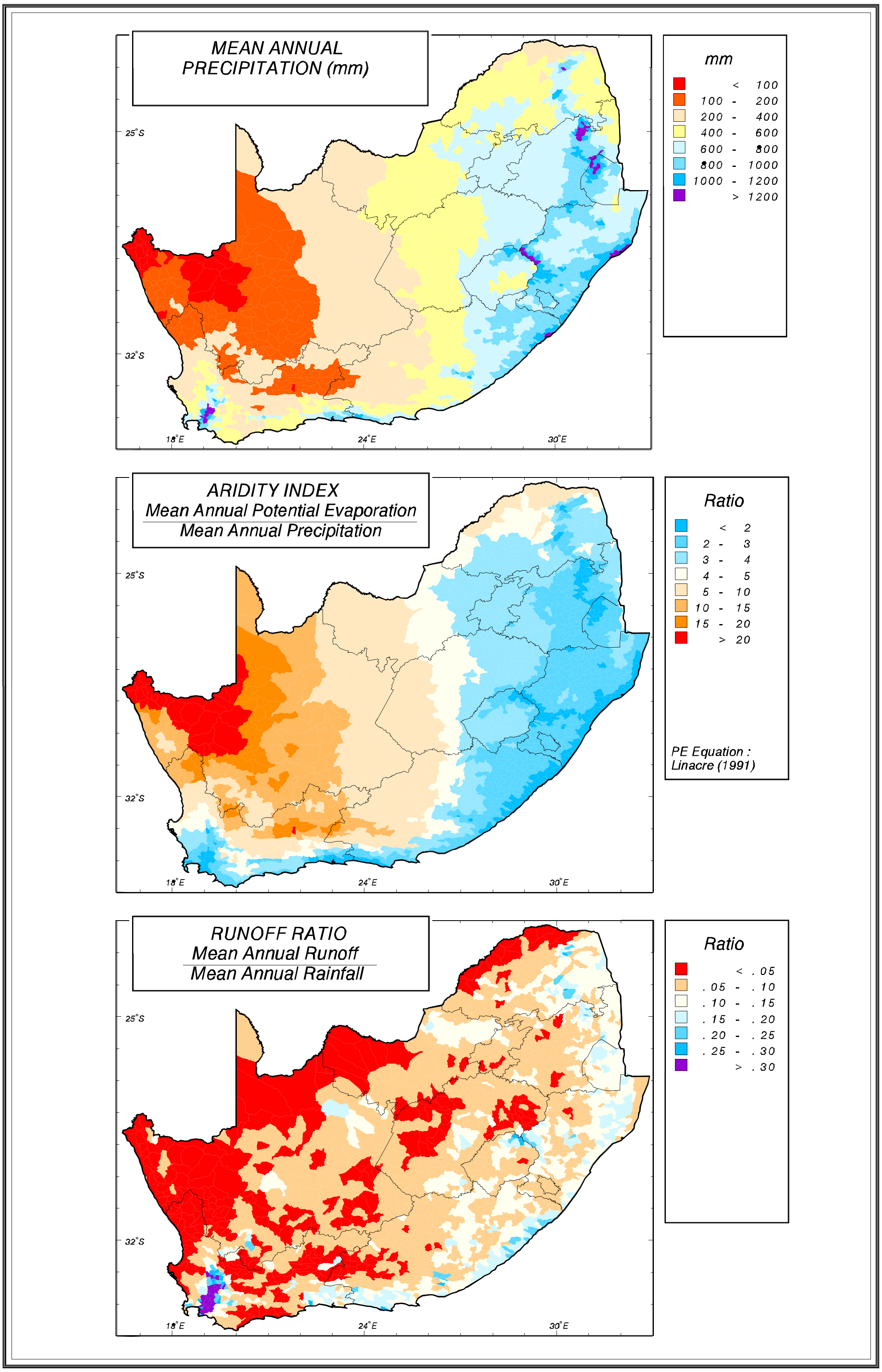

Figure 6.7 Indicators of South Africa's largely semi-arid hydrological environment: (top) Mean annual precipitation (mm), (middle) an aridity index expressed as the ratio of mean annual potential evaporation to precipitation and (bottom) the conversion ratio of mean annual runoff to rainfall (Source: Schulze, 1997a)

indicator of potential vulnerability the flood hazard example presented below as an 'assault' event illustrates the relative spatial differences over South Africa between the severity of the 1:50 year 1-day flood producing rainfall, and consequent runoff, compared with what could be considered the annual expected 1-day values, *viz*. the 1:2 year event. Ratios of 1:50 to 1:2 year rainfalls are generally between 2 and 4 (Figure 6.9, top), with lower ratios over central areas, but increasing to 10 in parts of the drier west. These rainfall ratios, however, manifest themselves as 1-day flood depths 4 -10 times higher in the eastern areas of South Africa, and up to 50 times and higher over significant tracts of the drier west (Figure 6.9, bottom). While floods may be an infrequent occurrence in the west, this example illustrates that rare floods have the potential to do severe damage because of their unexpectedly high relative magnitudes.

e) Example of uncertainty through use of short data sets

Statistical hazard determination is frequently fraught with uncertainties as a consequence of using short data sets to determine high recurrence interval values of design rainfall or runoff. To illustrate this for hydrological design purposes, the 1:50-year 1-day rainfall and runoff estimated for a short 22 year period1972-93 was plotted as a ratio against 1:50 year 1-day rainfall and runoff estimated for double the period, *viz*. the 44 years 1950-93. In each case the log normal extreme value distribution was applied to the annual maximum series which, in the case of runoff, was generated with *ACRU*. If the short records were representative of the expected population of the annual maximum series, the ratio would be ~ 1.

Figure 6.10 shows this clearly not to be the case. Large tracts of South Africa display rainfall ratios between 0.75 and 0.95 and even < 0.75, while other areas show ratios in excess of 1.25 (and even 1.50). Estimating design rainfalls from short record lengths may, therefore, result in severe underestimations or overestimations, with these errors amplified once design runoff is estimated from the rainfall (Figure 6.10, bottom). The importance of record length can therefore not be overemphasised, particularly in light of the worldwide trend, certainly in developing countries and evident also in South Africa, of declining hydrometeorological recording networks.

f) Example of secondary hazard modification through land use practices : The case of grazing management and hydrological responses

Land use practices have been shown in many examples to play a significant role in long term average hydrological responses, but perhaps even more dramatically so at the extremities of frequency distributions (e.g. Schulze, 1989; 2000). An example of secondary hazard modification by manipulating land management practices is given below.

Much of South Africa's natural grassland (veld) has recently been shown to be heavily over-utilised (Hoffman, Todd, Ntshona and Turner, 1999). Hydrologically, the degradation through overgrazing of veld from good to poor condition, with its reduction in vegetal cover from > 75% to < 50%, implies enhanced stormflows through reduced interception and evapotranspiration potentials as well as infiltrability, shortened catchment lag times which increased peak discharges and greater exposure to soil erodibility through removal of mulch and shorter drop fall heights. These variables were changed for each of the 1946 QCs covering South Africa in *ACRU* model simulations of stormflows, peak discharges and sediment yield to reflect veld in good vs poor management condition. Figure 6.11 (top) shows that annual stormflows from veld in degraded condition are generally 1.5 - 2.5 times as high as those from veld under good management. When converted to sediment yields, however, the factor difference becomes 2.5 - 7.5 times, and even > 7.5 times (Figure 6.11, bottom), clearly illustrating how a hazard, in this case stormflow and especially sediment yield, can be modified positively by good grazing management and/or rehabilitation of overgrazed lands.

g) Example of vulnerability modification through seasonal forecasting of runoff

Vulnerability modification is a form of risk mitigation which includes, *inter alia*, assessing the benefits of forecasting streamflows for the rainy season ahead. Statistically derived categorical seasonal rainfall forecasts four months ahead are made for eight regions of South Africa by the SA Weather Service, for three categories, *viz*. 'above-normal', 'near-normal' and 'below-normal' seasonal rainfalls. If seasonal rainfall forecasts were a random process, such three-category forecasts would be correct 33% of the time. If seasonal categorical rainfall forecasts are 'translated' into seasonal runoff forecasts, these could become

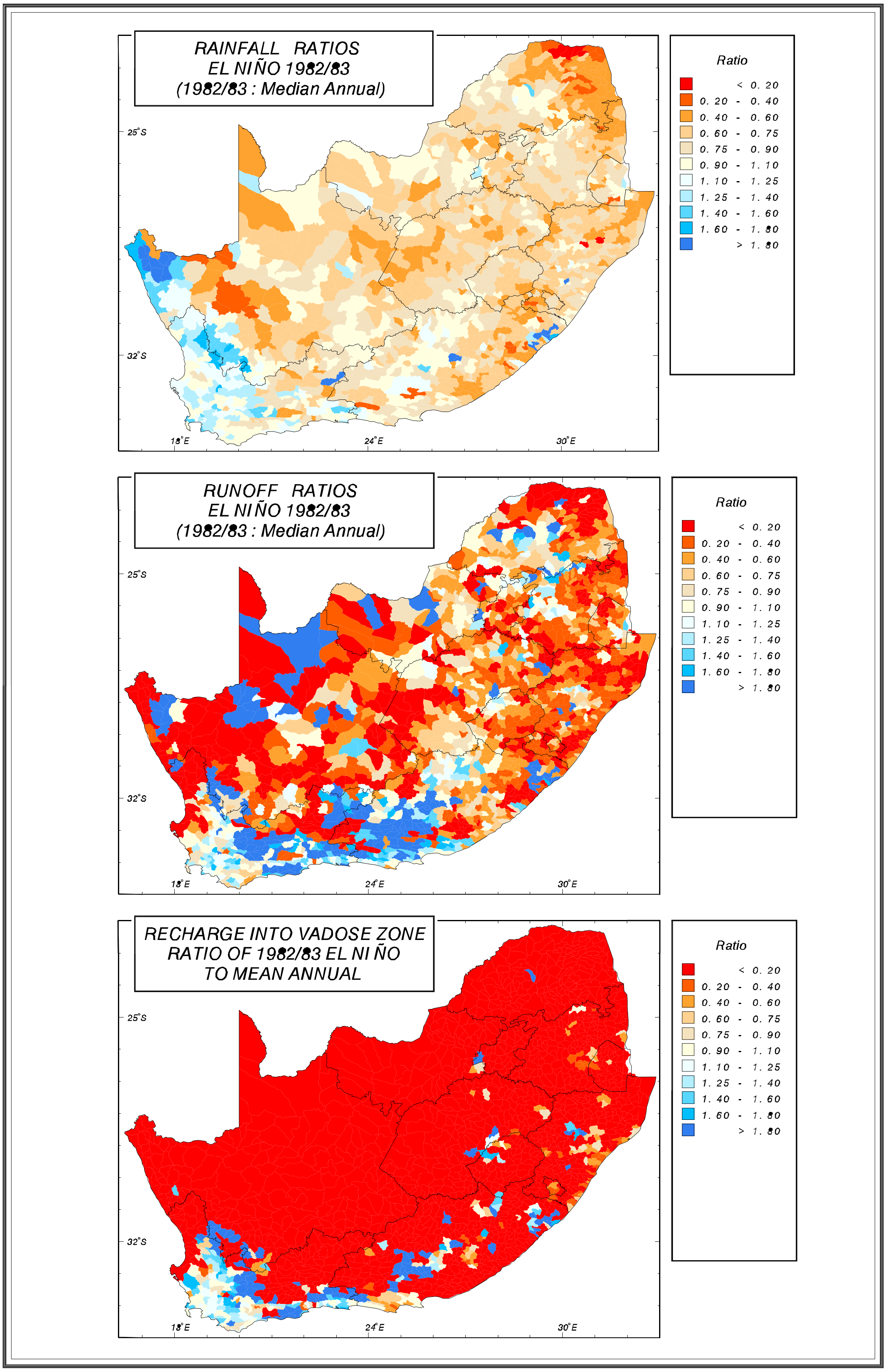

Figure 6.8 Indicators of hydrological amplifications of climate fluctuations: Ratios of the 1982/83 hydrological year's rainfall (top), simulated runoff (middle) and recharge to groundwater (bottom) to long term median values (after Schulze,1997a; 1997b)

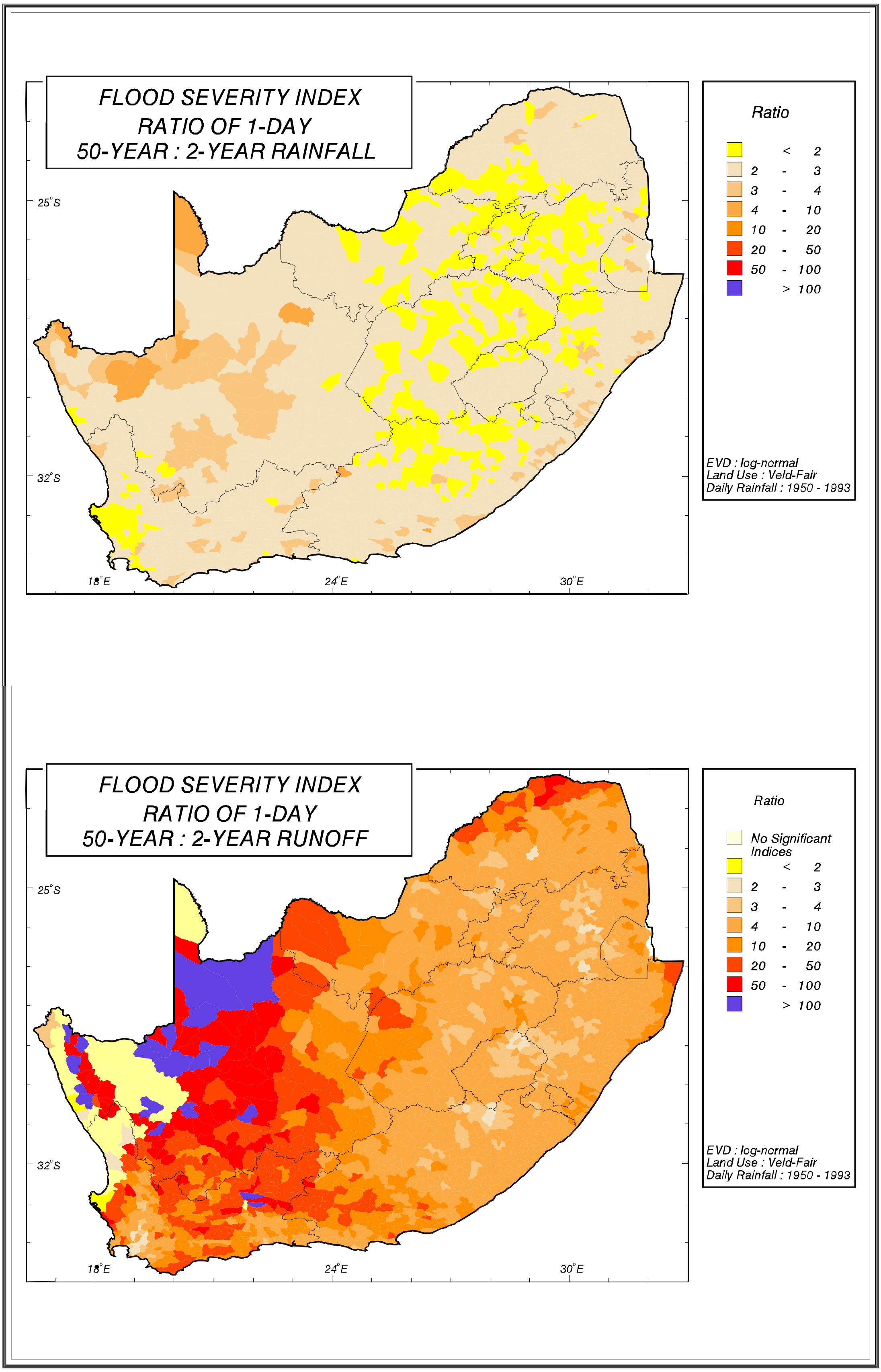

Figure 6.9 Ratios of 50 year : 2-year 1-day rainfalls (top) and runoffs (bottom) as indicators of potential vulnerability to flooding

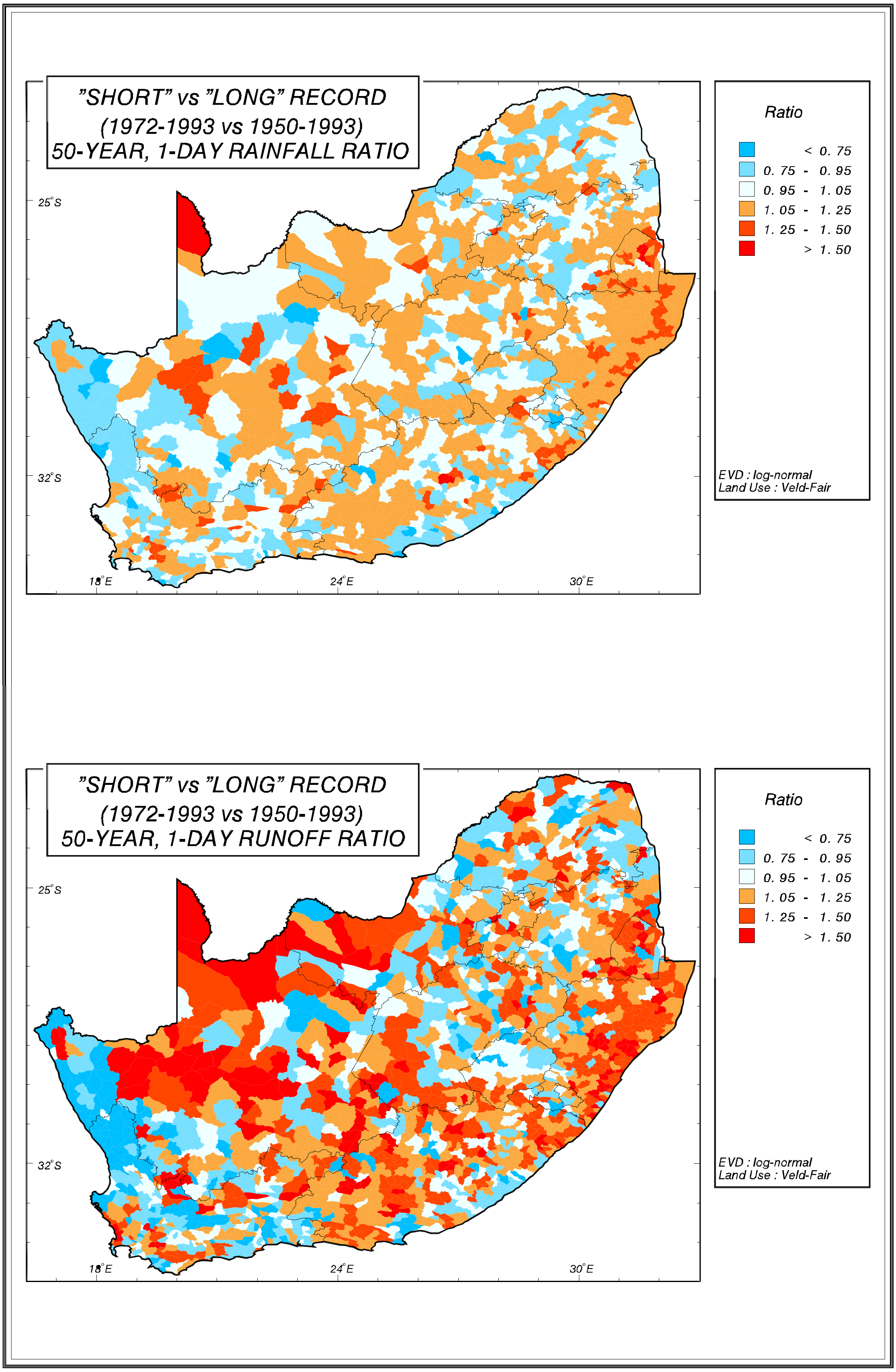

Figure 6.10 Ratios of 'short' (1972-93) to 'longer' (1950-93) design rainfall and runoff in South Africa for the 50-year return period 1-day event

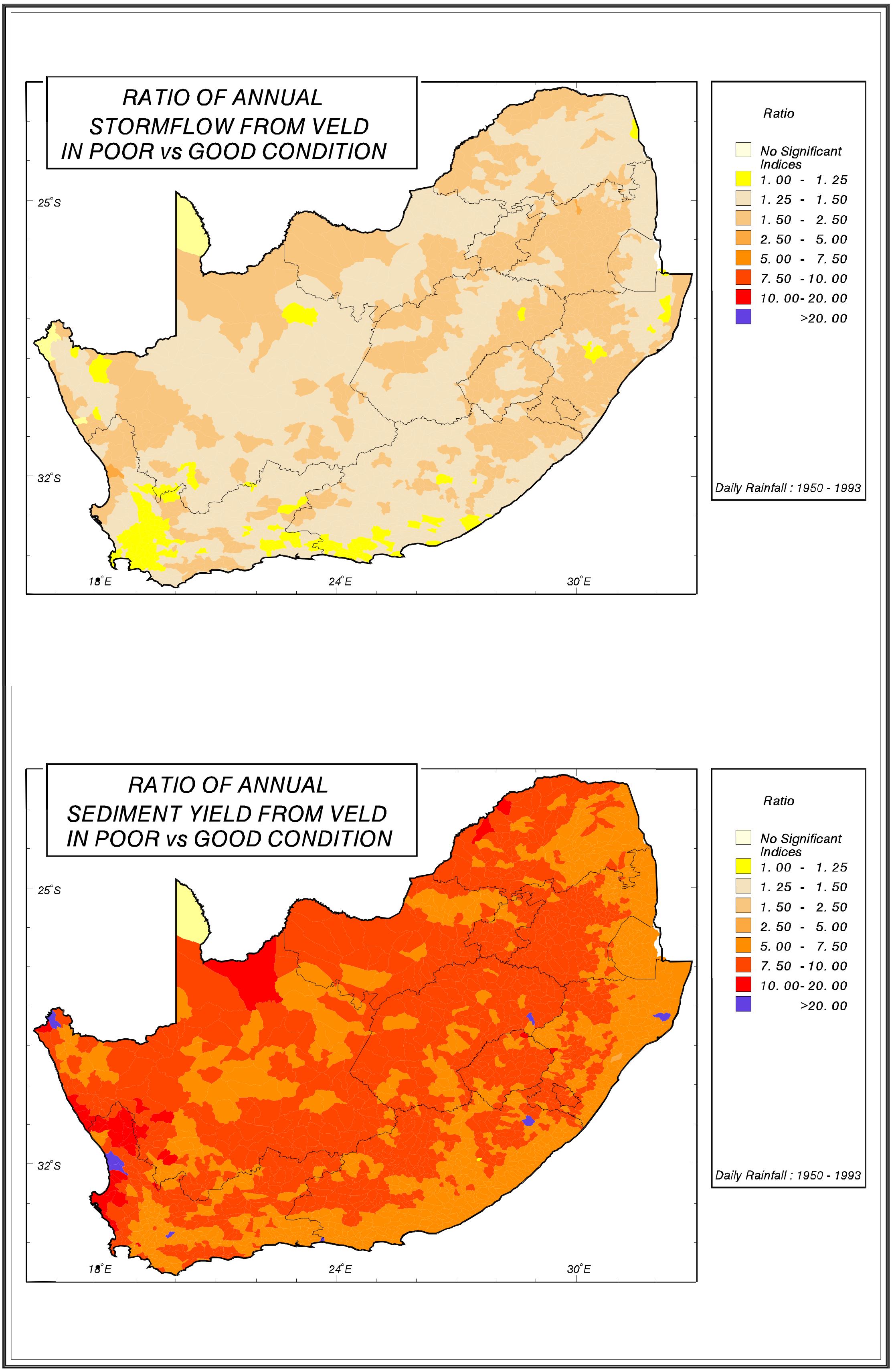

Figure 6.11 Ratios of annual stormflows (top) and sediment yields (bottom) in South Africa from veld in poor vs good hydrological condition

very valuable reservoir operations and irrigation application planning tools for water resources managers.

Seasonal categorical rainfall forecasts for the eight forecast regions in South Africa were downscaled to daily rainfall values using techniques described in Schulze, Hallowes, Lynch, Perks and Horan (1998) for application with the *ACRU* modelling system to over 1500 QCs in South Africa. A simple benefit analysis of forecasting skill was undertaken, in which a 'win' was recorded if, for the historical seasonal rainfall forecast, the simulated seasonal runoff was closer to the runoff simulated with actual historical rainfall than the median seasonal runoff, and a 'loss' was recorded when median runoff was closer to the actual than the forecast runoff. 'No difference' implies forecasted and median runoffs within 5% of one another. Figure 6.12 illustrates that, when excluding three seasons out of 15 for which the rainfall forecast accuracy proved 100% wrong, *viz*. 1981/2, 1987/8, 1990/1, most of southern Africa scores more 'wins' than 'losses'.

The impacts of reversible climate perturbations such as the El Niño phenomenon have already been illustrated. This forecast analysis indicates that even at the current level of seasonal forecast accuracy (around 62% if the 3 worst forecasts in 15 are omitted) these can potentially be 'translated' into an operational tool for water resources managers which could prove statistically more accurate than current practice of forecasting based on historical expected, i.e. median, runoffs with wide uncertainty bands, as shown in Figure 6.6.

h) Identifying potential future hazards : Are certain areas in South Africa hydrologically more sensitive than others to the individual forcing variables of climate change?

Superimposed onto an already highly variable climatic and even more variable hydrological regime over South Africa is the potential threat of irreversible greenhouse gas induced climate change, effects of which are likely to be amplified through the hydrological system (Schulze and Perks, 2000). The primary forcing function of greenhouse gas induced climate change is represented by effective changes in atmospheric CO_2 concentrations (ΔCO_2) which, in turn, trigger secondary forcing functions such as changes in temperature (ΔT) and in precipitation (ΔP). In an hydrological context, increases in levels of ambient CO_2 can result in

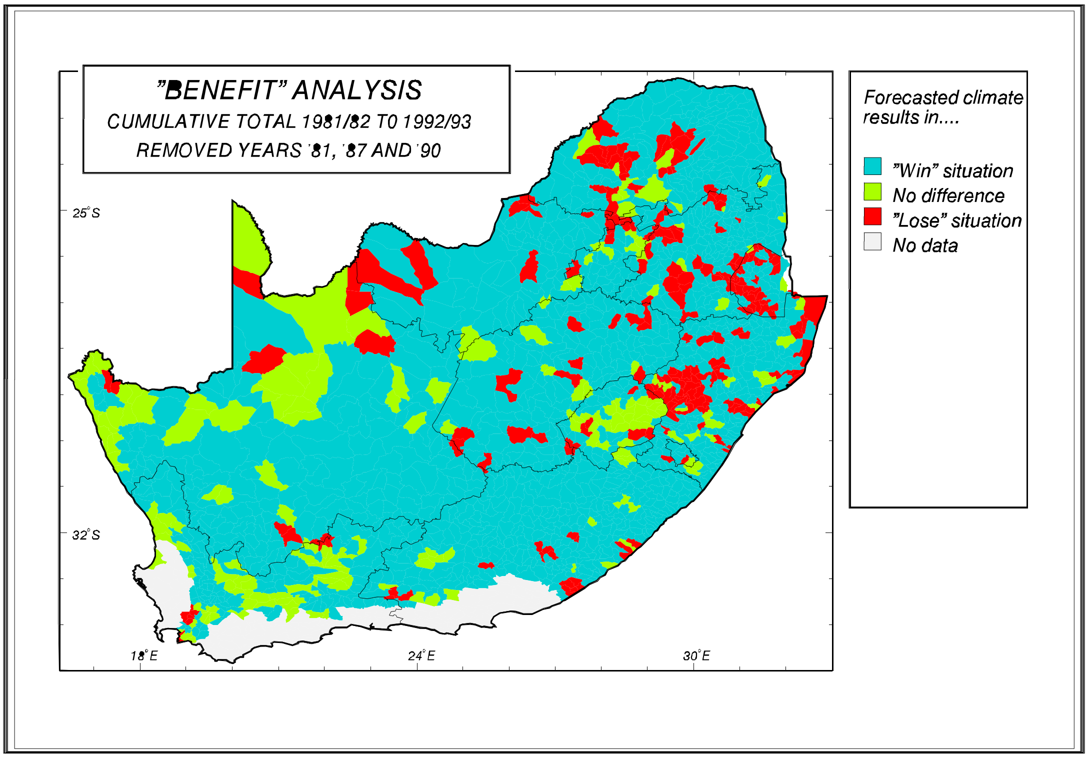

Figure 6.12 Example of a simple benefit analysis of seasonal runoff forecasts over South Africa (after Schulze *et al*., 1998)

increases in plant stomatal resistances which, hydrologically, imply reductions in transpiration with consequences and implications in the soil moisture regime and, hence, runoff generation. Changes in temperature, on the other hand, are an important determinant of potential evaporation, which drives the actual evaporation process and hence controls soil moisture and runoff processes. Temperature, furthermore, dynamically activates the potential rate of plants' seasonal growth cycles through the concept of thermal time. The most important climatic variable in hydrology, however, remains rainfall. Permutations of wet and dry day rainfall sequences and antecedent catchment wetness conditions are all crucial to the impact which magnitudes and intensities of episodic rainfall events have on the generation of runoff.

However, climate change impact studies remain fraught with uncertainties, for example, of rates, magnitudes and directions of elements of climate change output by General Circulation Models (GCMs) or of downscaling problems from GCMs to local catchments (e.g. Schulze, 1997b; Schulze and Perks, 2000). Climate changes and their impacts cannot yet be predicted with certainty, but are presented as plausible scenarios of likely change.

Figure 6.13 illustrates the relative sensitivities of ΔCO_2 (from 360-560 ppmv), ΔT (assumed to be a uniform increase of 2°C over southern Africa) and ΔP (changed through -10% to +10% of the present) to runoff. These are all realistic scenarios from GCM output reviewed for South Africa (Schulze and Perks, 2000). In each case the other two variables are held constant at present levels when running the daily *ACRU* model. Over most of South Africa long term runoff varies by < 4% in response to the CO_2 and transpiration feedback, except in the extreme southwest. Similarly, the hydrological system is relatively insensitive to temperature changes that affect evaporation and hence runoff. The increase of 2°C reduces MAR over most of the summer rainfall regions of South Africa by only 5% (Figure 6.13, middle). However, again in the southwest winter rainfall region the response to ΔT becomes more dramatic, with a 2°C increase in temperature by itself producing a simulated reduction in MAR in excess of 50-%. The reasons for this are that under present climatic conditions evaporation losses there are relatively low from the moist soils in winter, but that with global warming, faster drying soils between rainfall events will significantly reduce runoff. The most significant sensitivity to climate change, however, remains that to rainfall, with changes by one unit manifesting themselves as runoff changes by a factor of 2 to 5 (Figure 6.13. bottom), once more dominant in the extreme southwest.

6.8 CONCLUSIONS

This chapter commenced by defining and describing the concepts of risk , hazard and vulnerability before focussing attention on hydrological risk management. The framework was set by examining approaches to hydrological risk management, first of risk assessment with its two components of 'objective' hazard determination (including the many questions surrounding uncertainties) and subjective risk evaluation (including the roles of perception and acceptable risk) and thereafter of risk mitigation and control, which is made up of hazard modification (e.g. manipulating runoff) and vulnerability modification (e.g. preparedness and forecasting).

This conceptual framework was followed by examples, from South Africa, of hazard determination and risk mitigation. Examples of general hydrological hazard indicators were illustrated, as were those of statistical hazard indicators (in regard to floods and droughts), of hazard modification through land use practices and vulnerability modification through seasonal forecasting of water resources, before concluding with identifying possible future hydrological hazards by assessing the sensitivity of mean annual runoff in South Africa to potential climate change forcing variables.

The conceptual framework and the examples bring to the fore two overarching issues in hydrological risk management . The first is the question of uncertainty in risk-related hydrological studies - uncertainties regarding meteorological and catchment conditions, uncertainties around input data and uncertainties emanating from the models used in hydrological risk management. The second revolves around the recurring identification of the hydrological system's amplifying any perturbations of rainfall. It is the amplification and uncertainty issues which will need to be stressed to practitioners and managers of hydrological risk time and again and where researchers will need to focus their attention in future.

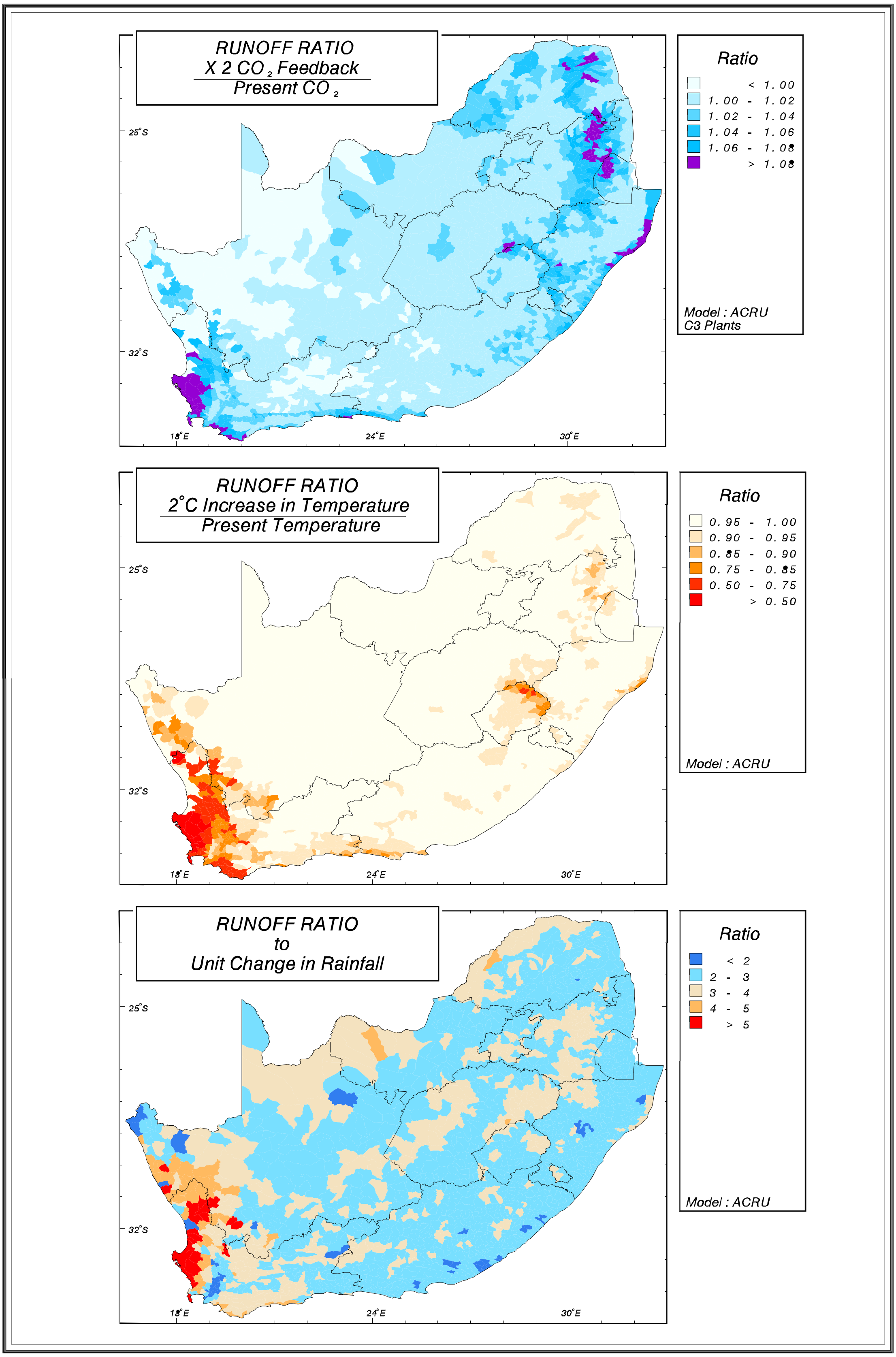

Figure 6.13 Sensitivities to climate change variables : CO_2 (top), temperature (middle) and rainfall (bottom) change impacts on mean annual runoff over South Africa (Schulze and Perks, 2000)

6.9 ACKNOWLEDGEMENTS

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CHAPTER 7

THE *ACRUforest* DECISION SUPPORT SYSTEM TO ASSESS HYDROLOGICAL IMPACTS OF COMMERCIAL AFFORESTATION PRACTICES IN SOUTH AFRICA

R.E. Schulze[1], M.J. Summerton[1,2], K.B. Meier[1,3], A. Pike[1] and S.D. Lynch[1]

[1]School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

[2]Now: Umgeni Water, P O Box 9, Pietermaritzburg 3200, South Africa
[3]Now: Land Resources International, Pietermaritzburg 3201, South Africa

ABSTRACT

The recent moves towards identifying streamflow reduction activities and focussing on integrated water resources management have renewed questions on water use by commercial forest plantations in South Africa. This chapter first describes the process representations and factors such as age, genera, soil conditions, macro- and meso-climate and management practices which forest hydrological models need to account for. The *ACRUforest* decision support system is comprised of the *ACRU* model, linked with extensive daily climate and soils databases at Quaternary Catchment scale and dynamic growth algorithms for different genera, macro-climates and management practices in South Africa. A feature of this interactive package is that it prompts the user with easy-to-answer questions which are then used with *ACRUforest* to provide answers to decision makers on forest hydrological impacts. The first questions relate to the location at which impacts are to be assessed, whereupon *ACRUforest* responds with typical altitude, mean annual precipitation and soils characteristics for that Quaternary Catchment. These default values can be changed by the user to be more representative of a particular plantation/location under review. Next, simple information is required on the baseline land cover from which the conversion to afforestation is taking place, followed by questions on which genera (pines, wattle or eucalypt), thinning practices, site preparation and rotation lengths are to be considered. From this information the relevant 45 year daily climate record is interrogated for both baseline and afforestation runs for *ACRUforest* to output daily time series of runoff characteristics from which various statistics on the hydrological impacts of the afforestation are produced for the decision maker. The chapter concludes with a discussion on what can and cannot be computed by *ACRUforest*.

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7.1 WHAT ARE WE LOOKING FOR IN A SOUND FOREST HYDROLOGICAL MODEL?

The declaration of plantation forestry as a 'Stream Flow Reduction Activity' under the National Water Act (NWA, 1998), as well as the quest towards integrated water resources management, all operative in a country with relatively scarce water resources and with increasing conflicts surrounding the allocation of available water to competing sectors, continues to focus attention on water use by commercial forest plantations in South Africa in comparison with that of other land uses (cf. Chapter 8).

Tree water use in different macro- and meso-environments consists of complex and interactive processes which cannot be 'captured' in simple empirical hydrological models. If one wishes to do justice to answering adequately the questions which hydrologists, environmentalists, foresters and policy makers are asking on hydrological responses from forested (and other agricultural) land uses, then one should be developing and applying agrohydrological models which, ideally,

- represent realistically the important forest hydrological processes such as
    - dry canopy transpiration, as distinct from
    - enhanced wet canopy evaporation, and
    - evaporation from the soil surface, as well as
    - aerodynamic processes
    - stomatal resistances to transpiration
    - rooting distribution by soil horizon
    - root colonisation
    - canopy interception and storage, and
    - litter interception
- distinguish between these process responses for different genera, furthermore
- consider the age of the plantation and the way in which process representations of different genera change over time, from planting through full canopy closure, maturity to felling
- take account of soil characteristics, such as
    - depths of various horizons
    - texture and
    - saturated drainage rates, and
- can represent management practices, which may include
    - physical site preparation, which in turn may change
        - infiltrability rates
        - soil water holding capacity when wet, and hence alter
        - soil water redistribution rates
        - effective rooting depths and densities
        - stormflow generating mechanisms as well as
        - baseflow generating mechanisms, and
    - thinning practices, with the model simulating effects of changes in, for example, leaf area index (LAI) and interception with the
        - number of thinnings per rotation
        - ages at which thinning takes place, and the
        - degree of thinning.

All these factors need to be processed by algorithms in the model with due consideration to

- long term macro-climatic conditions, which determine the overall and average rates of tree development and water use, as well as
- medium term climatic conditions, which modulate hydrological responses and tree water use on an inter-seasonal basis, e.g. 'wet' years vs 'dry' years, and
- short term climatic conditions such as *daily* rainfall and atmospheric demand (e.g. vapour pressure deficit) which trigger processes such as
    - the status of available soil water and hence
    - the degree of plant stress and
    - the duration of plant stress, or alternatively, daily rates of
    - stormflow generation and
    - baseflow generation.

Furthermore, if the impacts of afforestation on water resources are being evaluated the model needs, ideally, to be able to provide answers to questions on

- impacts relative to those of previous land covers or land uses, for example, to
  - baseline land cover conditions (e.g. Acocks' Veld Types)
  - previous cropping practices or
  - previous grazing practices, and if the latter, to the management condition of the grassland (e.g. whether the veld had been in hydrologically poor or good condition)

  and
- sensitivities to
  - absolute changes in water yield (i.e. in mm equivalents or m^3), or
  - relative (i.e. percentage) changes in water yield which, on a regional basis, may be entirely different to those of absolute differences

  as well as
- response changes over different time frames, such as
  - over the long term, or
  - in critically dry years (e.g. driest year in 5) or
  - in critical low flow months

  and also
- flow responses in regard to distinct runoff components, such as
  - stormflows, with the attendant changes to flood peaks and sediment yield, or
  - baseflows, with their different water quality characteristics.

Additionally, questions need to be answered on

- hydrological response changes at a range of spatial scales, for example, for
  - the plantation *per se*, or at
  - farm level
  - sub-Quaternary catchment level, with (say) regard to the immediate downstream user
  - individual Quaternary catchments or
  - linked Quaternary catchments, in which impacts of the combined upstream areas are considered

  and
- runoff responses from the different landscape elements of a hillslope, or catchment, such as the
  - upslope areas
  - midslope areas
  - warm or cool aspect slopes in regard to their varying solar radiation budgets, or the
  - riparian areas, with their uniquely different water use opportunities and strong influence on influent streamflows.

The hydrological impacts model to provide answers to all these important questions does not yet exist, but in response to a demand to answer many of the frequently asked questions on forest hydrological responses in South Africa rapidly, realistically and objectively, as well as in response to the challenges to forest hydrologists which were identified by Görgens and Lee (1992), the *ACRUforest* decision support has been developed in the School of Bioresources Engineering and Environmental Hydrology at the University of Natal, with support from the Water Research Commission and the forest industry through the Institute for Commercial Forestry Research.

7.2 WHAT IS THE SCIENTIFIC BASIS OF *ACRUforest*?

Hydrologically, the forest component of the *ACRUforest* programme is 'driven' by the development and water use relationships associated with LAI changes over time, from planting or regrowth to harvest, and including interim management practices. These relationships were derived from fieldwork, and the South African and international literature on tree water use, as reviewed by Summerton (1996), in conjunction with expert opinion obtained from four one-day workshops with South African forest hydrologists and forest company scientists (Summerton, 1996). Examples follow:

- Two examples illustrate the broad LAI changes with age by genera (Figure 7.1) and by regional difference (Figure 7.2), while a further two examples illustrate changes in root distribution (Figure 7.3) and root colonisation (Figure 7.4) for a specific genus (eucalypts) in a specific rainfall area with a specific mode of site preparation.
- Matrix tables have been prepared for LAI, canopy interception (mm/rainday), root distribution per soil horizon and root colonisation for each year after planting and for combinations of the
  - 4 growth areas
  - 3 genera (eucalypts, pine and wattle)
  - 2 rainfall zones (> 1000 mm; < 1000 mm MAP) as well as
  - 2 site preparation techniques (Summerton, 1996; Schulze, Summerton and Jewitt, 1998).
- *ACRUforest* distinguishes between tree water use under different macro-climatic conditions (i.e. areas of 'high' vs 'lower' annual rainfall) for four identified major tree growing regions, *viz*. the north east Cape, the Midlands of KwaZulu-Natal (extending into south eastern Mpumalanga), the northern coastal areas of KwaZulu-Natal and the Mpumalanga/Northern Province commercial forest belt.
- Two management scenarios can be simulated, *viz*. effects of thinning and effects of site preparation.
- Hydrologically the effect of thinning (as distinct from pruning) is to reduce the LAI (this reduction being assumed to be the same as the percentage of trees thinned) and the corresponding canopy interception, and thereby influence soil water extraction and effective rainfall. In the model the relationship assumed is that LAI 'recovery' takes place to the LAI level it would have been at without thinning. This recovery occurs linearly over three years, as illustrated in Figure 7.5.
- The site preparation methods considered are pitting and 'plough and rip'.
- 'Plough and rip' represents an intensive soil preparation which, in the model, changes the topsoil's water holding capacity at porosity because of bulk density changes with ploughing (Schulze, 1995), alters root distribution/colonisation patterns and also increases saturated redistribution rates (Schulze, 1995; Summerton, 1996; Schulze *et al*., 1998).

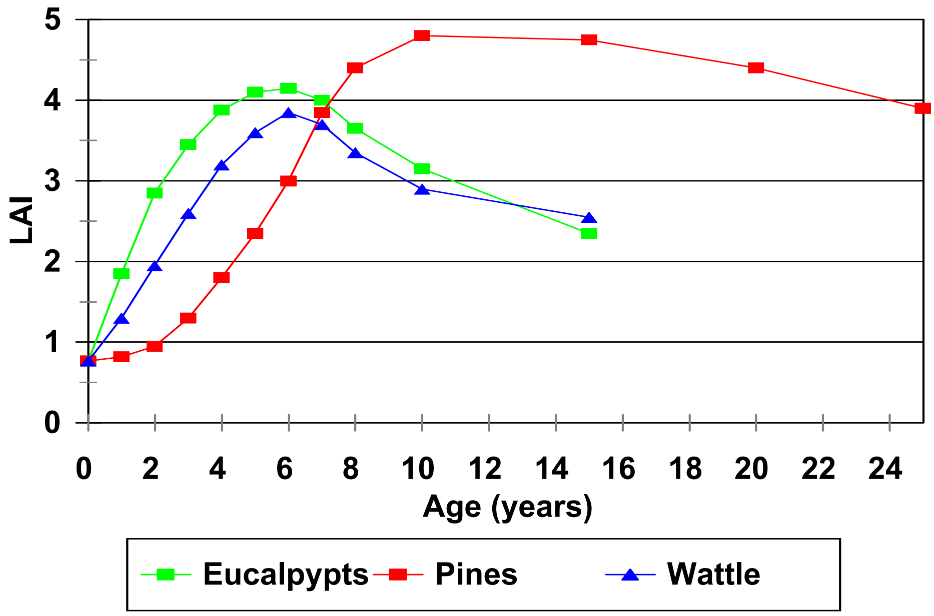

Figure 7.1 An example of LAI : age relationships for the three main genera grown commercially. These are the averaged curves for four major forestry areas in South Africa, two levels of site preparation and two rainfall regimes (after Summerton, 1996; Schulze *et al*., 1998)

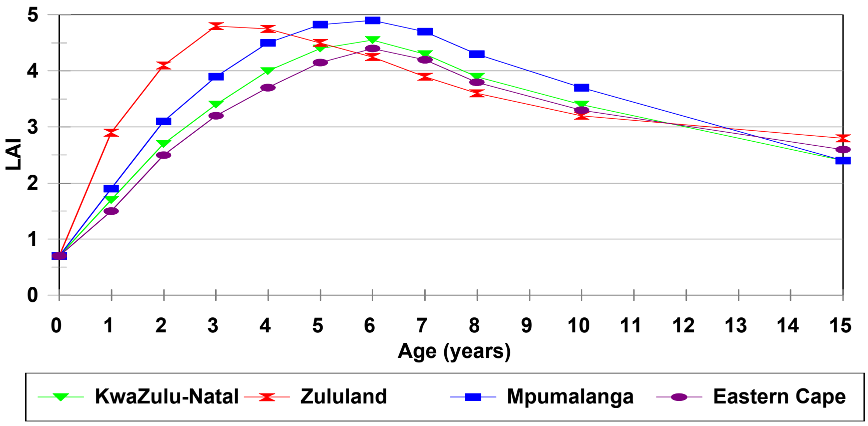

Figure 7.2 LAI values used in *ACRUforest* for the four major forestry areas in South Africa. The example used here is for eucalypts planted in a zone of relatively high rainfall (MAP > 1000 mm) with intensive site preparation (after Summerton, 1996)

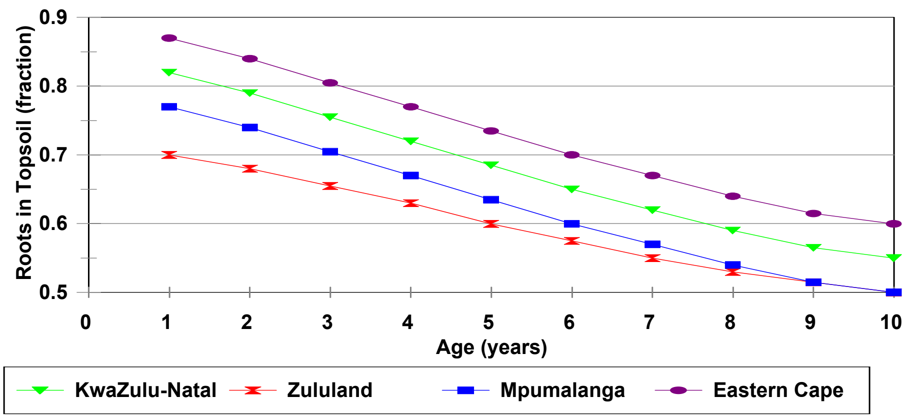

Figure 7.3 An example of the fraction of roots in the topsoil in the *ACRUforest* for four major forestry regions in South Africa for eucalypts on a site with intensive preparation (after Summerton, 1996; Schulze *et al*., 1998)

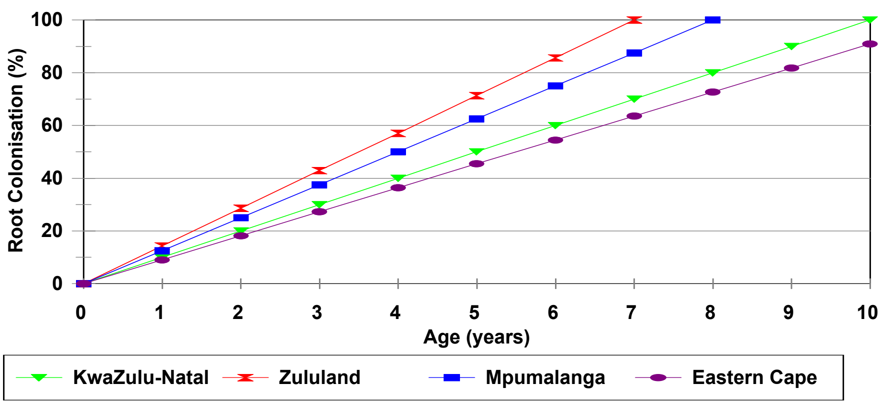

Figure 7.4 An example of tree root colonisation of the subsoil in *ACRUforest* for eucalypts in four major forest areas in South Africa, grown on a site with poor site preparation (i.e. pitting) in a high rainfall area (after Summerton, 1996; Schulze *et al*., 1998)

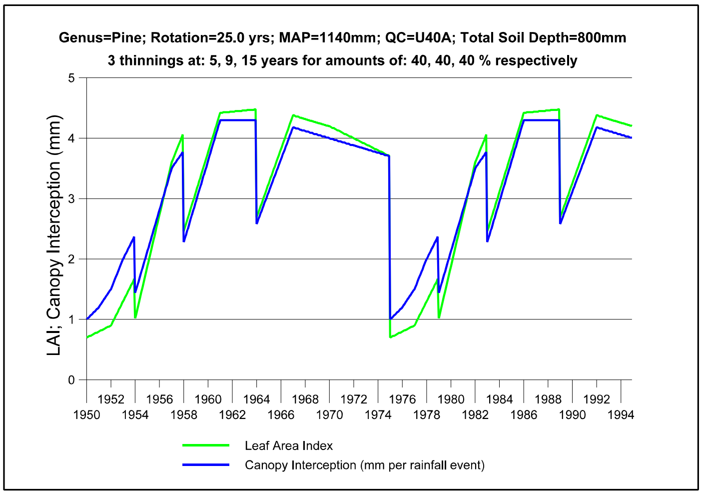

Figure 7.5 An example, using *ACRUforest*, of the effects of thinning on the LAI and canopy interception of pines in KwaZulu-Natal in a 'high' rainfall zone, i.e. > 1000 mm MAP

It should be stated that, despite the distinctions having been made in *ACRUforest* by genera, age, region and management practice, the values given and assumptions made remain broad generalisations of model input which do not necessarily apply at any individual site with its uniqueness of soil, aspect, location within the landscape and micro-climate (Roberts, 2002).

7.3 WHAT DOES THE *ACRUforest* DECISION SUPPORT CONSIST OF?

ACRUforest is an interactive computer package which prompts users with simple forest hydrology related questions.

a) Screen 1 : Title

The introductory screen displays the title, development team members and funders' logos (Figure 7.6).

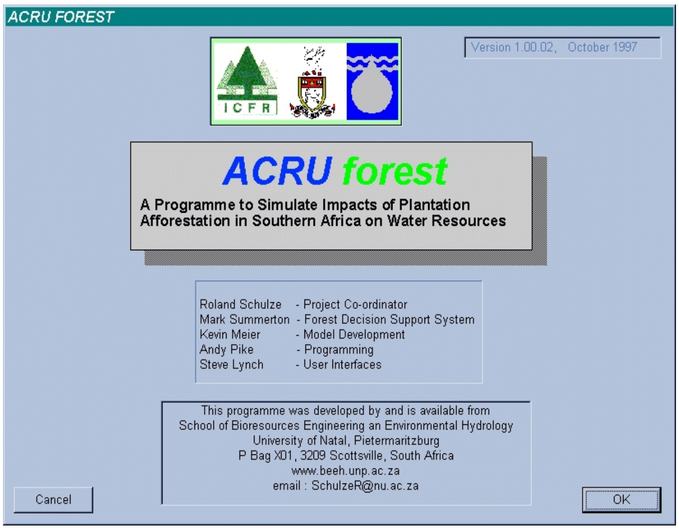

Figure 7.6 The *ACRUforest* title screen page

b) Screen 2 : Locational, physiographic and soils information

Screen page 2 is on the location of the plantation(s) as well as on physiographic and soils information. Locational information (Figure 7.7) can be input either as the

- Quaternary Catchment (QC) number or, if that is not known, as
- latitude/longitude co-ordinates, in which case the program identifies the QC internally.
- These location inputs are followed by an option to plot the South African boundary, together with the QC identified within it, as well as an enlarged graphical plot of the QC (Figure 7.8).

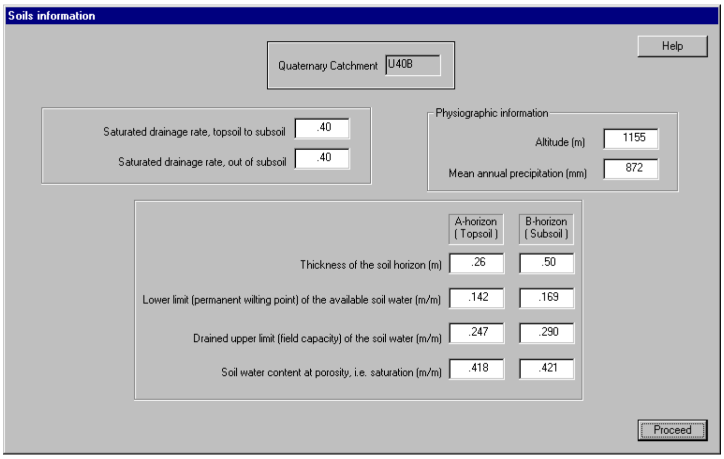

Figure 7.7 The *ACRUforest* screen page on locational, physiographic and soils information

The QC for which the afforestation impact is being undertaken contains pre-processed information on

- mean QC altitude (area-weighted from the 1' x 1' latitude/longitude grid of altitudes originally collated by Dent, Lynch and Schulze in 1989, and subsequently updated)
- mean annual precipitation, MAP (again area-weighted from the gridded 1' x 1' rainfall database developed by Dent *et al*. in 1989) and
- typical soil properties for the QC, such as topsoil and subsoil horizon thicknesses, retention characteristics at critical volumetric soil moisture contents and saturated drainage rates (area-weighted for the QC by Meier in 1997 and derived by Schulze, Angus, Lynch and Furniss in 1990 from soils information for 84 soil zones supplied by the erstwhile Soil and Irrigation Research Institute).

The typical values of soil variables may be overwritten with values more representative of those of the particular plantation or farm or QC under review. The new values will then be used in simulations. Similarly, the QC's MAP may be changed to a more representative local value, and the ratio of new to original MAP is then used to adjust daily rainfall input in the model.

c) Screen 3 : Original land cover

The third screen prompts the user to select the land cover from which a conversion to afforestation is taking place (Figure 7.9). This 'original' land cover can either be

- a baseline land cover, in which case the user has the choice of one of the 70 Acocks' (1988) Veld Types, or
- veld, in which case veld may be specified as being in good, fair or poor hydrological condition (as defined by percentage cover in Smithers and Schulze, 1995), or

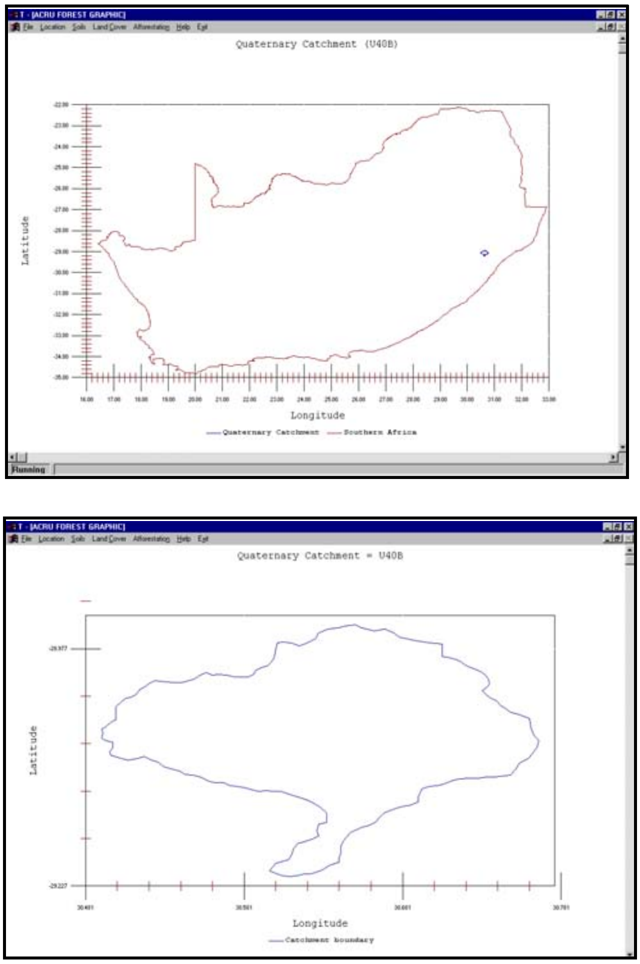

Figure 7.8 The *ACRUforest* option to plot the location of the Quaternary Catchment in question, (top) within southern Africa and (bottom) in more detail

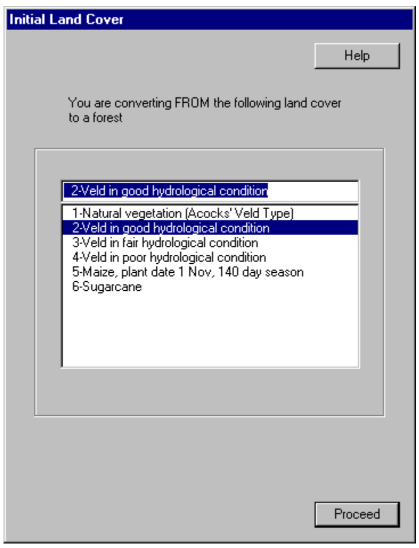

Figure 7.9 The *ACRUforest* screen page on 'original' land cover from which conversion to forestry takes place

- maize, with a plant date of 1 November and a 140 day growing season assumed and
- sugarcane, in which case overall 'whole farm' conditions (as given in the *ACRU* User Manual by Smithers and Schulze, 1995) are assumed.

d) Screen 4 : Information on forest plantation

The fourth screen contains the information required to simulate hydrological responses following a conversion to commercial forest plantations (Figure 7.10).

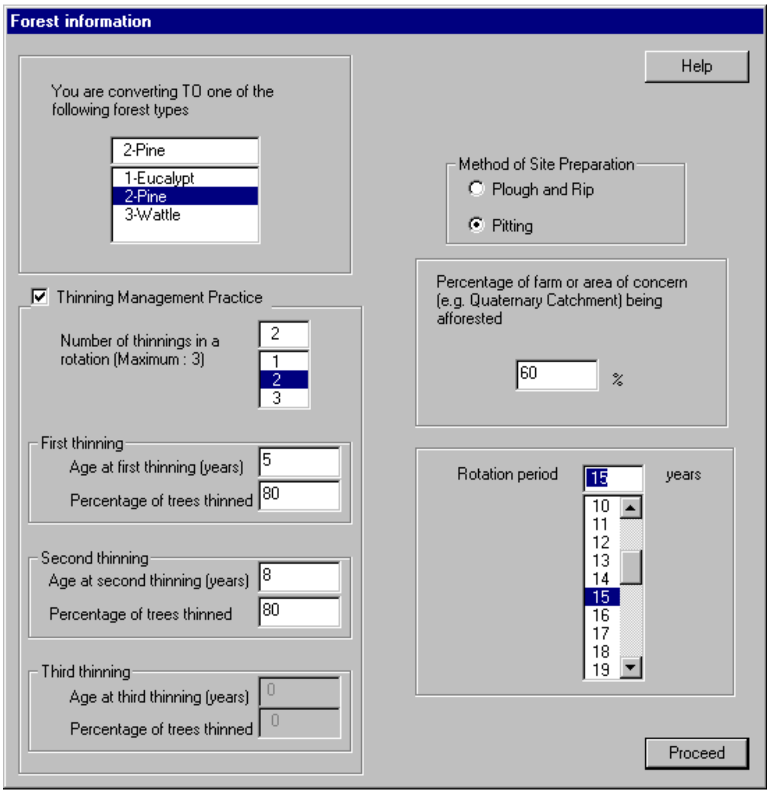

Figure 7.10 The *ACRUforest* screen page on forest plantation information

- *Genera*: First, one of the three major genera grown in South Africa is selected, i.e. either eucalypts, pines or wattle. This selection then utilises pre-programmed dynamic information on changes in LAI, interception loss, root distribution and root colonisation from time of planting to harvest. For examples of this dynamic information, see Schulze *et al*. (1998).
- *Thinning practices* : Still on the fourth screen, the information on thinning practices has to be input. This applies to pines and wattle only. First,
  - the number of thinnings per rotation are specified (maximum : 3), then
  - ages at which thinning is undertaken, and the
  - percentage of trees thinned (maximum : 80% per rotation) is input (Figure 7.10).
- *Site preparation* : Next, the method of site preparation is input (Figure 7.10). In the *ACRUforest* model two options are available, *viz*.
  - 'plough and rip' and
  - 'pitting'.
- *Rotation lengths* : Screen 4 on afforestation further requires input on rotation lengths, typically
  - 8 - 10 years for eucalypt and wattle plantations and
  - 15 - 30 years for pines, the latter depending on its use for either pulp (shorter rotation) or sawmill products (longer rotation).
- *Percentage of area* : Finally, the percentage of the farm, or area of concern (e.g. of a QC), being

afforested has to be input. This information is used to weight the impact of afforestation on the local or regional runoff.

e) *Model output*

Internally, the *ACRU* model retrieves pre-programmed month-by-month inputs of the water use coefficient, root distribution and interception loss values per rainday of the ‘original’ land cover for use in a baseline run.

The baseline simulation of *ACRU* utilises the soils and land cover information discussed above, with a 45 year (1950-1994) daily record of observed rainfall, where one of the 1300 carefully selected and quality controlled daily rainfall station records has been pre-assigned to each of the 1946 Quaternary Catchments covering South Africa, Lesotho and Swaziland (Meier, 1997).

This *ACRU* simulation first generates a 45 year daily simulation from the original land cover of, *inter alia*,

- transpiration losses,
- soil water evaporation losses,
- total evaporative losses,
- soil water content in the top- and subsoils,
- stormflow,
- recharge to the groundwater zone,
- baseflow and
- total runoff.

This procedure is repeated for the afforestation runs. All these values can then be summarised into

- monthly totals/averages for the 45 year time series, as well as into
- annual totals and
- statistical output, which includes
  - a month-by-month analysis of means and variances, and
  - a frequency analysis for ‘worst’ (dry year) conditions in 20, 10, 5 and 3 years, for median conditions and for ‘best’ (wet year) conditions in 3, 5, 10 and 20 years.

The model, therefore, outputs daily time series and statistical analyses for a 45 year simulation of daily hydrological responses for the original land cover, for the afforested land cover (including effects of genera, region, the management practices of thinning/site preparation and rotation length) and for the difference between the two simulations, which then represents the impact of the afforestation.

7.4 CONCLUDING THOUGHTS : WHAT *ACRUforest* CAN AND CANNOT BE USED FOR

The major objective of developing *ACRUforest* is as a rapid and deterministically based tool, using extensive South African spatial information and temporal rainfall databases at daily resolution, for assessing local and regional impacts of afforestation on a range of hydrological responses (e.g. evaporation, baseflow, stormflow, total runoff) by accounting for effects of different

- original land covers
- genera planted
- management practices applied
- rotation lengths and
- percentages of area under forest.

ACRUforest cannot distinguish between different species of a specific genus or between different clonal varieties, nor can it be used to assess riparian clearing impacts, or ‘real world’ (actual) catchment evaluations in which hydrological non-linearities are introduced by multiple land uses on multiple soil types, and where the impacts of dams, of irrigation and other abstractions or inter-catchment transfers have to be considered. In those circumstances, the standard semi-distributed *ACRU* system (Schulze, 1995; Smithers and Schulze, 1995) should be configured as, for example, was the case in the Pongola-Bivane forest vs irrigation impacts assessment (cf. Chapter 10). Furthermore, *ACRUforest* does not account for pests, diseases, fire, freezing, wind damage or theft, all of which can dramatically affect a forest's growth and water use (Roberts, 2002). In addition to researching some of those aspects in future, further refinements are required on the LAI curves, but particularly on root morphology and dynamics as well as differential water use in different landscape units from crest to riparian zone (cf. Chapter 11).

The *ACRUforest* decision support tool can be used as a rapid, 'on the fly' simulator for first assessments of potential forest hydrological impacts by relevant authorities. As a simulator it is considerably more versatile and powerful than the tool currently being used at the Department of Water Affairs and Forestry which was recently completed by Gush *et al*. (2001). An application of *ACRUforest* (Schulze *et al*., 1997), in which the economic viability and potential hydrological impact of 55 plantations in the former homelands were assessed, has shown clearly that plantations associated with high *absolute* reductions in streamflow (i.e. in mm equivalents or m^3) do not necessarily coincide with those with high *relative* (i.e. percentage) streamflow reductions; also that plantations which are highly sensitive in regard to long term reductions do not necessarily impact streamflows severely (in a comparative sense) in dry years (e.g. 1:5 'drought' year flows) or in the dry season (e.g. month of August, in the summer rainfall regions).

This begs one, as a concluding thought, to ponder whether the right questions are always being asked when it comes to assessing forest hydrological impacts, whether decision makers always appreciate the meaning of terms such as 'impacts' and 'sensitivities', and also whether the time has not come to evaluate impacts of other land uses and management strategies on a range of hydrological responses with equal vigour, if one is to allocate water equitably and engage in integrated water resources management in South Africa in a scientific manner.

7.5 ACKNOWLEDGMENTS

In addition to funding of this initiative by the Water Research Commission, the forest industry through the Institute for Commercial Forestry Research has supported the development of *ACRUforest*. Thanks also go to Dr Colin Everson of the CSIR for critically reviewing the model, on the basis of which major revisions were undertaken, and to Professor Peter Roberts for making helpful suggestions in his review of this chapter.

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Ch_*ACRUforest*

CHAPTER 8

PERTINENT QUESTIONS ON STREAMFLOW REDUCTIONS BY DIFFERENT LAND USES UNDER DIFFERENT CLIMATIC AND SOILS CONDITIONS : A COMPARATIVE CASE STUDY IN THE SUGARCANE BELT OF SOUTH AFRICA

R.E. Schulze and M.J.C. Horan

School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

ABSTRACT

Following upon a definition of streamflow reduction activities (SFRAs), a major challenge to hydrologists is identified, this being the ability to objectively quantify SFRAs in regard to different crops grown on different soils over a range of climatic regimes and management practices. A case is made for Acocks' Veld Types to be used as a baseline land cover against which to assess SFRAs. The major objective of this chapter is to map and graph regional differences in SFRAs in the so-called sugarcane belt of South Africa for competing crops grown under varying soils and local as well as inter-seasonal climatic conditions. After illustrating that SFRAs cannot be established by simple regional relationships, it is shown that significant regional differences in annual streamflows, those occurring in the driest year in 10, and in baseflows occur for the competing 'crops' of sugarcane, pines and eucalypts, with these differences amplified in shallow as against deep soils. Results also show that very different spatial patterns of streamflow reductions are exhibited, depending on whether they are expressed in absolute (i.e. mm; m^3) terms or in relative (% difference) terms. The chapter concludes that no simple generalisations may be made in regard to SFRAs, which are shown to be highly location specific, conditioned by soil depth and dependent on whether or not the season is considered to be average or dry.

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8.1 WHAT ARE STREAMFLOW REDUCTION ACTIVITIES?

a) What does the concept imply?

The concept of streamflow reduction activities, SFRAs, has become an integral component of South African water law since the adoption of the National Water Act (NWA) in 1998. This Act (NWA, 1998) makes provision for the regulation of 'land-based activities which reduce stream flow by declaring them to be Stream Flow Reduction Activities' (Part 4 - Introduction), whereby the Minister may 'declare any activity (including the cultivation of any particular crop or other vegetation) to be a stream flow reduction activity if that activity is likely to reduce the availability of water in a watercourse to the Reserve, to meet international obligations, or to other water users significantly' (Section 36, NWA 1998).

These SFRAs are identified in terms of factors such as 'the extent of stream flow reduction, its duration, and its impact on any relevant water resource and on other water users' (Part 4 - Introduction). Furthermore, the Minister may make regulations 'prescribing methods for making a volumetric determination of water to be ascribed to a stream flow reduction activity for purposes of water use allocation and the imposition of charges' (Section 26, NWA, 1998).

b) What are the challenges of this concept to hydrologists?

The quantification of the consumptive use of water by a particular land use is a complex process which cannot be accounted for by using generalised statements on water use (e.g. 'riparian wattle uses twice the amount of water as natural veld') or by assigning a quantity of water per day (e.g. 'a single eucalypt tree uses 600 litres of water per day'). These broad generalisations ignore the spatial differences (e.g. transpiration inequalities on north and south facing slopes), as well as temporal (annual, seasonal and daily variations in water availability and use) and physical differences (e.g. soil texture and water holding capacity) within and between catchments. The feedbacks between the different land uses in a catchment, the prevailing climatic conditions, the retention and drainage properties of the soil and the hydrological response of the catchment all need to be considered if the estimates of water use by a land use are to be realistic and defendable in the transparent, consultative environment in which water allocation is likely to take place in the future.

The challenge facing hydrologists and water resources managers in South Africa is to provide decision makers with relevant and well tested tools to assist in the objective quantification of the relative consumptive use of water by different crops and vegetation types under a multitude of unique combinations of management practices, climatic regions, soils and growth cycles. Daily time step, physical-conceptual hydrological models lend themselves to applications such as these. This chapter explores the application of the *ACRU* agrohydrological model to assessing SFRAs in a case study in the so-called sugarcane belt of South Africa.

8.2 STREAMFLOW REDUCTION : AGAINST WHICH BASELINE?

When assessing streamflow reduction activities (SFRAs) in light of the National Water Act, a pertinent question is 'Assessing, against what?' A baseline land cover is thus required against which to compare SFRAs of the land uses under scrutiny.

Several options are available by which a baseline land cover may be defined. Thus, it could be:

- veld (rangeland) in a specified hydrological condition, e.g. in good, fair or poor condition, as defined in Schulze, Smithers and Schmidt, (1993)
    - however, not all current land uses were converted from veld in, say, fair hydrological condition, and
    - veld in fair condition in coastal areas has different hydrological response attributes to that in the inland which experiences frost and, hence, senesces; or
- actual land cover or land use in a specified baseline year, e.g.
    - 1972, when the afforestation permit system was introduced or
    - 1996 , the baseline year of the CSIR's National Land Cover information derived from satellite imagery (Thompson, 1996)

- however, land cover in a specified year would depend largely on regional development levels at a specific point in time, which may be highly irregular for historical, political, economical or social reasons ; or

• a land cover representing 'natural' vegetation
  - however, no perfect classification of such a state of vegetation exists for South Africa; far less so one which is entirely useable from a hydrological perspective.

This latter option was nevertheless considered the most suitable and objective, and the vegetation classification selected was Acocks' (1988) Veld Types, which has been used previously in comparative hydrological studies in the Pongola catchment (Schulze, Pike, Lecler, Esprey, Howe and Zammit, 1996) and the Mgeni catchment (Kienzle, Lorentz and Schulze, 1997), as well as being the selected baseline land cover used in Gush, Scott, Jewitt, Schulze, Hallowes and Görgens (2001) for computations of SFRAs from afforested areas.

8.3 WHAT WERE THE OBJECTIVES OF THIS CASE STUDY?

This study had as its objective a regional comparative assessment, at a spatial scale of the Quaternary Catchment (QC), of streamflows generated from different competing land uses and the associated reductions (or increases) of the streamflows from the different land uses when evaluated against those of a baseline land cover. The region selected was that covered by the sugarcane production areas of South Africa. The land uses considered were sugarcane, eucalypt and pine plantations as well as grassveld in fair hydrological condition (i.e. with a defined canopy cover of 50 - 75%). The assessment evaluated comparative hydrological responses for two fixed, defined soil conditions representing shallow and deep soils, with total available moisture of 60 and 150 mm respectively, and for conditions representing a year of median responses and those for the driest as well as wettest years in 10.

Results are presented

• by way of maps which illustrate regional differences and similarities in runoff and in streamflow reduction activities, and
• graphs showing comparative hydrological responses at four selected case study locations with different climates in the dryland sugarcane production area.

The four selected case study locations are first, the three QCs in which Richard's Bay, Mt Edgecombe and Port Shepstone are found, where these represent climatic conditions of the northern, central and southern coastal sugarcane producing areas, and the QC in which Eston is located, this being taken as a QC representative of an interior cane growing area in KwaZulu-Natal. Information pertaining to the four locations is given in Table 8.1.

8.4 BACKGROUND INFORMATION

a) Location

The sugarcane production areas for this study were delimited by the SA Sugar Association Experiment Station, SASEX (Schmidt, 1998) and are represented by the 127 Quaternary Catchments shown in Figure 8.1 as two consolidated regions. The area excludes sugarcane producing regions of Swaziland. This delimitation incorporates the present cane growing regions of South Africa as well as potential areas, and is based on rainfall and temperature criteria for dryland production (Schulze, 1997) and topography and water availability for irrigated areas, with obvious consideration having been given to proximity to existing sugar mills. The units of spatial representation are the Department of Water Affairs and Forestry (DWAF) Quaternary Catchments. Detailed information on the Quaternary Catchments by number, their respective areas, mean altitudes, mean annual precipitation (MAP) and driver rainfall station numbers have been given in Schulze, Lumsden, Horan and Maharaj (1999). For *ACRU* simulations the QCs were treated as hydrologically independent (unlinked) catchments.

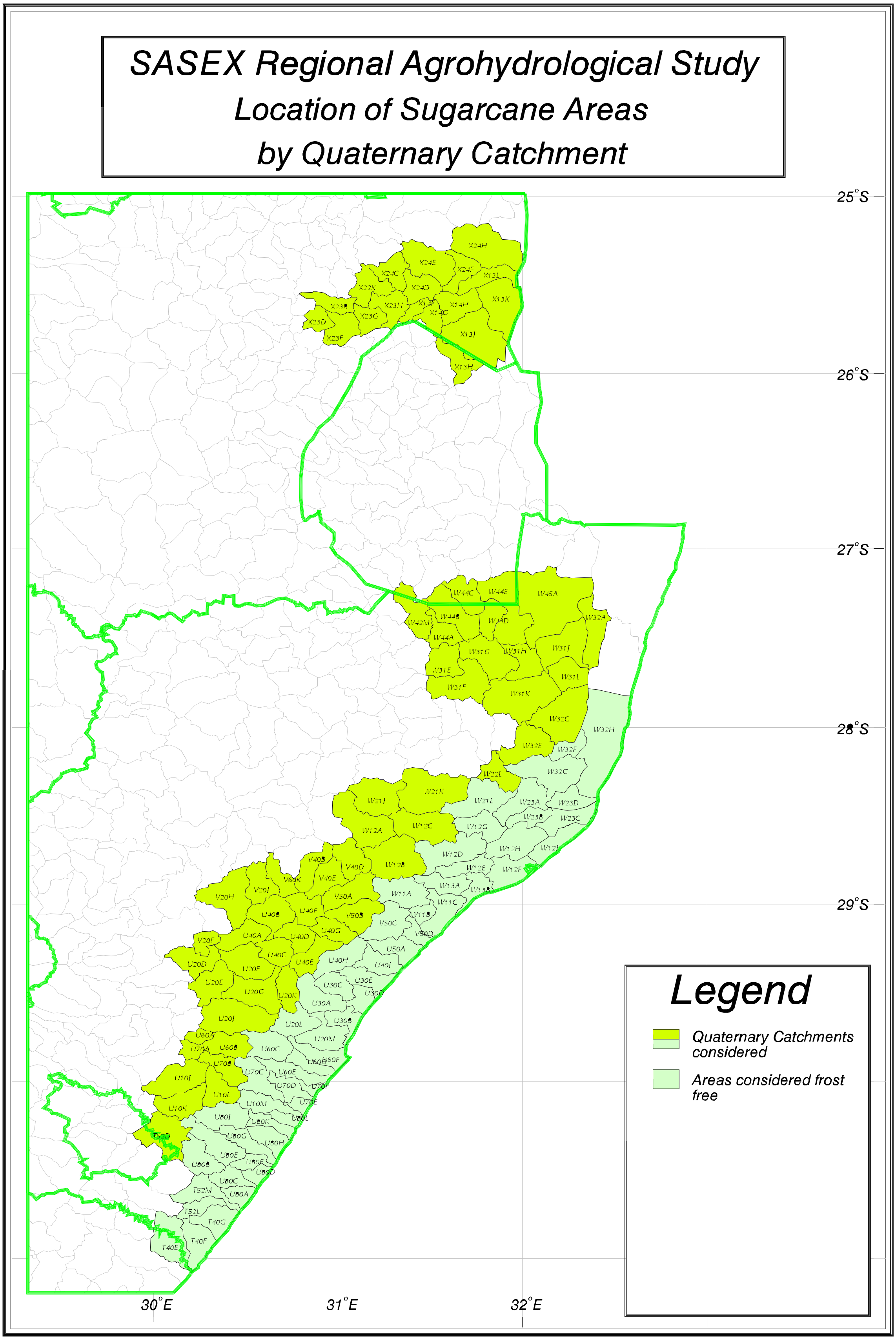


Figure 8.1 The study area : Sugarcane production areas, by Quaternary Catchment (after Schulze *et al*., 1999)

Table 8.1 Information pertaining to four selected locations used in detailed graphical comparisons

Location	Quaternary Catchment	Baseline Land Cover	Mean Altitude (m)	MAP of QC (mm)	MAE_p (mm)
Richard's Bay	W12J	Coastal forest & thornveld	39	1286	1830
Mt Edgecombe	U30B	Coastal forest & thornveld	141	983	1637
Port Shepstone	T40G	Coastal forest & thornveld	243	1056	1530
Eston	U70B	Ngongoni veld	808	859	1651

Location	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Richard's Bay	MP 50	112.0	118.5	105.8	86.9	66.5	45.5	48.3	61.2	83.3	111.6	97.2	94.4
	MP 10	51.9	41.6	44.0	31.7	15.5	12.2	13.5	10.1	25.4	40.5	52.0	33.6
	T_{max}	28.9	28.8	28.2	26.6	24.9	23.3	23.0	23.6	24.3	25.4	26.4	28.1
	T_{min}	20.6	20.6	19.8	17.6	15.0	12.3	12.1	12.7	15.2	16.6	18.2	19.7
	Pot Evap	195.2	173.6	178.5	143.8	113.5	86.1	108.1	125.2	135.0	180.5	183.5	206.5
Mt Edgecombe	MP 50	121.6	97.0	95.7	53.6	28.2	13.2	14.9	40.8	62.1	84.5	101.0	97.7
	MP 10	64.9	44.1	21.6	16.9	4.8	0.4	2.8	3.1	14.9	42.5	44.8	45.7
	T_{max}	27.7	27.8	27.3	25.8	24.6	22.7	22.5	23.1	23.7	24.2	25.2	27.1
	T_{min}	19.6	19.8	19.0	16.5	13.7	11.0	10.6	11.7	14.1	15.6	17.1	18.7
	Pot Evap	170.4	156.6	152.4	121.4	106.3	92.2	97.6	111.0	128.0	158.8	160.9	182.6
Port Shepstone	MP 50	104.4	85.2	84.1	45.4	40.0	16.9	15.2	46.4	60.8	107.9	115.8	96.7
	MP 10	46.3	43.2	29.9	16.6	3.9	1.2	1.6	5.8	34.1	35.6	53.3	61.0
	T_{max}	25.9	26.2	25.8	24.5	23.4	21.9	21.6	21.8	22.3	22.7	23.6	25.3
	T_{min}	18.9	19.1	18.2	15.8	13.2	11.0	10.6	11.4	13.4	14.7	16.2	17.8
	Pot Evap	149.7	134.5	138.3	114.2	98.5	93.5	99.0	114.3	123.6	147.6	150.9	165.8
Eston	MP 50	122.8	105.5	109.6	44.0	15.8	9.3	7.0	27.4	46.5	89.3	107.6	107.1
	MP 10	70.2	43.7	33.9	16.7	0.0	0.0	0.0	0.0	12.0	42.0	55.8	46.9
	T_{max}	26.2	26.4	25.8	24.1	22.2	20.2	20.3	21.5	22.8	23.4	24.1	25.9
	T_{min}	16.2	16.3	15.3	12.5	9.4	6.6	6.4	8.1	10.5	12.0	13.6	15.3
	Pot Evap	170.3	152.8	144.5	120.7	104.3	93.4	103.4	125.5	142.1	154.8	157.9	180.8

MP 50 = Median monthly rainfall (mm)
MP 10 = Monthly rainfall (mm) in driest year in 10
Pot Evap = Mean monthly total of potential evaporation (mm)
T_{max} = Monthly mean daily maximum temperatures
T_{min} = Monthly mean of daily minimum temperatures
MAE_p = Mean annual potential evaporation (mm)

b) Climatic information

For each QC the *ACRU* model was 'driven' by quality controlled daily rainfall from a rainfall station selected by Meier (1997). The station's daily data were adjusted to represent that of the QC using techniques described in Smithers and Schulze (1995) based on a national gridded database of mean annual precipitation developed by Dent, Lynch and Schulze (1989). Representative monthly means of A-pan equivalent reference potential evaporation and monthly means of daily maximum and minimum temperatures were derived for each QC using methods described in detail by Schulze (1997).

c) Soils

All simulations in this study were undertaken assuming soils of total available moisture capacity (*TAM*) equivalent to 60 mm and 150 mm, i.e. representing a shallow and a deep soil. *TAM* was assumed in this study to be the water held in a soil between its drained upper limit, i.e. its field capacity (*DUL*), and its lower limit of plant available water, i.e. its permanent wilting point (*PWP*). To obtain these values of *TAM*, a sandy clay loam with a *PWP* of 0.160 $m.m^{-1}$ and a *DUL* of 0.260 $m.m^{-1}$ for both the topsoil and subsoil horizons was assumed. The soil's water retention at saturation (*PO*) was set at 0.435 $m.m^{-1}$, but this *PO* value was increased to 0.470 $m.m^{-1}$ for the topsoil in simulations of sugarcane responses, because of bulk density changes in the topsoil associated with tillage practices. The thickness of the topsoil for both *TAM* specifications was set at 0.3 m, while the subsoil thickness was then varied between 0.3 m for a *TAM* of 60 mm and 1.2 m for a *TAM* of 150 mm. The soils were assumed not to have shrink-swell properties and saturated soil water redistribution was set to take place at 0.5 of 'excess' water (> *DUL*) per day for both soil horizons.

d) Land cover and land use

A GIS coverage of Acock's Veld Types was overlaid over the 127 QCs making up the potential sugarcane production areas and for each QC the overall dominant Acocks' Veld Type (i.e. the one with the largest proportion in the QC) was assumed to represent the baseline land cover of that QC. From Figure 8.2 it

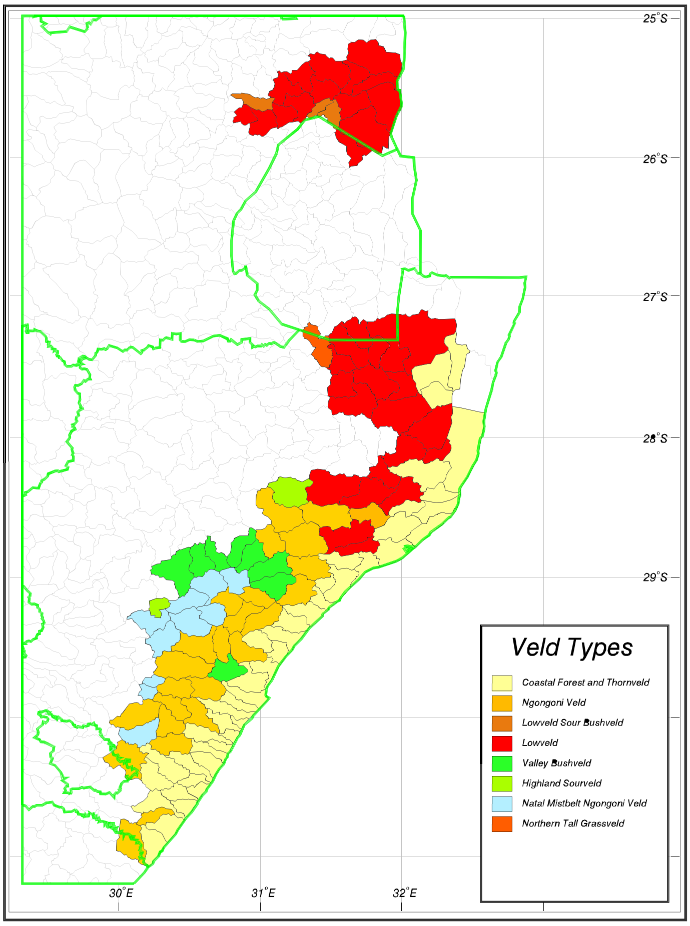


Figure 8.2 Dominant Acocks' Veld Types per Quaternary Catchment

may be seen that eight Veld Types were identified in the sugarcane belt. Their hydrological attributes are discussed in the following section

The hydrological attribute values for the Acock's Veld Types as well as for sugarcane, eucalypts, pines and veld in fair hydrological conditions are given in Table 8.2. Source of information for sugarcane was the WRC report on 'Impacts of Sugarcane Production and Changing Land Use on Catchment Hydrology' by Schmidt, Smithers, Schulze and Mathews (1998), while for eucalypts and pines values were derived from Summerton (1996) and for Acocks' Veld Types obtained from Schulze and Hohls (1993) and Schulze (1995;1999).

Certain features appearing in Table 8.2 require commenting on. These include

- the significant differences in the water use coefficients of Acocks' Veld Types, depicted diagrammatically in Figure 8.3 , which highlight again the necessity of using different natural vegetation attributes in different climate regions when undertaking SFRA assessments;
- the equally significant differences between other biomass indicators of land uses, as shown in Figure 8.4, where the range of crop water use coefficients, root distributions and canopy interception losses between competing land uses such as sugarcane, eucalypts, pines and veld is demonstrated clearly;
- similarly, the inter-vegetation and intra-seasonal ranges of the coefficient of initial abstraction, cI_a (Figure 8.5), which may be viewed as an infiltration index (Figure 8.5);
- the distinction between attributes of veld (fair) in the frost-free coastal zone (shown in Figure 8.1) and the interior, where frost causes senescence of grassland;

Table 8.2 Month-by-month input variables for baseline land cover categories and land uses (after Schulze *et al.*, 1999)

Land Cover/ Land Use	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Acocks # 1	Water Use Coefficient	.85	.85	.85	.85	.75	.65	.60	.65	.75	.85	.85	.85
Coastal Forest	Interception (mm) per Rainday	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
and Thornveld	Fraction of Roots in Topsoil	.75	.75	.75	.75	.75	.75	.75	.75	.75	.75	.75	.75
	Coefficient of I_a	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30
Acocks # 5	Water Use Coefficient	.65	.65	.65	.55	.50	.30	.30	.30	.45	.55	.60	.65
Ngongoni Veld	Interception (mm) per Rainday	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	Fraction of Roots in Topsoil	.90	.90	.90	.94	.97	1.0	1.0	1.0	.97	.94	.90	.90
	Coefficient of I_a	.15	.15	.20	.25	.25	.25	.25	.25	.25	.20	.20	.15
Acocks # 6	Water Use Coefficient	.75	.75	.75	.70	.65	.50	.50	.50	.65	.75	.75	.75
Zululand	Interception (mm) per Rainday	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Thornveld	Fraction of Roots in Topsoil	.80	.80	.80	.80	.90	.90	.90	.90	.80	.80	.80	.80
	Coefficient of I_a	.20	.20	.20	.25	.30	.30	.30	.30	.30	.25	.20	.20
Acocks # 9	Water Use Coefficient	.75	.75	.75	.70	.65	.60	.55	.60	.65	.70	.75	.75
Lowveld	Interception (mm) per Rainday	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Sour Bushveld	Fraction of Roots in Topsoil	.80	.80	.80	.80	.90	.90	.90	.90	.80	.80	.80	.80
	Coefficient of I_a	.20	.20	.25	.30	.30	.30	.30	.30	.30	.25	.20	.20
Acocks # 10	Water Use Coefficient	.75	.75	.75	.65	.55	.40	.40	.40	.60	.75	.75	.75
Lowveld	Interception (mm) per Rainday	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
	Fraction of Roots in Topsoil	.80	.80	.80	.80	.90	.90	.90	.90	.80	.80	.80	.80
	Coefficient of I_a	.20	.20	.25	.30	.30	.30	.30	.30	.30	.25	.20	.20
Acocks # 23	Water Use Coefficient	.78	.78	.78	.65	.55	.40	.40	.40	.60	.72	.78	.78
Valley Bushveld	Interception (mm) per Rainday	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
(Northern	Fraction of Roots in Topsoil	.75	.75	.75	.85	.90	.90	.90	.90	.80	.75	.75	.75
Variation)	Coefficient of I_a	.20	.20	.25	.30	.30	.30	.30	.30	.30	.25	.20	.20
Acocks # 44	Water Use Coefficient	.60	.60	.60	.45	.20	.20	.20	.20	.30	.50	.60	.60
Highland	Interception (mm) per Rainday	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Sourveld	Fraction of Roots in Topsoil	.90	.90	.90	.95	1.0	1.0	1.0	1.0	1.0	.95	.90	.90
	Coefficient of I_a	.15	.15	.15	.20	.25	.25	.25	.25	.25	.20	.20	.15
Acocks # 45	Water Use Coefficient	.63	.63	.63	.50	.35	.25	.25	.25	.40	.53	.63	.63
Natal Mistbelt	Interception (mm) per Rainday	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Ngongoni Veld	Fraction of Roots in Topsoil	.90	.90	.90	.94	1.0	1.0	1.0	1.0	1.0	.94	.90	.90
	Coefficient of I_a	.15	.15	.15	.20	.25	.25	.25	.25	.25	.20	.20	.15
Acocks # 64	Water Use Coefficient	.75	.75	.75	.50	.30	.30	.30	.30	.55	.70	.75	.75
Northern Tall	Interception (mm) per Rainday	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Grassveld	Fraction of Roots in Topsoil	.90	.90	.90	.95	1.0	1.0	1.0	1.0	.95	.90	.90	.90
	Coefficient of I_a	.15	.15	.15	.20	.25	.25	.25	.25	.25	.20	.20	.15
	Water Use Coefficient	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80
Sugarcane	Interception (mm) per Rainday	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	Fraction of Roots in Topsoil	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80
	Coefficient of I_a	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30	.30
Pines	Water Use Coefficient	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85
(8 years,	Interception (mm) per Rainday	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
pitted)	Fraction of Roots in Topsoil	.66	.66	.66	.66	.66	.66	.66	.66	.66	.66	.66	.66
	Coefficient of I_a	.35	.35	.35	.35	.35	.35	.35	.35	.35	.35	.35	.35
	Water Use Coefficient	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95
Eucalypts	Interception (mm) per Rainday	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
(5 years, pitted)	Fraction of Roots in Topsoil	.75	.75	.75	.75	.75	.75	.75	.75	.75	.75	.75	.75
	Coefficient of I_a	.35	.35	.35	.35	.35	.35	.35	.35	.35	.35	.35	.35
Veld in fair	Water Use Coefficient	.65	.65	.65	.50	.30	.20	.20	.35	.45	.60	.65	.65
condition	Interception (mm) per Rainday	1.2	1.2	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.2	1.2	1.2
Areas with	Fraction of Roots in Topsoil	.90	.90	.90	.94	.94	1.0	1.0	.94	.94	.93	.90	.90
frost	Coefficient of I_a	.15	.15	.15	.20	.30	.30	.30	.30	.30	.30	.20	.15
Veld in fair	Water Use Coefficient	.65	.65	.65	.55	.50	.40	.40	.40	.50	.60	.65	.65
condition	Interception (mm) per Rainday	1.2	1.2	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.2	1.2	1.2
Areas without	Fraction of Roots in Topsoil	.90	.90	.90	.94	.94	.94	.94	.94	.94	.93	.90	.90
frost	Coefficient of I_a	.20	.20	.20	.20	.30	.30	.30	.30	.30	.30	.20	.20

- sugarcane attributes assuming 'whole farm' operations, with cane at various stages of maturity, which results in intra-season averaged values of cane attributes, with the cane assumed to be burnt at harvest and cultivated with a mix of 50% conventional and 50% minimum tillage plus conservation structures (Schmidt *et al.*, 1998); and
- that eucalypt and pine plantations also assume 'whole farm' operations, hence attribute values are given for a typical 5 year old stand of pitted eucalypts (assuming a 10 year rotation) and

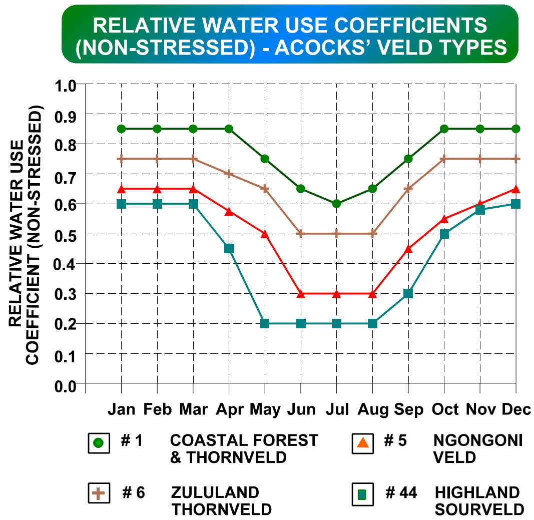


Figure 8.3 Water use coefficients for different Acocks' Veld Types in the sugarcane belt (after Schulze *et al*., 1999)

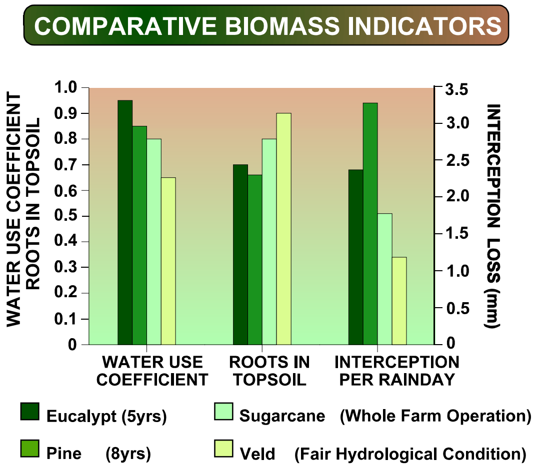


Figure 8.4 Comparative biomass indicators for competing land uses in the sugarcane belt (after Schulze *et al*., 1999)

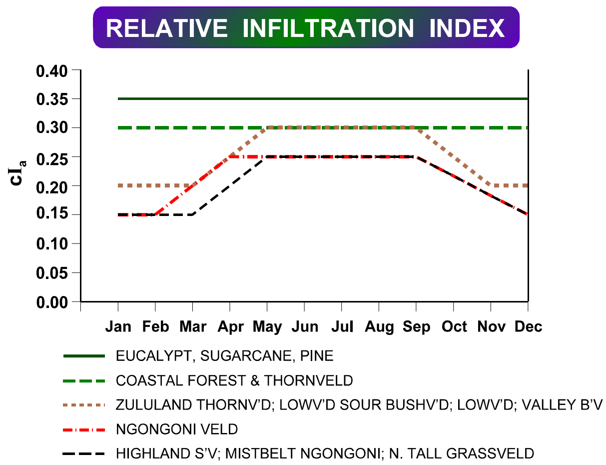


Figure 8.5 Differences in the coefficients of initial abstractions (cI_a), an index of infiltration, between baseline land covers and competing land uses (after Schulze *et al*., 1999)

an 8 year old pitted pine plantation (assuming a typical 15 year rotation when grown for pulp), with the values derived from the *ACRUforest* decision support tool described in detail in Summerton (1996) as well as in Schulze, Summerton, Meier, Pike and Lynch (1997) and in Chapter 7 of this Report, and where this tool is based on fieldwork, literature values and expert experience and is considered to yield more realistic simulations of forest hydrological impacts than other methods currently in use in South Africa.

It needs to be stressed at the outset that other management practices would have given rise to different sets of attributes and hence different hydrological responses, but that the ones selected are considered fairly representative of management scenarios in the sugarbelt.

Values of cI_a have been given in Table 8.2 for different baseline Veld Types and land uses. These account also for seasonal rainfall characteristics. Values of the critical soil depth from which stormflow generation takes place, D_{sc}, were input as the thickness of the topsoil horizon (0.30 m) for all baseline land covers and for veld, but not for sugarcane and afforestation, where from previous verification studies (Schulze, 1995; Schmidt *et al.,* 1998) a value of 0.35 m was used. For the *ACRU* stormflow delay factor, F_{sr}, a value of 0.3 was used for all QCs. Adjunct and disjunct impervious areas were assumed to be absent for these simulations of comparative hydrology. Finally, for the baseflow decay rate used in *ACRU*, F_{bfi}, a regional default value of 0.009 (i.e. 0.9% per day) was used in all simulations.

In this comparative study soil water evaporation and plant transpiration were considered as an entity of 'evapotranspiration', and not split into its components. Plant water stress was assumed to occur at 0.9 of *TAM* for pines (a conservative water user which closes its stomata at high soil water content already), at 0.1 of *TAM* for eucalypts (indicating eucalypts to be an aggressive water consumer with soil water extraction at maximum rates until the soil water content is nearly at its permanent wilting point already) and at a typical 0.4 of *TAM* for sugarcane, veld and Acocks' Veld Types.

For eucalypts and pines an enhanced wet canopy evaporation rate typical for trees, as described in Schulze (1995), was triggered while for the same two plantation trees the deeper rooting systems were assumed to be able to extract soil water to a depth of 0.25 m beyond the specified *TAM* value, as reported by Summerton (1996).

8.5 CAN STREAMFLOW REDUCTION ACTIVITIES BY A GIVEN LAND USE BE EXPRESSED BY SIMPLE REGIONAL CURVES?

Before the first detailed results are even shown, it is evident from the aforegoing sections that the methodology to set up the *ACRU* model implies some specialist modelling. Since, for a given land use such as sugarcane, the *ACRU* model's biomass attributes as well as the soil input variables for all QCs remain at fixed values, and only the climate changes from QC to QC, this begs the questions whether in the sugarcane belt the rainfall : runoff relationship, and hence SFRAs, cannot be expressed by a simple regional curve in order to simplify decisions.

To test this hypothesis, a runoff : rainfall scatter plot from the 127 QC results was produced for median annual conditions. Figure 8.6 illustrates very clearly that no such simple relationship exists and that for a given median annual rainfall a resultant runoff can vary markedly within the sugarcane production belt. In an attempt to reduce the scatter, plots were produced of only those QCs in areas with, say, a 13 month harvest cycle or a 16 or a 21 month cycle, but the plots did not improve.

One has to therefore conclude at the outset that no simple crop, or region specific, answers to questions around SFRAs will be available.

8.6 HOW DO ANNUAL STREAMFLOWS GENERATED FROM DIFFERENT LAND USES COMPARE UNDER MEDIAN YEAR HYDROLOGY CONDITIONS?

For this comparative hydrological study the median annual, rather than the mean, was selected as the simplest index of available water resources under different land use and soil conditions. The median is the statistically expected value at the 50th percentile, i.e. as many years will have higher streamflows than the median, as will have lower streamflows. In streamflow studies the means of annual flow are very often

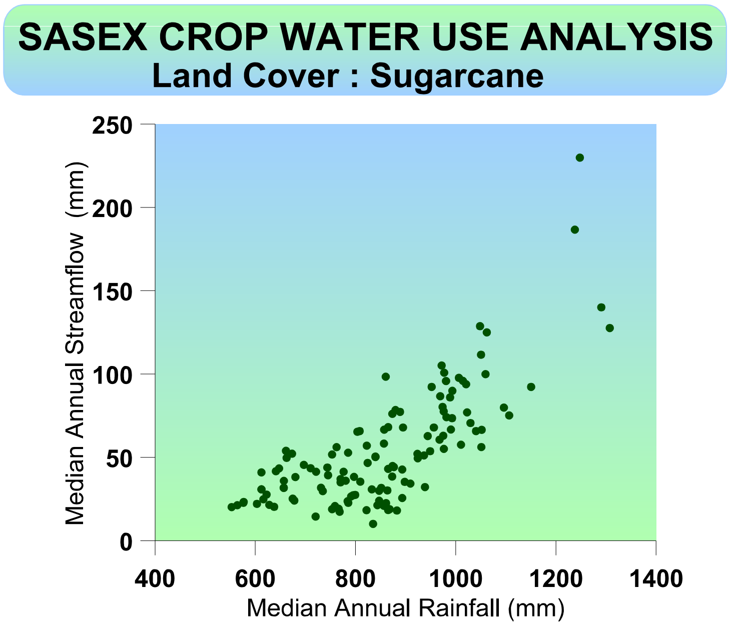


Figure 8.6 Scatterplot of the median annual streamflow to rainfall relationship for sugarcane grown on deep soils in 127 Quaternary Catchments (after Schulze *et al*., 1999)

distorted (skewed) by a few exceptional events and are thus not considered as valuable as medians in overall water resources assessments. It should also be noted that in this chapter the terms 'runoff' and 'streamflow' are used interchangeably, in both cases implying the total runoff from a QC, made up of the sum of stormflows and baseflows. In descriptions which follow, 'deep' soils imply those with a Total Available Moisture of 150 mm, while 'shallow' soils are assumed to have a *TAM* = 60 mm. In the two cases of eucalypts and pines, roots in each case can extract moisture from an additional 0.25 m of soil. In this specific hydrological comparison Figures 8.7 - 8.14 refer.

Perusal of Figures 8.7 - 8.14 highlights the following:

- Significant differences are simulated between the median annual streamflows ($M_{50}AR$), generated from the five land covers (LCs) which were considered.
- Veld in fair hydrological condition yields a markedly higher $M_{50}AR$ than the baseline Acocks' Veld Type along the coast, because the baseline land cover there is Coastal Forest and Thornveld (*cf*. Figure 8.2).
- Of the LCs considered, eucalypts produce lowest annual streamflows by a wide margin, especially in climatically marginal (i.e. drier, hotter) areas (cf. Figures 8.7, 8.11).
- The high and curvilinearly amplified dependence of streamflow on rainfall is evident not only for sugarcane (in Figure 8.6), but also for the other LCs (in Figures 8.7 - 8.12).
- On deep soils (*TAM* = 150 mm) considerably less streamflow is generated than on the shallow soils (*TAM* = 60 mm) on which the soil profile can be filled more rapidly and more baseflow can be produced (Figures 8.7 and 8.10). The response differences are not uniform, however, with streamflows from shallow soils increasing relative to decreases in rainfall, while in absolute terms the difference is considerably higher along the coast and elsewhere where rainfall is higher (cf. Figure 8.10).
- While annual streamflows from eucalypts are much lower than those of other land covers considered, it is significant from a comparative hydrological perspective, that sugarcane and pines yield essentially the same streamflow under median climatic conditions. Some reasons for this are that, while pine has a higher water use coefficient, as a feedback it is physically a more conservative water user and also has higher canopy interception rates (cf. Figure 8.4).

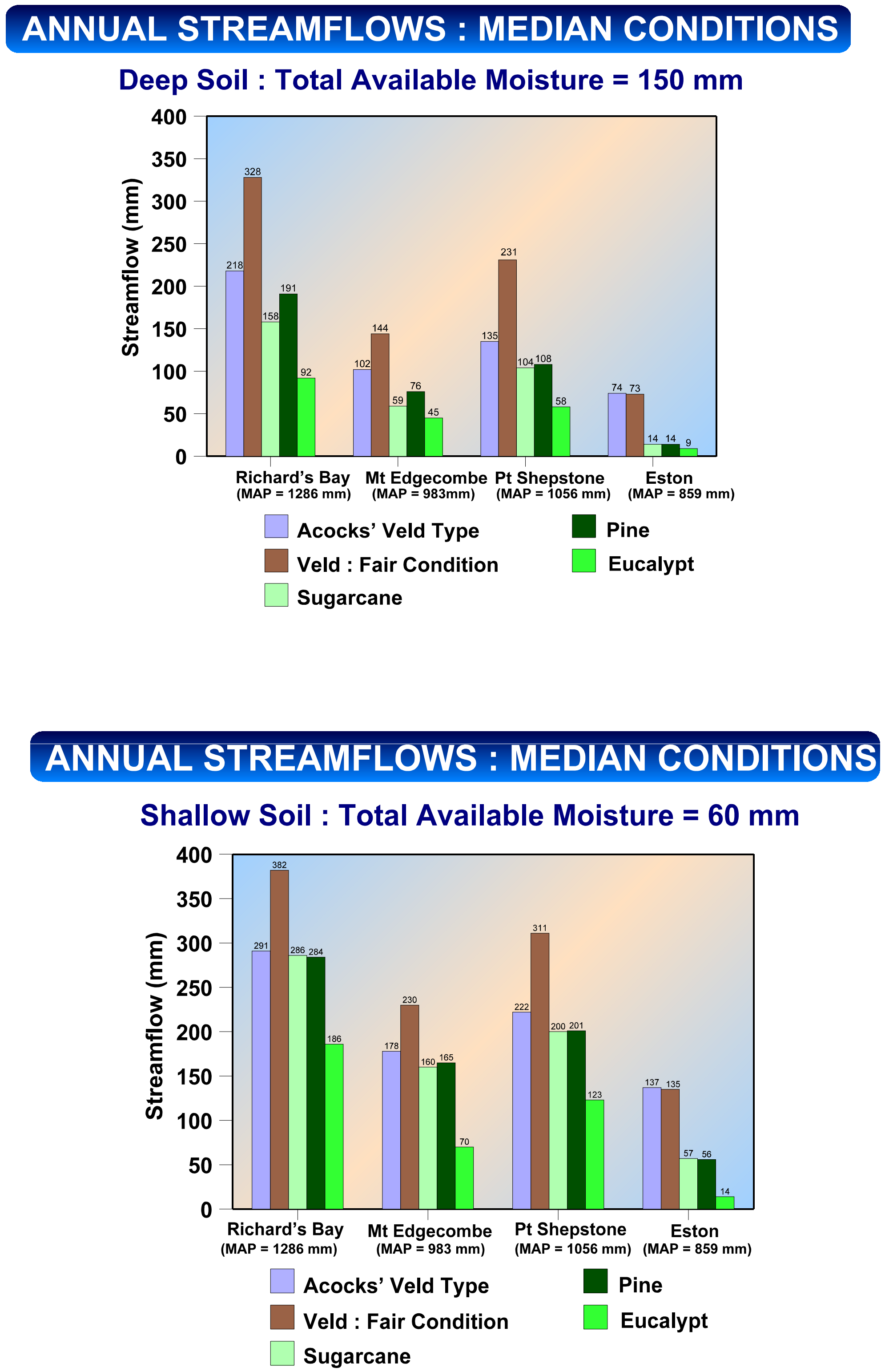


Figure 8.7 Comparative median annual streamflows at four locations, for deep and shallow soils (after Schulze *et al*., 1999)

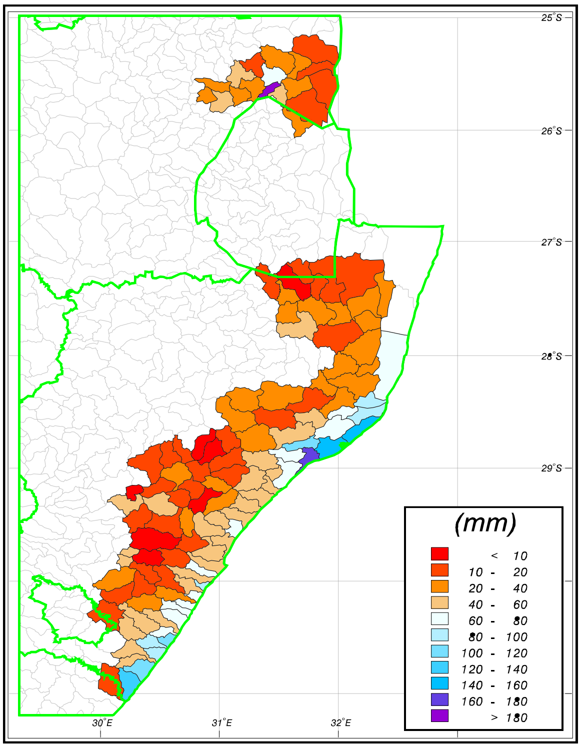


Figure 8.8 Median annual streamflows (mm) from sugarcane grown on deep soils (after Schulze *et al*., 1999)

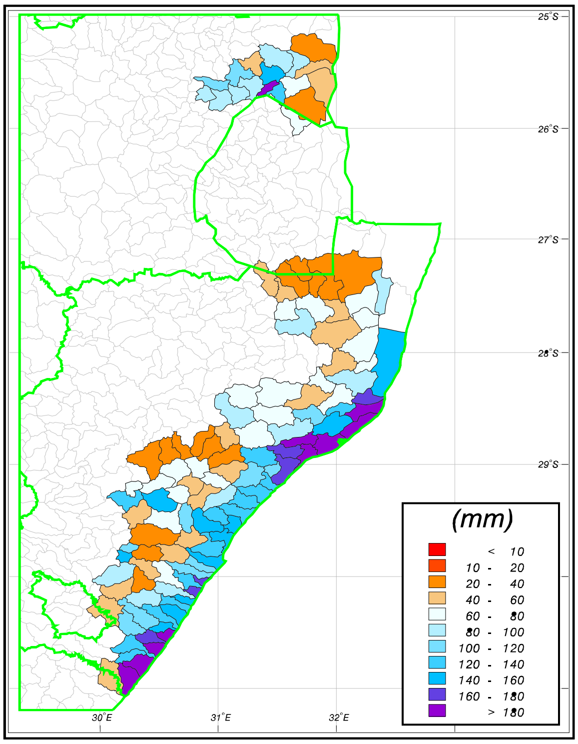


Figure 8.9 Median annual streamflows (mm) from sugarcane grown on shallow soils (after Schulze *et al*., 1999)

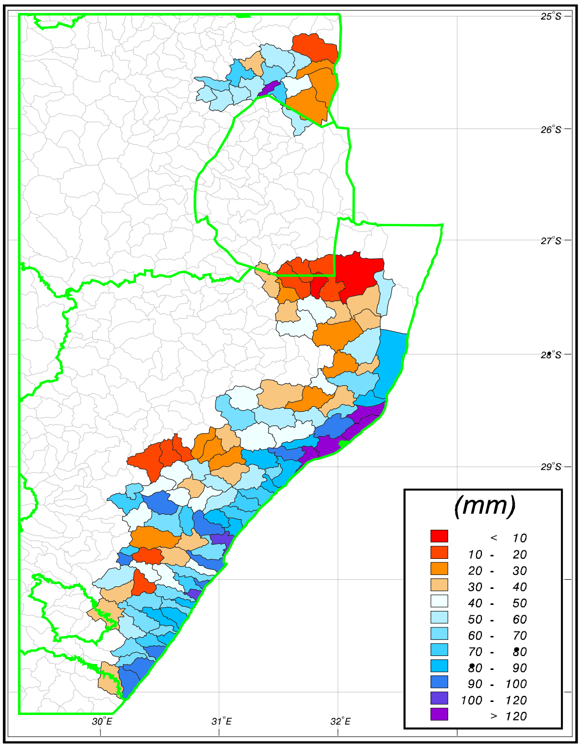


Figure 8.10 Differences in median annual streamflows (mm) between sugarcane grown on shallow vs deep soils (after Schulze *et al*., 1999)

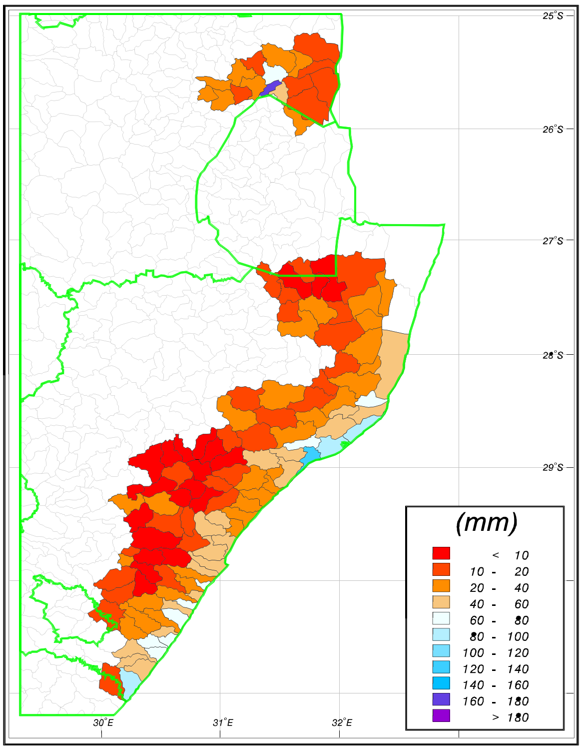


Figure 8.11 Median annual streamflows (mm) from eucalypts grown in deep soils (after Schulze *et al.*, 1999)

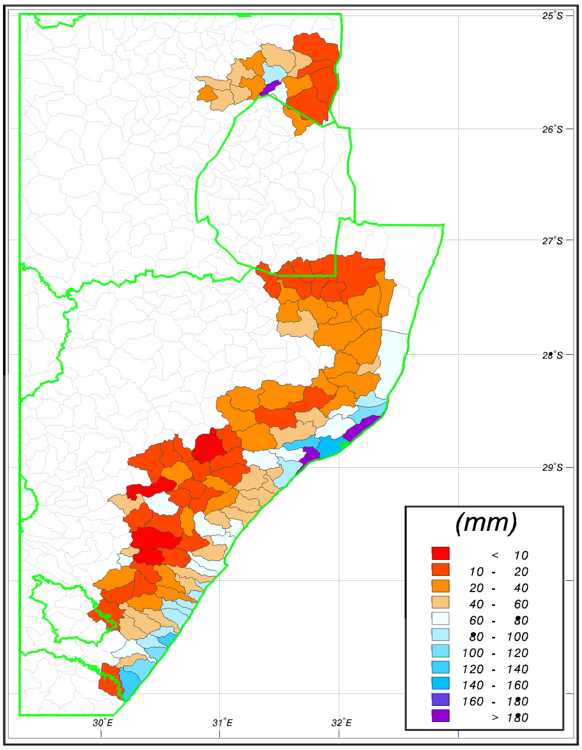


Figure 8.12 Median annual streamflows (mm) from pines grown in deep soils (after Schulze *et al.*, 1999)

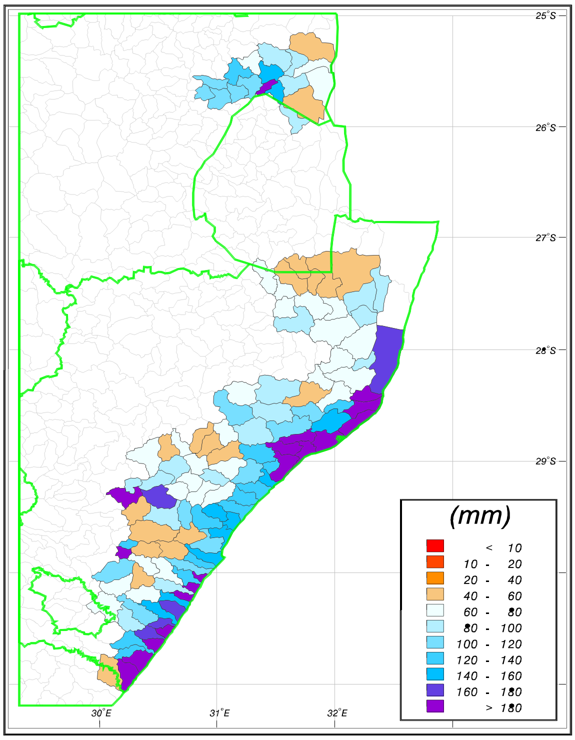


Figure 8.13 Median annual streamflows (mm) from veld in fair hydrological condition on a deep soil (after Schulze *et al.*,1999)

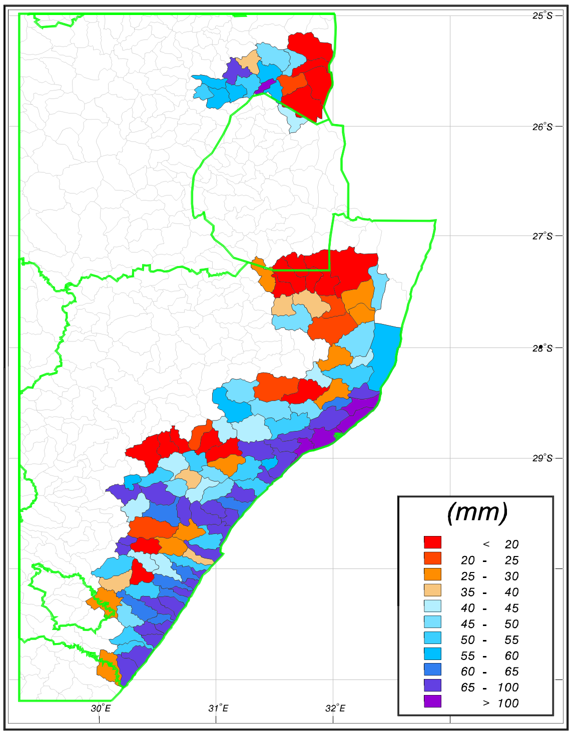


Figure 8.14 Differences in median annual streamflows between sugarcane and eucalypts both grown on shallow soils (after Schulze *et al.*,1999)

- If respective streamflow responses between sugarcane and eucalypts are compared, Figure 8.14 shows clearly that sugarcane yields considerably more $M_{50}AR$ than eucalypts, in some areas by as much as 100 mm p.a., in other areas by as little as 20 mm. The main reasons for this are that eucalypts are more aggressive water consumers (drying soil up to 10% of *TAM* before stress sets in), have a deeper root system and a slightly higher canopy interception per rainday (cf. Figure 8.4).

8.7 HOW DO ANNUAL STREAMFLOWS GENERATED FROM DIFFERENT LAND USES COMPARE IN THE DRIEST YEAR IN 10?

The hydrologically driest year in 10 (which does not necessarily coincide with the agriculturally or meteorologically worst year in 10) occurs when the amount of the streamflow for a given month, or streamflows accumulated for the hydrological year, would statistically be exceeded in 9 years out of 10. A hydrologically driest month, or sequence of months, in 10 years does not necessarily occur in the same year as the lowest total annual streamflow in 10 years.

For this particular comparative assessment Figures 8.15 and 8.16 refer, and they should be interpreted also in the light of the information contained in Figures 8.7 and 8.14.

- A comparison of Figures 8.7 and 8.15 shows that for both deep and shallow soils, streamflow in the driest year in 10 is less than that under median conditions by a factor of 3 - 4, but with shallow soils being more sensitive to runoff production in dry years.
- When differences in streamflows between the two competing uses of eucalypts and sugarcane are compared, these differences diminish considerably in dry vs median years, indicating clearly that in drought years, when flows are low anyway, land use differences play a less important role than in more average yeras (Figure 8.16 vs 8.14).

8.8 HOW DO ANNUAL BASEFLOWS GENERATED FROM DIFFERENT LAND USES COMPARE UNDER MEDIAN AND DRY YEAR CONDITIONS?

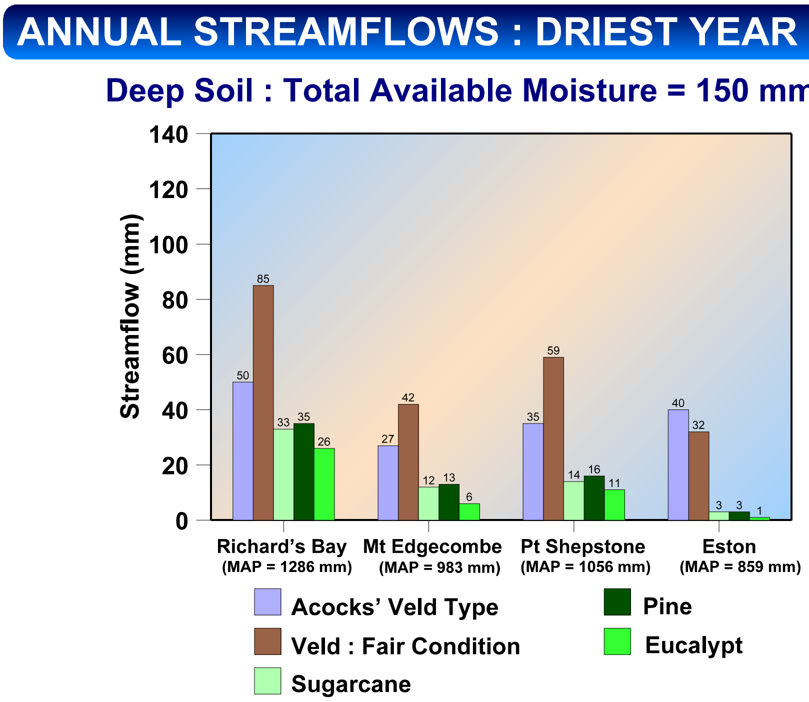
Baseflow, or ‘dry-weather streamflow’, is a very important component of total streamflow because it is usually the sole contributor to runoff in the non-rainy season and because it sustains flows into dams. Baseflow is often believed to be severely impacted by intensified land use practices such as the cultivation of sugarcane or exotic tree species, because of their deeper root systems and year-round potential for soil water extraction.

In the *ACRU* model baseflow is that flow resulting from the slow release of soil water which recharges the intermediate and groundwater zones through the soil profile when deep percolation takes place after the lower soil horizon’s soil water content is above its *DUL* . The model assumes that the watertable is ‘connected’ to the stream channel - a valid assumption in the runoff regime in the sub-humid and humid climates making up the sugarbelt.

The contribution of baseflow to total streamflow is significant, as shown by the values in Figure 8.17 and the frequently high percentages in Table 8.3.

The following points should be noted:

- Reference to Figure 8.17 shows that shallow rooted veld in fair hydrological condition produces more baseflow at coastal stations than does the denser coastal baseline land cover.
- As has been the case in previous runoff interpretations, it may be seen that sugarcane and pines produce very similar baseflows.
- However, eucalypts yield considerably less baseflow than competing intensive crops, because of their high water demands drying out the soil profile more than other crops do.
- With reference to Table 8.3, the first point to note is that expressing baseflows as *percentages* of total streamflows, rather than as absolute values, can give false impressions when absolute values are small.
- Secondly, the proportion of baseflow to total flow is highly dependent on the local climate regime, particularly with respect to the sequence of raindays and antecedent soil moisture conditions, as



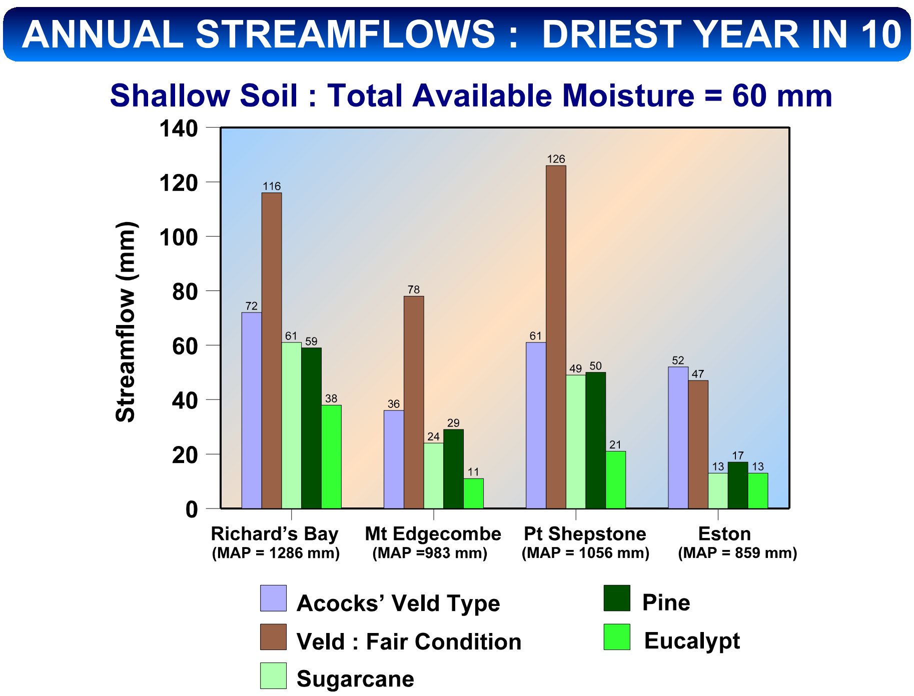


Figure 8.15 Comparative annual streamflows in the hydrologically driest year in 10 at four locations, for deep and shallow soil conditions (after Schulze *et al.*, 1999)

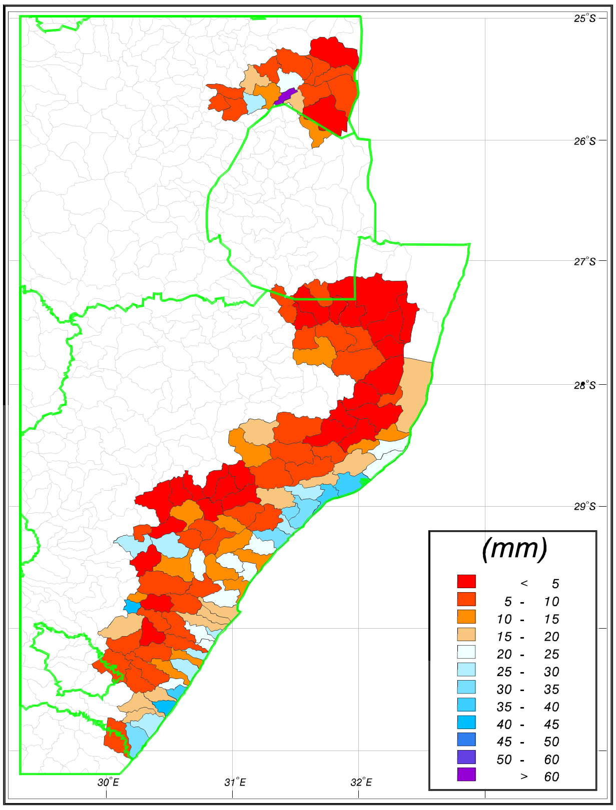


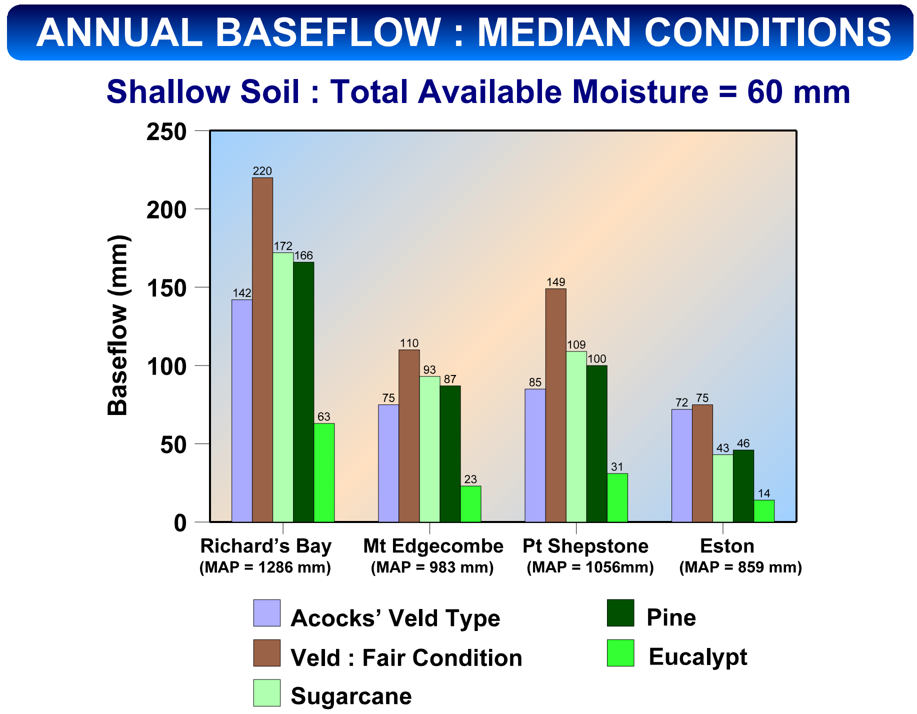
Figure 8.16 Differences in streamflows in the hydrologically driest year in 10 between sugarcane and eucalypts, both grown on shallow soils (after Schulze *et al*., 1999)

well as with tillage/conservation practices.

- In median condition years baseflows at coastal locations constitute 40 - 60 % of total flows, with a decrease from north (Richard's Bay) to south (Port Shepstone), while contributing relatively (but not absolutely) more at the inland case study location of Eston.
- As a percentage, sugarcane and pines yield more baseflow than the baseline land cover. Eucalypts, however, generate very little baseflow compared with other land covers.
- In the driest year in 10 the proportion of baseflow to total flow is less at Richard's Bay and Eston while being more at the other two locations, indicating once more the dependence of baseflow production on local rainfall regimes.

8.9 HOW DEPENDENT ARE STREAMFLOW REDUCTIONS ON THE BASELINE SELECTED FOR COMPARISON?

A major focus of the National Water Act of 1998 is on so-called 'Stream Flow Reduction Activities' (SFRAs) by land uses, with the premise that land uses could be levied in some way relative to the water they utilised. Since SFRAs have to be established against a baseline land cover, it stands to reason that certain land uses will generate less, and others more, than the baseline land cover which, for purposes of this comparative hydrology is the dominant Acocks Veld Type for a given Quaternary Catchment. The dependence of a streamflow reduction (or enhancement) on the baseline land cover cannot be overstressed.



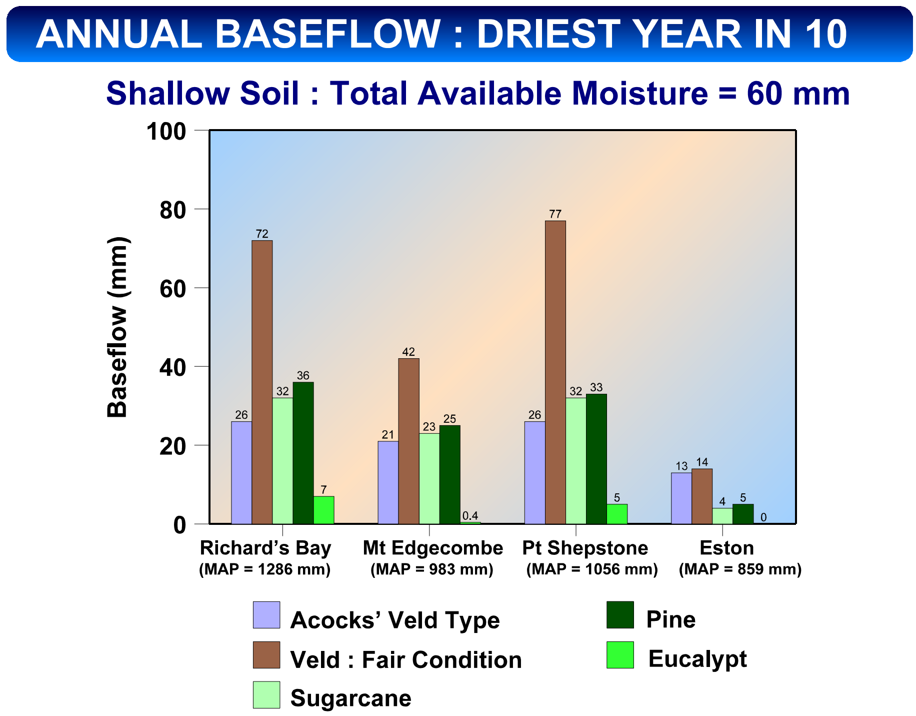


Figure 8.17 Annual baseflows under different land cover conditions at four locations for median and dry conditions (after Schulze *et al*., 1999)

Table 8.3 Percentage contribution of annual baseflow to annual total streamflow at four locations, under median and dry year flow conditions and on shallow soils, i.e. *TAM* = 60 mm (after Schulze *et al*., 1999)

Median Year Conditions

Land Cover	Percentage Contribution of Baseflow			
	Richard's Bay	Mt Edgecombe	Port Shepstone	Eston
Baseline	49	42	38	53
Veld (fair)	58	48	48	56
Sugarcane	60	58	55	75
Pines	63	53	50	82
Eucalypts	34	33	25	100

Driest Year in 10 Conditions

Land Cover	Percentage Contribution of Baseflow			
	Richard's Bay	Mt Edgecombe	Port Shepstone	Eston
Baseline	36	58	43	25
Veld (fair)	62	54	61	30
Sugarcane	52	95	63	31
Pines	61	86	66	29
Eucalypts	18	4	24	0

Figure 8.18 illustrates clearly that a conversion of the baseline Acocks Veld Type to veld in fair hydrological conditions would enhance streamflows along the coast, by as much as 90 mm, where it would replace Coastal Forest and Thornveld. On the other hand, veld in fair condition would reduce streamflows in certain interior cane producing areas where such veld would replace the sparse Ngongoni Veld, which has biomass attribute values even smaller than those of veld in fair condition.

8.10 DOES IT MATTER WHETHER STREAMFLOW REDUCTIONS ARE EXPRESSED IN ABSOLUTE OR RELATIVE TERMS?`

Streamflow reduction by a land use can be expressed in two ways, *viz*.

- as an *absolute* change, i.e. expressed as the difference, in mm or in m^3, between the streamflows from the baseline cover (Q_{BL}) and the land use under consideration (Q_{LU}), i.e. Q_{BL} - Q_{LU}, or
- as a *relative* change, i.e. expressed as the percentage streamflow reduction in relation to that of the baseline land cover, i.e. $100(Q_{BL} - Q_{LU})/Q_{BL}$.
- The absolute streamflow reduction for sugarcane is generally less than 25 mm along the coast, but more than 60 mm in the inland cane growing areas, with the transition between responses on the coast and the inland being very abrupt (Figure 8.19).
- In relative terms this translates to a streamflow reduction of < 20% along the coast and 40 - 60% inland (Figure 8.20).
- A comparison of Figures 8.21 and 8.19 shows clearly that eucalypts reduce streamflows considerably more than sugarcane does.
- Expressed as a percentage change, this converts to eucalypts' reducing median annual streamflows by 20 - 40 % along the coast to 60 - 90 % in the inland areas under cane (Figure 8.22).

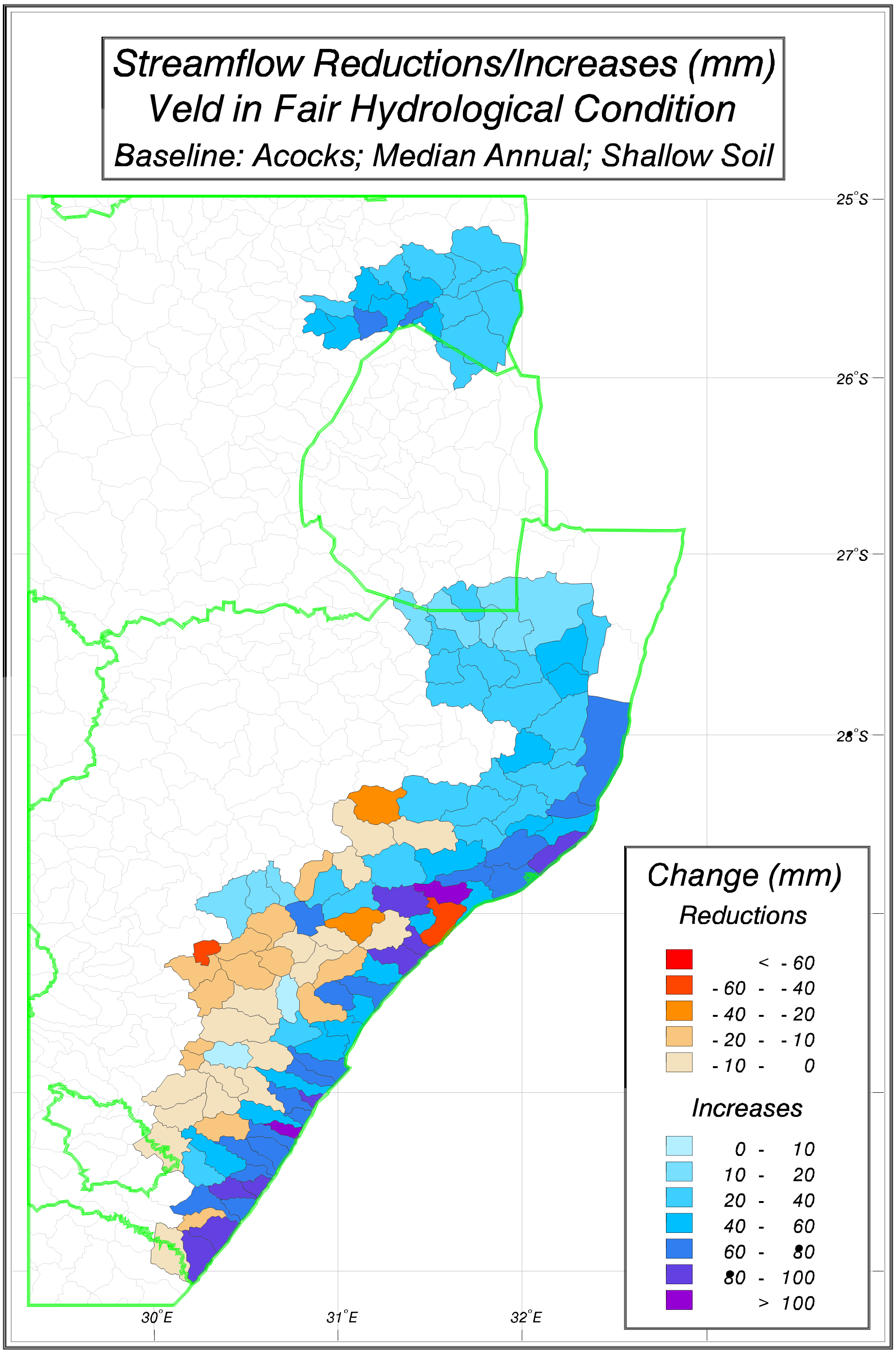


Figure 8.18 Streamflow increases and reductions (mm) between a baseline land cover of Acocks' Veld Types and veld in fair hydrological condition under median year conditions on a shallow soil with *TAM* = 60 mm (after Schulze *et al*., 1999)

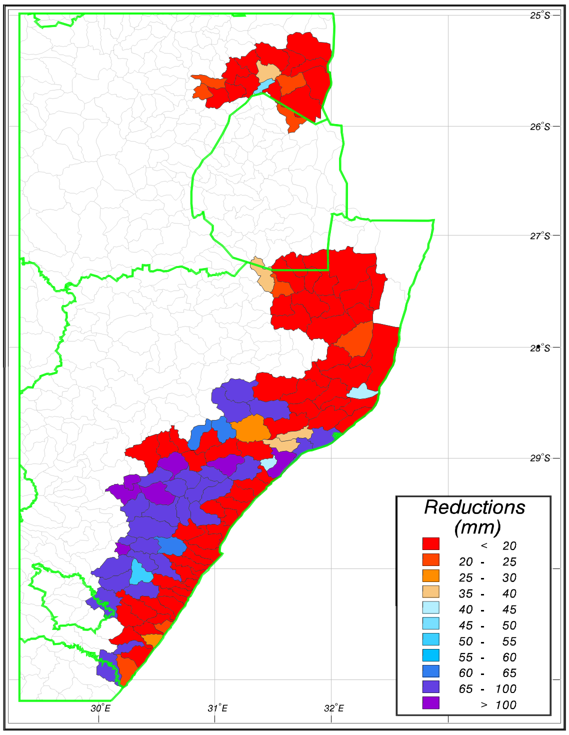


Figure 8.19 Streamflow reduction (mm) by sugarcane under median year conditions on a shallow soil (after Schulze *et al.,* 1999)

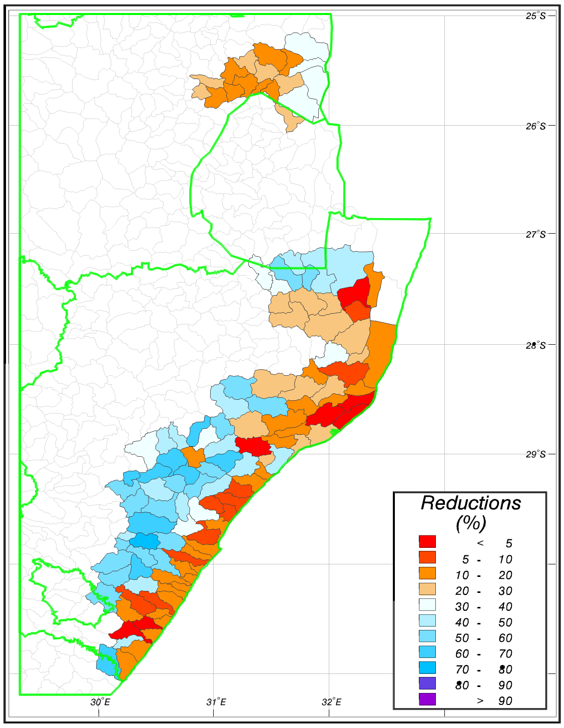


Figure 8.20 Percentage reduction in streamflows by sugarcane under median year conditions on a shallow soil (after Schulze *et al.,*1999)

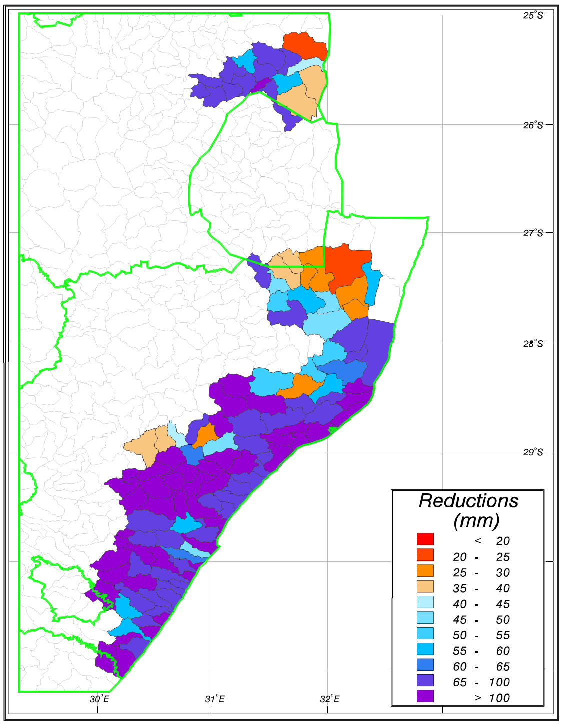


Figure 8.21 Streamflow reduction (mm) by eucalypts under median year conditions on a shallow soil (after Schulze *et al.,* 1999)

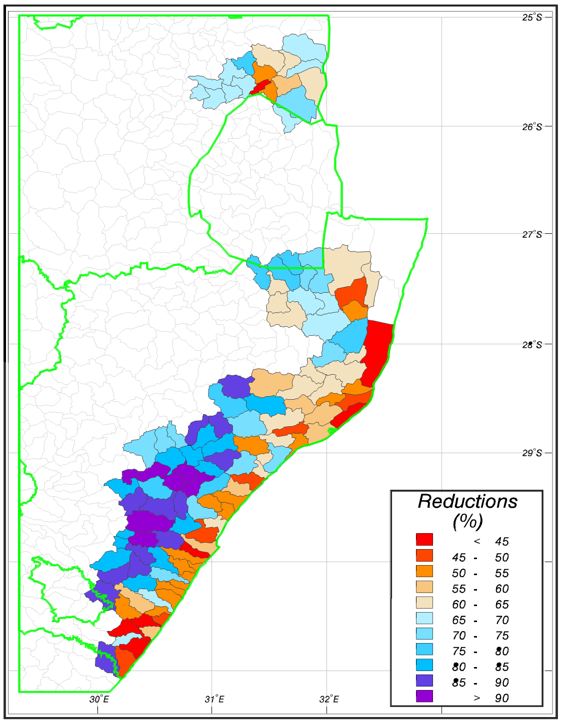


Figure 8.22 Percentage reduction in streamflows by eucalypts under median year conditions on a shallow soil (after Schulze *et al.,* 1999)

8.11 WHAT CONCLUSIONS MAY BE DRAWN FROM THIS STUDY?

This study on the comparative hydrology from different land uses in the sugarbelt of South Africa, has shown clearly that hydrological responses, even at the coarsest level of annual statistics, cannot be reduced to simple generalisations or simple curves of runoff : rainfall relationships. Rather, responses have been shown to be highly location specific, often with distinct north vs south coast contrasts and with further variation between coastal vs interior regions; and all that despite holding soils characteristics and biomass attributes of the various individual competing land uses constant over the entire region. Significant differences in total streamflows from a range of land uses exist according to the simulations undertaken, as do differences in baseflows. Soils have a marked influence on runoff responses, as does the climate of a particular season, particularly in dry years.

The results illustrate that ‘Stream Flow Reduction Activities’, even at the coarse annual level and at Quaternary Catchments scale, are hydrologically a complex issue which become even more so when, for example,

- intra-seasonal (e.g. monthly) time scales, or
- differences in hydrological responses within individual QCs, or
- different management practices within a single land use

are considered.

8.12 ACKNOWLEDGEMENTS

This project was undertaken collaboratively with financial support from the South African Sugar Association Experiment Station at Mt Edgecombe. Their support is acknowledged with thanks.

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CHAPTER 9

IRRIGATION WATER USE BY SUGARCANE IN SOUTH AFRICA : A CASE STUDY ON WATER USE REQUIREMENTS, WATER USE EFFICIENCIES, YIELD GAINS AND WATER LOSSES

R.E. Schulze, T.G. Lumsden and M.J.C. Horan

School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

ABSTRACT

Irrigation is the major user of water in South Africa and, with around 85 000 ha of sugarcane under irrigation, any increases in the efficiency of its water use is a matter of major interest to the sugar industry and to water resources managers. In this chapter on sugarcane : irrigation water relationships net irrigation demand, water use efficiency, incremental yield through irrigation and water losses through deep percolation and stormflow from irrigated fields are evaluated for the 127 Quaternary Catchments making up the so-called sugarcane belt. Consideration is given to influences of soil depth, harvest date and inter-seasonal climatic variability on irrigation water use and losses. Net irrigation requirement is found to vary markedly between wet and dry years while the incremental yield through irrigation is of the order of 7.5 - 9.0 t/ha/100 mm irrigation. Deep percolation and stormflow from irrigated sugarcane fields range from 40 mm to over 200 mm, with both highly influenced by a season's rainfall regime. In virtually all evaluations performed, the total irrigation water use as well as losses to deep percolation decrease as the cycle of irrigation increases from 7 to 14 to 21 days - a factor of great importance in demand water management of irrigated sugarcane.

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9.1 WHY UNDERTAKE A STUDY ON IRRIGATION WATER USE BY SUGARCANE?

Irrigation remains the major user of available water in South Africa. Of the approximately 420 000 ha under sugarcane some 20%, i.e. 85 000 ha, is irrigated, half of that being under full irrigation at Pongola, Komati and Malelane and the other half under supplementary irrigation. Irrigation is, therefore, of considerable importance to demand side management of water, as any increases in its efficiency of application can potentially lead to major savings in water within a catchment. Since most water for irrigation is abstracted from streamflows either directly from the stream or indirectly through storage reservoirs, it furthermore constitutes a 'Stream Flow Reduction Activity' which merits detailed regional evaluation for a range of management scenarios.

The objectives of this study on sugarcane : water relationships were to make regional assessments, using the *ACRU* modelling system (Schulze, 1995), within the sugarcane production areas of South Africa, of

- the differences in net irrigation demand by sugarcane under different scenarios of irrigation scheduling
- the water use efficiency of irrigating under different scheduling procedures
- the incremental yield benefit by applying irrigation and of
- the associated 'inefficiency' of the different modes of scheduling in regard to water losses from irrigated fields by deep percolation on the one hand, and stormflow on the other

with the view to being able to make recommendations on a more efficient use of irrigation water within a broader framework of Integrated Water Resources Management.

In this assessment consideration is given in each case to differences resulting from deep vs shallow soils, harvest dates, as well as to those caused by inter-seasonal variations of climatic conditions (Schulze, Lumsden, Horan and Maharaj, 1999).

The sugarcane production areas of South Africa are those 127 Quaternary Catchments (QCs) defined by SASEX (1998), and shown in Figure 8.1 of Chapter 8. In these QCs sugarcane is either already under production or it has, from climatic considerations, the potential to be grown there. Since the Pongola and Malelane production areas are two of the three major areas in which sugarcane is grown under full irrigation, further graphs are also presented in this chapter for those two locations, in addition to those at the other four case study sites at Richard's Bay, Mt Edgecombe, Eston and Port Shepstone which have already been described in Chapter 8. Information pertaining to Malelane and Pongola is given in Table 9.1.

Table 9.1 Information pertaining to two additional selected case study locations where sugarcane is irrigated (Source : Schulze, 1997)

Location	Quaternary Catchment	Baseline Land Cover	Mean Altitude (m)	MAP of QC (mm)	MAE_p (mm)
Malelane	X 24 E	Lowveld	400	650	1993
Pongola	W 44 B	Lowveld	405	660	1983

Location	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Malelane	MP 50	78.7	76.3	53.6	37.2	7.4	1.2	0.1	5.0	9.3	39.4	75.6	98.6
	MP 10	6.2	22.3	10.5	6.2	0	0	0	0	0	13.4	18.7	30.4
	T_{max}	30.8	30.5	29.7	27.9	26.4	24.1	24.3	25.9	27.5	28.1	28.8	30.3
	T_{min}	19.6	19.5	18.4	15.7	11.6	8.3	8.3	10.6	13.6	15.5	17.3	18.8
	Pot Evap	211.6	202.1	180.4	141.7	124.6	101.9	115.3	142.8	183.0	187.0	197.7	205.0
Pongola	MP 50	93.6	84.1	66.2	32.2	8.8	4.3	3.7	8.0	20.0	63.4	79.6	92.3
	MP 10	25.8	20.1	14.5	10.9	0.7	0	0	0	2.6	24.9	49.2	30.7
	T_{max}	30.3	30.1	29.3	27.5	25.6	23.5	23.6	25.1	26.7	27.3	28.2	29.9
	T_{min}	19.1	19.0	18.0	15.2	11.5	8.1	8.1	10.4	13.4	15.3	16.9	18.3
	Pot Evap	217.9	189.0	179.9	149.4	126.6	104.8	119.2	142.8	167.5	189.1	191.8	204.6

MP 50 = Median monthly rainfall (mm)
MP 10 = Monthly rainfall (mm) in driest year in 10
Pot Evap = Mean monthly total of potential evaporation (mm)
T_{max} = Monthly mean daily maximum temperatures
T_{min} = Monthly mean of daily minimum temperatures
MAE_p = Mean annual potential evaporation (mm)

9.2 SOME IRRIGATION TERMS USED : WHAT DO THEY MEAN?

A number of terms require clarification before results are presented:

- *Irrigation* : is the application of water to the crop which is supplementary to that obtained from rainfall. In this study it has been assumed that an unrestricted supply of water is available for irrigation.
- *Net Irrigation* : is the amount of irrigation, in mm equivalents, that is actually applied to the crop. It does not include wind/spray drift losses, other field application losses, canal conveyance losses, or off-channel balancing dam losses.
- *Water Use Efficiency*: *WUE* is the sugarcane yield per unit area for a unit of irrigation application, in this study expressed as t/ha/100 mm of net irrigation.
- *Yield Increment by Irrigation* : is the additional tonnage obtained by irrigation of sugarcane, above the yield from dryland production, under otherwise identical conditions of, say, soil depth or harvest date or seasonal climate, and is expressed as ($Y_{irrigated}$ - $Y_{dryland}$)/100 mm net irrigation.
- *'X' Day Cycle*: implies an irrigation application every *X* days, e.g. every 7 or 14 or 21 days in this regional assessment. The application amount can vary each time, because water is applied only until the soil's drained upper limit (i.e. 'field capacity') is reached. Irrigation is applied throughout the growing season whenever the *X*-day cycle has been completed, except when 'heavy' rain has fallen, in which case the remainder of the cycle is skipped and a new cycle commences on the day after rainfall. The threshold for 'heavy' rainfall varies with cycle length, e.g. in this study
  - for daily irrigation = 10 mm - for a 14 day cycle = 100 mm
  - for a 7 day cycle = 50 mm - for a 21 day cycle = 150 mm
- *Daily Irrigation*: has, in this study, been simulated for two conditions, *viz*.
  - refilling the soil profile daily to its drained upper limit (*DUL*), which implies that the soil can only lose a single day's evapotranspired water before it is replenished again, thus inferring that much of any rain falling on such a wet soil will inevitably be lost as either stormflow or as deep percolation; or
  - refilling the soil profile daily to 70% of its total available moisture content (*TAM*), this being a form of deliberate under-irrigation, or deficit irrigation. This is designed to facilitate any day's rainfall to first fill the remaining 30% of *TAM* before its *DUL* is attained. Irrigating daily to only 70% *TAM* implies a soil water 'deficit' of 18 mm for a soil of *TAM* = 60 mm and of 45 mm for a soil of *TAM* = 150 mm, these being the amounts of daily rainfall that can infiltrate before any percolation/stormflow losses are incurred. This is therefore considered a very effective, if logistically difficult, mode of irrigation scheduling.

9.3 WHAT *ACRU* MODEL VARIABLES WERE INPUT SPECIFICALLY FOR THIS CASE STUDY?

A number of irrigation inputs have already been described above. Other inputs and assumptions are outlined below:

- Canopy interception losses for sugarcane under conditions of irrigation were set at 1.8 mm per rainday (Schulze, 1995).
- Irrigated soils were assumed to be a sandy clay loam with the volumetric water holding capacity at saturation being set at 0.442 m/m, at *DUL* = 0.260 m/m and at the lower limit of plant available water = 0.160 m/m.
- The coefficient of initial abstraction was input at 0.25 for the summer months November to February which frequently receive high intensity convective rainfall, and at 0.30 for the remaining months with generally lower intensity rainfall (Schmidt, Smithers, Schulze and Matthews, 1998).
- The sugarcane water use coefficient K_{ds} was calculated by the sigmoidal K_{ds} : degree days relationship (Hughes, 1992), as given by the equations in Chapter 13, with a maximum K_{ds} of 1.0 and a minimum of 0.3.
- The critical leaf water potential for irrigated sugarcane was input at -1200 kPa, implying cane to be a relatively stress-resistant crop and that soil water stress would, according to Slabbers' (1980) equation, set in at 0.63 of *TAM* on a day with 10 mm potential evaporation and at 0.32 of *TAM* when atmospheric demand was only 5 mm.
- Other variables were set at their default values as given in the *ACRU* User Manual (Smithers and Schulze, 1995).

9.4 HOW DO NET IRRIGATION WATER REQUIREMENTS FOR SUGARCANE VARY WITHIN THE STUDY AREA, BETWEEN SEASONS AND WITH SOIL DEPTH?

Irrigation water requirements for sugarcane, if one wishes to maintain the crop in a non soil water stressed condition for most of the time, is high over most of the sugarbelt of South Africa, as illustrated by Figures 9.1 to 9.4.

a) Are there regional differences?

Most certainly, yes. Net irrigation requirement by sugarcane is in the range of 850 mm p.a. in the relatively moist areas, where irrigation is applied when needed to supplement rainfall, to 1400 mm p.a. in areas where essentially full irrigation is practised, as in the Pongola and Malelane areas (Figure 9.1).

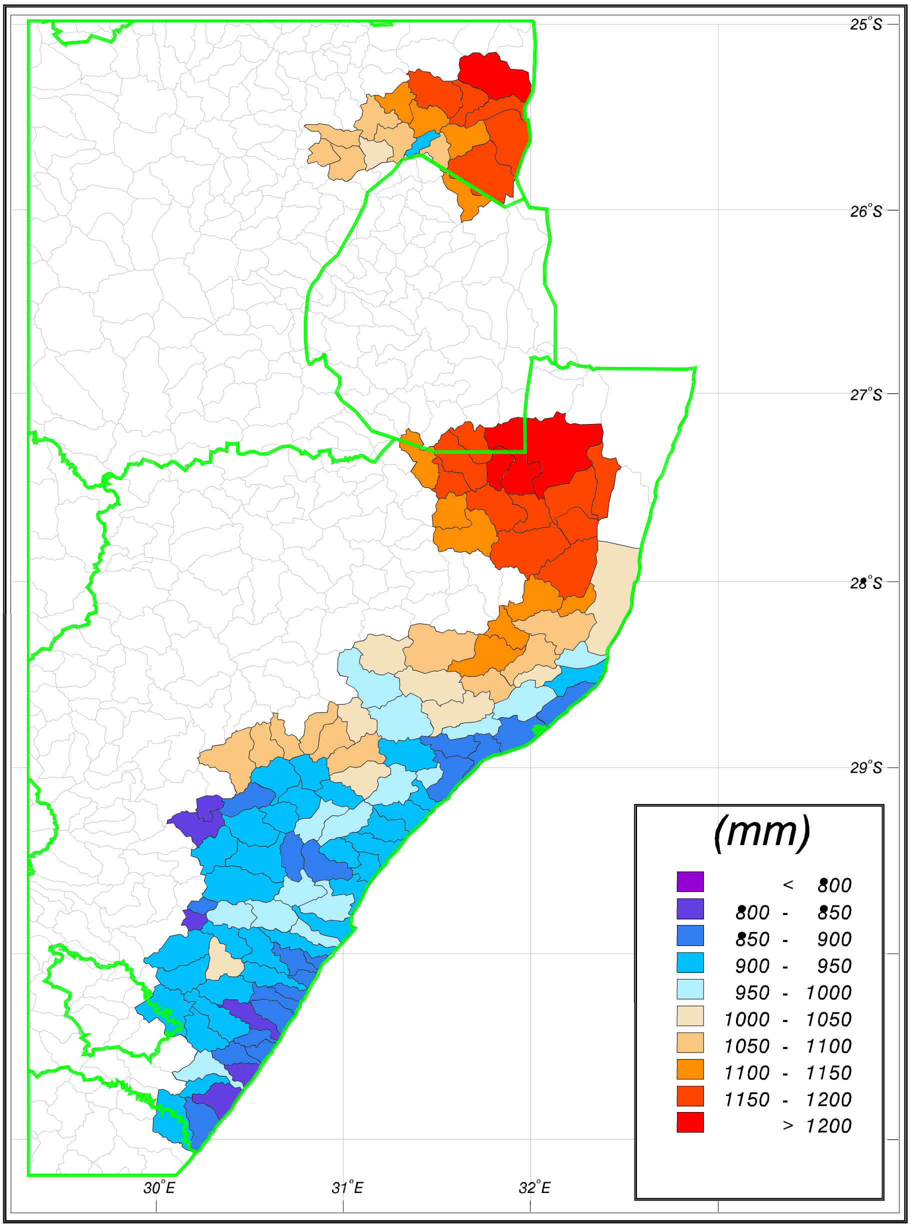


Figure 9.1 Net annual irrigation requirements (mm) for sugarcane under median climatic conditions and for a 14 day irrigation cycle on shallow soils, i.e. *TAM* = 60 mm (after Schulze *et al.*, 1999)

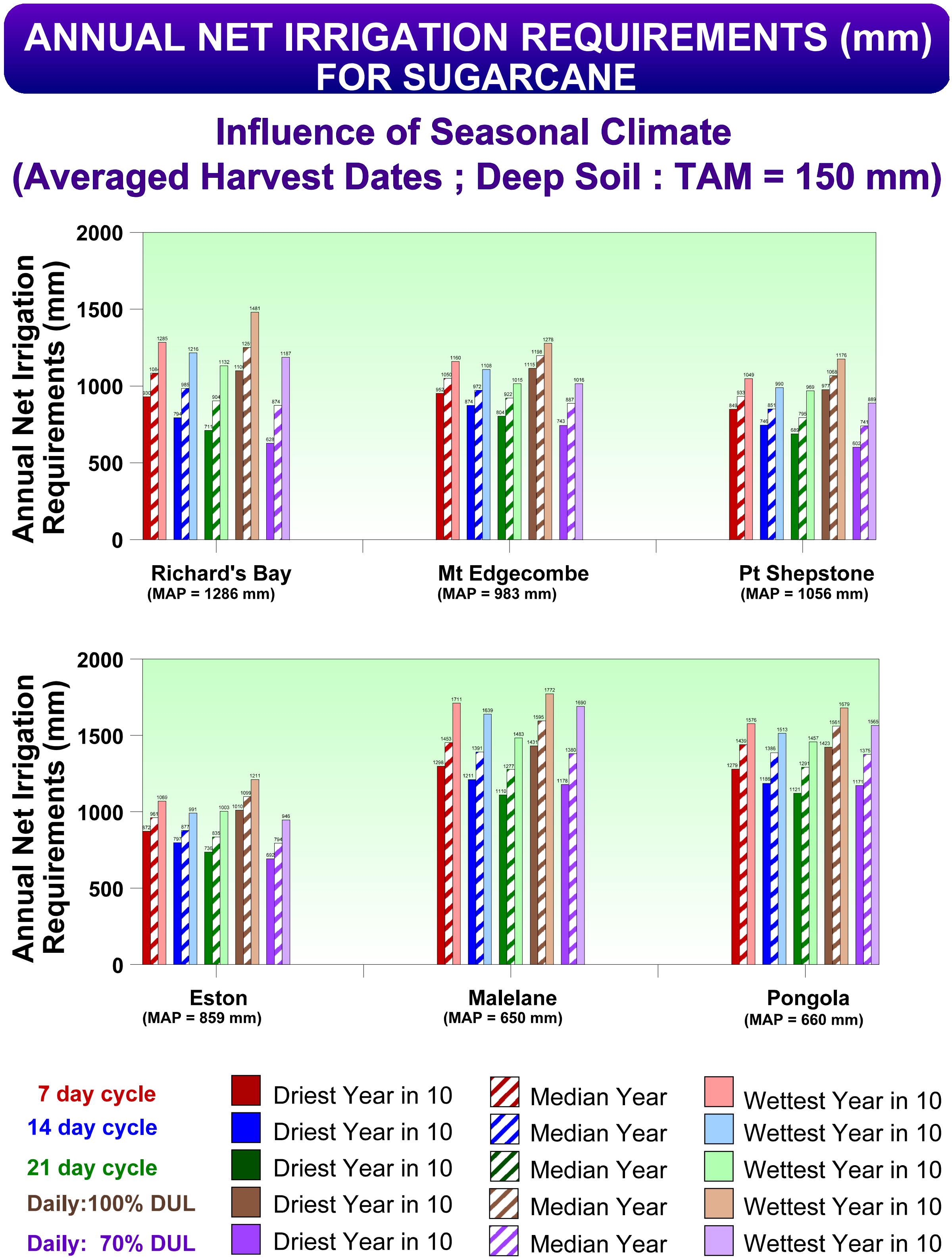


Figure 9.2 Net annual irrigation requirements (mm) for sugarcane grown on deep soils (*TAM* = 150 mm) under different climatic conditions (after Schulze *et al*., 1999)

ANNUAL NET IRRIGATION REQUIREMENTS (mm) FOR SUGARCANE

Influence of Soil Depth (Averaged Harvest Dates ; Median Conditions)

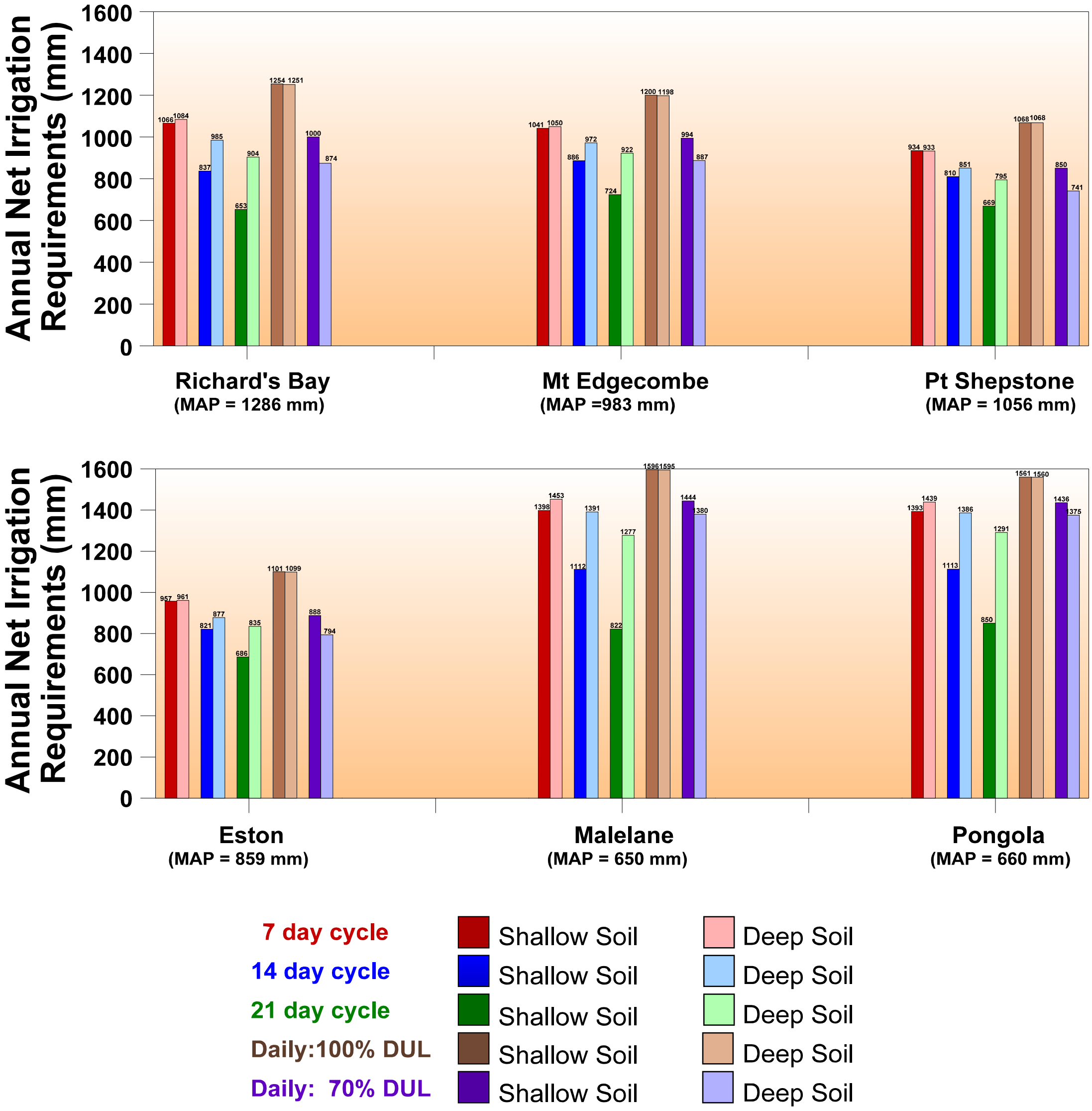


Figure 9.3 Net annual irrigation requirements (mm) for sugarcane grown in shallow vs deep soils (*TAM* = 60 mm vs 150 mm) under median climatic conditions (after Schulze *et al*., 1999)

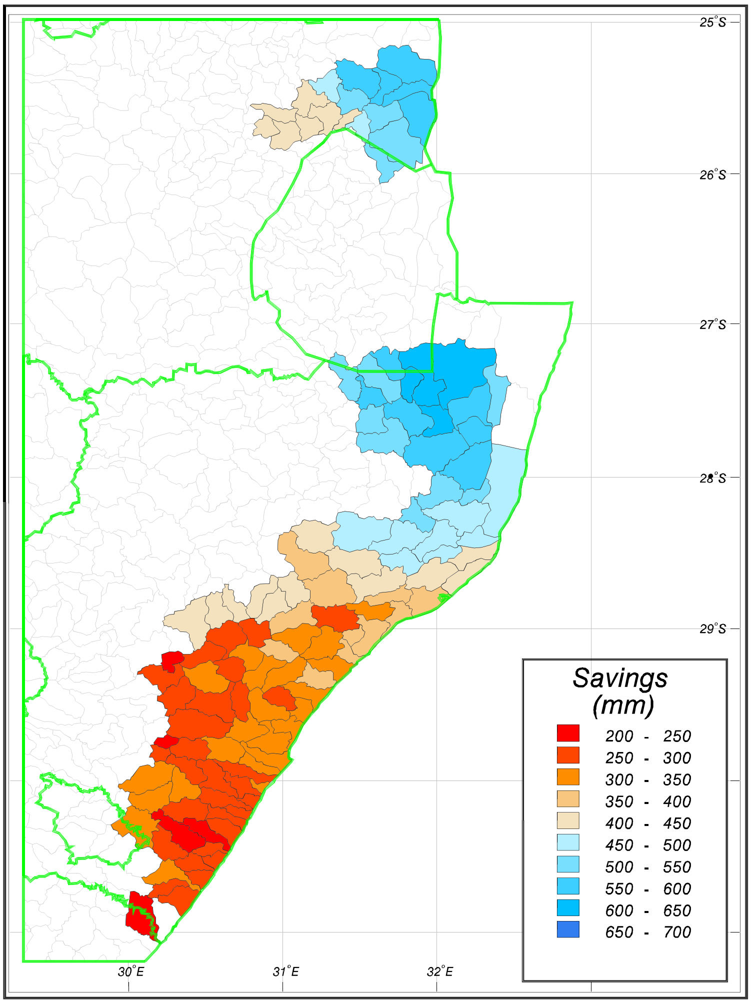


Figure 9.4 Savings (mm) in irrigation water application on sugarcane between a 7 and 21 day cycle under median climatic conditions and on shallow soils, i.e. *TAM* = 60 mm (after Schulze *et al*., 1999)

b) What are the differences in irrigation requirements between dry, average and wet years?

The irrigation requirements can vary quite markedly from year to year, as illustrated in Figure 9.2, which shows that the difference in irrigation demand in the driest year in 10 is between 200 and 500 mm more than in the wettest year in 10.

c) Does soil depth make a difference to annual net irrigation requirements?

The influence of soil depth, and hence water holding capacity, assumes importance when irrigating at less frequent intervals such as every 14 or 21 days, under which scenarios shallow soils require progressively less irrigation than deeper soils. The difference is in the region of 130 to 250 mm less water where irrigation supplements rainfall and up to 450 mm less where full irrigation is practised, as at Malelane and Pongola (Figure 9.3). A reversal of this trend is evident in the case of daily deficit irrigation to 70% *TAM*, in which case deeper rather than shallower soils have a lower irrigation demand (Figure 9.3).

d) What water savings can, therefore, be effected by appropriate scheduling?

- What is evident time and again in interpreting Figures 9.2 to 9.4 is that considerable water savings may be effected if the application cycle time were to be increased from, say, 7 to 14 or to 21 days.

Figure 9.4 illustrates this point clearly, highlighting that the water savings under median climatic conditions range from 100 mm in the south to over 300 mm in the northern cane producing areas.

- Overall the most efficient of the five modes of scheduling are, first, the daily deficit irrigation application whereby soil water levels are maintained at 70% of *DUL* and, secondly, the 21 daily cycle (Figures 9.2 and 9.3). Of these two, the daily irrigation to 70% of DUL is initially more expensive and requires considerable managerial input.
- The least efficient of the five methods of scheduling would be daily irrigation maintaining soil water content at 100% *DUL* (Figures 9.2 and 9.3). This method is also wasteful of water in that it produces considerable deep percolation and stormflow losses (see later sections).

9.5 WHAT IS THE WATER USE EFFICIENCY (WUE) OF IRRIGATED SUGARCANE IN SOUTH AFRICA?

a) WUE defined . . . a reminder

The reader is reminded that of the many definitions of Water Use Efficiency (WUE) in the literature the one used in this study is that WUE equals tons sugarcane/ha/100 mm net irrigation.

b) How does WUE vary regionally?

- WUEs in the sugarbelt of South Africa are lowest in those areas where full irrigation is practised, e.g. at Malelane and Pongola, and highest in the high rainfall areas along the North Coast where a relatively small amount of supplementary irrigation converts to relatively high yields of sugarcane (Figure 9.5).
- Within the sugarcane producing areas the WUE ranges from 12 to 18 t/ha/100 mm net irrigation, i.e. regional differences of 5 - 6 t/ha/100 mm net irrigation occur (Figures 9.5, 9.6 and 9.7).

c) How does WUE vary with method of scheduling?

- WUE is lowest for daily irrigation scheduling to 100% of *TAM* (Figures 9.6 and 9.7).
- Within the range of irrigation cycles from 7 to14 to 21 days the highest WUE is achieved at the longer cycle, with the increase of WUE between a 7 and a 21 day irrigation cycle varying from 2½ t where full irrigation is practised and increasing to over 5 tons/ha/100 mm net irrigation along the North Coast (Figures 9.6 and 9.7).
- In fact, from the simulations undertaken, a very strong case can be made from a number of perspectives, for a longer rather than a shorter cycle of sugarcane irrigation to be applied, with reasons including reductions in deep percolation and stormflows from irrigated sugarcane lands (see later sections) as well as enhanced yield increments per unit of irrigation when compared with dryland yields (see next section).

d) How does WUE vary with soil depth and with harvest date?

- Harvest date (i.e. whether the cane is harvested in autumn, winter or early summer) has very little bearing on WUE (Figure 9.6).
- Similarly, soil depth is not a critical determinant of differences in WUE when applying a 7 day irrigation cycle, but assumes some importance at longer cycle times where it decreases WUE by 1½ - 2½ t/ha/100 mm net irrigation. For daily irrigation regimes, however, deeper soil display higher WUEs by 1.7 - 2.2 tons in areas where supplementary irrigation is practised (Figure 9.7).

9.6 BY HOW MUCH DOES YIELD OF SUGARCANE INCREMENT THROUGH IRRIGATION?

This section addresses the question as to what the increment in sugarcane yield is when it is irrigated, relative to the dryland yield, per 100 mm of net irrigation water applied, and whether regional patterns of this increment exist. The following emerge from an interpretation of Figures 9.8, 9.9 and 9.10.

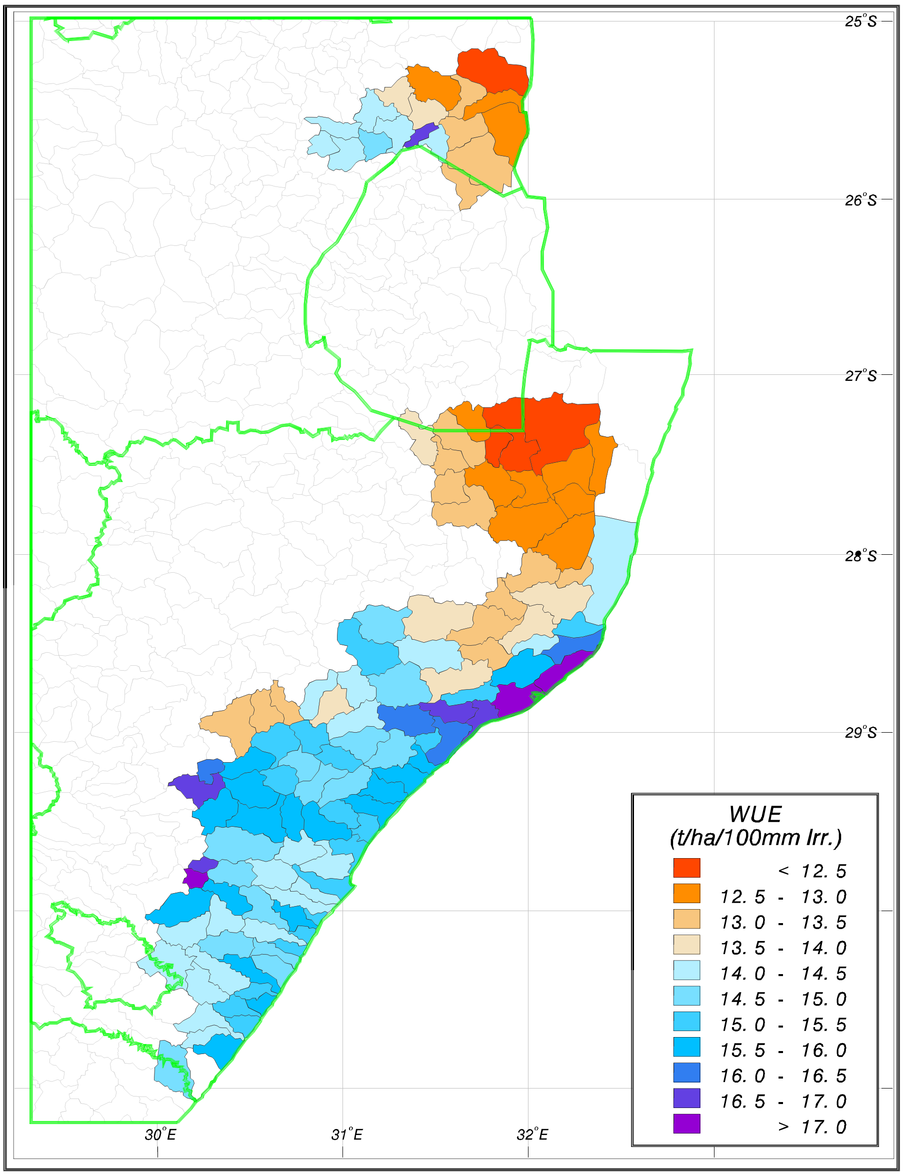


Figure 9.5 Water Use Efficiency (t/ha/100 mm net irrigation) of irrigated sugarcane grown on a 14 day cycle on shallow soils, i.e. *TAM* = 60 mm (after Schulze *et al*., 1999)

a) *How is yield increment (YI) defined? . . . a reminder*

Yield Increment by Irrigation is the additional tonnage obtained by irrigation of sugarcane, above the yield from dryland production, under otherwise identical conditions of, say, soil depth or harvest data or seasonal climate, and is expressed as ($Y_{irrigated}$ - $Y_{dryland}$)/100 mm net irrigation.

b) *How does YI vary regionally?*

The yield increment (YI) map (Figure 9.8), using a typical 14 day cycle of irrigation and assuming averaged harvest dates in a year of median irrigation water application on a shallow soil as a base, shows a fairly narrow range of YIs from 7.5 to just over 9 tons/ha/100 mm net irrigation. No distinct regional patterns emerge except that the hot, low rainfall areas where full irrigation is practised benefit by an additional 1 ton/ha yield/100 mm net irrigation. There is also a tendency, although it is not distinct on the map, for climatically marginal inland regions to exhibit lower YIs.

WATER USE EFFICIENCY - IRRIGATED SUGARCANE
(tons/ha/100 mm net irrigation)

Influence of Harvest Dates
(Shallow Soil : TAM = 60 mm)

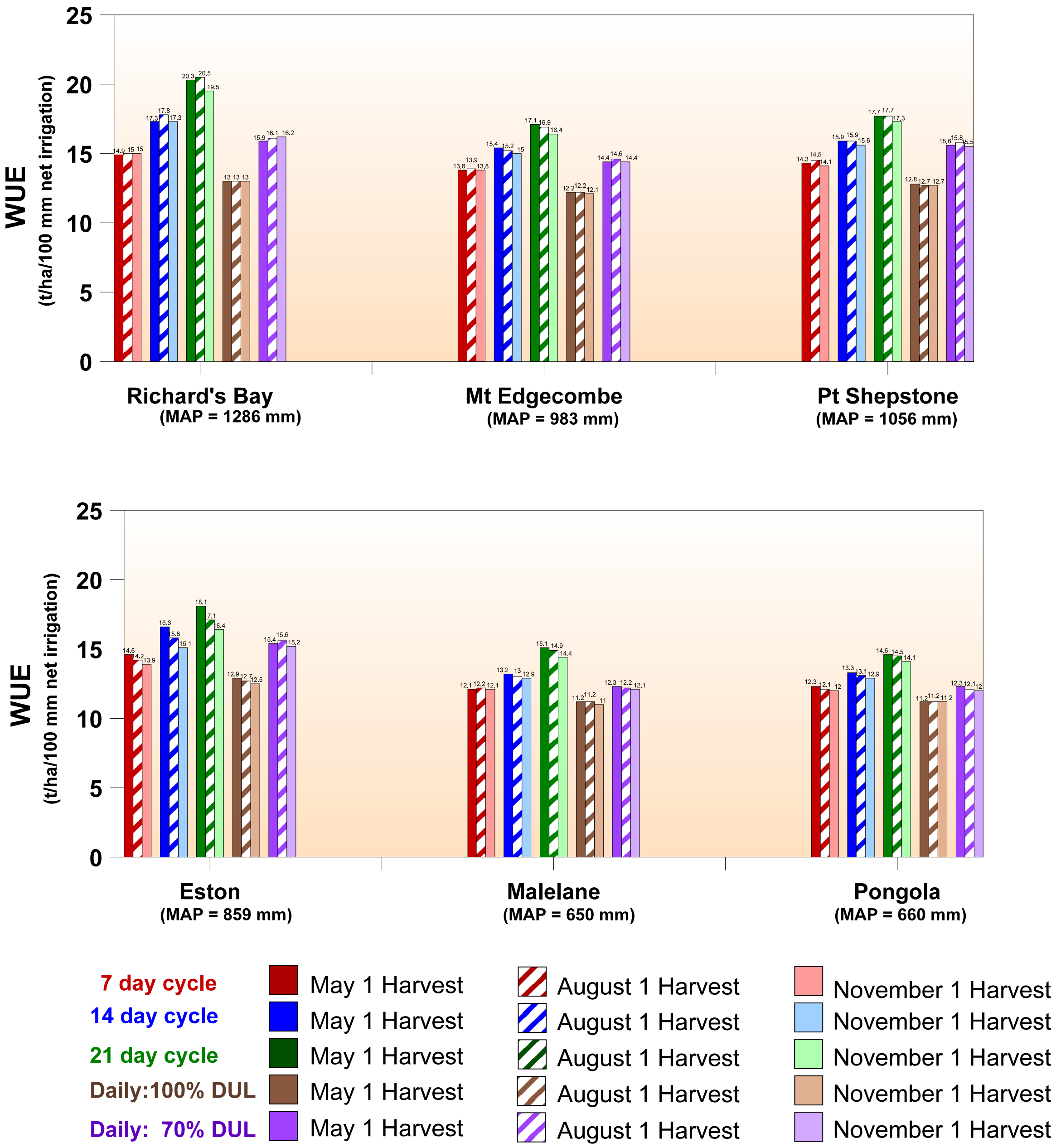


Figure 9.6 The influence of harvest dates on the Water Use Efficiency (t/ha/100 mm net irrigation) of irrigated sugarcane grown on shallow soils (*TAM* = 60 mm) and under median climatic conditions (after Schulze *et al.*, 1999)

WATER USE EFFICIENCY - IRRIGATED SUGARCANE (tons/ha/100 mm net irrigation)

Influence of Soil Depth (Averaged Harvest Dates)

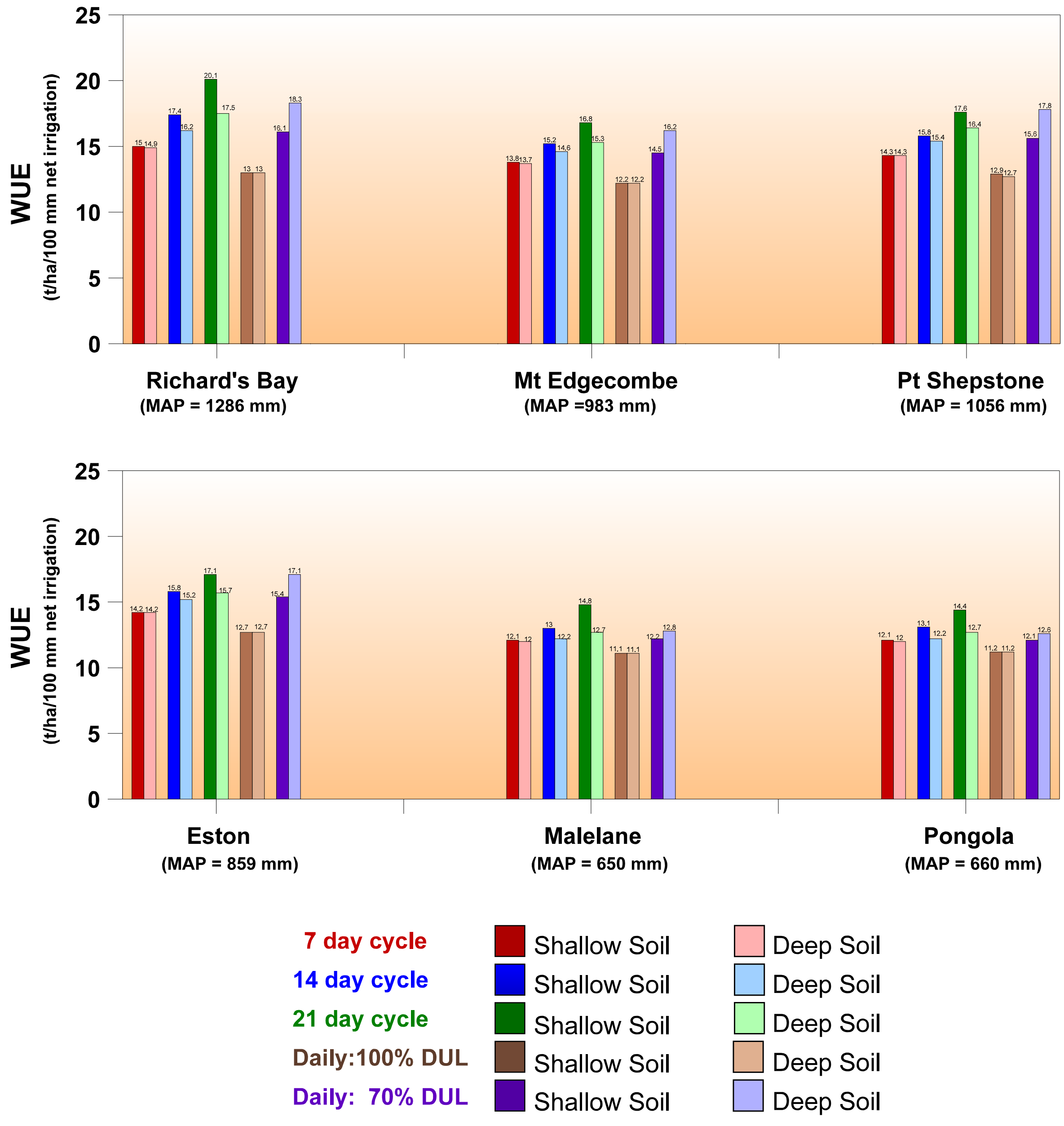


Figure 9.7 The influence of soil depth on the Water Use Efficiency (t/ha/100 mm net irrigation) of irrigated sugarcane grown under median climatic conditions and assuming averaged harvest dates (after Schulze *et al*., 1999)

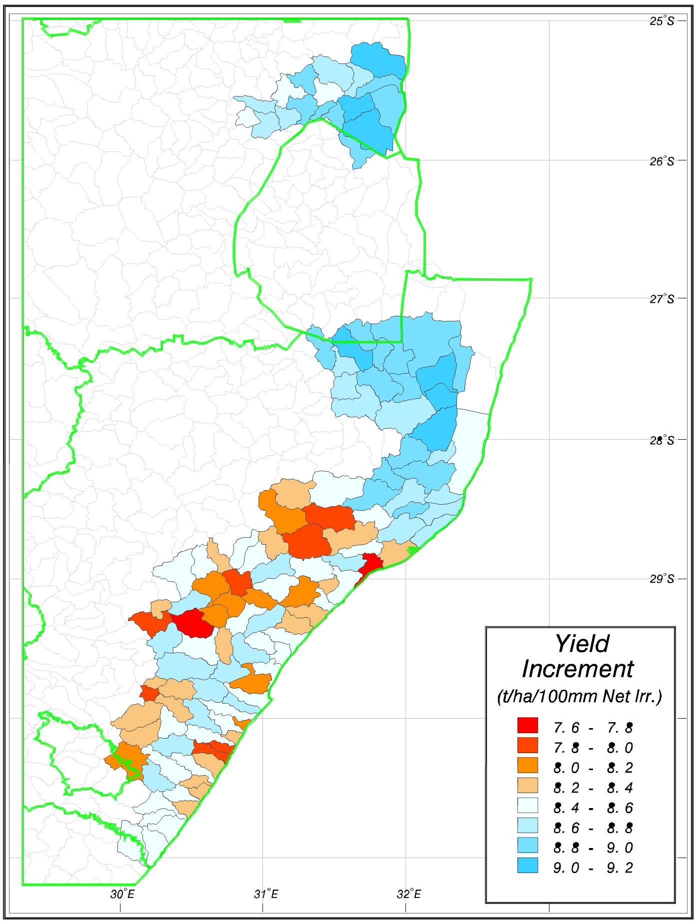


Figure 9.8 Increment (t/ha/100 mm net irrigation) of irrigated over dryland sugarcane yields with a 14 day irrigation cycle when cane is cultivated on shallow soils, i.e. *TAM* = 60 mm (after Schulze *et al*., 1999)

c) Do YIs change with modes of irrigation scheduling?

As a rule YIs increase with longer irrigation cycles (Figure 9.9). This supports suggestions made elsewhere in this chapter that farmers should consider strongly changing to longer (e.g. 21 day) irrigation cycles.

d) Do harvest dates have a significant influence on YIs?

Figure 9.9 shows that, with the exception of the cooler interior sugarcane growing areas of the Midlands of KwaZulu-Natal (e.g. Eston), harvest dates along the warmer coastal and lowveld areas do not influence YIs.

e) What effect does soil depth have on the YI?

As may be expected, simulations with the *ACRU* model of YI by irrigation are slightly higher on shallower (i.e. *TAM* = 60 mm) than on deeper (*TAM* = 150 mm) soils, with shallower soils benefiting by an additional ¾ - 1 ton in areas of supplementary irrigation, but only by approximately ½ ton where full irrigation is practised (Figure 9.10).

YIELD INCREMENT BY IRRIGATING SUGARCANE
(Additional tons/ha/100 mm net irrigation)

Influence of Harvest Dates
(Shallow Soil : TAM = 60 mm)

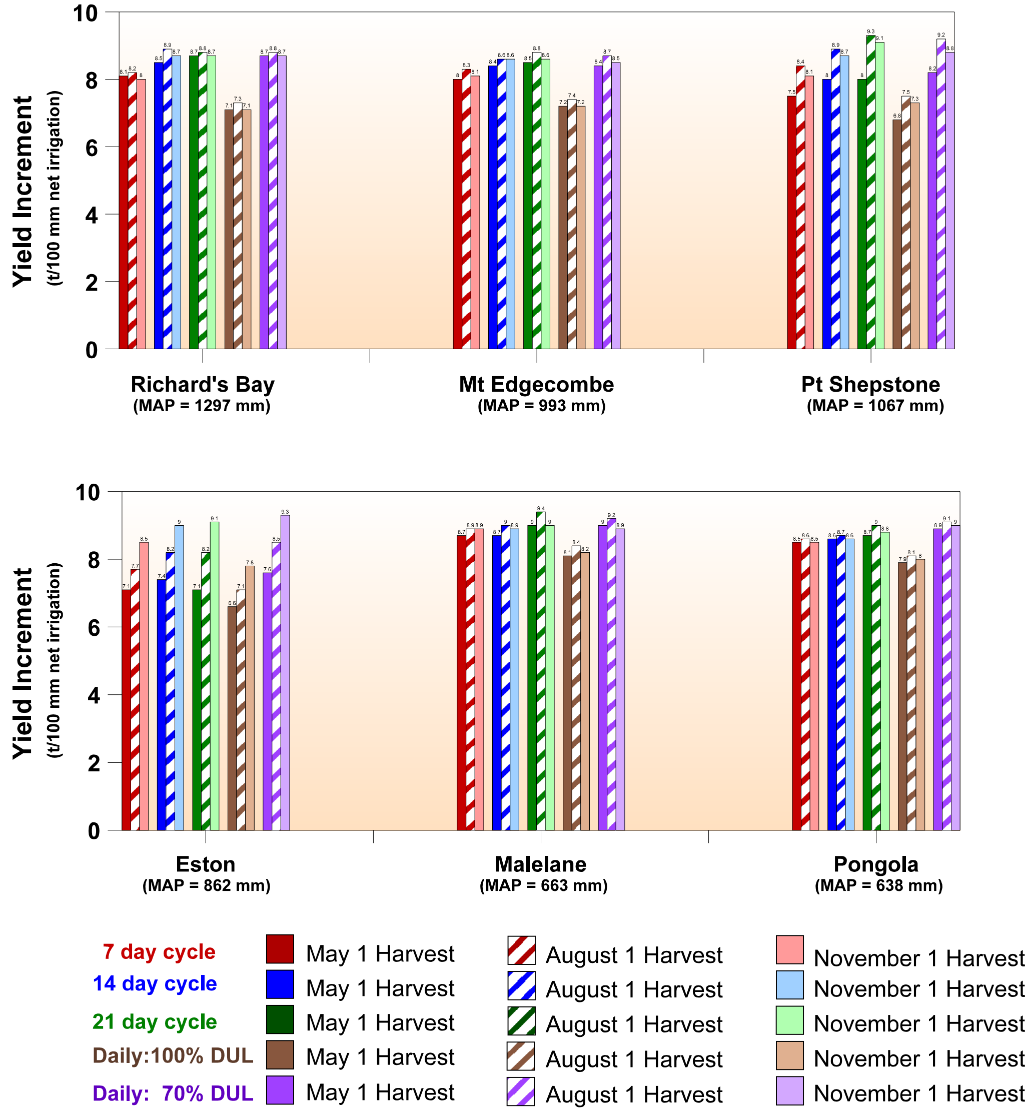
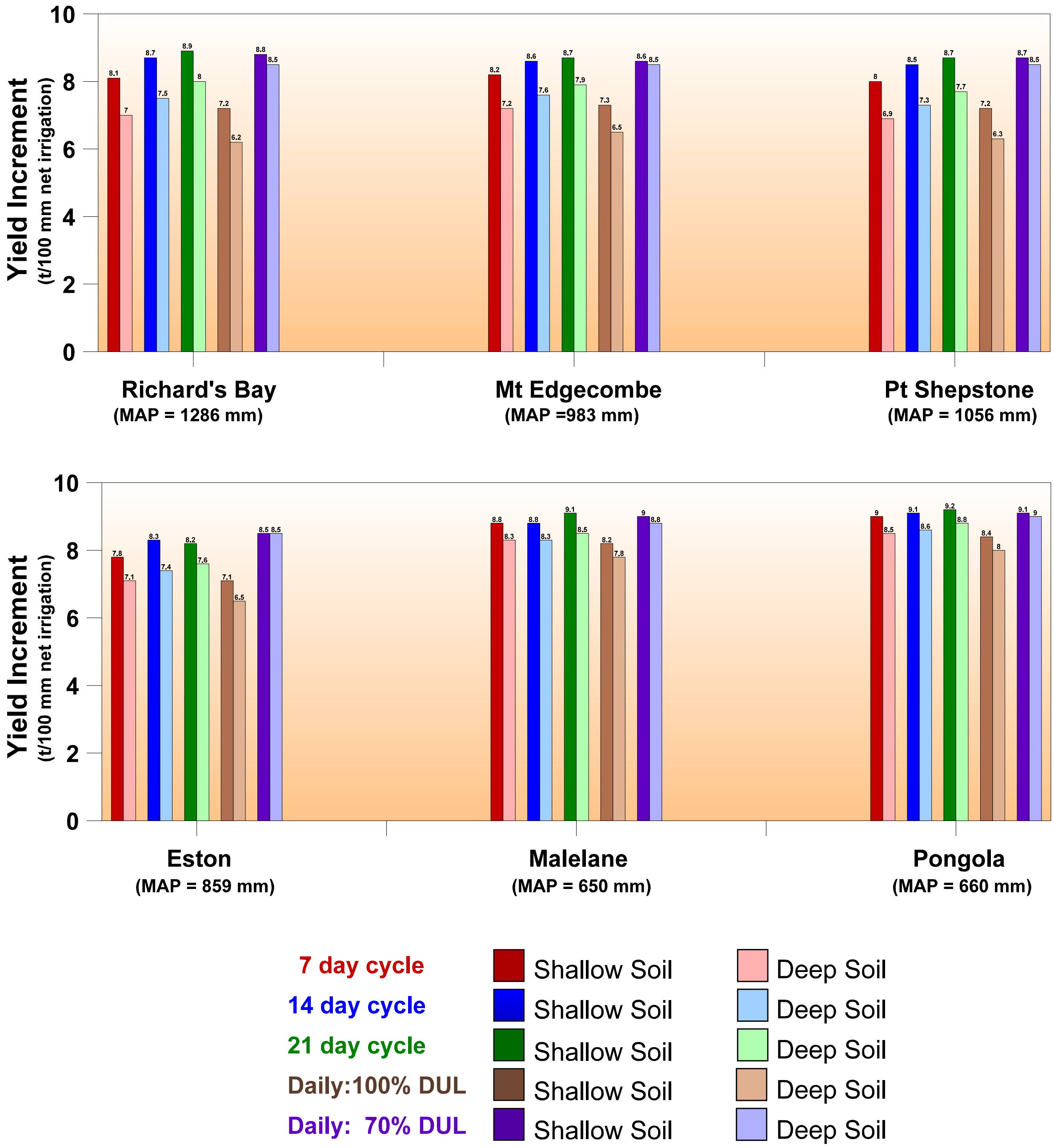


Figure 9.9 The influence of modes of irrigation scheduling and harvest dates on increments of irrigated over dryland sugarcane yields (t/ha/100 mm net irrigation), with sugarcane grown on shallow soils (*TAM* = 60 mm) and assuming median climatic conditions (after Schulze *et al*., 1999)

YIELD INCREMENT BY IRRIGATING SUGARCANE
(Additional tons/ha/100 mm net irrigation)

Influence of Soil Depth
(Averaged Harvest Dates ; Median Conditions)



9.7 HOW MUCH WATER IS LOST TO DEEP PERCOLATION WHEN SUGARCANE IS IRRIGATED?

a) *Deep percolation : What are causes, what are effects?*

In addition to field application losses (e.g. spray drift, conveyance) two further water losses take on significance in the management of irrigated sugarcane, *viz*. deep percolation and surface runoff losses. Because rainfall forecasts are seldom taken account of in irrigation management, it may occur that rain falls on a just recently irrigated field, causing a 'push through' of soil water to beyond the irrigated crop's maximum root depth. Such deep percolation constitutes not only a water loss to the system, but also a leaching of costly fertilizers which can cause considerable contamination of groundwater and, after return flows into the river channel system, of the streamflow to downstream users.

b) *How does deep percolation vary regionally?*

The map of deep percolation losses (Figure 9.11) for a typical 14 day cycle on shallow soils which has been derived using *ACRU* model output from averaged harvest dates in a year of median climatic conditions, shows that these losses can vary from 40 to nearly 300 mm p.a. These therefore constitute significant losses. Losses tend to be higher along the coast than inland (Figure 9.11).

c) *To what extent does soil depth affect deep percolation losses?*

With the exception of the daily irrigation schedule to 100% *DUL*, in which case shallow soils expectedly yield considerably more percolation losses than deeper soils, soil depth has little effect on deep percolation losses for the other modes of irrigation scheduling (Figure 9.12).

d) *Does the mode of irrigation scheduling affect deep percolation?*

- The method of irrigation scheduling has an important bearing on deep percolation losses, with losses decreasing as the irrigation cycle length increases from 7 to 14 to 21 days (Figures 9.13 and 9.14).
- As expected, the highest deep percolation losses are associated with daily irrigation to 100% *TAM*, while much lower losses occur with daily irrigation to 70% *TAM* because, with the latter mode of scheduling, a buffer of available soil moisture is invariably present.

e) *How do high, average and low rainfall years affect deep percolation?*

Deep percolation losses are highly responsive to the season's rainfall regime, especially along coastal areas. In the wettest year in 10, for example, losses can be up to 150 mm higher than under median conditions, while in the driest year in 10, equally, deep percolation losses can be up to 150 mm p.a. less than the median (Figure 9.13).

9.8 HOW MUCH WATER IS LOST TO STORMFLOW WHEN SUGARCANE IS IRRIGATED?

Stormflow losses also occur from irrigated sugarcane fields for reasons similar to those of deep percolation losses, *viz*. that it may rain on a just previously irrigated area and the high soil water content enhances the generation of stormflow.

Soil depth, irrigation cycle and inter-seasonal patterns of stormflow losses are very similar to those of deep percolation losses and they will therefore not all be repeated here, save to say that the spatial patterns illustrated in Figure 9.14 show that stormflow losses can average up to 200 mm p.a. along the coastal areas, but decrease to 40 mm p.a. in the interior cane production areas as well as in those hot, dry areas where full irrigation is the norm for most of the year.

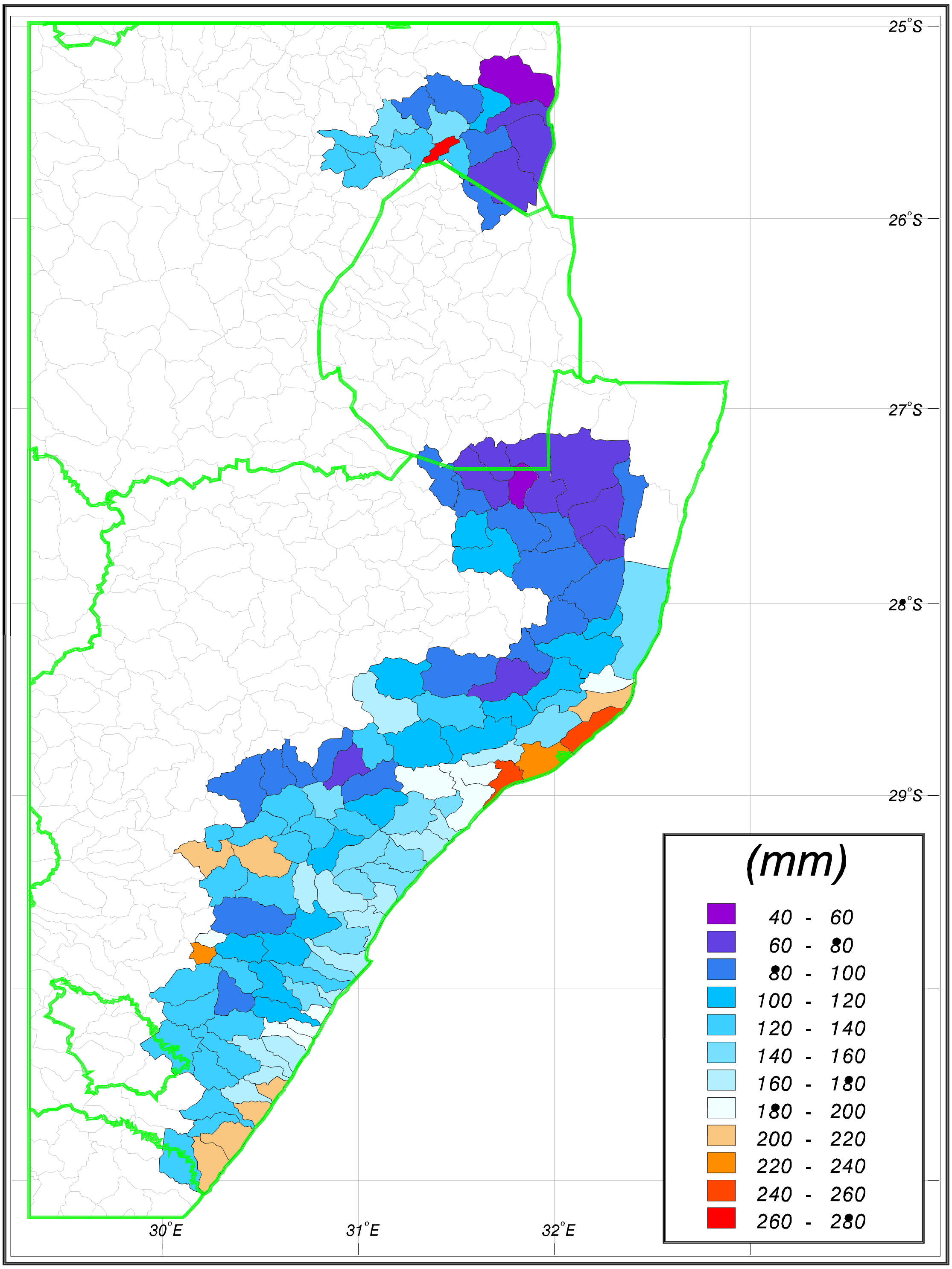


Figure 9.11 Deep percolation losses from sugarcane for a 14 day irrigation cycle, assuming median climatic conditions and cane grown on a shallow soil, i.e. *TAM* = 60 mm (after Schulze *et al*., 1999)

IRRIGATION PERCOLATION LOSSES (mm) FROM SUGARCANE

Influence of Soil Depth (Averaged Harvest Dates ; Median Conditions)

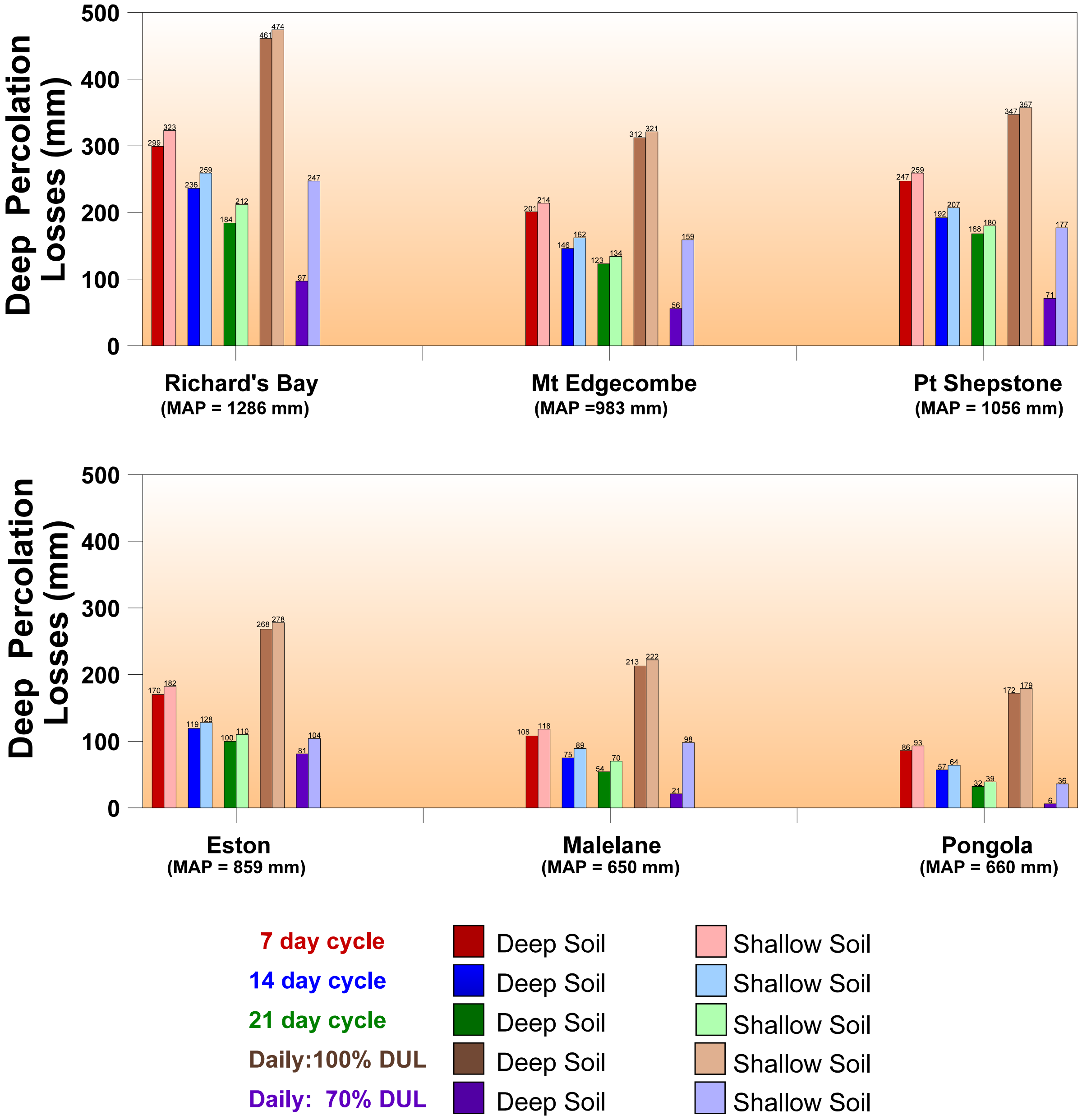


Figure 9.12 The influence of soil depth on deep percolation losses (mm) from irrigated sugarcane grown under different modes of scheduling and under median climatic conditions (after Schulze *et al.*, 1999)

IRRIGATION PERCOLATION LOSSES (mm) FROM SUGARCANE

Influence of Seasonal Climate (Averaged Harvest Dates ; Shallow Soil : TAM = 60mm)

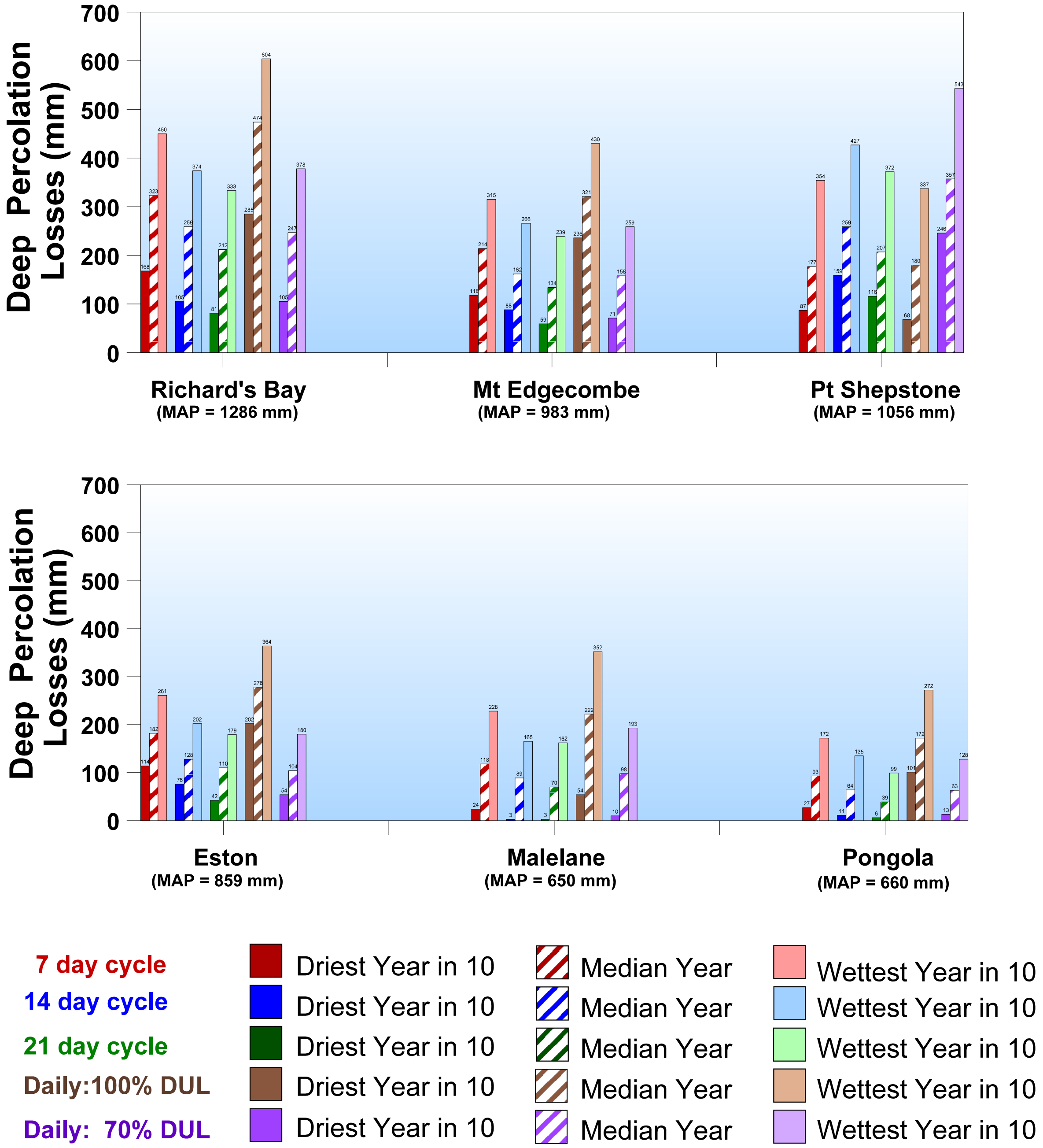


Figure 9.13 The influence of seasonal climatic conditions on deep percolation losses (mm) from irrigated sugarcane grown on shallow soils, i.e. *TAM* = 60 mm (after Schulze *et al*., 1999)

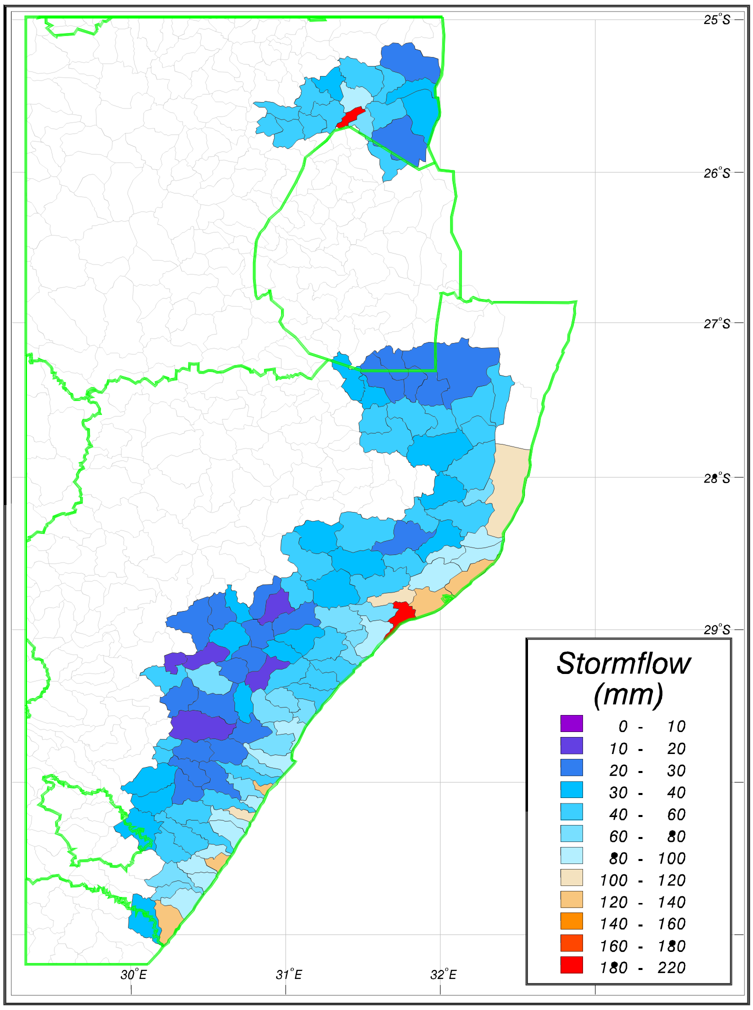


Figure 9.14 Stormflow losses (mm) from sugarcane for a 14 day irrigation cycle under median climatic conditions on shallow soils, i.e. *TAM* = 60 mm (after Schulze *et al*., 1999)

9.9 WHAT CAN THE SUGARCANE INDUSTRY LEARN FROM THIS CASE STUDY?

This hydrological investigation into the irrigation of sugarcane has considered a range of modes of applying the irrigation water over a range of soils, harvest dates and natural climatic conditions. Results on the net irrigation application, WUE and yield increment, as well as on water losses to deep percolation and stormflow have illustrated that both the benefits of irrigation (e.g. WUE, yield increments) as well as detrimental aspects (percolation, stormflows) are highly dependent on the mode of scheduling. If improved demand side management of water and/or water levies become an important issue in Integrated Water Resources Management then , from these simulations with the *ACRU* model, it appears that a strong case should be made for irrigation to be applied over longer cycles. These, while they may produce slightly lower sugarcane yields and require larger individual applications of water, result in considerably reduced total irrigation water requirements, enhanced WUEs as well as in gains of yield increments per unit of water applied, and in marked reductions in water losses to deep percolation and to stormflow. All of these factors contribute towards improved holistic management of a catchment's water resource.

9.10 ACKNOWLEDGEMENTS

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CHAPTER 10

WHICH LAND USE UTILISES MORE WATER? A COMPARATIVE SENSITIVITY STUDY OF HYDROLOGICAL RESPONSES TO CHANGES IN AREAS UNDER AFFORESTATION AND IRRIGATION IN THE PONGOLA-BIVANE CATCHMENT

V. Taylor and R.E. Schulze

School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

ABSTRACT

Many conflicts surrounding an equitable allocation of water to competing users in a catchment revolve around the impacts which various forms of land use have on the distribution of water in time and space. This chapter addresses conflicts between water uses by commercial afforestation and sugarcane under irrigation in the Pongola-Bivane catchment in northern KwaZulu-Natal. The *ACRU* agrohydrological model is used in this sensitivity study to illustrate that these two land uses impact streamflows very differently and that hydrological responses are highly dependent on the *climatic regime*. For a relatively ‘moist’ and relatively ‘dry’ subcatchment (SC) within the Pongola-Bivane system it is shown by simulation modelling that afforestation water use by *Eucalyptus grandis* is markedly different for the macro-climates representing those two subcatchments. Furthermore, percentage reductions in low flows are shown to be less than those of mean annual flows in the moist SC, while being higher in the dry SC. For both SCs relative impacts in dry years are higher than in median years, and those, in turn, higher than in wet years for stormflows and baseflows. Reductions in streamflows by irrigation are significantly higher in the dry compared to the wet SC. The additional water use by irrigated sugarcane per hectare is 9 - 15 times that of afforestation, and this ratio increases for both drier (vs wetter) SCs as well as for drier (vs average or wet) seasons by a factor of up to 30. The study illustrates clearly that relative water use by competing sectors within agriculture is a complex issue which cannot be resolved with conceptually simplistic models.

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10.1 THE AFFORESTATION vs IRRIGATION DEBATE : HYPOTHESES RELATED TO THIS COMPARATIVE SENSITIVITY STUDY

Many conflicts surround the equitable allocation of the remaining finite amount of water available to competing users in a catchment once the human and ecological reserves have been satisfied. This chapter assesses some hydrologically related issues of land use in the Pongola-Bivane catchment in northern KwaZulu-Natal, a catchment which is subjected to diverse and conflicting demands on its water resources, primarily from large-scale irrigation of sugarcane and commercial forestry concerns.

Three hypotheses are presented, *viz*.

- that hydrologically sensitive land uses, in this case irrigated sugarcane and commercial afforestation, can impact hydrological responses significantly when those land uses increase within a catchment;
- that the relative sensitivity of the two land uses is highly dependent on prevailing average macro-climatic conditions (i.e. it can differ significantly between a relatively moist vs dry area within a catchment) as well as on dry vs wet years; and
- that comparable percentage reductions in streamflows between these two competing land uses therefore vary considerably with macro- and inter-seasonal climatic conditions.

This case study is a contribution to dispelling the still commonly held notion by many hydrologists, engineers and water resources managers that prognoses on land use impacts can be made in a relatively simplistic manner.

These three hypotheses are assessed by simulation modelling with the physical-conceptual *ACRU* modelling system (Schulze, 1995), which has, *inter alia*, been specifically structured to be sensitive to land use change impacts on various hydrological responses.

In regard to afforestation, for example, the model accounts for and distinguishes between rooting patterns, growth rates, enhanced wet canopy, evaporative demand, soil moisture extraction patterns and site preparation influences of the main genera of commercially grown trees in South Africa (cf. Chapter 7; Schulze, Summerton and Jewitt, 1998). In the case of irrigated sugarcane cognisance is taken, *inter alia*, of seasonal crop water demand patterns, modes of scheduling and water abstraction, rooting patterns, conveyance/spray drift/interception losses and the generation of stormflow and deep percolation from the irrigated land.

Many verification studies have been carried out on various internal state variables of the model, e.g. interception and soil moisture, as well as final products of the model, e.g. streamflows (including the Pongola; Schulze *et al*., 1996) and sediment yield, to instil credibility in the practical application of the model (Schulze, 1995). In the context of modelling impacts of those land uses pertinent to this study, soil water extraction patterns under irrigation, with different crops and climatic regimes, have been simulated successfully by the *ACRU* model (Dent, Schulze and Angus, 1988), as have hydrological responses from sugarcane fields (Smithers, Mathews and Schulze, 1996), while forest water use and impacts on streamflows have been verified with success using the *ACRU* model at different locations in South Africa by Schulze and George (1987), Jewitt and Schulze (1999) and by Gush *et al*. (2001).

10.2 WHAT ARE THE GENERAL CHARACTERISTICS OF THE PONGOLA-BIVANE CATCHMENT?

The Pongola-Bivane catchment upstream of the irrigation weir offtake at gauging station W4H003, is located in northern KwaZulu-Natal with extensions of the catchment into Mpumalanga province and Swaziland. It covers 5 789 km^2, of which the Bivane tributary's catchment upstream of the recently constructed Paris dam is 1 262 km^2. Latitudinally the catchment extends from 27˚05' S to 27˚44' S and 30˚17' E to 31˚30' E (Figure 10.1). The Pongola-Bivane has been delineated into 20 subcatchments (SCs), generally corresponding with Department of Water Affairs and Forestry (DWAF) Quaternary Catchments, and of which SCs 8 - 13 make up the Bivane upstream of Paris dam. Subcatchment mean altitude varies from 714 to 1750 m, while the mean annual precipitation (MAP) was computed in Schulze *et al*. (1996) to decrease from an average of 1071 mm in the relatively moist SC 10 to 747 mm in the

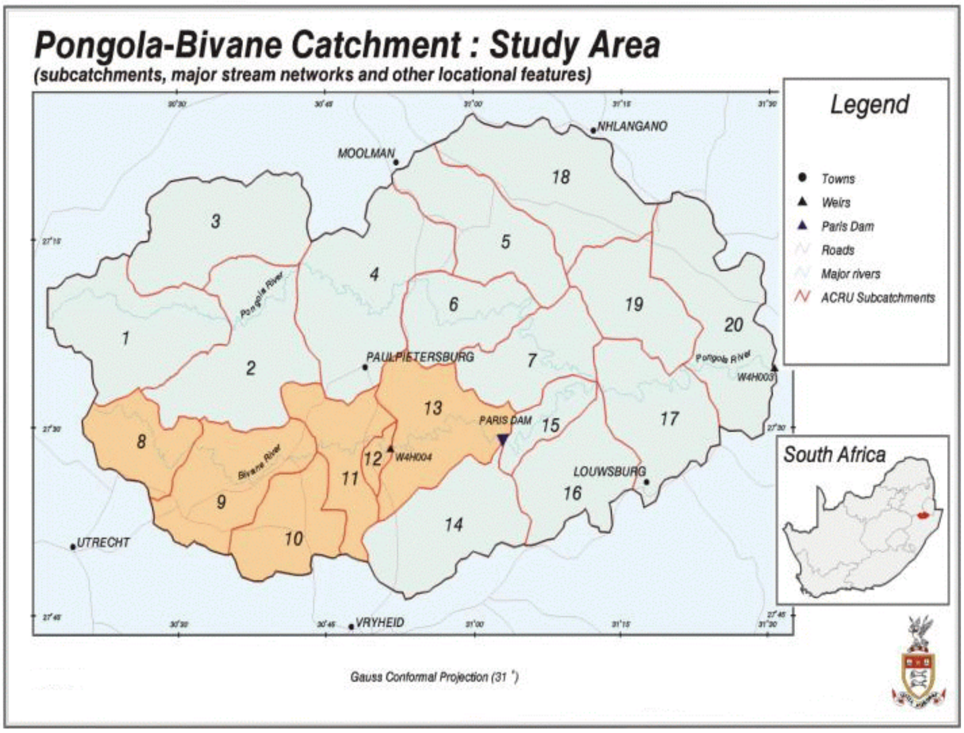

Figure 10.1 The Pongola-Bivane catchment : Subcatchments, major stream networks and other locational features (after Schulze *et al.*, 1996)

relatively dry SC 19. Details of climate, soils and land uses are given in Schulze *et al.* (1996; 1997).

10.3 HOW DO THE ABOVE HYPOTHESES RELATE TO THE BROADER HYDROLOGICAL ISSUES WITHIN THE PONGOLA-BIVANE CATCHMENT?

Within the Pongola-Bivane catchment, land use practices, both current and proposed, have given rise to concerns that adequate water supplies for all stakeholders will not be sustainable, even in the immediate future, particularly in low flow winter months. As a result, a moratorium on any further commercial afforestation in the catchment was implemented by the Ministry of Water Affairs and Forestry in the mid-1990s, as increased afforestation had, over a period of years, been perceived by downstream irrigators to adversely affect the runoff of the Pongola-Bivane river system (Impala Irrigation Board, 1995). Consequently, the then Afforestation Permit Policy Committee (APPC) rejected an afforestation permit in the upper Pongola catchment on the premise that low flows from the river were required for irrigation 100 km downstream at Pongola and to supply rural communities with water (Van der Zel, 1996).

At the same time towards the late 1990s the large Paris dam (118 x $10^6 m^3$) was being constructed at the outlet of SC 13 on behalf of the Impala Irrigation Board (Figure 10.1), to supplement water from the Pongola river at W4H003 for the provision of sugarcane irrigation requirements as well as supplying approximately 260 000 rural inhabitants with potable water.

One of the recommendations had been that the forest industry contribute to the costs of the Paris dam as a compensation for forestry related reductions in streamflows upstream of the dam, and in exchange for a recommendation that the moratorium on further afforestation be lifted (Bosch and Associates, 1995; 1996). The forest industry resisted this, and the entire water resource conflict was assessed by application of the *ACRU* modelling system to the Pongola-Bivane system. As a consequence of simulations with the model, the proposal to consider 'compensating' for forest water use of additional afforestation by removal of alien riparian vegetation was initiated by DWAF and investigated by Jewitt, Horan, Meier and Schulze (cf. Chapter 11).

10.4 WHAT WERE THE INPUTS AND ASSUMPTIONS FOR THIS COMPARATIVE SENSITIVITY STUDY?

a) Subcatchment selection

In this study the sensitivities of streamflow to increasing the areas under the critical land uses of commercial plantation afforestation and irrigated sugarcane are assessed for a relatively 'moist' SC, for which SC 10 was selected, and for a relatively 'dry' SC, which was represented by SC 19 (Figure 10.1). The 'moist' SC, DWAF Quaternary Catchment W41C, has a mean altitude of 1377 m. Recorded values from SA Weather Service daily rainfall station 372283W for the 50 year period 1945 - 94 were used to 'drive' the hydrology. The subcatchment weighted MAP is 1070.6 mm (Taylor, 1997). With a January mean of daily maximum temperatures (T_{max1}) of 26.0° C and a July mean of daily minima (T_{min7}) of 3.1° C the 'moist' SC is also relatively cool. For the 'dry' SC, Quaternary Catchment W42L (SC 19) at a mean altitude of 810 m was selected. Daily rainfall driver station 409320W was used for its simulations and its weighted MAP is 747.4 mm (Taylor, 1997). This relatively warm SC has a T_{max1} of 29.2° and a T_{min7} of 6.7° C. The respective annual means of A-pan equivalent potential evaporation (Schulze, 1997) are 1823 mm ('moist') and 1912 mm ('dry').

b) Soils

In order to compare only climatically related differences in hydrological responses from the two land uses in the sensitivity studies, the soils of the two SCs were considered to be the identical, namely a sandy clay, with the following values representing respectively the top- and subsoil horizons : thickness 0.29 m and 0.48 m; soil water content at porosity 0.413 and 0.419 m.m^{-1}, at drained upper limit 0.265 and 0.301 m.m^{-1} and at permanent wilting point 0.182 and 0.222 m.m^{-1}. Under afforested conditions the thickness of the subsoil was increased by 0.25 m to an effective 0.73 m to account for the deeper rooting of trees (Summerton, 1996). More details on these SCs are given in Taylor (1997).

c) Baseline land cover

The following land cover and other input information was used in the sensitivity studies : The baseline land cover was considered to be veld in fair hydrological conditions (Schulze, 1995), equivalent to Acocks' (1988) Veld Type #63, with monthly water use coefficients, rooting distributions, interception losses and coefficients of initial abstraction (Table 10.1) as in Schulze *et al*. (1996).

d) Forest plantations

The forest plantation was assumed to be *Eucalyptus grandis*, at an average age of 5 years and with a pitted site preparation. The plantations' vegetation and stormflow attributes given in Table 10.1 are from Schulze *et al*. (1996), and are based on Summerton's (1996) findings. For the sensitivity study on afforestation it was further assumed that no irrigation was being practised in the SC, that there were no reservoirs present, no inter-catchment transfers or domestic abstractions, nor that there were any adjunct or disjunct impervious areas.

e) Irrigated sugarcane

For the sensitivity study on irrigated sugarcane a maximum rooting depth of 0.8 m was input, with the monthly crop water use coefficient varying between 0.72 and 0.93 (Table 10.1; Schulze, 1995). Interception losses were set at 1.8 mm per rainfall event. The irrigation schedule, typical for the Impala Irrigation Board's irrigators, was 35 mm net irrigation in a 12 day cycle. This schedule was broken only when soils were wetted by a daily rainfall of 40 mm or more. Conveyance and spray drift losses were set at 10% each and abstractions for irrigation were taken from the run-of-river generated from within the SC. It was, furthermore, assumed that in the sensitivity study on irrigation water use, no afforestation was present in the SC, nor any reservoirs, domestic abstractions, water transfers or impervious areas.

Table 10.1 Monthly input of hydrological attributes of various land cover and land uses in the Pongola-Bivane catchment (after Schulze *et al*., 1996)

Land Cover/Use	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Veld (Acocks #63)	Water use coefficient	0.65	0.65	0.65	0.50	0.30	0.20	0.20	0.35	0.50	0.60	0.65	0.65
	Interception loss	1.20	1.20	1.20	1.10	1.10	1.00	1.00	1.00	1.10	1.20	1.20	1.20
	Roots in topsoil	0.85	0.85	0.85	0.85	0.90	1.00	1.00	1.00	0.95	0.90	0.85	0.85
	Coef of initial abstraction	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
Eucalypts, aged 5 years and pitted	Water use coefficient	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	Interception loss	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
	Roots in topsoil	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
	Coef of initial abstraction	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Sugarcane	Water use coefficient	0.90	0.92	0.93	0.91	0.88	0.82	0.78	0.74	0.72	0.74	0.81	0.85
	Interception loss	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
	Roots in topsoil	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
	Coef of initial abstraction	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30

Interception loss = mm/rainday

10.5 HOW SENSITIVE ARE HYDROLOGICAL RESPONSES WITHIN THE PONGOLA-BIVANE SYSTEM TO CHANGES IN THE AREA UNDER AFFORESTATION IN RELATIVELY 'MOIST' vs 'DRY' SUBCATCHMENTS?

The impacts of increasing the extent of afforestation on accumulated, annual and seasonal streamflows (Q) were assessed for both the relatively moist subcatchment (MSC) and the relatively dry subcatchment (DSC) by eight *ACRU* runs on each SC, commencing with 0% afforestation (i.e. a baseline run) and then incrementing the percentage of afforestation by 10% until 70% of a SC was effectively under trees. It was considered that in practice 70% approximated an upper limit of afforestation that could be achieved, allowing for firebreaks, riparian and infrastructural areas.

Figure 10.2 depicts plots of the impacts of varying percentages of afforestation, between 0% and 60% at 20% intervals, on accumulated streamflows for the 50 year period 1945 - 1994. A number of deductions may be made from Figure 10.2 :

- The first is the marked difference in accumulated streamflows (Q_Σ) between the MSC and the DSC, where the MSC with 60% afforestation still yields 1.7 times as much streamflow as 0% afforestation in the DSC. This illustrates clearly the influence of macro-climate, and particularly rainfall, on streamflow generation - a factor which cannot be overstressed when land use influences on Q are evaluated.
- Secondly, for both the MSC and the DSC the progressive reduction of Q_Σ with increasing afforestation is evident. In this sensitivity study the reduction is near-linear with increased afforestation because the same climate input are used and because other non-linearities introduced, for example, by dams, irrigation, abstractions, impervious areas or other land uses are not considered. In actual catchment situations reductions would *not* be linear.
- Analysis of Figure 10.2 shows that in *absolute* terms afforestation impacts are more marked in MSCs than in DSCs. In this example, reductions of 4200 mm vs 2100 mm respectively occur over the 50 year study period in the MSC and DSC, i.e. a factor difference of 2.0. The explanation forthese differences in streamflow reductions is simply that the higher the rainfall, the higher the evaporative losses and that the lower the rainfall, the more frequently vegetation is under soil moisture stress anyway. Timber yield will, of course, also be correspondingly higher in the MSC.

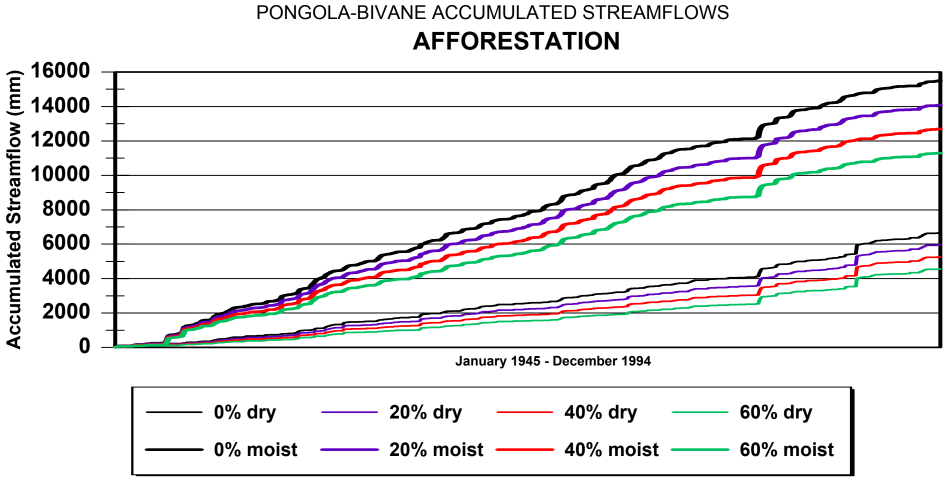

Figure 10.2 Accumulated streamflows for a 50 year period, simulated from relatively moist and dry subcatchments in the Pongola-Bivane system for different percentages of afforestation (after Taylor, 1997)

- However, in *relative* terms the impact of afforestation is higher on DSCs than on MSCs. In this example, a 32% reduction occurs for a 60% afforestation on the DSC vs 27% for the MSC. This illustrates clearly the hypothesis that in climatically marginal (i.e. drier) areas, land intensification has a relatively more significant influence on hydrological responses than in wetter hydroclimates.
- For reasons ranging from flood routing to drought period studies, and from sediment yield production to water quality aspects it is vital to distinguish between stormflow and baseflow generation mechanisms, as is done, for example, by the *ACRU* model. Figure 10.1 already shows that for major flood producing events, the runoff generated from grassland vs predominantly afforested catchments is essentially identical. Consequently, once a sizeable storage reservoir has been constructed on a river, upstream land cover modification is of relatively little consequence to sustained water delivery to downstream users, as the dams are not filled by the low flows, but by high flows. It is during sustained dry periods, however, that differences in accumulated water yield between catchments under shallow rooted, senescing grasslands and deep rooted, evergreen forests become evident. From the plots of the MSC in Figure 10.2, for example, it may be deduced that for the relatively dry period 1977 - 1983, a grassland catchment (0% afforestation) would yield the equivalent of 83 mm streamflow p.a. while the same MSC, but with 60% forest coverages, would yield only 55 mm p.a.
- The view is generally held that afforestation inevitably reduces low flows relatively more than total flows. Figure 10.3 illustrates that this is not necessarily the case, however. In this figure mean annual streamflow of the MSC is shown to have a higher relative reduction with increasing afforestation than the accumulated 5 month low flows, which in this region is the summated flow of the consecutive months May to September. In the DSC, however, not only are higher percentage reductions of flows shown, but under drier macro-climatic conditions in this case, the accumulated low flows are impacted relatively more by afforestation than in the MSC.
- In regard to the distinction between stormflows (Q_S) and baseflows (Q_B) in wet and dry years, the results of the frequency analyses which are summarised in Table 10.2 are pertinent. The table shows percentage reductions in runoff variables between a 100% grassed (Acocks' Veld Type #63) and a 100% forested (*E. grandis*, aged 5 years) land cover.

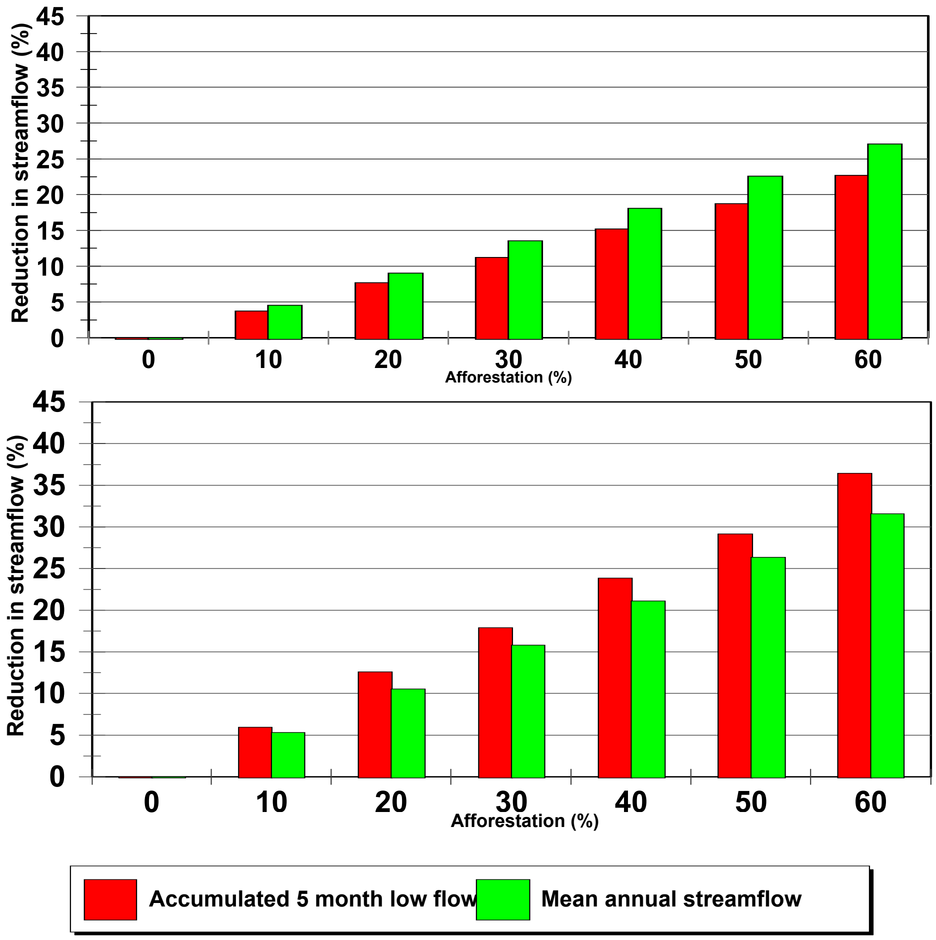

Figure 10.3 Comparison of relative reductions in streamflows for mean annual and accumulated 5 month low flows in relatively moist (top) and dry(bottom) subcatchments of the Pongola-Bivane system, for increasing percentages of afforestation (after Taylor, 1997)

Table 10.2 Percentage reductions of runoff components for forested (vs grassland) land cover in relatively moist and dry subcatchments of the Pongola-Bivane system in dry, median and wet years (after Taylor, 1997)

Variable	Relatively Moist Subcatchment			Relatively Dry Subcatchment		
	1:5 dry year	Median year	1:5 wet year	1:5 dry year	Median year	1:5 wet year
Annual Streamflow	66.0	46.1	40.4	78.0	67.1	59.0
Annual Stormflow	63.0	52.1	47.6	70.1	66.7	52.3
Annual Baseflow	69.8	45.7	39.7	100.0	87.7	60.3

10.6 HOW SENSITIVE ARE HYDROLOGICAL RESPONSES WITHIN THE PONGOLA-BIVANE SYSTEM TO CHANGES IN THE AREA UNDER IRRIGATION IN RELATIVELY 'MOIST' vs 'DRY' SUBCATCHMENTS?

The fundamental difference between impacts of afforestation and of irrigation is that, while afforestation alters the actual streamflow generating mechanisms of both Q_S and Q_B, irrigation alters the streamflow available to downstream users by direct water abstractions, either from a reservoir or from the run-of-river flows. Furthermore, in the case of irrigation, not only is the water available to downstream users impacted in regard to quantity, but frequently there is also a negative impact on the downstream water quantity via return flows from often heavily fertilised irrigated fields.

In the irrigation impacts study on a MSC and DSC within the Pongola-Bivane system, irrigation of sugarcane was incremented at intervals of 2.5% of the catchment's area, from 0% (the grassveld baseline run) to 10% of the catchment being under irrigation.

- Upon initial analysis Figure 10.4 shows very similar trends of accumulated flows under different areal extents of irrigation as Figure 10.2 did for increasing the percentage under afforestation.
- However, while for both the MSC and DSC the relative reduction for a 10% area under irrigation is around 36%, in absolute terms the MSC's accumulated 50 year streamflows are reduced by 5600 mm vs only 2400 mm for the DSC, a factor difference of nearly 2.3 compared with 2.0 for afforestation. Impacts of irrigation on a DSC thus appear more severe than in the case of afforestation, especially during periods of low flows.
- This is borne out in the interpretation of Figure 10.5, in which the lowest combined 5 month flow sequences are shown to be reduced approximately 2 - 2.7 times more than the annual flows in both DSC and MSC. This was not the case in the corresponding analysis on afforestation (Figure 10.3), where low flows and annual flows were reduced by similar percentages.

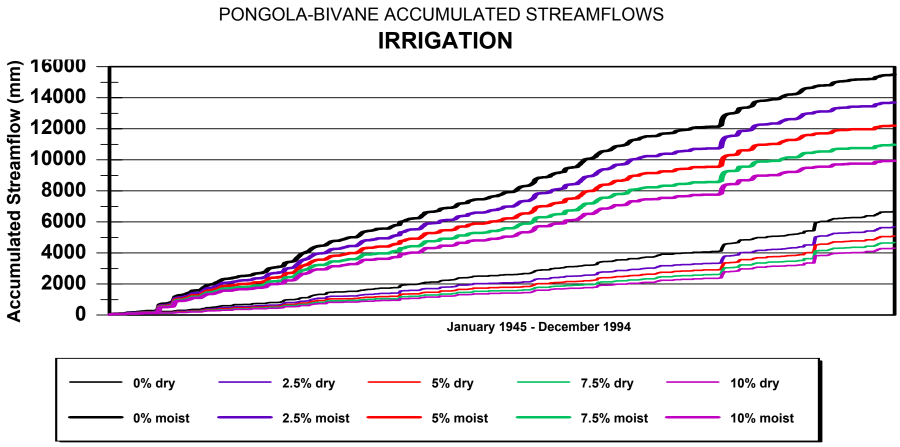

Figure 10.4 Accumulated streamflows for 50 years simulated from relatively moist and dry subcatchments in the Pongola-Bivane system for different percentages of irrigation in the catchment (after Taylor, 1997)

10.7 AFFORESTATION vs IRRIGATION : HOW DO IMPACTS ON STREAMFLOW REDUCTIONS COMPARE ON A UNIT AREA BASIS?

In areas of water conflict the impact of any one critical land use on streamflow reduction (or enhancement) is frequently compared against the impact that a competing land use may have on streamflows. In the case of the Pongola-Bivane system the conflict arises between water use by afforestation and irrigation, as already alluded to. Applying the assumptions regarding afforestation and irrigated sugarcane as already specified in a previous section, a comparison was carried out on the number of hectares of afforestation to *E. grandis* which would have the same impact on streamflow reductions as 1 ha irrigated sugarcane would.

Figure 10.6 illustrates that this ratio can be as high as 32.4 in dry years on a DSC for a 5% streamflow reduction, to as little as 9.1 (i.e. 9.1 ha afforestation reduces streamflows by as much as 1 ha of irrigated sugarcane). Figure 10.6 also shows that this ratio depends on macro-climatic conditions (i.e. DSC vs MSC) as well as whether sustained dry or wet periods are being experienced. For the commonly 'permitted' 10% reduction in streamflows by the erstwhile APPC, the ratio varies between 9.5 and 16.3.

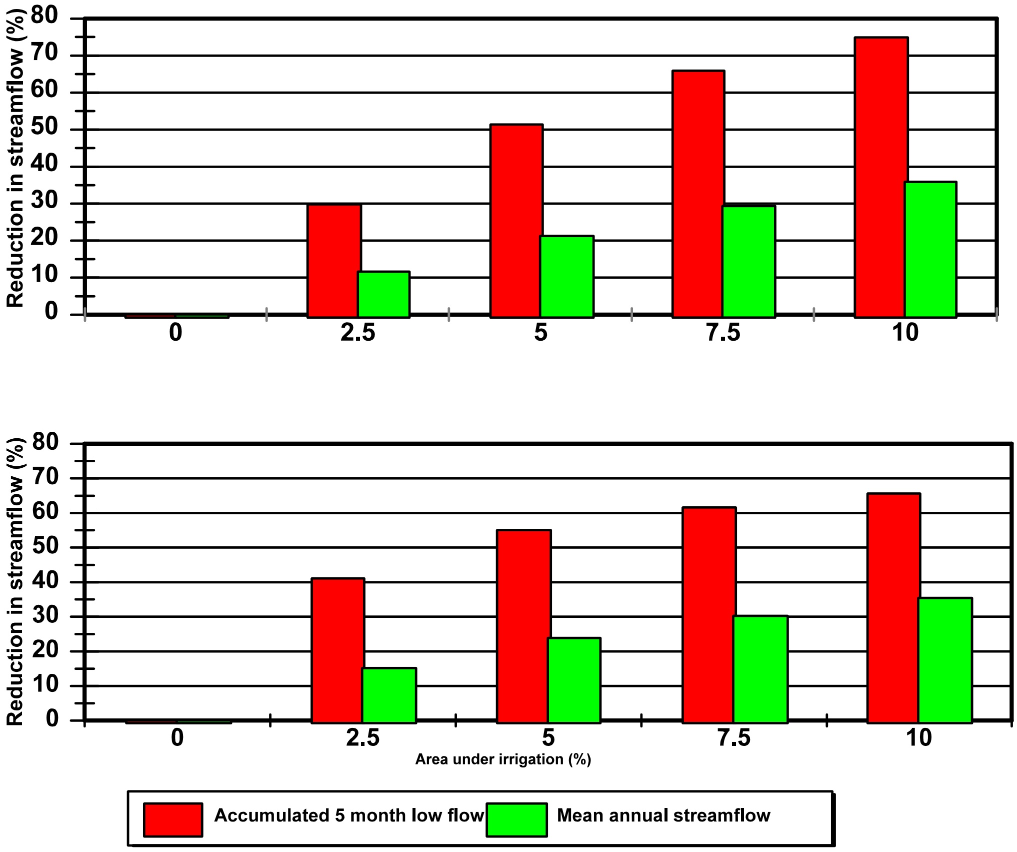

Figure 10.5 Comparison of relative reductions in streamflows for mean annual and accumulated 5 month low flows in a relatively moist (top) and dry (bottom) subcatchment of the Pongola-Bivane system for different percentages of irrigation (after Taylor, 1997)

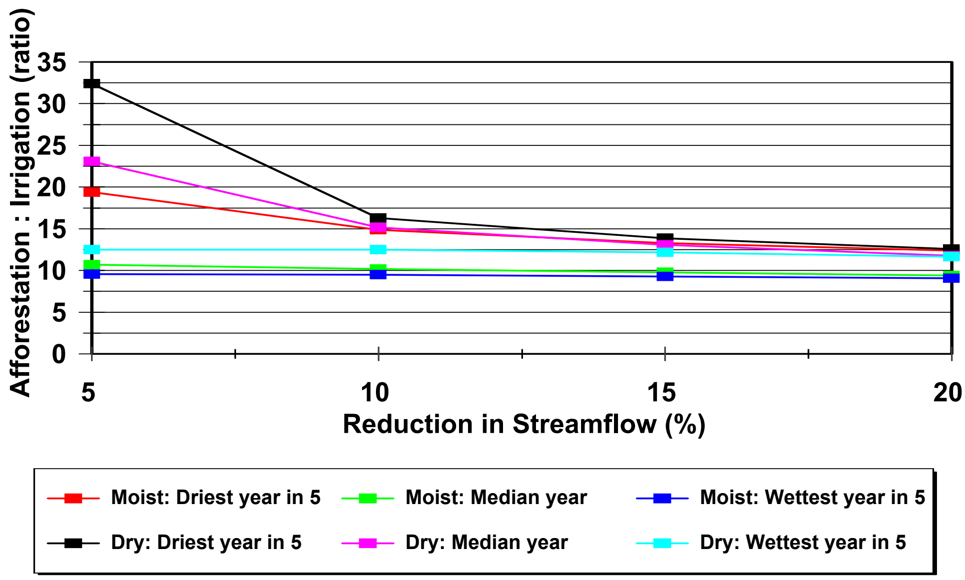

Figure 10.6 Ratio of the area of afforestation to a unit area of irrigated sugarcane for different percentages of streamflow reduction, macro-climatic and seasonal conditions in the Pongola-Bivane system (after Taylor, 1997)

Generally, the drier the catchment and season, the higher the ratio, i.e. more ha under afforestation would utilise as much water as 1 ha of irrigated sugarcane would. Obviously for different types of plantations (e.g. pines) or irrigation practices (e.g. annual crops, or different scheduling procedures) the ratios would be different.

10.8 WHAT CONCLUSIONS MAY BE DRAWN FROM THIS SENSITIVITY STUDY?

Certain land uses are more sensitive than others in their influence on hydrological responses. Two such land uses in a southern African context are afforestation to exotic evergreen tree species and irrigation. This chapter has shown that relative influences of these two land uses can be quite different on total flows, stormflows and baseflows, and that response differences can be highly dependent on the macro-climatic region one is working in.

What can be concluded from the afforestation component of the study is, first, that it should be reiterated that forest water usage is, in relative terms, considerably more demanding in drier areas than in moister areas. This is testified by the higher percentage reductions for all three variables under each of the three scenarios assessed. In absolute (i.e. m^3 or mm equivalent) terms, however, a second conclusion is that the moister the area, the greater the streamflow reduction by plantation forestry. Thirdly, runoff reductions are, relatively, more severe in dry years than in wet years. Fourthly, reductions in the baseflows generated tend to be consistently more severe than those of stormflows in the DSC, while in the MSC this is the case only in dry years. In a MSC, stormflows from forested catchments are reduced relatively more than baseflows under both median and wet year condition. These 'mixed messages' already indicate that issues surrounding streamflow reduction activities are, in hydrological terms, not simple.

The fundamental difference between impacts of afforestation and irrigation again needs to be stressed once more, *viz*. that while afforestation alters the actual streamflow generating mechanisms of both Q_S and QB, irrigation alters the streamflow available to downstream users by direct water abstractions, either from a reservoir or from the run-of-river flows. Furthermore, in the case of irrigation, not only is the water available to downstream users impacted in regard to quantity, but frequently there is also a negative impact on the downstream water quantity via return flows from often heavily fertilised irrigated fields.

In the final analysis this sensitivity study has shown that within the Pongola-Bivane system (and there is no reason to believe that results would be significantly different elsewhere) the unit area ratio (i.e. per ha) of water use by irrigated sugarcane vs afforestation by *Eucalyptus grandis* is generally of the order of 9 - 15, i.e. 1 ha irrigated sugarcane utilises as much additional water as 9 - 15 ha afforestation. This ratio increases to > 30 for smaller percentage reductions in streamflow. The ratio also tends to be higher in drier years and for drier subcatchments.

In a more general context this chapter highlights that, where different sectors are competing for a finite volume of water in a variable climate and conflicts over water arise which need to be managed or resolved objectively by modelling, there is a definite need for models which can separate stormflow and baseflow generating mechanisms (cf.Chapter 2), and for models which have been structured in a mechanistic/deterministic manner to account for the influences of land use and associated management practices under both dryland and irrigated conditions. In the light of serious potential conflicts over effective water use looming in South Africa, and the National Water Act's emphasis on more integrated water resources management (NWA, 1998), focus will have to move away from more simplistic and calibrated water balance models operating in time steps which obliterate much of the information required to make certain crucial water related decisions, to more deterministic and short time step based models which can give intrinsically 'correct' answers for the 'correct' hydrological reasons.

10.9 ACKNOWLEDGEMENTS

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CHAPTER 11

CAN ADDITIONAL STREAMFLOWS FROM CLEARING OF ALIEN INVASIVE VEGETATION IN RIPARIAN ZONES BE USED TO COMPENSATE FOR AFFORESTATION ELSEWHERE? A CASE STUDY FROM THE PONGOLA-BIVANE CATCHMENT

G.P.W. Jewitt.[1] M.J.C. Horan,[1] K.B. Meier[2] and R.E. Schulze[1]

[1] School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

[2] Land Resources International, Pietermaritzburg, South Africa

ABSTRACT

There is a growing concern regarding the extent of uncontrolled invasion and infestation of alien vegetation in South Africa, particularly along the moister riparian areas of a catchment where seed dispersion and alien tree establishment conditions are optimal. This study set out to simulate the impact of alien invasive vegetation on median annual and mean four month low flows in the Pongola-Bivane catchment to assess scenarios of compensatory forestry, i.e. granting permits for commercial afforestation elsewhere in the catchment, where the additional water used by the forest would be compensated for by the reduction in water use by the removal of alien vegetation. In order to achieve the above objectives, the 20 subcatchments making up the Pongola-Bivane were each further delineated by land use into sub-subcatchments, of which one was the riparian zone, into which streamflows from other upstream subcatchments were routed, and out of which streamflows were routed downstream. The *ACRU* model was modified to account for any subsurface flows from upslope to feed into the riparian zone as influent flows, and also to account for the percentage of alien infestation of the riparian zone as well as the density of infested aliens. Hydrological responses were simulated for scenarios of current land use, of riparian zone invasive vegetation removed and replaced by a natural vegetation of grass, and of differences in water use by different percentages and densities of alien infestation vs water use when riparian zones were cleared. The potential for compensatory commercial afforestation was then calculated per subcatchment. It was found to range from 0% to 18 - 20%. The economic feasibility of compensatory forestry in the Pongola-Bivane was established. A net benefit analysis undertaken showed clear economic benefits of compensatory forestry for different scenarios.

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11.1 WHAT ARE THE HYDROLOGICAL CONCERNS ABOUT ALIEN INVASIVE VEGETATION IN SOUTH AFRICA?

There is growing concern regarding the extent of uncontrolled invasion and infestation of alien vegetation in South Africa. It has been suggested that invading alien plants are causing the loss of almost 7% of the annual flow in South Africa's rivers each year (Versfeld *et al*., 1998). In KwaZulu-Natal, preliminary assessments suggest that over 922 000 ha, or more than 10% of the surface area, is infested to some degree while for the entire South Africa the estimate is 10 000 000 ha of land. Acacia species (predominantly wattle) are the most widespread invasive species and are becoming increasingly common along river channels (Versfeld *et al*., 1998).

Riparian areas are usually found to be the most heavily infested areas of a catchment as it is in these moister areas that seed dispersion and tree establishment conditions are optimal. It is often suggested that, because of the continuous availability of water, trees growing in the riparian zone use substantially more water than those growing elsewhere in the catchment, though there has been little conclusive research to support this assumption. Available research suggests that trees in the riparian zones transpire more water than their counterparts elsewhere in the catchment (Dye *et al*., 2000) and that initial clearing of vegetation from riparian zones will provide more streamflow in the river channel (Scott and Lesch, 1995; Rountree and Beyers, 2000). However, these studies all emphasise that results are still not conclusive because of complexities arising from the variability in physiographic and climatic conditions of the various study areas, as well as the short-term nature of these experiments.

The removal of such vegetation has been the focus of the so-called 'Working for Water' programme. This programme has focussed largely on the clearing of alien vegetation in the riparian zones as it is in these areas where infestation is usually most dense, and where the alien vegetation is assumed to have the greatest impact on the water resource. Examples of alien invasive riparian growth and the removal/replacement thereof are illustrated in Figure 11.1.

There are areas in South Africa where a moratorium on additional commercial afforestation has been enforced because of downstream water supply concerns. A question raised is whether clearing of alien invasive vegetation in the riparian zones, such as deep rooted and high water demanding wattle, and replacing it with shallower rooted and less water demanding vegetation, such as grassland, can be compensated for by the establishment of commercial plantations elsewhere in a catchment and still result in an improvement of the water supply and an economic benefit to the grower.

11.2 WHAT DID THIS STUDY SET OUT TO SHOW?

There was, up until 2000, a moratorium on permits being issued for additional commercial afforestation in the 5 789 km^2 Pongola-Bivane catchment in KwaZulu-Natal. However, a detailed land use survey undertaken in 1996 (Schulze *et al*., 1997) showed that approximately 130 km^2 of the catchment's riparian area is infested by wattle and a further 15 km^2 of the non-riparian areas are covered by so-called exotic clumps. Exotic clumps are non-riparian patches of alien invasive vegetation. In previous reports (e.g. Schulze *et al*., 1996), they had been classified according to genus (pine, wattle, eucalyptus) and density (sparse, intermediate, dense). It was suggested that a commitment by stakeholders to the removal of alien invasive vegetation may be compensated by, for example, a partial lifting of the afforestation moratorium under specific circumstances.

The aims of this case study were therefore:

- to assess the impact of alien invasive vegetation on the median annual runoff, seasonal runoff and mean four month low flows in the Pongola-Bivane catchment upstream of the gauging weir W4H003, and
- to assess scenarios of compensatory land use, i.e. the potential granting of planting permits for commercial afforestation, where the additional water used by forests planted elsewhere in the catchment would be compensated by the reduction in water use by the removed alien vegetation.

Figure 11.1 Examples of alien invasive riparian growth and removal/replacement thereof

This case study built on the framework and databases developed by a series of previous studies in the Pongola-Bivana catchment (Schulze *et al*., 1996; 1997; 1998) and adds value to these by way of more detailed consideration of land use impacts in the Pongola-Bivane with the use of the *ACRU* agrohydrological modelling system (Schulze, 1995).

11.3 HOW WAS THE PONGOLA-BIVANE CATCHMENT CONFIGURED FOR MODELLING?

The 5 789 km^2 Pongola-Bivane system under study is that catchment upstream of the Department of Water Affairs and Forestry (DWAF) weir W4H003 (Figure 11.2). Straddling the northern border between KwaZulu-Natal and Mpumalanga provinces and with a small area extending into Swaziland, the catchment stretches latitudinally from 27˚05' S to 27˚25' S and longitudinally from 30˚15' E to 31˚40' E. Altitudinally the means for the QCs range from 714 m in the east to 1 750 m in the west. Mean annual precipitation (MAP) ranges from 1 071 mm in the west to 747 mm in the east. For the purposes of simulation with the *ACRU* model, the catchment was delineated into 20 subcatchments, generally corresponding with the DWAF Quaternary Catchments (QCs) for the area (Figure 11.3).

Quaternary (and smaller) subcatchments making up the study area were further discretised into land use units by area. One of the sub-subcatchments in each of the 20 Quaternary or smaller units within the Pongola-Bivane catchment was a delineated riparian zone. The area of each of these sub-subcatchments was calculated from the land cover database (Table 11.1) and the area of actual alien riparian vegetation was also calculated as a percentage of the total riparian zone occurring within each catchment. The soils and vegetation parameters could then be adjusted in each riparian zone's sub- subcatchment so that the *ACRU* model could simulate the hydrological processes occurring within those zones accurately.

The streamflows from the grassland sub-subcatchments within each of the 20 basic subcatchments, together with streamflows from the other contributing land use sub-subcatchments, were routed through the riparian zone. Flows from any upstream subcatchments contributing to a particular subcatchment were also routed through that riparian zone, as depicted in Figure 11.3.

11.4 WHAT IS THE CURRENT LAND COVER AND LAND USE STATUS OF THE PONGOLA-BIVANA CATCHMENT?

Land cover and land use were derived from 1:30 000 aerial photographs flown in 1996 and verified/updated by intensive field work in 1997 and 1999. Eighteen land use classes were identified and their percentage coverage in each of the 20 subcatchments is given in Table 11.1. It is evident from Table 11.1 that riparian wattle and exotic clumps together make up over 5% of the land cover in one of the 20 subcatchments and over 3% in a further eight of the 20 subcatchments. Mapped land use distribution is shown in Figure 11.4. For the purpose of assigning areas to the sub-subcatchments the 18 identified land uses were regrouped into eight categories. The riparian alien wattle and replacement grassland land cover related model input is shown in Table 11.2. Note that, when compared with the replacement grassland, the alien wattle has a higher water use coefficient, high interception per rainday and higher infiltrability (i.e. coefficient of initial abstraction), in addition to remaining in relatively vigorous growth throughout the year.

11.5 WHAT ADAPTATIONS HAD TO BE MADE TO THE *ACRU* MODEL AND ITS INPUT TO ACCOUNT FOR ENHANCED RIPARIAN ZONE WATER AVAILABILITY?

For the purposes of this study the *ACRU* model routes the contributing areas' surface flows into the riparian sub-subcatchments as surface and near surface stormflow, Q_s. Baseflows are routed from the contributing areas to the riparian zone sub-subcatchments as subsurface flows, Q_b (Figure 11.5). This can increase the soil moisture of the riparian zone, as would be expected to occur naturally . The subsurface flow into the riparian sub-subcatchment first 'fills' the subsoil horizon to saturation. Once this is exceeded, then the topsoil horizon is filled, until the excess water overflows from the soil, and is aggregated to the stormflow generated from the catchment. This increased soil moisture is then available to the vegetation of the riparian zone for plant water use. The remaining subsurface (baseflow) and surface flows of the riparian zone are combined before being routed downstream as channel flow. Any flows exceeding the capacity of the channel becomes overflow from the channel and is available for re-infiltration into the topsoil horizon of the riparian zone. Any outflow from the riparian zone is then routed

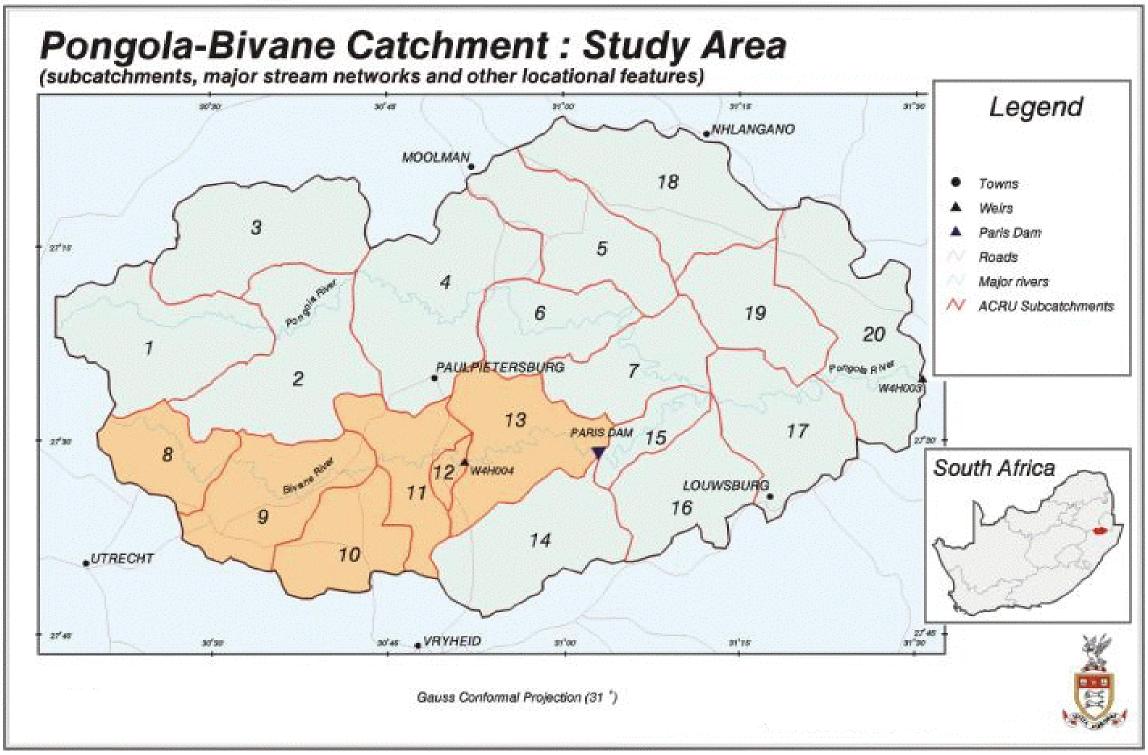


Figure 11.2 Location and subcatchment delineation of the Pongola-Bivane catchment (Schulze *et al*., 1997)

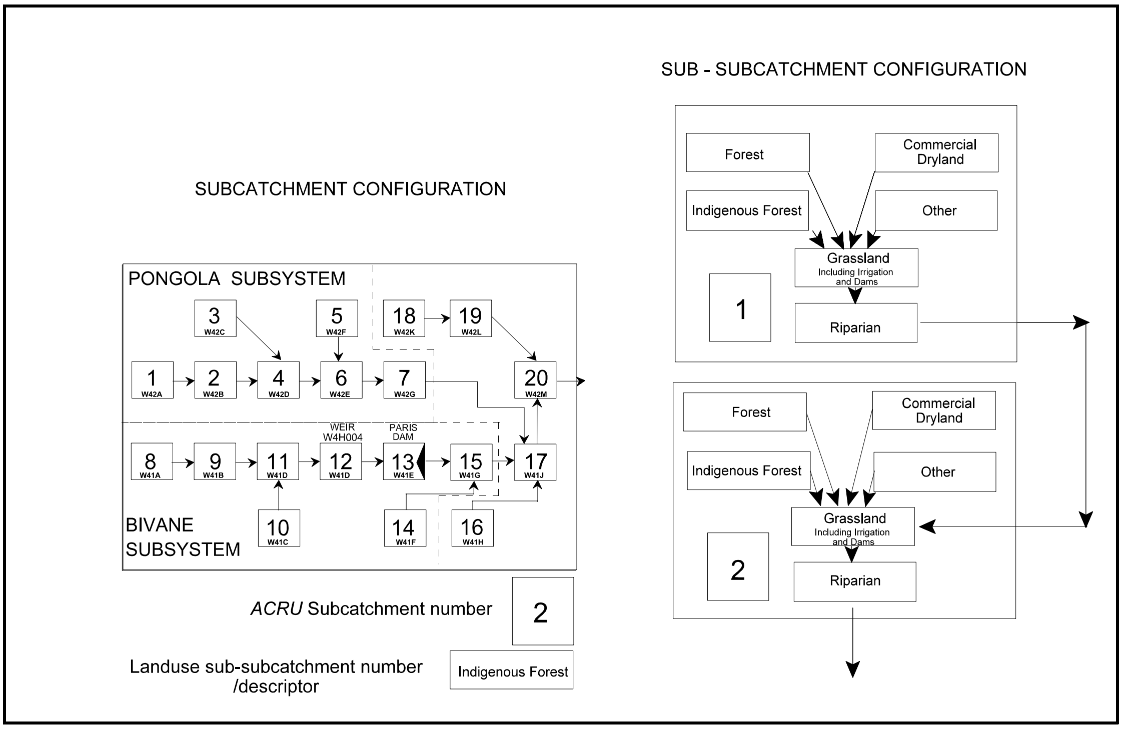


Figure 11.3 Pongola-Bivane study area : Subcatchment configuration (after Schulze *et al*., 1998)

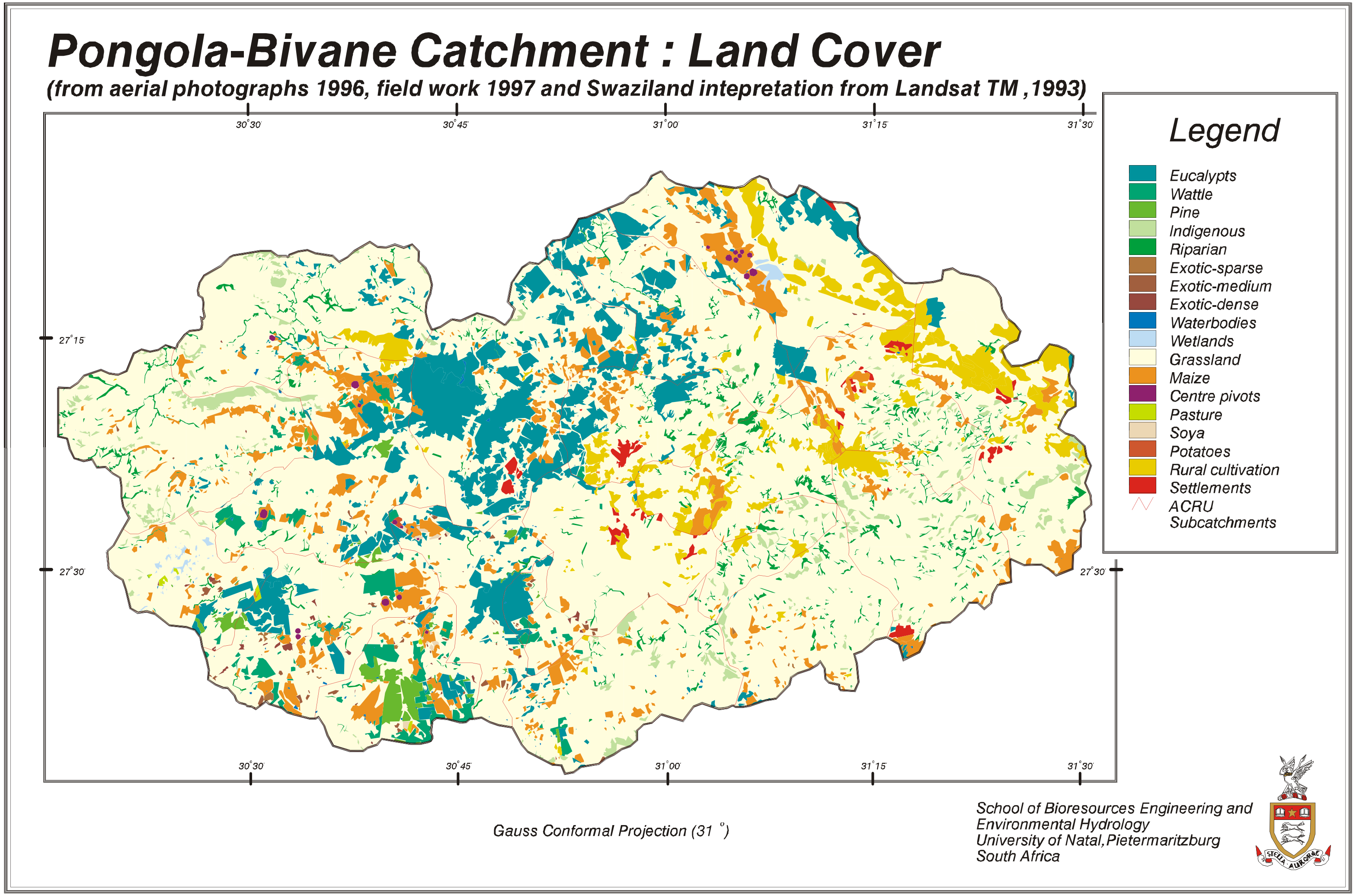


Figure 11.4 Land cover and land use in the Pongola-Bivane study area derived from aerial photographs 1996 and field work 1997, with Swaziland's land use interpreted from Landsat TM images (after Schulze *et al.*, 1998)

Table 11.1 Distribution of present land cover and land use from 1996 aerial photographs and 1997 field work for each subcatchment by percentage (after Schulze *et al*., 1997)

Sub- and Quaternary Catchment Numbers		Area (km^2)	Euca-lypts	Wattle	Pines	Indige-nous	Exotic Clumps			Riparian Wattle	Water Bodies	Wet-lands	Centre Pivot	Maize	Soya	Pot a-toes	Pasture	Settle-ment	Rural Culti-vation	Grass-land
							Sparse	Medium	Dense											
1	W42A	389.68	0.74	0.91	0.28	6.04	0.00	0.08	0.04	3.35	0.06	0.00	0.00	6.13	0.00	0.00	0.00	0.00	0.04	82.34
2	W42B	419.03	13.32	4.12	1.34	0.60	0.00	0.07	0.00	1.09	0.17	0.00	0.42	12.05	0.00	0.00	0.00	0.00	0.88	65.94
3	W42C	381.42	3.88	0.09	0.00	2.60	0.00	0.02	0.02	3.45	0.07	0.00	0.12	2.52	0.00	0.00	0.00	0.00	3.82	83.42
4	W42D	485.10	43.34	0.04	0.06	0.48	0.00	0.01	0.00	0.64	0.22	0.00	0.00	5.94	0.00	0.00	0.00	0.92	0.37	47.97
5	W42F	310.01	20.52	0.09	0.00	0.46	0.00	0.06	0.03	2.63	0.01	0.00	0.00	4.01	0.00	0.00	0.00	0.00	1.50	70.70
6	W42E	226.79	18.42	0.42	0.00	0.20	0.00	0.03	0.02	3.32	0.0.9	0.00	0.00	5.09	0.00	0.00	0.00	2.34	8.63	61.43
7	W42G	243.60	0.00	0.00	0.00	0.17	0.00	0.02	0.00	3.35	0.00	0.00	0.00	7.75	0.00	0.00	0.00	0.00	16.40	70.31
8	W41A	183.10	6.30	0.40	2.49	1.07	0.00	0.70	0.48	1.31	0.11	2.22	0.00	4.49	0.00	0.00	0.82	0.00	0.00	76.61
9	W41B	305.41	9.68	7.33	0.99	0.00	0.57	0.68	0.92	1.46	0.17	0.00	0.57	11.48	0.00	0.00	0.16	0.00	0.00	68.77
10	W41C	218.88	15.70	14.04	12.89	0.23	0.08	0.71	0.32	0.59	0.22	0.00	0.09	12.49	0.67	0.00	0.33	0.00	0.00	51.64
11	W41D	212.40	19.73	1.39	0.77	0.00	0.00	0.78	0.22	1.03	0.21	0.00	0.25	5.89	0.79	0.42	0.00	0.00	0.00	68.51
12	W41D	31.72	55.18	6.77	0.46	0.00	0.00	2.09	0.00	0.95	0.09	0.00	0.00	3.21	0.00	0.00	0.00	0.00	0.00	31.26
13	W41E	310.15	2.30	1.32	0.00	0.00	0.00	0.33	0.28	0.95	0.02	0.00	0.00	2.03	0.00	0.00	0.00	3.69	2.00	87.08
14	W41F	335.64	1.82	1.16	0.17	4.92	0.00	0.05	0.01	1.82	0.10	0.00	0.00	6.11	0.00	0.00	0.00	0.00	0.56	83.27
15	W41G	101.83	0.00	0.24	0.00	6.10	0.00	0.00	0.00	6.20	0.00	0.00	0.00	0.90	0.00	0.00	0.00	0.00	5.29	81.28
16	W42H	263.24	0.75	0.07	0.00	2.73	0.16	0.00	0.00	2.73	0.02	0.00	0.00	4.23	0.00	0.00	0.00	0.00	0.62	88.69
17	W42J	303.18	0.31	0.00	0.00	4.20	0.00	0.00	0.00	4.12	0.03	0.00	0.00	4.72	0.00	0.00	0.00	1.02	5.02	80.58
18	W42K	407.89	11.80	0.11	0.00	1.34	0.00	0.03	0.04	0.52	0.32	1.21	0.82	10.80	0.00	0.00	0.00	0.17	12.54	61.53
19	W42L	247.11	1.83	0.00	0.00	2.69	0.00	0.01	0.00	4.14	0.02	0.00	0.00	7.04	0.00	0.00	0.00	2.13	9.61	72.52
20	W42M	412.61	1.62	0.00	0.00	3.47	0.00	0.0 2	0.03	1.75	0.01	0.00	0.00	5.42	0.00	0.00	0.00	1.08	19.91	66.67

Table 11.2 Month-by-month land cover model input of riparian wattle and replacement grassland

Land Cover	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Riparian Invasive Wattle	Water use coefficient	0.90	0.90	0.90	0.88	0.85	0.86	0.89	0.90	0.92	0.92	0.90	0.90
	Interception loss	2.00	2.00	2.00	2.00	1.90	1.85	1.85	1.85	1.90	1.95	2.00	2.00
	Roots in topsoil	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	Coefficient of I_a	0.25	0.25	0.25	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.25
Replacement grassland (≡ Acocks #64)	Water use coefficient	0.75	0.75	0.75	0.65	0.55	0.40	0.40	0.50	0.65	0.75	0.75	0.75
	Interception loss	1.80	1.80	1.80	1.70	1.60	1.50	1.50	1.60	1.80	1.80	1.80	1.80
	Roots in topsoil	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
	Coefficient of I_a	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20
Pines (age 8 years)	Water use coefficient	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	Interception loss	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30
	Roots in topsoil	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
	Coefficient of I_a	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Eucalypts (age 5 years)	Water use coefficient	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	Interception loss	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
	Roots in topsoil	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
	Coefficient of I_a	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Indigenous Forest	Water use coefficient	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	Interception loss	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	Roots in topsoil	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	Coefficient of I_a	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35

NB : Interception loss = mm/rainday; Roots in topsoil = fraction

into the downstream grassland sub-subcatchment (Figure 11.3). This process is illustrated in Figure 11.5. In this study the baseflow was partitioned within the model, based on the degree of infestation of the riparian zone (next section), in order to account for different water use characteristics of naturally vegetated and infested areas of the riparian zone (Figure 11.6) .

11.6 HOW WERE AREAS OF RIPARIAN INFESTATION CALCULATED?

The land use which had been mapped and identified in the Pongola-Bivane (Schulze *et al*., 1996; 1997; 1998) was used for the calculation of the riparian zone infestation. The area of riparian alien invasive plants was obtained from these studies (Schulze *et al*., 1998). These areas were deemed to represent the areas per subcatchment which were densely infested, i.e. where more than 75% of the area consisting alien wattle. In order to assess the total riparian zone within a catchment, the rivers captured from 1:50 000 topographical sheets were buffered to 30 m on each side using the buffering facility available in the ARC/INFO Geographical Information System (ESRI, 1996). These assumptions of riparian zone area and percentage infestation concur with findings of the field evaluation undertaken in 1999. This process yielded a network of polygons 60 m wide following the river patterns. The area of these polygons was calculated per subcatchment, to determine the total defined riparian zones. A diagrammatic representation of this is shown in Figure 11.7. The ratio of the mapped invasive vegetation to the total defined riparian zone was calculated as a percentage per subcatchment (Table 11.3), and these values were then entered into the *ACRU* menu for computation in the riparian zone sub-routine (previous section).

11.7 WHAT ASSUMPTIONS HAD TO BE MADE FOR COMPENSATORY FORESTRY?

- Any catchment afforested to 20% or more, was not permitted any additional (compensatory) afforestation (Schulze *et al*., 1998)
- Each subcatchment within the Pongola-Bivane system was considered as its own entity and the compensatory afforestation modelled for each subcatchment, before the influences of upstream contributions were reviewed. It is, therefore, possible that the balanced conditions are met on a Quaternary Catchment basis (or the 20% benchmark being reached), but downstream accumulated streamflows are in excess of the uncleared conditions.
- The alien invasive vegetation in the riparian zone was assumed to be 5 year old wattle growing without any site preparation, with the trees growing in close proximity to each other and with a grass and litter understorey. The model input values for this are shown in Table 11.2.

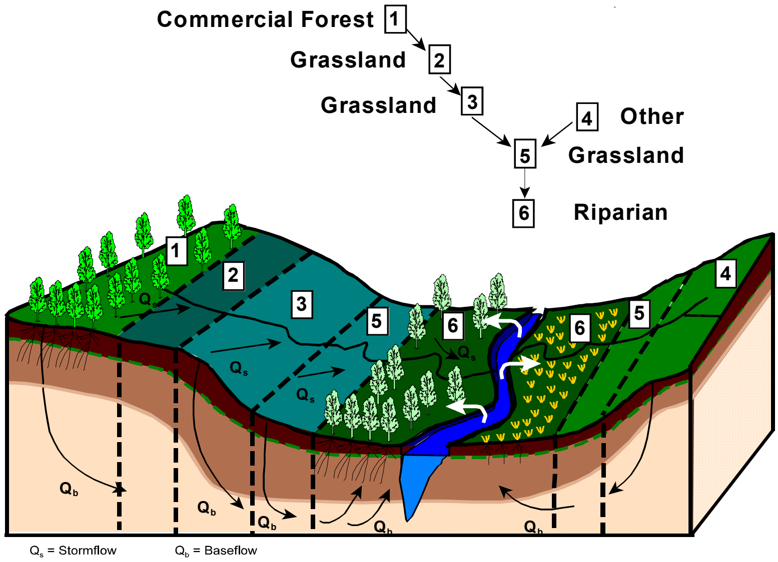


Figure 11.5 Schematic representation of the riparian zone and its contributing sub-subcatchments (after Meier *et al*., 1997; Schulze, 2000)

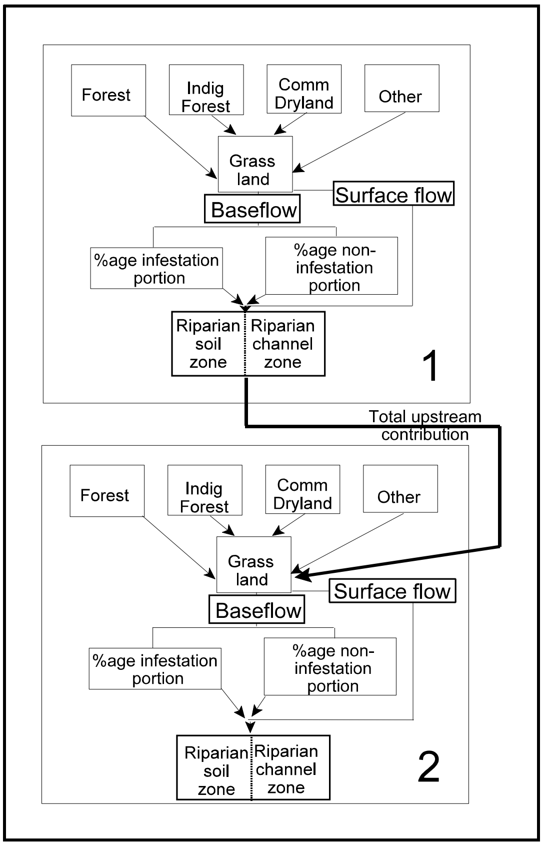


Figure 11.6 Land use sub-subcatchment linkages and baseflow partitioning, as designed for the *ACRU* model for this study

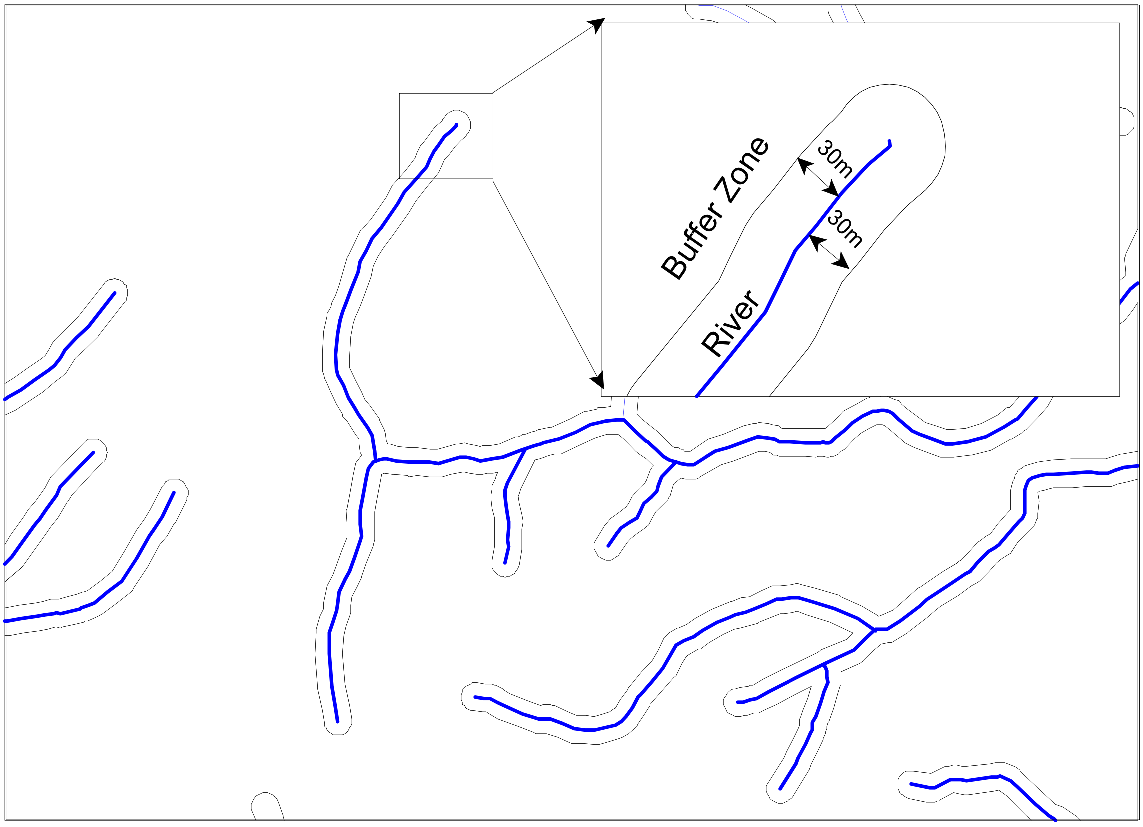


Figure 11.7 An example of the rivers depicted on a 1:50 000 topographical map (blue) and the 30 metre buffer zone as generated by ARC/INFO (black)

Table 11.3 Total riparian zones, dense infested areas and percentages of dense infestation in the Pongola-Bivane study area

QC Number	Riparian area (km^2)	Riparian infestation (km^2)	Percentage infestation	QC Number	Riparian area (km^2)	Riparian infestation (km^2)	Percentage infestation
1	50.78	13.04	25.68	11	24.87	2.19	8.81
2	41.70	4.59	11.01	12	3.33	0.30	9.00
3	50.69	13.14	25.92	13	56.34	2.95	5.24
4	48.82	3.11	6.37	14	48.85	6.10	12.49
5	31.69	8.16	25.75	15	17.49	6.31	36.08
6	39.46	7.54	19.11	16	35.33	7.17	20.30
7	41.40	13.02	31.45	17	50.45	12.48	24.74
8	26.22	2.40	9.15	18	34.86	2.10	6.02
9	38.25	4.46	11.66	19	37.87	10.23	27.02
10	21.14	1.29	6.10	20	63.61	7.23	11.37

- The cleared riparian zone was deemed to consist of the indigenous grassland of the area, mainly Acocks Veld Type # 64 (Acocks, 1988). The land cover related model input values for this are also shown in Table 11.2.
- The *ACRU* model afforestation inputs for the compensatory forestry are detailed in Table 11.2.
- It was assumed that any compensatory afforestation would consist of the genera already planted in that catchment, in the same proportion as current conditions.
- The land use extracted from the database was deemed accurate, but it was noted that this database was not originally assembled specifically for a riparian zone study.

11.8 HYDROLOGICAL RESULTS : WHAT DID THEY SHOW?

a) What scenarios were simulated?

Hydrological responses from the following catchment land use scenarios were simulated:

- current land use conditions
- all riparian zone invasive vegetation removed and replaced with natural vegetation according to Acocks' (1988) Veld Types
- differences in water use between an assumed 10% of all riparian zones covered by dense alien infestation and those 10% zones under cleared conditions and
- differences between water use between an assumed 25% sparse infestation of all riparian zones and cleared conditions.

b) Scenario 1 : Streamflows and low flows under current land use conditions

Table 11.4 (top; columns 6, 7) shows streamflow and 4 month low flow at the outlet of each subcatchment for present land use conditions. Results depict the mean depth of streamflows over the entire upstream area at the outlet of each subcatchment. Riparian zones, and afforested area information was obtained from the present land cover data base.

Subcatchments 4 - 5 and 9 -12 already contain the full complement of 20% afforestation; thus further compensatory afforestation in these catchments was not investigated. The riparian zones in these catchments are modelled in both cleared and present states, however, to provide insight into the potential for increased water availability for downstream users. In most cases, the median conditions are extracted in preference to the means, to moderate the influence of extreme events or outliers from the data sets. However, in order to calculate the 4 month low flows, the means of streamflows from June to September were summed. The sum of mean values from *ACRU* output, but not the sum of median or percentile values, may be accumulated, as explained in the *ACRU* User Manual (Smithers and Schulze, 1995).

c) Scenario 2 : Streamflows and low flows under conditions of riparian alien exotic infestations replaced by veld

In order to simulate the potential conditions which could exist if all riparian zones were cleared of alien vegetation, the model parameters relating to land cover for the riparian zone were adjusted from those depicting exotic infestation, to those reflecting the characteristics of the natural grassveld for the area. In this case, the veld was considered to be Acock's Veld Type #64. Results from this scenario are shown in columns 8 and 9 of Table 11.4 (top).

d) Scenario 3 : Impacts on streamflows of clearing the riparian zones

Table 11.4 (bottom) shows the differences in simulated streamflows between current and cleared conditions. There are noticeable differences between both median annual streamflow and mean low flows. These differences are noted in both the upper and lower areas of the study catchment.

e) Scenario 4 : Potential increases in afforested areas after riparian zone clearance (compensatory afforestation)

The differences in median annual streamflows between existing and cleared conditions were then used as a basis for the estimation of the area of compensatory forestry that could be planted in each

Table 11.4 Median annual streamflows and 4 month mean low flows for areas under present land cover conditions (columns 6, 7), with alien exotic infestations replaced by veld in the riparian zone (columns 8, 9) and, in the table below, the differences in streamflows between cleared and uncleared riparian zone scenarios

Sub-catchment Number	Sub-catchment area (km^2)	Area afforested (km^2)	Percentage afforestation	Area of dense riparian infestation by exotics (km^2)	Streamflow (mm): Median conditions (annual)	4 month low flow: Mean conditions (mm)	Streamflow (mm): Median conditions (annual)	4 month low flow: Mean conditions (mm)
					Land cover under present conditions (incl. riparian infestation)		Cleared riparian zones	
1	389.68	7.97	2.04	13.04	398.2	38.1	410.3	43.2
2	419.03	79.00	18.85	4.59	323.8	29.8	331.9	33.4
3	381.42	15.28	4.00	13.14	305.9	29.3	320.5	34.5
4	485.10	210.77	*43.45	3.11	268.1	25.5	277.4	28.9
5	310.01	64.15	*20.69	8.16	174.5	18.7	188.4	22.2
6	226.79	42.85	18.89	7.54	251.8	23.5	260.0	27.1
7	243.60	0.06	0.00	13.02	241.0	23.1	249.9	27.0
8	183.10	18.99	10.37	2.40	333.9	32.7	342.9	38.1
9	305.41	62.15	*20.35	4.46	236.7	23.6	244.7	28.0
10	218.88	73.85	*33.74	1.29	154.1	19.2	162.9	22.0
11	212.40	48.63	*22.90	2.19	193.2	21.7	200.1	25.3
12	31.72	20.46	*64.50	0.30	188.7	21.0	195.5	24.6
13	310.15	13.11	4.22	2.95	173.6	18.9	180.0	22.3
14	335.64	10.80	3.22	6.10	175.6	16.7	189.5	21.0
15	101.83	0.24	0.23	6.31	172.3	17.7	181.5	21.5
16	263.24	2.58	0.98	7.17	144.7	13.0	154.9	17.5
17	303.18	0.95	0.31	12.48	205.5	21.1	216.8	25.1
18	407.89	48.91	11.99	2.10	233.8	28.7	239.1	31.3
19	247.11	4.56	1.85	10.23	249.9	29.1	259.6	33.1
20	412.61	6.93	1.68	7.23	211.5	23.4	222.6	27.4

* designates over 20% afforestation

Sub-Catchment Number	Difference in median annual streamflows (mm)	Difference in 4 month low flows (mm)
1	12.1	5.1
2	8.1	3.6
3	14.6	5.2
4	9.3	3.4
5	13.9	3.5
6	8.2	3.6
7	8.9	3.9
8	9.0	5.4
9	8.0	4.4
10	8.8	2.8
11	6.9	3.6
12	6.8	3.6
13	6.4	3.4
14	13.9	4.3
15	9.2	3.9
16	10.2	4.5
17	11.3	4.0
18	5.3	2.6
19	9.7	4.0
20	11.1	4.0

subcatchment. As noted previously, subcatchments where afforestation already exceeds 20% were not considered for compensatory forestry and the water 'available' from clearing riparian zones in these catchments is transferred to the next downstream subcatchment. Thus, the estimated areas of compensatory forestry may reflect more than the water available from clearing in that particular subcatchment. The results of this scenario are presented in Table 11.5 and illustrated by Figure 11.8.

Table 11.5 Differences in streamflows and areas between present land cover conditions, and compensatory afforestation after alien exotic clearance from the riparian zone

Sub-catch-ment No.	Sub-catch-ment area (km^2)	Streamflow (mm) Median conditions (annual)	4 month low flow Mean conditions (mm)	Stream-flow (mm) Median conditions (annual)	4 month low flow Mean conditions (mm)	Difference in Median Conditions (mm)	Difference in 4 month low flow (mm)	Present affores-tation (km^2)	Total afforestation with compensa-tion (km^2)	Additional compensatory afforestation (km^2)	Percentage of catchment afforested after compensation	Percentage of new (compensatory) forest area
		Present (infested) conditions		Compensatory Afforestation conditions								
1	389.68	398.2	38.1	398.4	41.9	-0.2	-3.8	7.97	32.72	24.75	8.4	6.35
2	419.03	323.8	29.8	325.0	32.7	-1.2	-2.9	79.00	83.81	4.81	20.0	1.15
3	381.42	305.9	29.3	306.0	32.8	-0.1	-3.5	15.28	45.28	27.30	11.9	7.15
4	485.10	268.1	25.5	271.2	28.0	-3.1	-2.5	210.77	210.77	0.00	43.5*	0.00
5	310.01	174.5	18.7	188.4	22.2	-13.9	-3.5	64.15	64.15	0.00	20.1*	0.00
6	226.79	251.8	23.5	254.2	26.5	-2.4	-3.0	42.85	45.36	2.51	20.0	1.10
7	243.60	241.0	23.1	243.7	26.2	-2.7	-3.1	0.06	48.72	48.66	20.0	19.98
8	183.10	333.9	32.7	333.5	37.1	0.4	-4.4	18.99	28.26	9.27	15.4	5.06
9	305.41	236.7	23.6	241.5	27.6	-4.8	-4.0	62.15	62.15	0.00	20.3*	0.00
10	218.88	154.1	19.2	162.9	22.0	-8.8	-2.8	73.85	73.85	0.00	33.7*	0.00
11	212.40	193.2	21.7	197.6	25.0	-4.4	-3.3	48.63	48.63	0.00	22.8*	0.00
12	31.72	188.7	21.0	193.0	24.5	-4.3	-3.5	20.46	20.46	0.00	64.5*	0.00
13	310.15	173.6	18.9	174.2	21.6	-0.6	-2.7	13.11	62.13	49.02	20.0	15.80
14	335.64	175.6	16.7	175.5	19.7	0.1	-3.0	10.80	47.12	36.32	14.0	10.82
15	101.83	172.3	17.6	173.4	20.7	1.1	-3.1	0.24	20.37	20.13	20.0	19.76
16	263.24	144.7	13.0	144.7	16.3	0.0	-3.3	2.58	30.70	28.12	11.7	10.68
17	303.18	205.5	21.1	210.1	24.0	-4.6	-2.9	0.95	60.64	59.69	20.0	19.68
18	407.89	233.8	28.7	233.8	30.8	0.0	-2.1	48.91	61.48	12.57	15.1	3.08
19	247.11	249.9	29.1	250.0	32.1	-0.1	-3.0	4.56	32.42	27.86	13.1	11.27
20	412.61	211.5	23.4	213.7	26.2	-2.2	-2.8	6.93	82.52	75.59	20.0	18.30

* Catchments which are already 20% afforested

** A negative value in the difference column indicates that increase in streamflow caused by riparian clearance is greater than the reduction caused by afforestation due to the threshold 20% being reached in that catchment, or upstream

The results suggest that relatively large areas of land may be afforested in the lower reaches of the catchment. However, it should be noted that the suitability of these areas for commercial forestry was not considered. It is likely that catchment physical and climatic factors would render large proportions of these areas unsuitable for afforestation, however.

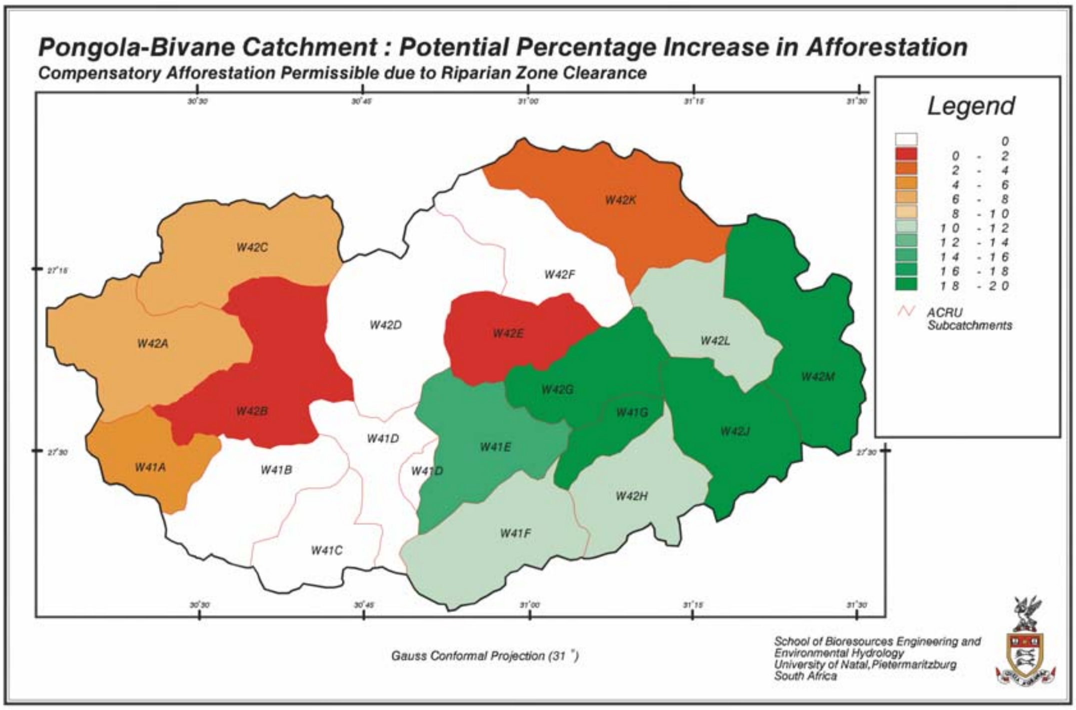


Figure 11.8 Pongola-Bivane Catchment : Potential percentage increases in afforestation. Compensatory afforestation permissible due to riparian zone clearance

Table 11.6 offers an alternative approach to assessing the results of the first two scenarios. The streamflow reductions shown are the estimated increase in volume of water used per hectare of afforestation in each subcatchment when converted from natural grassland and the estimated increases depict potential increase in water yield from the riparian zone by the clearing of alien exotics and the re-establishment of the natural veld type in these areas. Streamflow reductions and increases differ due to differing hydro-climatic and tree characteristics, with water use by trees is estimated to be highest in the upper and wetter subcatchments of the Pongola-Bivane catchment.

Table 11.6 Streamflow increases (m^3. $annum^{-1}$) by converting riparian infested areas to riparian grassland (per hectare) and reductions (m^3.$annum^{-1}$) by converting non-riparian grassland to non-riparian forestry (per hectare) for each catchment in the Pongola-Bivane study area

QC number	Streamflow increases (m^3. $annum^{-1}$) by converting infested riparian zone to grassland	Streamflow reductions (m^3. $annum^{-1}$) by converting grassland to forestry
1	3 616	1 946
2	7 029	1 404
3	4 238	1 812
4	11 231	1 303
5	5 281	1 479
6	4 512	1 242
7	4 060	1 200
8	6 866	1 912
9	4 999	1 375
10	14 931	1 288
11	9 408	1 137
12	2 432	688
13	7 565	967
14	7 648	1 258
15	4 761	617
16	3 745	978
17	4 373	1 612
18	10 294	1 699
19	3 913	1 600
20	5 136	1 323

f) Scenario 5 : Potential impacts of riparian zone clearance assuming sparse infestation

A further scenario was considered in which the impact of clearing riparian zones of alien invasives assumes that the riparian zones mapped were sparsely infested, i.e less than 25% of the riparian zone was assumed to be covered by exotic trees with the balance consisting of the Acocks' Veld Type for that area. The results of this modelled scenario are presented in Table 11.7.

11.9 WHAT IS THE ECONOMIC FEASIBILITY, AND WHAT ARE THE ECONOMIC BENEFITS, OF COMPENSATORY FORESTRY?

In order to assess the economic benefits of the compensatory forestry approach, a comparison of the costs of clearing alien invasive vegetation and the economic benefits that could be obtained from the establishment and ultimate harvesting of an area of commercial forestry was performed. This comparison is made for ratios of the area of compensatory forestry established versus the area of riparian zone cleared ranging from 1 ha commercial forestry for clearing 1 ha of riparian zone to 5 ha commercial forestry for clearing 1 ha of riparian zone.

a) Costs

The cost of clearing alien invasive vegetation in the study area was based on information from existing Working for Water projects in KwaZulu-Natal. This cost equates to R 6 000 per ha to treat densely infested acacia species through an initial clearing operation as well as three follow-up operations (Pitchford, 2000).

Table 11.7 Differences between the cleared and uncleared riparian zone scenarios for sparse infestation for median annual and four month low flow conditions, Pongola-Bivane study area

Sub-catchment Number	Catchment area (km^2)	Streamflow (mm): Median conditions (annual)	4 month low flow: Mean conditions (mm)	Streamflow (mm) : Median conditions (annual)	4 month low flow : Mean conditions (mm)	Difference in Median Conditions (mm)	Difference in 4 month low flows (mm)
		Cleared Conditions		Sparsely Infested Conditions			
1	389.68	410.3	43.2	406.8	42.0	3.5	1.2
2	419.03	331.9	33.4	329.8	32.6	2.1	0.8
3	381.42	320.5	34.5	317.1	33.2	3.4	1.3
4	485.10	277.4	28.9	274.5	27.9	2.9	1.0
5	310.01	188.4	22.2	185.4	21.2	3.0	1.0
6	226.79	260.0	27.1	257.7	26.0	2.3	1.1
7	243.60	249.9	27.0	247.2	25.9	2.7	1.1
8	183.10	342.9	38.1	340.7	36.9	2.2	1.2
9	305.41	244.7	28.0	244.5	27.0	0.2	1.0
10	218.88	162.9	22.0	159.8	21.3	3.1	0.7
11	212.40	200.1	25.3	198.8	24.6	1.3	0.7
12	31.72	195.5	24.6	194.1	23.8	1.4	0.8
13	310.15	180.0	22.3	178.4	21.6	1.6	0.7
14	335.64	189.5	21.0	186.9	20.0	2.6	1.0
15	101.83	181.5	21.5	179.1	20.6	2.4	0.9
16	263.24	154.9	17.5	152.7	16.1	2.2	1.4
17	303.18	216.8	25.1	213.9	24.0	2.9	1.1
18	407.89	239.1	31.3	237.8	30.7	1.3	0.6
19	247.11	259.6	33.1	257.1	32.2	2.5	0.9
20	412.61	222.6	27.4	219.8	26.4	2.8	1.0

The costs per hectare of implementing and running forestry operations in this are for a 12-year forestry rotation were estimated as:

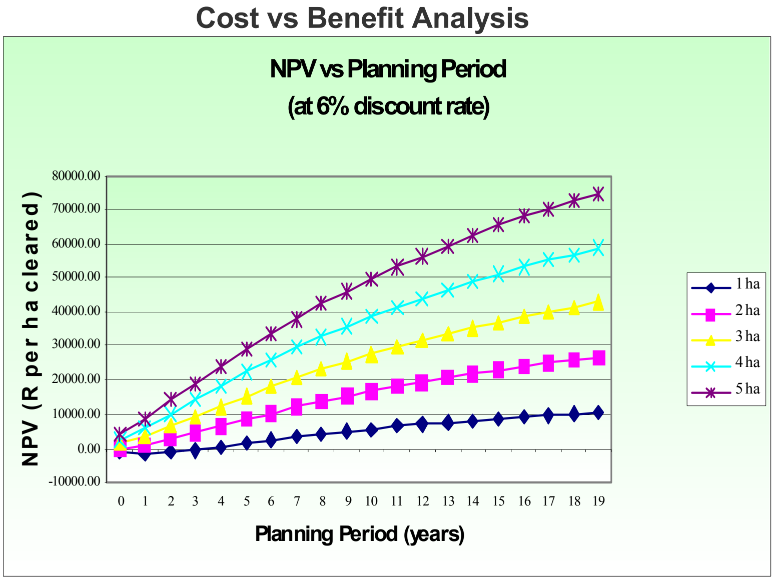
Crop Establishment	R 3 000 per annum for the first 2 years of rotation
Silviculture	R 750 per annum for the next 8 years of rotation
Harvest and transport costs	R 6 000 per annum for the last 2 years of rotation.

b) Benefits

At present pulp timber can be sold in the Pongola area for R 205 per tonne. It is reasonable to assume a yield of approximately 200 tonnes of timber per ha of forestry harvested. Hence the gross profit on one hectare of timber would equate to R 41 000 over a 12 year rotation.

c) Cost vs Benefit

The ratios of the cost of clearing one hectare of alien invasive vegetation versus the benefit obtained for compensated forest area have been summarised in Figure 11.9 (top). The cost vs benefit in this graph are indicated as a Nett Present Value (NPV) at 6% discount rate over 20 years. An assumption made in this example is that the costs and benefits are divided equally through the 12 year rotation. However, if the costs and benefits are assumed to occur within their actual year of rotation, as would be expected if compensatory forest permits are issued, the resulting NPV is less attractive. This is illustrated in Figure 11.9 (bottom), which shows the resulting MPV at 6% discount rate over 20 years.



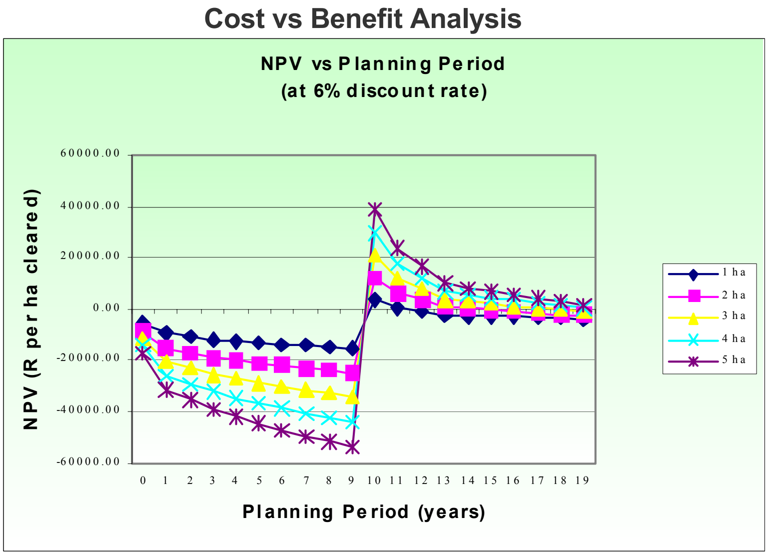


Figure 11.9 Economic benefits for different ratios of compensatory forestry at a 6% discount rate: (top) costs and benefits are divided equally through the 12 year rotation and (bottom) costs and benefits are assumed to occur within the actual year of rotation

11.10 WHAT CONCLUSIONS MAY BE DRAWN FROM THIS STUDY?

The following points highlight the major conclusions of this study:

- Alien invasive vegetation in the riparian zones of the Pongola-Bivane catchment uses a substantial amount of water.
- Several Quaternary Catchments in the study area have less than 20% of their area covered by commercial afforestation. From the modelling undertaken, and from a water use perspecive, the clearing of alien invasive vegetation from the riparian zones can be compensated for by the establishment of new commercial afforestation in these catchments.
- Such ‘compensatory afforestation’ should only be permitted if the riparian zones are maintained free of alien invasive vegetation.
- Clearing of alien invasive vegetation in the riparian zones and maintaining this clearing in addition to the establishment of new commercial afforestation, if managed correctly, will provide more water to downstream users than is the case under existing, uncleared catchment conditions.

- There are definite economic benefits to the implementation of an alien vegetation clearing programme in return for compensatory forest permits, even when a compensation ratio of 1 : 1 is considered. However, since timber is a long rotation crop, cash flow constraints during the first rotation may hinder the implementation of this concept. After the first rotation a positive NPV is likely to be maintained for any compensatory ratio of 1 : 1 or higher.

The clearing of alien invasive vegetation from the riparian zones can be compensated by the establishment of new commercial afforestation in these catchments. This is both hydrologically and economically feasible.

11.11 ACKNOWLEDGEMENTS

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RiparianClearance

CHAPTER 12

HOW DO SIMULATED SEDIMENT YIELDS VARY SPATIALLY AND TEMPORALLY UNDER DIFFERENT LAND USES AND STATES OF DEGRADATION OR REHABILITATION? A CASE STUDY FROM THE MBULUZI CATCHMENT IN SWAZILAND

D. Dlamini and R. E. Schulze

School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

ABSTRACT

Soil erosion is a serious concern in the Mbuluzi catchment in Swaziland, especially upstream of the Mnjoli Dam. Sediments deposited in reservoirs result in the reduction of their storage capacities. Besides scouring and washing away the topsoil which leads to the loss of crop production media, soil erosion and sediment transportation may have negative impacts on the availability and management of water resources.

Owing to the unavailability of any measured records of sediment loads of the streams in the Mbuluzi catchment which to analyse and from which to make generalisations regarding the spatial extent and magnitudes of sediments, the *ACRU* agrohydrological modelling system was used to simulate sediment yield for individual events on a day-by-day basis. The simulations were for hydrologically homogeneous individual subcatchments, of which 40 were delimited in the Mbuluzi, with each subcatchment further discretised into seven dominant land use classes which were assigned critical sediment yield attributes.

Simulation results indicate that the highest sediment yields (exceeding 20 $t.ha^{-1}annum^{-1}$) are generated in the upper middle section and the north eastern part of the catchment. These areas are occupied predominantly by rural communities who practice subsistence agriculture and communal grazing. A comparison of sediment yields simulated under different land uses shows that subsistence agriculture and communal rangelands, i.e. grasslands in poor hydrological condition, produce the highest and second highest sediment yields respectively, while land under forest and rehabilitated grasslands generate the lowest sediment yields. Through an assessment of impacts on present sediment yields of different possible land use changes, it was found that allowing land to be degraded to an overgrazed condition could lead to increases in subcatchment sediment yields by a factor of up to 20 times, while employing land rehabilitation and conservation measures solely by grazing management could result in the reduction of more than 50 % of present sediment yields in certain parts of the catchment.

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12.1 WHAT ARE THE MAJOR CONCERNS REGARDING SEDIMENT YIELDS IN SWAZILAND?

Soil erosion is a serious concern in Swaziland that poses a threat to the sustainability of small scale and subsistence agricultural production (Mushala, 2000) through the scouring and washing away of topsoil which leads to the loss of crop production media. Of particular significance in Swaziland's Mbuluzi catchment is that most rural communities, who are practising subsistence agriculture and communal grazing, and whose areas of occupance have been identified by Mushala (2000) as those affected by very severe soil erosion, are upstream of the Mnjoli Dam. The Umbeluzi Catchment Association, whose affiliation in addition to nature conservation establishments in the catchment includes the Royal Swaziland Sugar Company (a major sugarcane growing and milling company that relies on the dam for its water needs), has indicated that a concern exists regarding the water quality implications and deposition of sediments in the reservoir and subsequent reduction of its storage capacity. An increase in the concentrations of suspended solids in flowing water causes degradation of the environmental quality of rivers. Depending on their chemical composition, sediments may carry plant-usable nutrients such as phosphorus and other fertiliser residues from agricultural lands. Nutrient rich water leads to eutrophication in reservoirs. Eutrophication may, furthermore, lead to increased evaporation and hence water losses. The dense vegetation in dams may also clog pipes and kill aquatic fauna through reduction of dissolved oxygen. Sediments, particularly those which are derived from densely populated areas without proper sanitary facilities may also carry pathogens such as *Escherichia coli (E.coli)*. High concentrations of suspended solids, nutrients and pathogens in water create the need for expensive purification, especially before the water is suitable for domestic and industrial (manufacturing) use.

12.2 WHAT WERE THE OBJECTIVES OF THIS STUDY?

Several soil erosion studies have been undertaken in the Mbuluzi catchment (Figure 12.1), among which are mapping of the spatial distribution of soil erosion (Mushala, 2000) and a detailed survey of the physical, chemical and mineralogical characteristics of soils and saprolites (Scholten, Felix-Henningsen and Mushala, 1995; Mushala, Scholten and Felix-Henningsen, 1996). However, the rates of loss at eroded areas, sediment discharge in streams, impacts of different land uses and their changes, as well as seasonal variation of sediment yields have not been investigated to date, largely as a result of the unavailability of measured records of sediment loads. In order to undertake such studies, the *ACRU* model (Schulze, 1995), which has been verified elsewhere in southern Africa (the Mgeni catchment) as a simulator of event based sediment yield under similar climatic conditions (Kienzle, Lorentz and Schulze, 1997) was used to simulate sediment yield for individual events on a day-by-day basis. The simulations were for hydrologically homogeneous individual subcatchments, of which 40 were delimited in the Mbuluzi, with each subcatchment further discretised into seven dominant land use classes. The simulated time series of sediment yields were used in assessing the spatial and temporal variation of sediment yields, and establishing the effects of different land uses and their changes, in the catchment.

The assessment of the effects of land use management on sediment yields was undertaken by developing prognostic scenarios representing possible future conditions of the catchment. These scenarios were a catchment in poor hydrological condition depicting land degradation as a result of overgrazing, as well as the same catchment in good hydrological condition characterising rehabilitated land following the implementation of sound land and pasture management measures. The impacts were then evaluated by computing the differences between sediment yields simulated under current conditions and those simulated for each of the above scenarios.

This study makes a contribution towards the understanding of the spatial extent and severity of soil loss and sediment yield in the Mbuluzi catchment, thus providing information regarding the vulnerability of the environment to the uses to which it is put. This is essential for the planning and implementation of sound integrated water resources management.

12.3 THE MBULUZI CATCHMENT: WHERE IS IT LOCATED, WHAT ARE ITS CLIMATE CHARACTERISTICS?

The Mbuluzi river originates in the northwest of the Swaziland and drains an area of 2 958.9 km^2 before flowing into Mozambique in the east. The Swaziland component of catchment area stretches latitudinally from 25°54' to 26°30' S and longitudinally from 31°02' to 32°06' E (Figure 12.1).

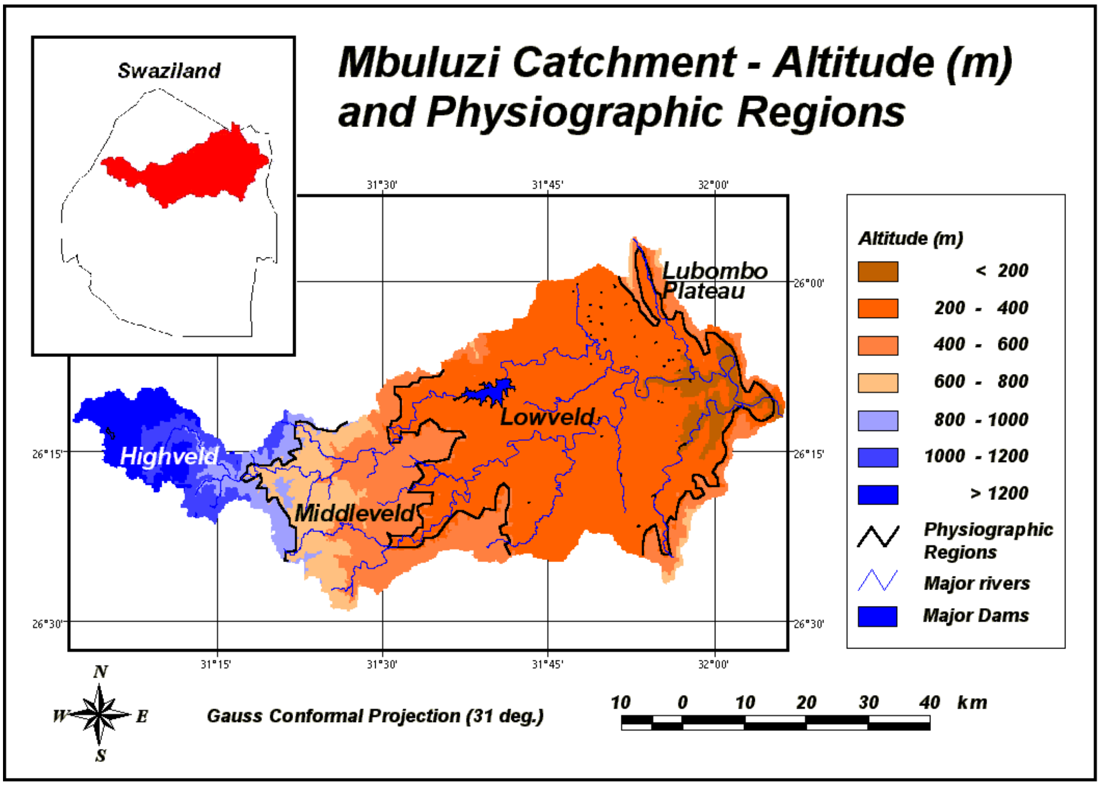

Figure 12.1 Mbuluzi catchment in Swaziland with the distribution of elevation zones (after Dlamini *et al*., 2001)

Except for the semi-arid lowveld, most of the catchment has a sub-humid temperate climate. The catchment receives most of its rainfall during the summer season from October to March. These rains are mainly from convective storms in the higher altitudes of the highveld and from more maritime air mass regimes in the east. Mean Annual Precipitation (MAP) rarely exceeds 700 mm in the lowveld, while it may be in the excess of 1200 mm in some parts of the highveld. Temperatures vary with altitude. The lowveld is the hottest region in the catchment with monthly means of daily minima and maxima respectively exceeding 11˚C and 26˚C in winter (July), and 22˚C and 33˚C in summer (January). With mean temperatures ranging between 16˚C and 23˚C in summer and 6˚C and 20˚C in winter, the highveld is the coolest part of the catchment. Owing to high temperatures, especially in summer, the lowveld has the highest potential evaporative demand, with January A-pan equivalent values in excess of 200 mm, while the values in the cooler highveld barely exceed 180 mm in January. Evaporation is at its lowest in June, when the mean monthly A-pan equivalent values are less than 100 mm throughout the catchment (Schulze, 1997).

12.4 WHAT MODELLING METHODOLOGY WAS APPLIED?

a) *The ACRU/MUSLE model and its configuration*

The *ACRU* agrohydrological modelling system (Schulz, 1995; Smithers and Schulze, 1995) was selected for this study. The model was configured for the Mbuluzi catchment upstream of the Swaziland border with Mozambique to simulate streamflows and sediment yields from 40 subcatchments over a 46-year period from 1950 to 1995.

The Mbuluzi and its subcatchments were delimited from 1:50 000 topographical maps. The resultant coverage was overlaid on a 200 m digital elevation model (DEM) from which subcatchment information such as area, mean elevation and average slope were calculated using GIS. In *ACRU*, sediment yields are modelled on a day-by-day basis by activating the Modified Universal Soil Loss Equation, MUSLE

(Williams, 1975). This version of the equation, which is imbedded in *ACRU,* overcomes the inability of the standard USLE equation to directly determine soil loss estimates for individual storm events, and eventually eliminates the need to determine sediment delivery ratios which were used by the USLE to estimate the proportion of eroded soil which leaves the catchment (Williams and Berndt, 1977).

The *ACRU*/MUSLE sediment yield module uses factors that characterise physical conditions on the surface of a catchment as input information. Event-based sediment yield is calculated from

$$Y_{sd} = \alpha_{sy} (Q_v.q_p)^{\beta_{sy}} K.LS.C.P.$$

where	Y_{sd}	=	sediment yield from an individual stormflow producing event (tonne)
	Q_v	=	stormflow volume for the event (m^3) from the area under study, i.e. the catchment, subcatchment or land use class
	q_p	=	peak discharge ($m^3.s^{-1}$) for the event
	K	=	soil erodibility factor
		=	rate of soil loss per rainfall erosion index unit (tonne.h.N^{-1} ha^{-1})
		=	f(soil texture, organic matter, structure, permeability, antecedent soil mois- ture condition)
	LS	=	slope length and gradient factor
		=	f(gradient)
	C	=	cover and management factor
		=	f(vegetation height, canopy cover, litter/mulch, surface roughness)
	P	=	support practice factor
		=	f(slope, conservation practices)
	α_{sy}, β_{sy}	=	location specific coefficients.

Each of these factors was averaged from values derived for each of the seven dominant land use classes within individual subcatchments. Thus, while geographical location of the sediment sources within each subcatchment were not distinguished, the fractions of sediment yield per land use within a subcatchment were computed according to the percentages of the individual land uses making up a subcatchment. From the values for the seven land use classes, the factors were then area-weighted for entire individual subcatchments.

Sources and methods of preparing the input information are described below.

b) Soil erodibility

In the soil erodibility factor, which characterises the susceptibility of soils to be eroded, high values indicate more susceptible soils while those soils that are resistant to erosion tend to have low values. For the entire Mbuluzi the soil erodibility factor was estimated on the basis of mapped information of soil erosion classes (Mushala, 2000) in conjunction with soil texture and lithologic information obtained from the Swaziland Soil Map (Murdoch, 1968).

c) Morphology

Field measurements of slope lengths and gradients were not conducted. However, the *ACRU* model has an option to internally compute the average slope length and gradient factor from average slope gradient (%) using algorithms developed by Schulze (1979). The coverage of the Mbuluzi catchment with its subcatchment delineation was overlain on a 200m x 200m Digital Elevation Model (DEM) and the average slope for each pixel was calculated using GIS. These pixel values of slope were averaged per subcatchment and the slope length and steepness factor were computed internally within the *ACRU* model.

d) Land cover and management

The calculation of cover factors requires detailed vegetation information on canopy cover, height of canopy and mulch cover, as indicated in the sediment yield equation. This input was derived from a combination of information collected during a comprehensive fieldwork by the senior author in the Mbuluzi catchment

(Dlamini, 2001), from other information derived for the catchment from the CSIR's 1996 National Land Cover Classification (Thompson, 1996), and from graphs and tables contained in the *ACRU* User Manual (Smithers and Schulze, 1995) to estimate monthly cover factors (Table 12.1) for the dominant land cover classes found within the Mbuluzi catchment.

Table 12.1 Estimates of cover factors for dominant land covers and land uses used in modelling sediment yield responses of the Mbuluzi catchment (after Dlamini *et al*., 2001)

Land Cover	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Grassland (G)	0.009	0.008	0.008	0.030	0.050	0.050	0.050	0.050	0.050	0.030	0.010	0.009
Grassland (F)	0.089	0.087	0.087	0.120	0.200	0.200	0.200	0.200	0.200	0.180	0.120	0.090
Grassland (P)	0.150	0.150	0.150	0.150	0.300	0.300	0.300	0.300	0.350	0.350	0.300	0.200
Bush (G)	0.050	0.050	0.050	0.050	0.060	0.080	0.080	0.080	0.080	0.080	0.050	0.050
Bush (P)	0.070	0.070	0.070	0.070	0.080	0.100	0.100	0.100	0.100	0.100	0.070	0.070
Forest & Woodland (G)	0.047	0.044	0.046	0.049	0.052	0.060	0.060	0.060	0.060	0.052	0.049	0.047
Forest & woodland (P)	0.056	0.053	0.055	0.059	0.062	0.072	0.072	0.072	0.072	0.062	0.059	0.056
Indigenous forest	0.008	0.007	0.007	0.008	0.009	0.009	0.010	0.010	0.010	0.010	0.009	0.008
Subsistence agriculture	0.150	0.090	0.030	0.150	0.340	0.360	0.380	0.400	0.450	0.750	0.700	0.350
Irrigated agriculture	0.009	0.009	0.009	0.009	0.200	0.200	0.200	0.150	0.080	0.030	0.010	0.009
Urban settlements	0.006	0.006	0.006	0.006	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.006
Bare ground	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439

Key:
G Good hydrological condition of grassland component, i.e. cover > 75%
F Fair hydrological condition of grassland component, i.e. 50% > cover < 75%
P Poor hydrological condition of grassland component, i.e. cover < 50%
NB Based on fieldwork undertaken, all the crops under subsistence agriculture were assumed to be maize (planted in mid-November and maturing in March) while the irrigated crops were input as sugarcane (ratoon crop with harvesting period beginning in May and ending in August).

e) The MUSLE coefficients, α_{sy} and β_{sy}

According to Simons and Senturk (1992), the MUSLE coefficients α_{sy} and β_{sy} are location specific, hence must be determined for specific catchments in specific climatic regions. Kienzle and Lorentz (1993) report that very little research has been undertaken on calibrating these coefficients. In this study, default values of 8.934 and 0.56 for α_{sy} and β_{sy} respectively, were therefore used. Having been originally calibrated for catchments in selected catchments in the USA by Williams (1975), these values for α_{sy} and β_{sy} have been adopted extensively with varying degrees of success (Williams and Berndt, 1977; Williams, 1991; Kienzle *et al*., 1997).

f) Conservation practices

Conservation practices have a reduction effect on overall soil loss. Factors representing the effects of support practices were estimated from Table 12.2 in conjunction with slope and farming practices that are found in the Mbuluzi catchment.

Table 12.2 Conservation practices values for contour tilled lands and lands with contour banks (after Wischmeier and Smith, 1978)

Land Use	Land Slope (%)	Support Practice Factor
Cultivated lands Usubsistence and large-scale irrigated agriculture)	1 - 2	0.4
	3 - 8	0.5
	9 - 12	0.6
	13 - 16	0.7
	17 - 20	0.8
	21 - 25	0.9
Pastures and communal rangelands	All	1.0

12.5 WHERE ARE THE SEDIMENT PRODUCING AREAS IN THE MBULUZI CATCHMENT, ON A SUBCATCHMENT BASIS?

The *ACRU* model was used to simulate daily sediment loads for each of the 40 subcatchments (Figure 12.2) for the period 1945 - 1995. From the daily values, monthly and annual average sediment yields were computed for each subcatchment. Because of different catchment and subcatchment areas the sediment yields for the catchment in tonnes were converted to a unit sediment yield of $t.ha^{-1}$ for comparative purposes.

Mean annual sediment yield values are presented in Figure 12.3. For the 40 subcatchments, they ranged from 0.59 to 96 $t.ha^{-1}$. The highest (> 20 $t.ha^{-1}$) values of sediment yields were simulated in Subcatchment (SC) 32 (cf. Figure 12.2) in the northeastern part of the catchment. This subcatchment has the highest average slope, at 16%, and is occupied by rural communities with more than 20% of the land under subsistence agriculture, the remainder being grazed and browsed bushlands and forests. Other high mean annual sediment yields were simulated in the upper-middle parts such as SC 10, with 17.09 $t.ha^{-1}$. This region also is predominantly rural, with subsistence agriculture being the main farming activity, while all the unimproved grasslands (which cover more than 70% of the land) are used as communal pastures. During fieldwork, lands with relatively steep slopes were found to be cultivated. Bare patches of land, badlands (gullies) and livestock and human pathways, which are sources of sediments, were also observed in the rangelands, during fieldwork.

Moderate to high sediment yields were generated in the subcatchments with MAP greater than 1000 mm in the higher altitude areas (e.g. SC 1). Subcatchments such as SC 24 in the middle and lower-middle sections exhibit the lowest mean annual simulated sediment yields, with values less than 2.5 $t.ha^{-1}$. These subcatchments have low average slopes (< 4%) and the land use consists of mainly well-managed privately-owned and government-owned demonstration cattle ranches. Moderately low mean annual sediment yields between 2.5 and 5 $t.ha^{-1}$ were simulated in those subcatchments with large-scale irrigated sugarcane estates (e.g. SC 29). Besides these areas having low slopes, the land is covered by good crop canopy for most part of the year, especially during the rainy season.

12.6 HOW DO SEDIMENT YIELDS FROM DIFFERENT LAND USES COMPARE WITH ONE ANOTHER?

A comparison of sediment yields simulated under different land uses, using SC 6 by way of example (Figure 12.4), indicates that subsistence agriculture and rangelands, i.e. grasslands in poor hydrological condition, produce the highest and second highest sediment yields respectively, while land under forest and rehabilitated grasslands generate the least sediment yields. The sediment yields under subsistence agriculture are highest in November, which is the ploughing and planting month for maize (the crop most

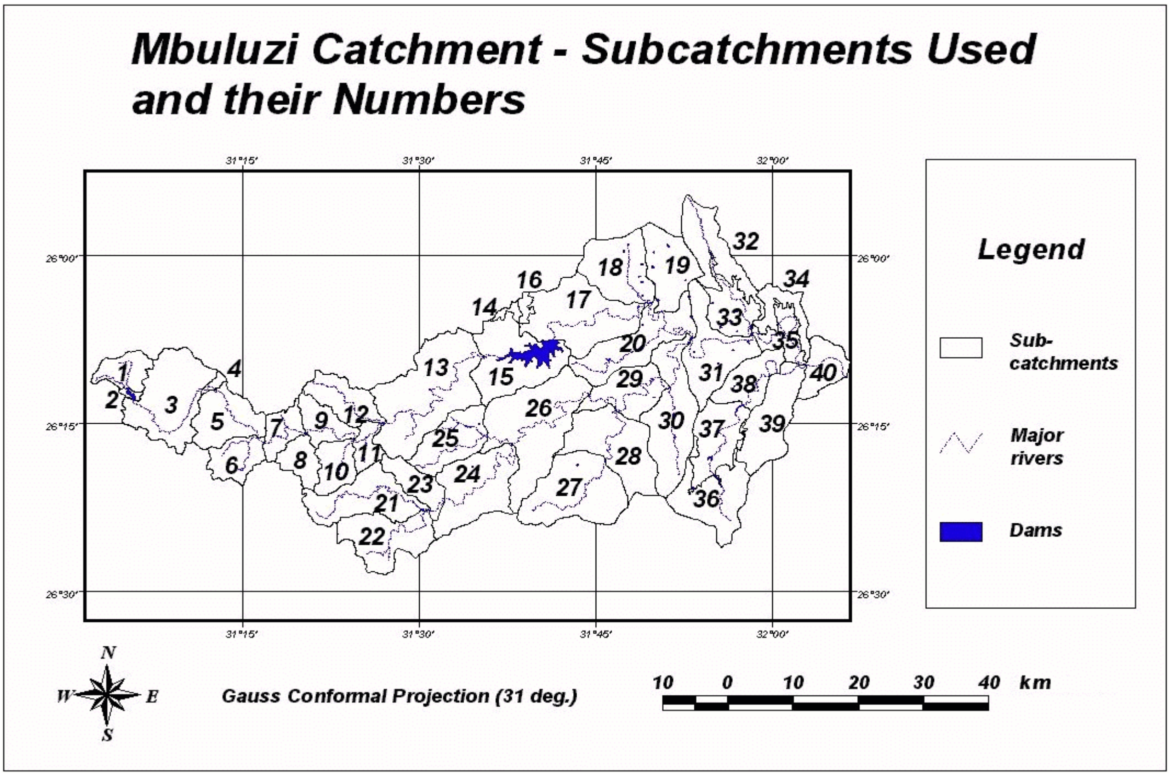

Figure 12.2 Subcatchments used in modelling and their numbers (after Dlamini *et al*., 2001)

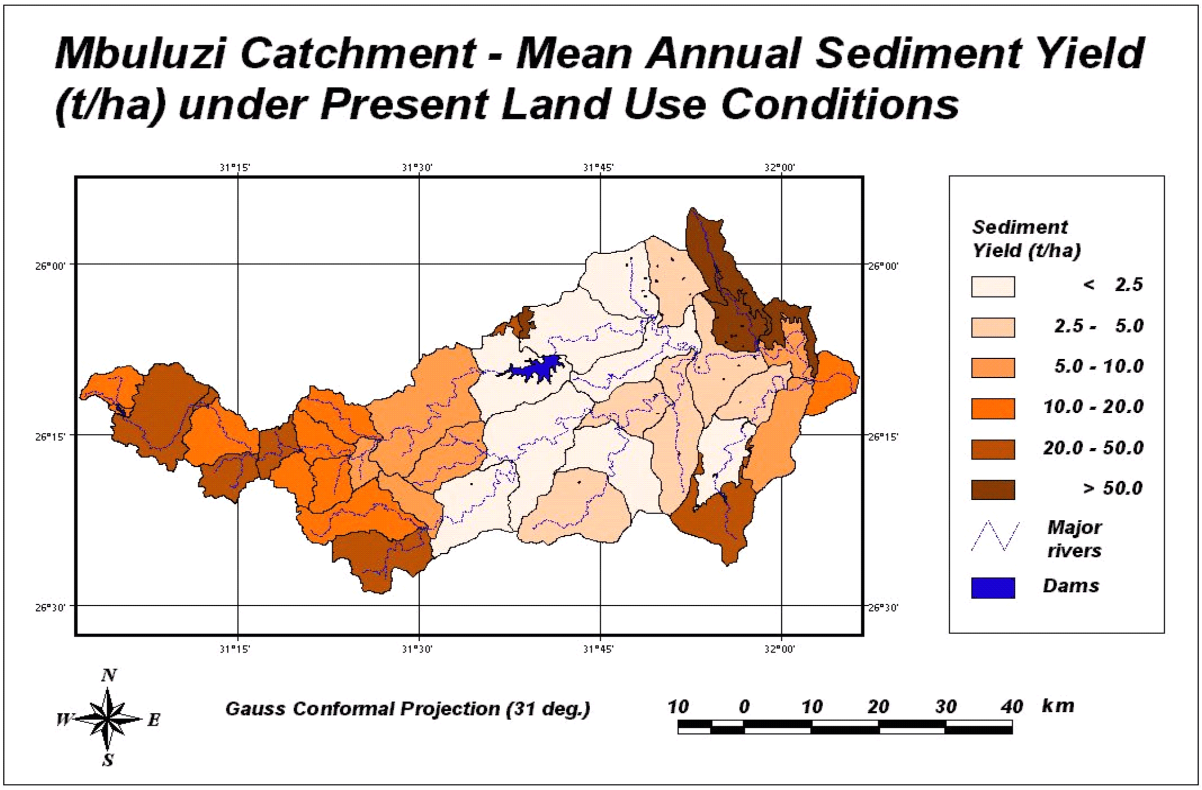

Figure 12.3 Simulated mean annual sediment yields ($t.ha^{-1}$) in the Mbuluzi catchment (after Dlamini *et al*., 2001)

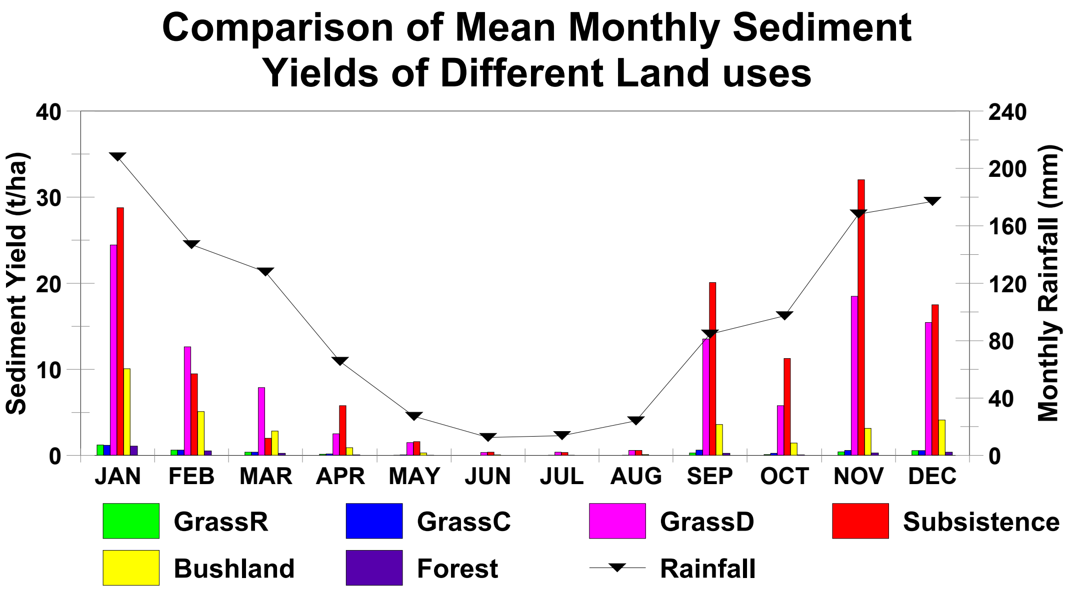

Figure 12.4 Comparison of sediment yields simulated under different land uses in Subcatchment 6 (after Dlamini *et al*., 2001). Under grasslands, R designates rehabilitated (i.e. well managed) conditions, C current and D degraded (overgrazed) conditions

commonly grown by rural Swazis), when the soil is exposed. Of note is that sediment yields simulated in the grassland in poor hydrological condition (Grass D) are higher than those of subsistence agriculture between February and March. This is a consequence of the mature stage maize has reached then, plus the improvement in ground cover following the growth of weeds, coinciding with the continued grazing and degradation of the grasslands.

It is common practice in the rural areas to allow livestock to freely roam the maize fields after harvesting between April and the beginning of planting period, leaving rangelands to recover. Hence, the higher sediment yields under the subsistence agriculture over that period.

12.7 WHAT IS THE IMPACT OF VELD DEGRADATION AND REHABILITATION ON SEDIMENT YIELDS?

One objective of this study was to assess the effects of land use management on sediment yields. The following 'what-if' scenarios were developed and their resultant sediment yields were analysed in relation to yields generated under present land use conditions:

- Scenario A: *Worst case scenario*, where the present land covers and uses on which grazing can take place were all replaced with a grassland in very poor hydrological condition(i.e. < 25% canopy cover with < 20% mulch) to represent land that is badly degraded as a result of deforestation plus overgrazing, and
- Scenario B: *Best case scenario*, where all present land covers and uses on which grazing can take place were substituted with a grassland in good hydrological condition (i.e. grassland with average drop height of 0.5 m, canopy cover > 75% and mulch cover > 50%) to represent rehabilitated veld conditions.

For each of the above scenarios, peak discharge and sediment yield-related *ACRU* model variables were adjusted accordingly before performing separate simulations. The variables that were modified were:

- monthly water use coefficients
- monthly interception values in mm per rainday
- fractions of active root system in the topsoil horizon (month-by-month) and
- coefficients of initial abstractions (month-by-month), all according to the values recommended

in the *ACRU* User Manual, as well as
- runoff curve numbers (Smithers and Schulze, 1995),
- cover factors (month-by-month) (cf. Table 12.1), and
- practice support factors (cf. Table 12.2).

Results of these simulations are presented as maps in Figures 12.5 to 12.8. These show differences between sediment yields under current land use conditions and those simulated under both degraded and rehabilitated scenarios for each of the 40 subcatchments. Substituting those areas of the present land cover on which grazing can take place with grass cover in poor hydrological conditions resulted in the increases of simulated sediment yields in all the subcatchments. The mean annual sediment yields increased by between 3 and more than 355 $t.ha^{-1}annum^{-1}$ (Figure 12.5). In relative terms, these increments vary between twice and more than 20 times the current sediment yields (Figure 12.6). The highest increases correspond with those subcatchments that are generating moderate to high sediment yields at present, while the subcatchments with low sediment yields show smaller changes. This observation could imply that most of the areas currently generating high sediment yield may not yet have reached their maximum sediment production capacity, i.e. soil loss potential. These are the areas in which conservation and remediation efforts should be focussed, in order to minimise land degradation already occurring and to avert the further deterioration of the current situation.

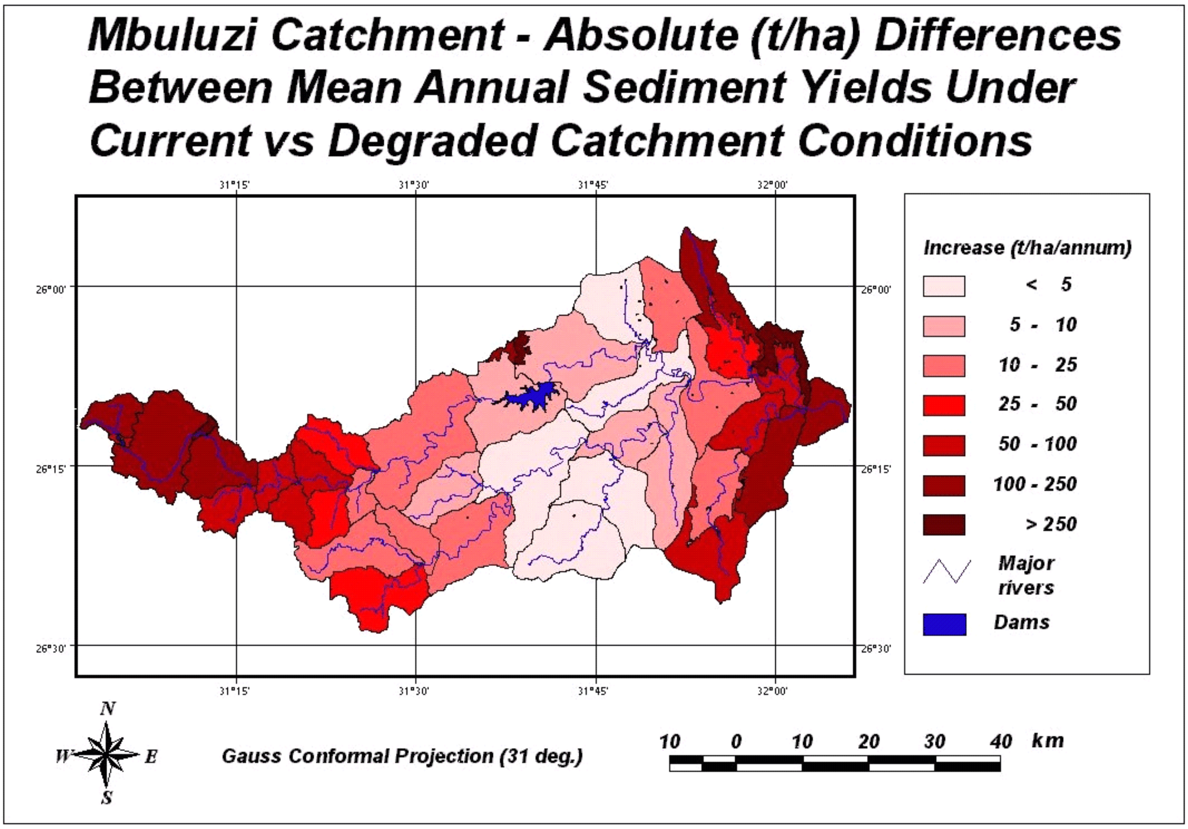

Figure 12.5 Absolute ($t.ha^{-1}$) differences between simulated mean annual sediment yields under current vs degraded conditions (after Dlamini *et al*., 2001)

The mean annual sediment yields were reduced in all the subcatchments after replacing those areas of the present land cover which can be grazed with a grass cover in good hydrological condition. High reductions ranging from 5 to more than 25 $t.ha^{-1}.annum^{-1}$ are found in subcatchments in the upper-middle and upper sections of the catchment. Again, these are the subcatchments that are presently producing high sediment yields. The middle region has low annual reductions of less than 2.5 $t.ha^{-1}$ (Figure 12.7). There are some relatively high percentage reductions (ranging from 37.5 to more than 50%) in certain subcatchments, however (Figure 12.8). These may be explained by the fact that the present sediment

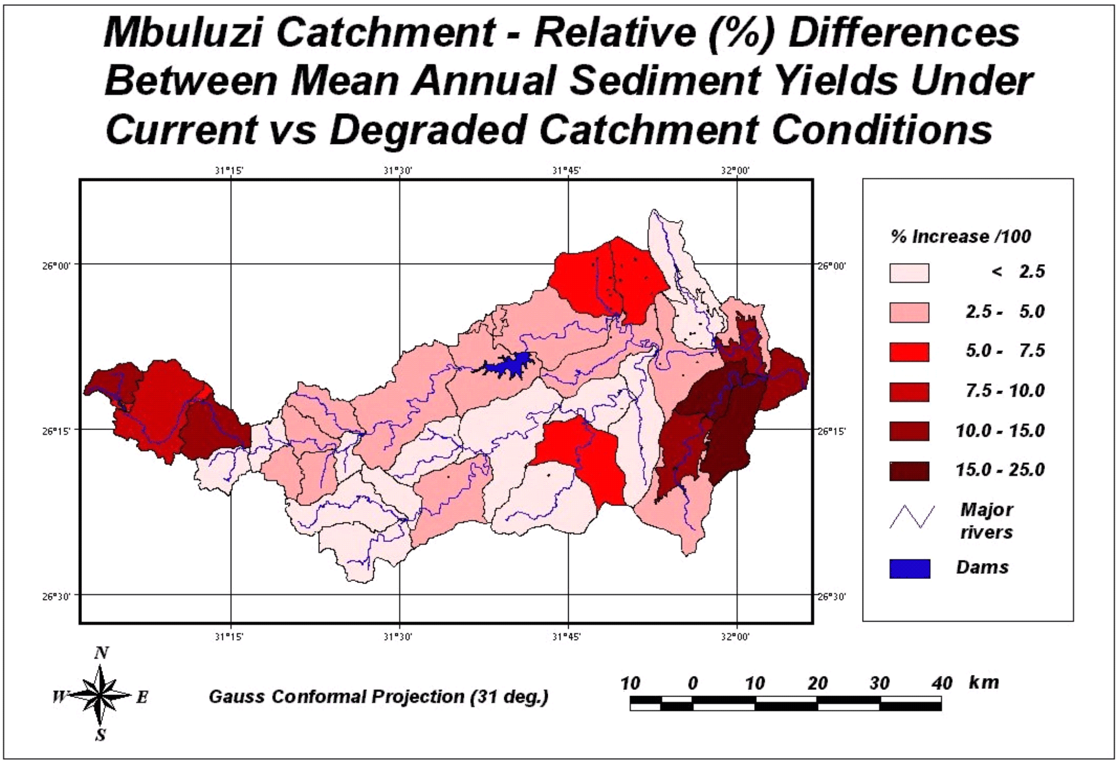

Figure 12.6 Relative (%) differences between simulated mean annual sediment yields under current vs degraded conditions (after Dlamini *et al*., 2001)

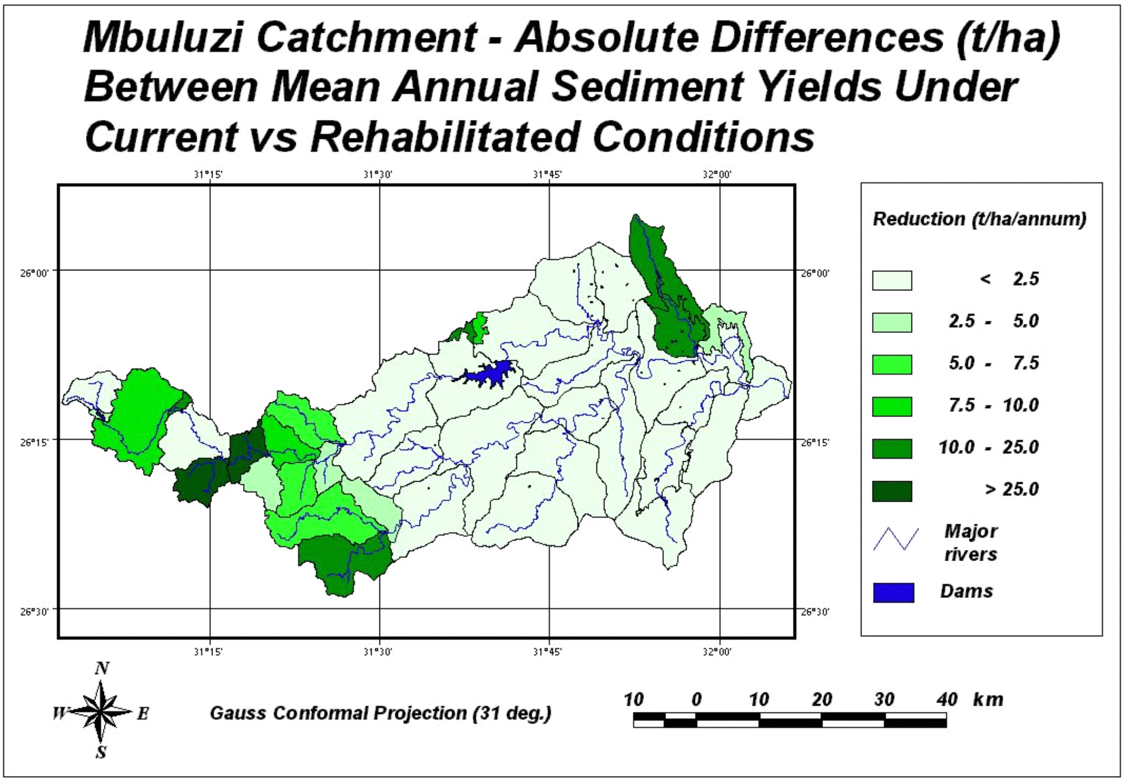

Figure 12.7 Absolute ($t.ha^{-1}$) differences between simulated mean annual sediment yields under rehabilitated vs degraded conditions (after Dlamini *et al*., 2001)

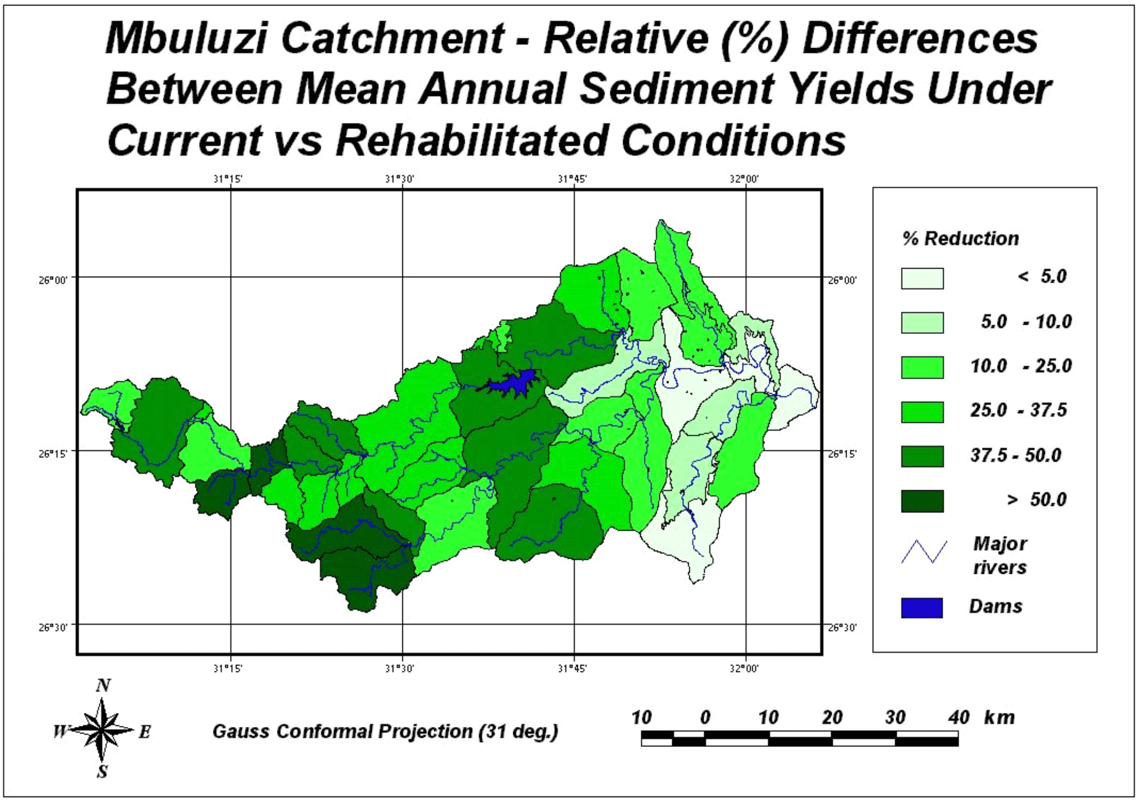

Figure 12.8 Relative (%) differences between simulated mean annual sediment yields under rehabilitated vs degraded conditions (after Dlamini *et al*., 2001)

yields are low, hence an insignificant change in absolute terms will become significant in relative terms. Considering that the same subcatchments showed minimal increments of sediment yields in the degraded scenario, it may be assumed that this region is relatively stable and not a high risk one in terms of the severity soil erosion.

12.8 WHAT CONCLUSIONS MAY BE DRAWN FROM THIS CASE STUDY?

This study has shown that the upper middle sections of the Mbuluzi catchment have high simulated sediment generation rates. Studies by Scholten *et al*. (1995) and Mushala *et al*. (1996) show that this area is vulnerable owing of the prevalence of saprolitic soils, which are highly susceptible to erosion. The erosion hazard is compounded by the types of uses the land is put to. Subsistence agriculture and communal grazing are the dominant land uses in this section of the catchment, and were found to be the land uses that resulted in the highest and the second highest sediment generation rates respectively. By their location upstream of the Mnjoli Dam, the major sediment source areas pose potential threats to the sugarcane industry further downstream, as this industry relies on the dam for irrigation and other water needs. However, the rate and extent of sediment deposition in the dam was not established. Owing also to limitations of the MUSLE module, as well as the spatial unit adoptedfor sediment yield modelling, *viz*. the subcatchment (which was then subdivided into dominant land uses in a spatially non-explicit manner), the specific processes responsible for sediment generation and their exact location could not be determined.

However, the capability of representing characteristics of different types of land cover and use which enabled the simulation of associated sediment yields was further taken advantage of to simulate potential impacts of possible future land use changes on sediment yield. Allowing the catchment land cover to be further degraded indicates that sediment yields would increase in all parts of the catchment, even those that are generating relatively low sediments currently, while employing soil conservation and land rehabilitation measures can reduce soil losses significantly.

12.9 ACKNOWLEDGEMENTS

This study was undertaken in collaboration with the University of Swaziland in a European Union co-funded project with an abbreviated title 'Integrated Water Resources Management Systems'. This support is acknowledged gratefully, as is the assistance from the erstwhile Computing Centre for Water Research.

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CHAPTER 13

APPLYING SEASONAL RAINFALL FORECASTS TO FORECASTING SUGARCANE YIELDS USING A MODELLING APPROACH : CAN IT BENEFIT THE SUGARCANE INDUSTRY?

T.G. Lumsden[1], R.E. Schulze[1], N.L. Lecler[1] and E.J. Schmidt[2]

[1]School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

[2]SA Sugar Association Experiment Station, Mt Edgecombe, South Africa

ABSTRACT

The main objective of this study involved the development and evaluation of a sugarcane yield forecasting system for the Eston Mill Supply Area in the midlands of KwaZulu-Natal using yield simulation models and seasonal rainfall forecasts. Following a verification analysis, the daily time step *ACRU*-Thompson model was selected and used to generate sugarcane yield forecasts for a number of seasons, through the application of seasonal categorical rainfall forecasts in the model. The categorical rainfall forecasts were supplied by the South African Weather Service. These rainfall forecasts first had to be translated into daily rainfall values for input into the model. The modelled sugarcane yield forecasts were then evaluated against observed yields as well as against forecasts generated by more traditional methods, these methods being represented by the so-called Simple Rainfall Model (SRM) developed and used by the sugarcane industry and Mill Group Board (MGB) estimates for the Eston mill. The skill of the statistically based categorical seasonal rainfall forecasts was found to be disappointingly poor.

When comparing the *ACRU*-Thompson cane yield forecasts to those generated by the SRM, the former was found to be more consistent in the accuracy of its predictions. When *ACRU*-Thompson cane yield forecasts were compared to MGB forecasts, it was noted that the accuracy of the MGB forecasts improved relative to those of the *ACRU*-Thompson model only at a 4.5 month lead time, but were worse for longer lead times. This lead time is relatively short and would not allow time for changes in major planning decisions. The *ACRU*-Thompson yield forecasts would thus offer a better alternative for longer lead time planning. When comparing *ACRU*-Thompson yield forecasts to the median yield for the Eston MSA, the modelled forecasts gave a better representation of seasonal yield for seasons more strongly influenced by ENSO events. As rainfall forecasts were found to generally be poor, the benefit of using the *ACRU*-Thompson model in these seasons must relate to the use of observed rainfall up to the time of forecast.

A simple cost-benefit analysis was conducted to assess whether economic benefits could be derived from the application of the various yield forecasting systems. The analysis indicated that the *ACRU*-Thompson system could potentially give rise to greater net economic benefits when compared to traditional forecasting methods (SRM, MGB). This cost-benefit analysis centred around improvements in forecast accuracies (and thus improvements in mill operating decisions) and the cost of implementing a yield forecasting system. There are potentially many other benefits and costs associated with yield forecasting, particularly at scales other than the Mill Supply Area, e.g. at farm and national scales.

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13.1 ARE THERE BENEFITS TO BEING ABLE TO FORECAST SUGARCANE YIELDS?

In the sugar industry there are numerous benefits that can be derived from having accurate and timely forecasts of seasonal sugarcane yields. Such forecasts can potentially be applied in decision- making at national, mill supply area (MSA) and individual grower scale. For example,

- *At the national scale*, forecasts could be used in the
  - development of marketing and pricing strategies, in the
  - early signing of export contracts, and in the
  - provision of forward cover for exchange rate fluctuations.
- *At the mill supply area (MSA) scale*, forecasts could be applied in the
  - planning of mill operations such as the determination of opening and closing dates,
  - haulage scheduling, and in the
  - determination of crushing and extraction rates.
- *At grower scale*, crop forecasts could be used in decisions relating to
  - cash flows,
  - in the planning of harvest and haulage scheduling and in
  - crop husbandry decisions such as fertilizer applications and irrigation scheduling (Schmidt, 1998).

As an illustration of the potential benefits of having accurate and timely cane yield forecasts, an analysis of the economic implications of selecting the length of the milling season was obtained from Hildebrand (1998a), who applied the Length of Milling Season (LOMS) model (Hildebrand, 1998b). The analysis, which was conducted for the Noodsberg Mill in the Midlands of KwaZulu-Natal, considered the effect of varying the mill opening date when crushing a 1.5 million ton cane crop. The LOMS model predicted that the optimum length of the milling season was between 12 April and 24 December. If the crop was overestimated by 2.8% and the mill was opened a week early, the model predicted a reduction in profit of R128 000 for the area. This loss in profits increased to R807 000 for an opening date four weeks early (crop overestimated by 11.2%). If the crop was underestimated by 2.8% and the mill was opened a week late, losses in profit of R566 000 were predicted, with this loss increasing to R1 937 000 for an opening date four weeks late (crop underestimated by 11.2%). Losses in profit were ascribed to poorer cane quality, less favourable ratooning and increased growing and milling costs at certain times of the year. The above analysis did not account for benefits that could have been derived from improved marketing, pricing and export strategies, were accurate crop forecasts available.

13.2 WHAT WERE THE BACKGROUND AND OBJECTIVES OF THIS STUDY?

From the above analysis, an accurate and timely forecast of seasonal cane yield is thus seen as being of great value to the sugar industry, and has the potential to result in savings of many millions of Rands annually. Forecasting techniques used traditionally in South Africa's sugar industry are successful to a degree, but are generally simple in nature, with their success frequently depending on the experience of those involved. Advances by climatologists have resulted in increasingly accurate and timely seasonal climate forecasts. These advances, coupled with the ongoing advances made in the field of crop yield simulation modelling, present the sugar industry with the possibility of obtaining improved crop yield forecasts. The lead time (i.e. advance warning) of these forecasts would, in particular, be an improvement on those of traditional techniques, as well as in other factors such as the flexibility offered by simulation modelling in the representation of a variety of seasonal scenarios.

A research project, in collaboration with the South African Sugar Association Experiment Station (SASEX) was, therefore, initiated to investigate whether improved sugarcane yield forecasts could be derived from seasonal climate forecasts used in conjunction with crop yield simulation modelling. It was decided that the project would focus on a case study conducted at the scale of a mill supply area. The Eston Mill Supply Area in the midlands of KwaZulu-Natal was selected for this purpose because of the availability of good observed cane yield, soils and climate data. The main objective of the project can be stated as:

> *The development and evaluation of a sugarcane yield forecasting system for a mill supply area, using crop yield simulation modelling and seasonal climate forecasts.*

In order to achieve this objective the following elements of research were conducted:

- An evaluation of sugarcane yield simulation models of differing complexity was undertaken, in order that the ability of the models to accurately predict historical yields be verified, thus leading to the identification of a model suitable for application in cane yield forecasting;
- the inputs required by the above models at their scale of application were assembled and assessed;
- the sugarcane growth cycles practised in the selected mill supply area and the formation of a strategy to represent these in the models was investigated, given that these cycles are an important and influential form of management;
- the seasonal climate forecasts (relating to rainfall) used in yield forecasting were evaluated to assess their accuracy;
- a methodology developed to translate the seasonal rainfall forecasts into a form suitable for application in the selected yield simulation model was applied and evaluated;
- a comparison was made of the historical yield forecasts generated by the proposed yield forecasting system and observed yield data, and against forecasts derived from traditionally employed methods; and
- a simple benefit analysis was undertaken of the yield forecasting system to determine whether benefits could be derived from its use.

Based on the findings of the research, recommendations regarding practical application of the system in industry and the direction of future research, were also made.

The simulation models evaluated for possible application in sugarcane yield forecasting were the *ACRU*-Thompson model (Schulze, Domleo, Furniss and Lecler, 1995; as modified by Lumsden, Lecler and Schulze, 1998) and the CANEGRO-DSSAT model (Inman-Bamber, 1991; as modified by Inman-Bamber and Kiker, 1997).

The traditional yield forecasting methods against which the results from selected yield simulation models were compared were a so-called Simple Rainfall Model, SRM, developed for and by the sugar industry (Cousens,1998), and the estimates of the local mill group board, MGB.

The latter two represent a base against which more complex yield simulation models could be compared. The *ACRU*-Thompson and CANEGRO-DSSAT yield models represent, respectively, intermediate and higher levels of model complexity. The range in model complexities has implications in terms of the effort required to set up and operate the models, as well as in their potential to provide other useful information, such as the response of a crop to varying management strategies.

The rainfall forecasts used in this research were kindly provided by the South African Weather Service (Landman and Bartman, 1998). These rainfall forecasts were categorical in nature, in that they indicated simply whether the forthcoming months' rainfall was forecasted to be in one of three categories, *viz*. above-normal, near-normal or below-normal. This type of forecast is typical of seasonal rainfall forecasts, and requires a methodology to be developed to 'translate' the forecasts into a form suitable for input into the yield models.

In this project cane yields are defined as the mass of stalks (at field moisture content) in tonnes per hectare. This is distinct from sucrose yield, which is mass of extracted sucrose per hectare. Although the end value of a crop is based on the sucrose yield, the cane yield is important in terms of many functions such as mill operations planning, harvest and haulage scheduling and crop management, all of which would benefit from advance estimation of the seasonal yield.

13.3 WHAT MODIFICATIONS WERE MADE TO THE *ACRU*-THOMPSON SUGARCANE YIELD MODEL TO FACILITATE THIS STUDY?

In the existing *ACRU*-Thompson model (Schulze *et al*., 1995) sugarcane yields are estimated assuming an annual crop (July to June). Water use by the crop is estimated through 12 monthly values of crop water use coefficients. These values may be set to 0.8 for each month for average on-farm conditions (Schulze *et al*., 1995). Given the effect of growth cycles on sugarcane yields, it was considered important that the various growth cycles occurring in the Eston area be represented in the modelling framework. In order to cater for a variety of growth cycle lengths and harvest dates, the *ACRU*-Thompson model was modified (Lumsden *et al*., 1998) through the introduction of dynamic equations relating crop water use to daily temperature. These equations, taken from the research of Hughes (1992), allow for the calculation of daily water use coefficients. The equations are as follows:

$$K_c = 0.297 + (1.32x10^{-6}xGD_a^2) - (6.83x10^{-10}xGD_a^3) - K_{red}$$

$$K_{red} = 0.05 + (1.32x10^{-6}xGD_r^2) - (6.83x10^{-10}xGD_r^3)$$

where

K_c = sugarcane water use coefficient
GD_a = accumulated degree days since planting (°C day)
GD_r = accumulated degree days since initiation of ripening (°C day)
K_{red} = reduction in water use coefficient after ripening
Degree day = $((T_{max}+T_{min})/2) - 12$ (°C day)
T_{max} = daily maximum temperature (° C)
T_{min} = daily minimum temperature (° C)

Limits to K_c, taken from Hughes (1992), were

K_c ≤ 1.00 for the plant crop
≤ 0.96 for a first ratoon crop
≤ 0.92 for second and subsequent ratoons
≥ 0.50 during ripening

with GD_a ≤ 1300 °C day (in order to prevent negative values of K_c).

Daily observed maximum and minimum temperatures are input into the equations to allow for the calculation of the water use coefficients. If these temperatures are not available, then monthly long term means of temperatures may be specified, with these temperatures then being translated internally in the *ACRU* model to daily values by Fourier Analysis.

As the crop's water use coefficients are related to temperature, they reflect the climate regime experienced by the crop during its growth cycle, thus allowing for the representation of different harvest dates. The use of temperature based relationships also overcomes the limitation in the existing *ACRU*-Thompson model which restricts the length of growth cycles to 12 months. The influence of two different harvest dates on the seasonal water use coefficient curve of a 12 month crop are illustrated in Figure 13.1. The curves were derived from temperatures recorded at Eston.

The curve of the crop harvested in October rises rapidly after growth commencement, reflecting the warm temperatures experienced by this crop in its initial growth stages during the summer months. In contrast, the curve of the crop harvested in April rises slowly after growth commencement, reflecting the colder winter temperatures experienced in the early stages of this crop's growth cycle.

13.4 THE STUDY AREA : ESTON MILL SUPPLY AREA (M.S.A.)

The Eston Mill Supply Area is situated in the midlands of KwaZulu-Natal, South Africa, and is located around latitude 29˚55'S and longitude 30˚30'E. Figure 13.2 shows the Eston MSA and indicates the boundaries of farms falling within the MSA. The farms that were included in the analysis (numbering 85) constituted a large proportion of the total number of farms, and were believed to be a representative sample of the MSA. Mean annual precipitation (MAP) in the MSA ranges from approximately 600 to 1000 mm. The annual means of daily maximum and minimum temperatures derived from records of two representative climate stations in the MSA, are 23.2˚C and 13.2˚C respectively. The range in altitude within the MSA is from approximately 400 to1000 m. An altitude gradient runs from north west to south east in the area.

13.5 CAN THE SUGARCANE YIELD MODELS MIMIC OBSERVED M.S.A. YIELDS ADEQUATELY?

For yield forecasting, the average yield of the MSA is important, as this affects activities such as mill operations planning. To verify the performance of the models at this scale, the simulated and observed farm yields were aggregated to obtain average MSA yields for each year of simulation. The average

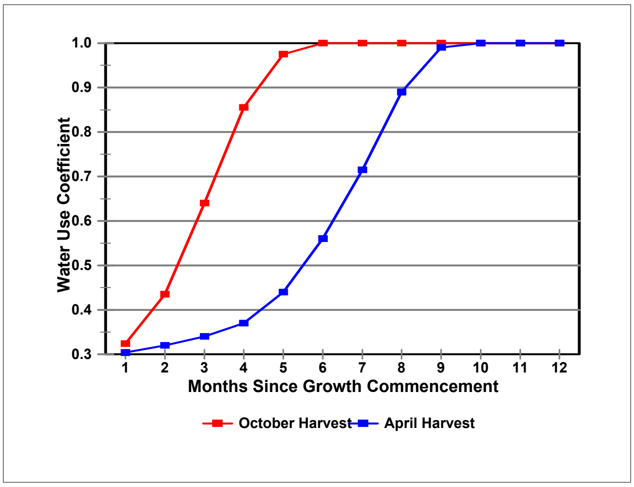

Figure 13.1 Seasonal water use coefficient curves of two 12 month sugarcane crops harvested in the Eston area in October and April (Lumsden *et al*., 1999)

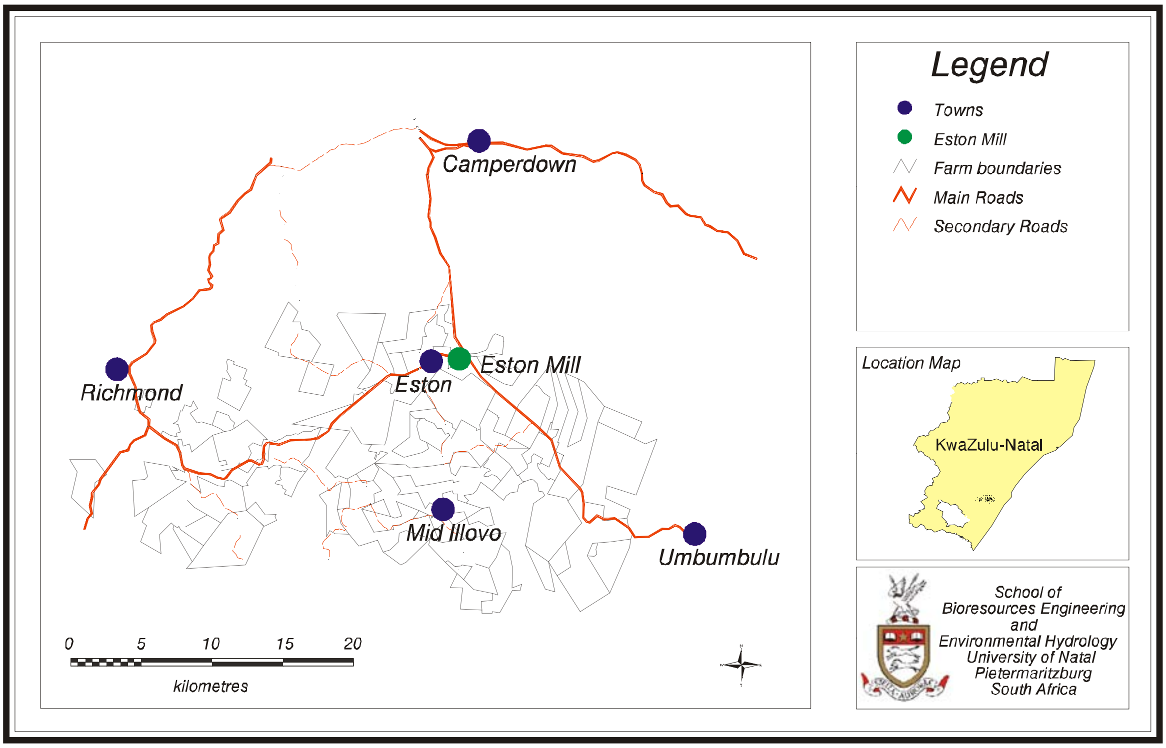

Figure 13.2 Eston mill supply area : Farm boundaries and other features (after Lumsden *et al*., 1999)

MSA yields for *ACRU*-Thompson, CANEGRO-DSSAT and the SRM are plotted against time in Figure 13.3, along with the observed yields. These plots verify that the *ACRU*-Thompson model has generally captured the trend in the year to year variation of yield well. The CANEGRO-DSSAT model has over- and under-simulated yields and has not captured the trend in year to year yield variation as well. The SRM simulated yields reasonably well. This model is calibrated against observed rainfall, and would thus be expected to give good simulations in those years where rainfall has dominated seasonal yields.

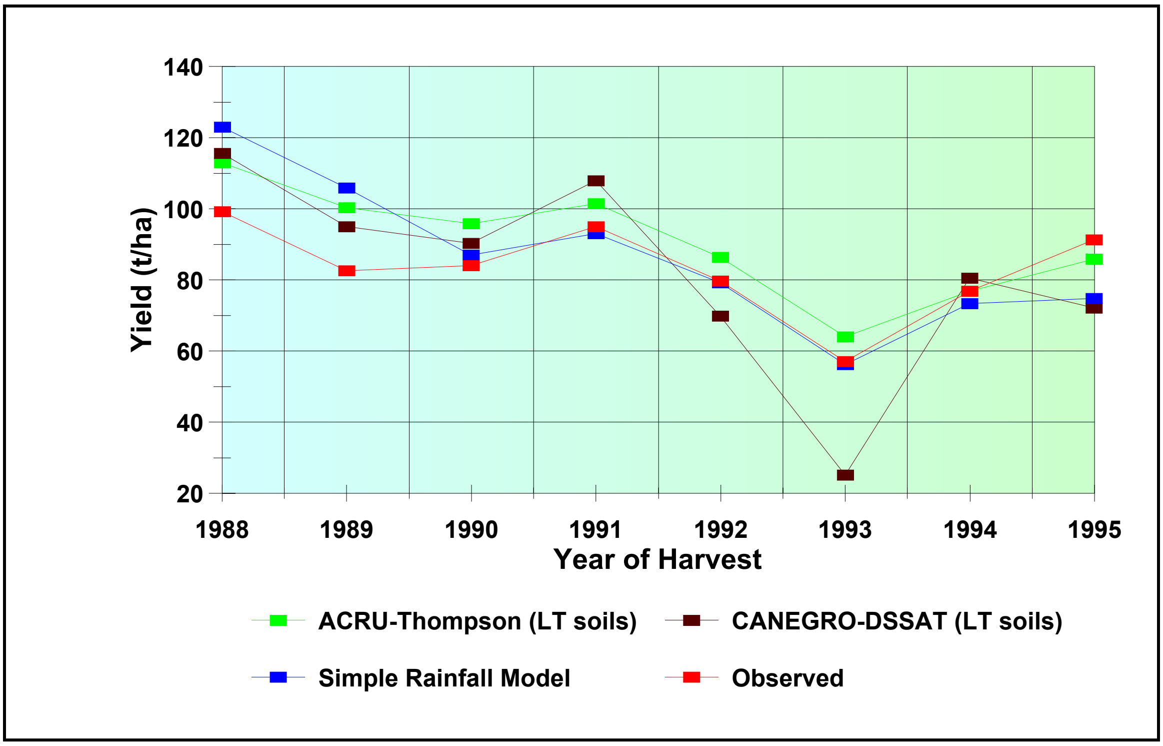

Figure 13.3 Average simulated (*ACRU*-Thompson, CANEGRO-DSSAT, Simple Rainfall Model) and observed mill supply area yields versus time (after Lumsden *et al*., 1999)

13.6 WHAT SEASONAL RAINFALL FORECASTS WERE USED FOR YIELD FORECASTING?

Categorical seasonal rainfall forecasts were obtained from the South African Weather Service, SAWS (Landman and Bartman, 1998). These rainfall forecasts were derived from statistical models that relate sea surface temperatures of various oceans around the globe to rainfall over South Africa. The relationships upon which the models are based are linked to the El Niño-Southern Oscillation (ENSO) phenomenon, which has been shown to influence rainfall over southern Africa, even though the origins of the phenomenon are distant from the region (Lindesay, Harrison and Haffner, 1986; Van Heerden, Terblanche and Schulze, 1988).

The SAWS rainfall forecasts were considered to be as appropriate for application as any other seasonal rainfall forecasts available for South Africa. They are categorical in nature and forecast rainfall as being either above-normal, near-normal or below-normal. On each date of forecast, rainfall is predicted for two successive three month periods, allowing for a total lead time of six months. Forecasts are updated at monthly intervals. The rainfall forecasts are usually issued by SAWS for broad areas within the provinces of South Africa, as this scale gives the greatest skill in forecasting. However, for this study, forecasts were obtained from the SAWS specifically for the Eston rainfall station in order that the forecasts be consistent with the proposed local scale of modelling. Forecasts were obtained for the period 1988 to 1998. Categories of rainfall derived retrospectively from the observed rainfall records for those seasons were also obtained. These categories of rainfall correspond to a 'perfect' forecast, while those generated by the SAWS statistical rainfall model are the 'actual' forecast.

13.7 WITH WHAT SKILL CAN CATEGORICAL SEASONAL RAINFALL FORECASTS BE MADE AT ESTON?

The forecasts from the Eston station were evaluated as follows: Above-normal rainfall forecasts were assigned a categorical value of 3, while near-normal and below-normal forecasts were assigned values of 2 and 1 respectively. Forecast skill was assessed by subtracting the values of the perfect forecasts from those of the actual forecasts. This assessment is presented in Figure 13.4 for the Eston station.

Evaluation of Rainfall Forecast Skills
Eston Station Forecasts:
Forecast Difference = Actual Forecast - Perfect Forecast

Month of Forecast	Lead Time (months)	87	88	88	89	89	90	90	91	91	92	92	93	93	94	94	95	95	96	96	97	97	98	98
SEP	12.5 / 0.5	1	-2	0	0	-1	0	1	-1	2	0	2	1	-1	0	0	0	0	-2	0	0	0	-1	
DEC	9.5		-2	-2	0	1	0	-1	-1	1	1	1	1	2	1	2	0	-1	-2	2	0	-2		
JAN	8.5		-2	0	0	0	-2	0	1	0	1	0	1	0	1	0	0	0	-1	0	1	0	0	0
MAR	6.5		-2	2	-1	2	-1	1	1	1	0	2	2	1	1	0	-2	2	2	-2	-2	2	0	1
MAY	4.5		1	2	1	0	0	1	2	2	2	2	1	2	-1	1	0	1	0	1	0	0	1	1
JUN	3.5		2	-1	2	-2	1	0	1	2	2	2	1	1	0	0	2	0	-2	0	2	0		

KEY		**% Occurrence**
Green	Forecasts Identical	34
Yellow	Forecasts Differ by 1 Category	35
Red	Forecasts Differ by 2 Categories	31

Figure 13.4 Evaluation of rainfall forecast accuracy for the Eston station forecasts (after Lumsden *et al*., 1999)

The differences between actual and perfect forecasts are presented in the form of a colour- coded table, where rows relate to the month of forecast generation, and columns to the year of the forecast period. Each block in the table corresponds to a 3-month forecast period (horizontal direction). If actual and perfect forecasts are identical, then the relevant block in the table is coded green. Forecasts not identical are coded yellow for a difference of 1 category between perfect and actual, and red for a difference of 2 categories. The percentage occurrences of the various block colours are indicated in Figure 13.4. These percentages indicate that the forecasts exhibit poor skill for Eston station. The poor skill of the forecasts indicate that they are not, as yet, ideally suited to the scale of application. The location of the MSA in KwaZulu-Natal may also be a contributing factor, as this region is known to have relatively poor forecast skills when compared with other regions of the country (Schulze, Hallowes, Lynch, Perks and Horan, 1998).

13.8 HOW ARE THE CATEGORICAL SEASONAL RAINFALL FORECASTS 'TRANSLATED' INTO A FORM SUITABLE FOR INPUT INTO YIELD MODELS?

The rainfall forecasts obtained were categorical in nature, and required 'translation' into a form suitable for application in the *ACRU*-Thompson and SRM models. For decision-making purposes, certain dates within a season were recommended by industry representatives as being appropriate for the generation of yield forecasts. These dates of forecast and the corresponding lead times are indicated in Table 13.1.

Table 13.1 Recommended dates of forecast and corresponding lead times for the generation of yield forecasts (Lumsden *et al*., 1999)

Forecast	Date of Forecast	Lead Time (months)
1	End of September	12.5
2	End of January	8.5
3	End of March	6.5
4	End of May	4.5
5	End of September	0.5

The rainfall forecasts obtained were used to infer rainfall for the months following the various forecast dates. The translation of the forecasts into a suitable form was achieved through the use of an analogue year concept, where years in the historical rainfall record resembling a particular forecast were identified, and the data from those years extracted and used to make up the rainfall record. In the case of the *ACRU*-Thompson model, all years resembling a particular forecast were used successively to create a number of daily rainfall files, each of which was then used in turn to simulate a yield for the season. This resulted in an ensemble of yield outcomes being generated for a particular season. A forecasting methodology giving rise to a range in possible yields for a season is desirable, as it allows for an appreciation of the uncertainty associated with any decisions based on the yield forecasts. Figure 13.5 illustrates diagrammatically the development of forecast rainfall files for the *ACRU*-Thompson model for a hypothetical crop harvested in October 1995.

The forecast represented in Figure 13.5 is the first for the 1995 season (as at 30 September 1994) for a crop starting on 16 October 1993 and harvested on 16 October 1995. The rainfall file is filled with observed daily rainfall for the period leading up to this forecast date. During the first and second three-month rainfall forecast periods, all combinations of years (indicated by use of arrows) corresponding to the given categorical forecast are identified, and their daily data used to fill the rainfall file for these periods. Figure 13.5 indicates that the categorical forecasts were above-normal and below-normal respectively, and that three associated years were identified in each case. In practice there were generally many more (in the order of 10 to 15) years in the 40 year historical record that were identified as having rainfall resembling that of the categorical forecast. For the months following the second forecast period, there is an equal chance of above-normal, near-normal or below-normal rainfall occurring. In order to represent this equal probability all simulations were performed in triplicate, with the period of remaining seasonal rainfall being filled with above-, near- and below-normal rainfall for that period. This increased the number of yield outcomes for a season, and reflected a wider range in yields possible. As a season progresses and the forecast date becomes later, the period of observed rainfall increases, while the period of remaining seasonal rainfall decreases, thus resulting in greater certainty in the representation of rainfall for that season. Both 'actual' and 'perfect' seasonal rainfall forecasts were used to create two distinct sets of rainfall files, both of which were used to forecast yields. These two sets of yield forecasts were then compared later during the analysis of results.

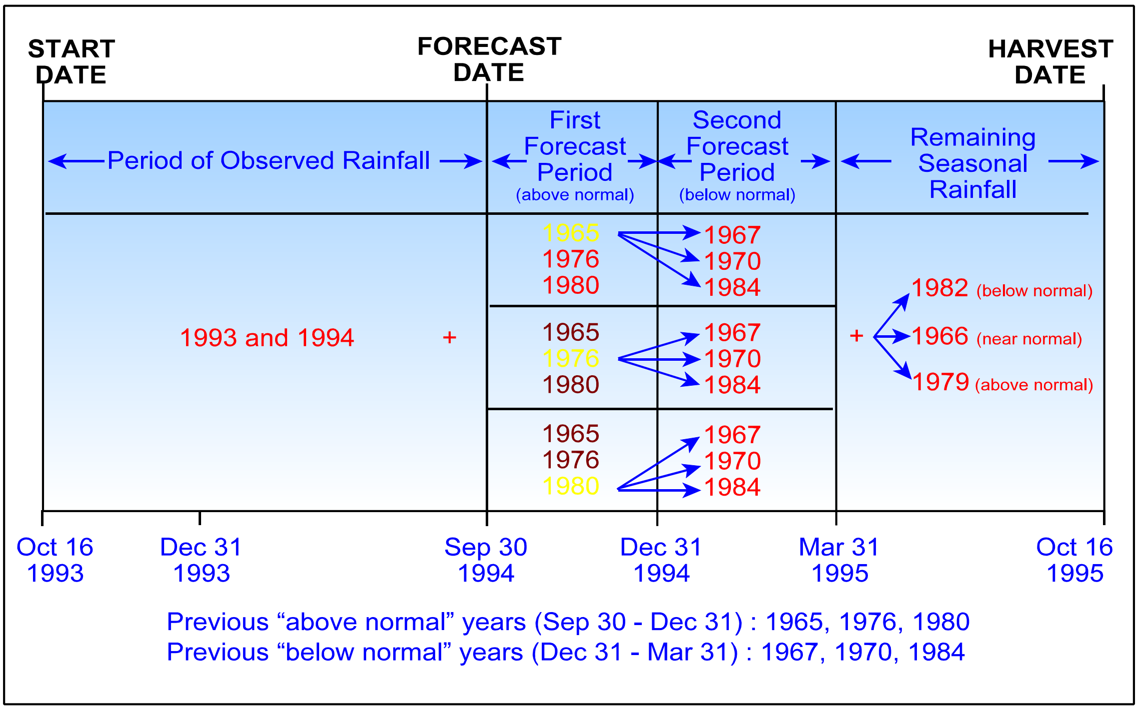

Figure 13.5 Use of combinations of years of rainfall data in the development of a forecast rainfall file for the *ACRU*-Thompson Model for a hypothetical crop harvested in October 1995 (after Lumsden *et al*., 1999)

13.9 HOW ACCURATE ARE THE YIELD FORECASTS?

The *ACRU*-Thompson, Simple Rainfall Model and Mill Group Board sugarcane yield forecasts were plotted against time in Figure 13.6 for the various lead times. The observed yields for those seasons where data were available, were also plotted. The *ACRU*-Thompson and SRM forecasts were those derived from actual rainfall forecasts. The MGB forecasts only became available at a 6.5 month lead time, and are thus not indicated in all of the plots. The forecasts for the 0.5 month lead time are not shown for any of the forecasting methods, as there were negligible differences between the 0.5 month lead time forecasts and those of the preceding 4.5 month lead time.

The graphs indicate that forecasts become more accurate as the lead time shortens. The *ACRU*-Thompson and SRM forecasts were in many cases very similar, except for some seasons (e.g. 1990, 1995) where the SRM undersimulated yield ratios. The MGB forecasts, when they became available, gave a good representation of observed yield ratios. To give a better representation of the relative performances of the forecasting methods, the mean absolute difference (over a number of years) between each of the forecasts and the corresponding observed yields was calculated at each of the lead times and plotted in Figure 13.7. This plot indicates that the *ACRU*-Thompson forecasts were closer to the observed yields than the other forecasts, and that this trend was consistent across all lead times. However, the differences between the various forecasts were noted to be small. All forecasts were closer to the observed yields than the observed median yield.

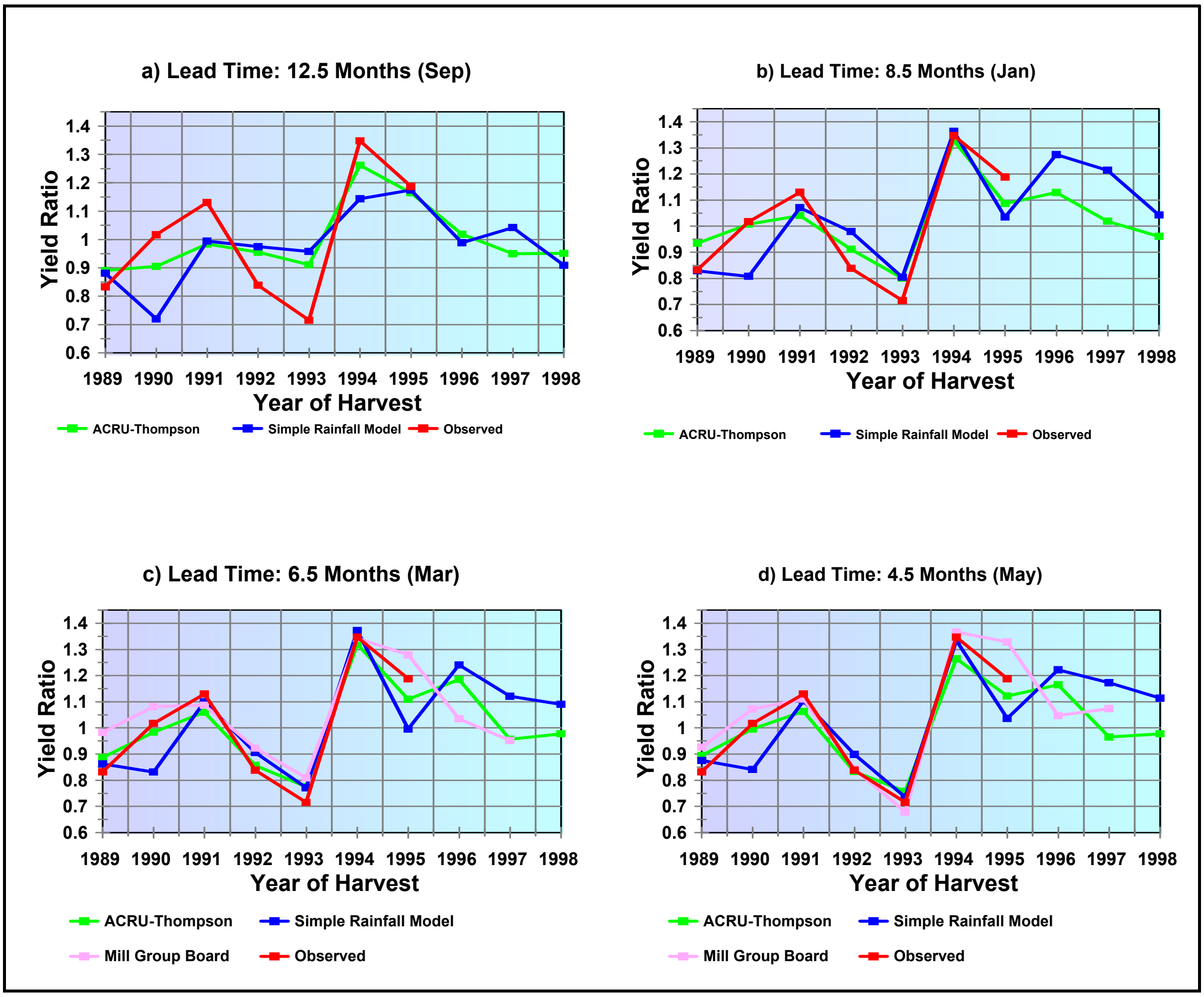

Figure 13.6 Eston Mill Supply Area yield forecasts by the *ACRU*-Thompson model, the Simple Rainfall Model and Mill Group Board estimates at various lead times (Lumsden *et al*., 1999)

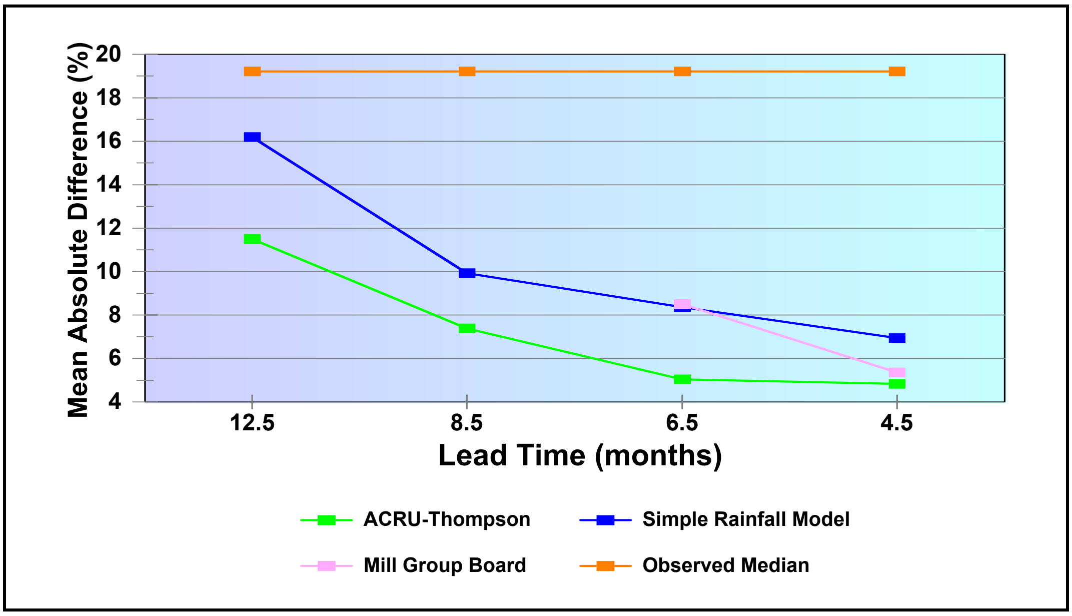

Figure 13.7 Mean absolute difference (over a number of seasons) between forecasted and observed yields at various lead times (after Lumsden *et al*., 1999)

13.10 DO YIELD FORECAST ACCURACIES IMPROVE AS A SEASON PROGRESSES?

Reference to Figures 13.6 and 13.7 indicates that yield forecasts do improve as a season progresses, with the biggest improvement occurring between the 12.5 and 8.5 month lead times (September and January forecasts). There is little improvement after the 6.5 month lead time, except for the MGB forecasts. These forecasts allow for improvements later in the season, as they are adjusted at each lead time, based on available crop production figures for earlier periods in the season. The other methods of forecasting were only adjusted by more indirect means, through the updating of model inputs (observed rainfall records), which then influence the yields forecasted.

13.11 IF RAINFALL FORECASTS WERE PERFECT, WOULD YIELD FORECASTS IMPROVE?

For the *ACRU*-Thompson model, yields forecasted using actual and perfect rainfall forecasts were plotted against time for the various lead times (Figure 13.8). The plots indicate that there is little difference between the two sets of yield forecasts, except for the 8.5 month lead time where differences are slightly larger. This is so despite the actual and perfect rainfall forecasts being generally quite different (Figure 13.4). By the 6.5 month lead time there is almost no difference between the sets of yield forecasts. This could be ascribed to the onset of the winter season, where growth is reduced as a result of lower temperatures and rainfall (regardless of the rainfall forecast). The crops are also nearing the end of their cycles.

13.12 CAN BENEFITS BE DERIVED FROM THE USE OF YIELD FORECASTS BY THE *ACRU*-THOMPSON MODEL?

Analyses were performed to assess whether benefits could be derived from the use of *ACRU*-Thompson yield forecasts, versus traditional forecasting methods. These benefit analyses are shown in Figure 13.9 for an assessment of *ACRU*-Thompson versus use of the median yield, MGB and SRM forecasts. For each harvest season and lead time, a comparison was made between the *ACRU*-Thompson forecast and the other forecasts in terms of their accuracy relative to the relevant observed yield. If the *ACRU*-Thompson was better than the other forecast, then the block representing that harvest season and lead time was shaded green, in order to indicate a 'benefit' from the use of the *ACRU*-Thompson forecast. If it was worse than the other forecast, the block was shaded red (indicating a loss), and if the forecasts were within 2.5% of each other the block was shaded grey (indicating a neutral situation).

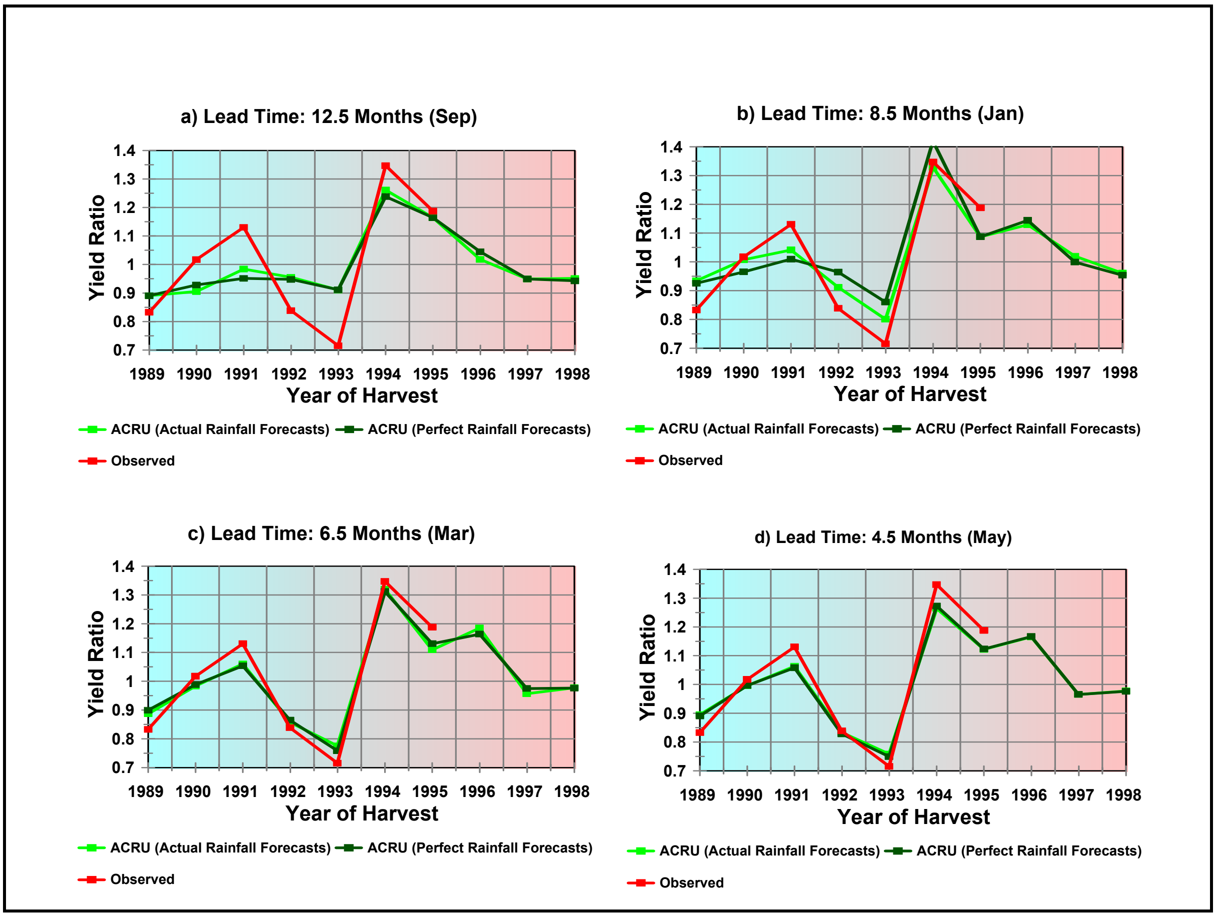

Figure 13.8 *ACRU*-Thompson yield forecasts at various lead times for the Eston Mill Supply Area, using actual and perfect rainfall forecasts (Lumsden *et al*., 1999)

In the case of the comparison with the median yield, the *ACRU*-Thompson forecasts gave rise to benefits throughout all lead times, except for the 1990 and 1991 harvest seasons. The above applied to *ACRU*-Thompson yield forecasts derived from both actual and perfect rainfall forecasts. This was as a result of the observed yields in those years being close to the median yield, which may be explained by weak or variable ENSO activity experienced during the growth cycles of those seasons' crops.

13.13 DO THE BENEFITS DERIVED FROM YIELD FORECASTS EXCEED THE COST OF IMPLEMENTING THE FORECASTING SYSTEM?

The above benefit analyses were taken further by performing a simple (first-level) economic analysis, where the benefits of forecasting were assessed against the costs of implementing the methods. The economic benefits of forecasting were expressed in terms of the savings associated with improved accuracy in yield forecasting.

a) *Economic benefits associated with improved accuracy in yield forecasting*

In order to assess the economic benefits of forecasting, consideration was first given to the costs associated with inaccurate yield forecasts derived from the different methods, including use of the observed median. The costs associated with the different methods were compared to those of the observed median, which formed the base for comparisons. The improved accuracy of the various methods relative to the observed median, and the lower costs associated with them, were considered to be the economic benefits (savings) of forecasting.

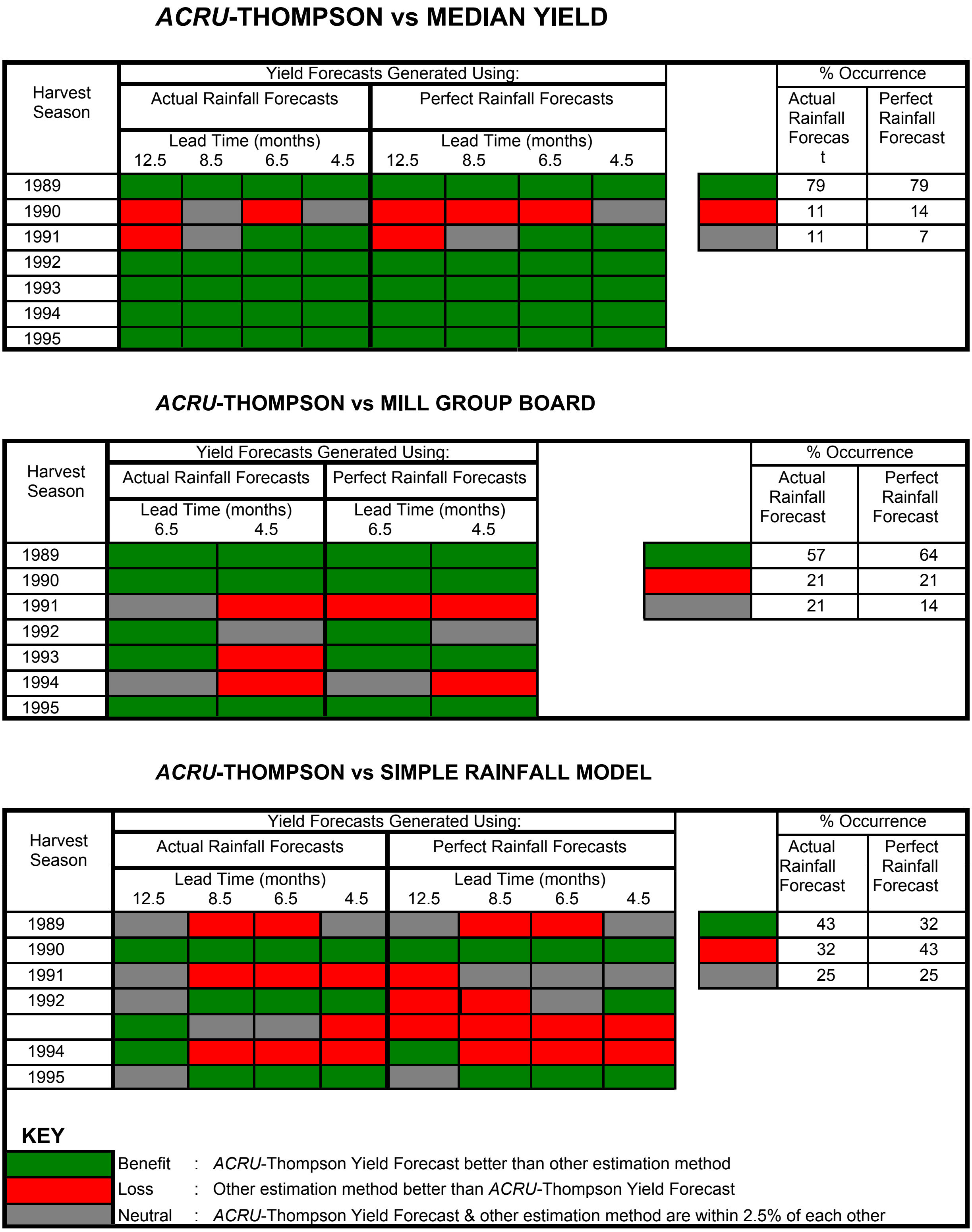

Figure 13.9 Benefit analysis of the use of *ACRU*-Thompson yield forecasts versus those using other estimation methods (after Lumsden *et al*., 1999)

The economic costs associated with inaccurate forecasts were derived from those predicted by the LOMS model for the Noodsberg Mill Supply Area (Hildebrand, 1998a). Costs accounted for in the LOMS model relate to both the miller and the growers in the area. LOMS model results were not available for the Eston Mill Supply Area. Although the cost structures at the Noodsberg Mill are different to those at Eston, it is believed that some value can be derived from use of the Noodsberg costs, as they provide a good idea of the relative costs associated with application of the different methods. The absolute costs of applying the different methods would not necessarily be representative for Eston.

The costs of over- or underestimating a 1.5 million ton crop for a milling season are plotted graphically in Figure 13.10. The costs of under-estimating a crop are greater than that of over-estimating, as an under-estimation implies that a mill must operate later into the wet season in order to complete the crushing of a crop. This period is less favourable for milling.

The costs associated with inaccurate yield forecasts generated by the various yield forecasting methods were estimated for the Eston MSA for the 1988 to 1995 harvest seasons. These costs were estimated for the March forecasts (6.5 month lead time) as it was believed that 6-8 month lead times would have the most influence on mill operating decisions. The costs were determined by first considering the estimation errors used in the development of the benefit analyses tables in Figure 13.9, i.e. differences in yield were calculated between each model forecast and the corresponding observed yield. These differences were then used to predict the costs of forecast inaccuracy through reference to the cost curves in Figure 13.10. Where estimation errors were greater than the maximum errors shown in Figure 13.10, a linear extrapolation of the cost curves was assumed. The average costs per season, over the period considered, were then calculated for each forecasting method. These costs are shown for the Eston Mill Supply Area in Figure 13.11 for the different forecasting methods applied (based on Noodsberg LOMS model cost figures). The use of the observed median yield as a predictor of the yield of a season is also represented in Figure 13.11.

The average seasonal cost of inaccurate yield forecasts is lowest for the *ACRU*-Thompson forecasts, followed by the MGB and SRM forecasts. The MGB forecasts are associated with lower costs than the SRM because the estimation errors of the former are more consistent, whereas the SRM forecasts result in both large and small estimation errors, depending on the season. The SRM gave rise to a large under-estimation in the 1995 harvest, thus further contributing to the lower average costs of the MGB forecasts relative to those of the SRM forecasts.

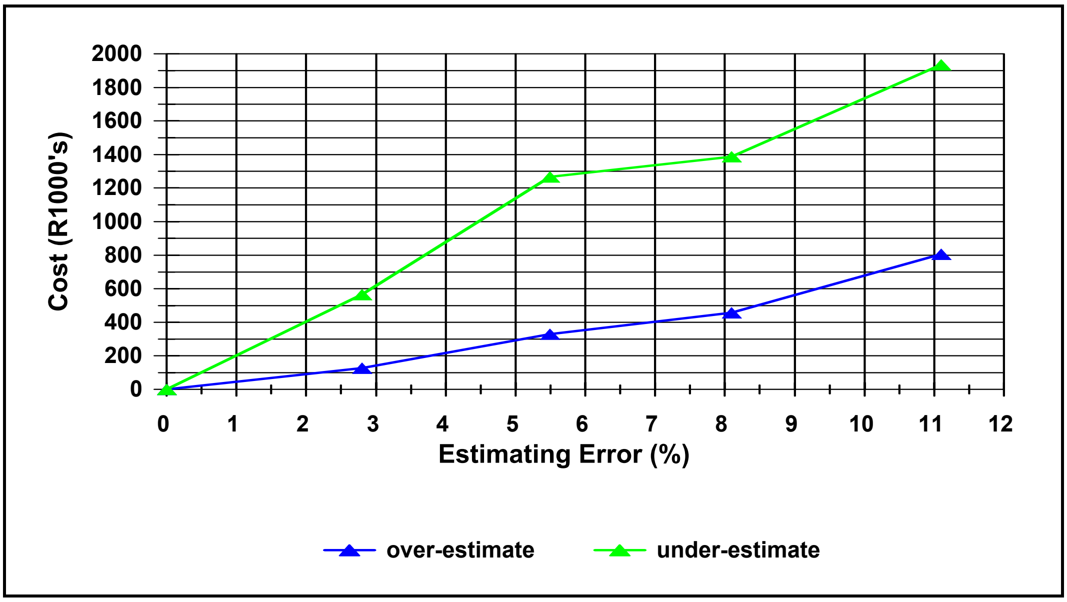

Figure 13.10 Costs to the Noodsberg miller and growers of poor estimation of a 1.5 million ton cane crop, according to the LOMS model (after Hildebrand, 1998a)

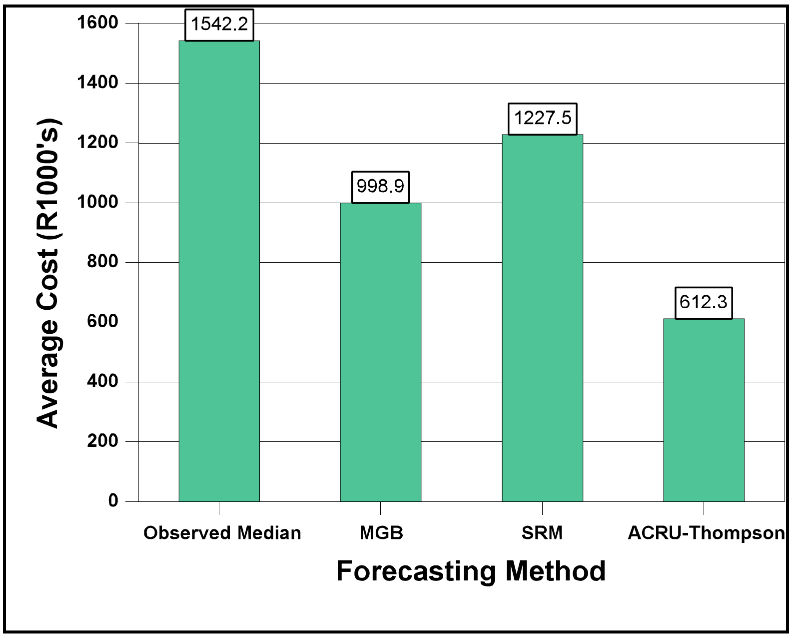

Figure 13.11 Average seasonal cost of inaccurate crop estimation in March when applying different forecasting methods (after Lumsden *et al*., 1999)

The average seasonal economic benefits (savings) of the different forecasting methods relative to the observed median are presented in Table 13.2 . These savings are determined from the costs reflected in Figure 13.11.

Table 13.2 Average seasonal economic benefits of the use of various yield forecasting methods for the Eston MSA relative to use of the observed median yield (after Lumsden *et al*., 1999)

Method of Forecasting	Economic Benefit (R1000s)
Mill Group Board	543.3
Simple Rainfall Model	314.7
ACRU-Thompson	929.9

b) Costs associated with implementing different yield forecasting methods

The costs associated with implementing the *ACRU*-Thompson and SRM forecasting methods on a monthly interval were estimated, based on the time required to set up and maintain each method. A labour cost of R150 per hour was assumed. No costs were associated with computer hardware, software or data. The estimated time required to complete each step in the setting up and maintenance of the methods is contained in Lumsden *et al*. (1999), along with other associated costs. Maintenance costs were separated into monthly and annual costs. The implementation costs of the two methods are summarised in Table 13.3, with a total of costs being given after one year of implementation.

The estimated cost, after one year of implementing of the SRM system, was approximately 18% of that estimated for the *ACRU*-Thompson system over the same period.

Table 13.3 Summary of implementation costs of *ACRU*-Thompson and Simple Rainfall Model based yield forecasting systems (after Lumsden *et al*., 1999)

Task	*ACRU*-Thompson		Simple Rainfall Model	
	Required time (h)	Cost (R)	Required time (h)	Cost (R)
Initial setup	494	74 100	105	15 750
Monthly maintenance	12 * 41	73 800	12 * 8	10 800
Annual maintenance	1 * 36	5 400	1 * 5	750
Total after one year	1 022	153 300	182	27 300

c) Net economic benefits of the forecasting methods

The economic benefits of the different yield forecasting methods can be assessed against their costs of implementation in order to estimate the net economic benefit of the methods. The average net economic benefits that could be expected for the forecasting methods after one year of implementation are estimated in Table 13.4. No costs of implementation were attributed to the MGB forecasts as this system of forecasting is already operational. Maintenance costs relating to this system were ignored.

The net economic benefit of the *ACRU*-Thompson method is highest, followed by those of the MGB and SRM methods. These net economic benefits account for initial setup costs, implying that in subsequent years the net benefits would increase for the *ACRU*-Thompson and SRM methods.

Table 13.4 Average expected net economic benefit of various yield forecasting systems after one year of implementation (after Lumsden *et al*., 1999)

Method of Forecasting	Net Economic Benefit (R1000's)
Mill Group Board	543.3
Simple Rainfall Model	287.4
ACRU-Thompson	776.6

13.14 WHAT MAY BE CONCLUDED FROM THIS STUDY?

The main objective of this project involved the development and evaluation of a sugarcane yield forecasting system for the Eston Mill Supply Area using yield simulation models and seasonal rainfall forecasts. The *ACRU*-Thompson and CANEGRO-DSSAT models were initially evaluated to verify their ability to accurately simulate historical yields, given an observed rainfall record. The *ACRU*-Thompson model was selected and used to generate yield forecasts for a number of seasons, through the application of seasonal rainfall forecasts in the model. These rainfall forecasts had previously been translated into daily rainfall values for input into the model. The sugarcane yield forecasts were then evaluated against observed yields as well as against forecasts generated by more traditional methods, these methods being represented by a Simple Rainfall Model (SRM) and Mill Group Board (MGB) estimates.

The skill of the statistically based categorical seasonal rainfall forecasts was found to be disappointingly poor. The very localised scale of the forecasts could possibly account for this inaccuracy. The location of the MSA within KwaZulu-Natal may also be a contributing factor, as seasonal rainfall tends to be less predictable in this region than in others in South Africa (Schulze *et al*., 1998).

When comparing the *ACRU*-Thompson yield forecasts to forecasts generated by the SRM, it was found that the *ACRU*-Thompson model was more consistent in the accuracy of its predictions over the various seasons considered. This is as a result of its accounting for a variety of yield influencing factors such as daily rainfall characteristics (amounts, persistencies), soil properties and temperature distribution, compared to the SRM which only accounts for monthly rainfall totals. This trend was particularly noticeable in seasons when rainfall did not have a strong influence on yields. When *ACRU*-Thompson yield forecasts were compared to MGB forecasts, the accuracy of the MGB forecasts was noted to improve relatively at the 4.5 month lead time. This lead time is relatively short and would not allow a great deal of time for planning decisions. The *ACRU*-Thompson yield forecasts would thus offer a better alternative for longer lead time planning. When comparing *ACRU*-Thompson yield forecasts to the median yield for the Eston MSA, the *ACRU*-Thompson model gave a better representation of the seasonal yield for those seasons which were more strongly influenced by ENSO events. As rainfall forecasts were generally of low accuracy, the benefit of using the *ACRU*-Thompson model in these seasons must relate to the use of observed rainfall up to the time of forecast. The length of observed record available at this point in the season, and the model's ability to simulate the factors relating to seasonal crop growth, enables the model to better represent the observed yield (as compared to the median).

A simple net economic benefit analysis was conducted to assess whether economic benefits could be derived from the application of the various yield forecasting systems. The analysis indicated that the *ACRU*-Thompson system could potentially give rise to greater net economic benefits when compared to those from traditional forecasting methods (SRM, MGB). The benefits associated with applying the forecasting methods were derived from economic figures for the Noodsberg area. The calculation of the benefits of the different methods relative to the median yield ensured that the analysis was more representative for the Eston MSA. The relative net economic benefits of the methods were of interest, as the absolute net benefits would not necessarily have been representative of Eston. This cost-benefit analysis centred around improvements in forecast accuracy (and thus improvements in mill operating decisions) and the cost of implementing a yield forecasting system. There are potentially many other benefits and costs associated with yield forecasting, particularly at scales other than the Mill Supply Area, e.g. at farm and national scales.

13.15 ACKNOWLEDGEMENTS

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CHAPTER 14

THE POTENTIAL THREAT OF SIGNIFICANT CHANGES TO HYDROLOGICAL RESPONSES IN SOUTHERN AFRICA AS A RESULT OF CLIMATE CHANGE : A THRESHOLD ANALYSIS ON WHEN THESE COULD OCCUR, AND WHERE THE VULNERABLE AREAS ARE

R.E. Schulze and L.A. Perks

School of Bioresources Engineering & Environmental Hydrology
University of Natal, Pietermaritzburg, South Africa

ABSTRACT

In climate change studies, thresholds represent magnitudes of a response variable, e.g. runoff, to a change in driving variables, e.g. precipitation and temperature, at which that response becomes significantly different to its value under present climatic conditions. Threshold analyses were carried out using the *ACRU* hydrological modelling system to simulate where and at what point in time a significant change in mean annual runoff (MAR) and mean annual recharge of soil water into the vadose zone could be expected to occur in southern Africa. ‘Significant’, in this study, is defined as a + or - 10% change from present mean annual values. Temperature and precipitation output for a future climate scenario represented by an effective doubling of atmospheric carbon dioxide was obtained from the 1998 version of the Hadley Centre’s General Circulation Model (GCM) which excluded sulphate forcing, *viz*. the HadCM2-S GCM. The threshold analyses allowed the identification of areas where changes exceeding + or - 10% in mean annual runoff and recharge into the vadose zone could occur either sooner, or later, than in other areas, giving an indication of the potential vulnerability of regions in southern Africa to climate change.

The chapter describes the derivation, from GCMs, of precipitation and temperature changes associated with a climate change scenario represented by an effective doubling of atmospheric CO_2 concentrations, their downscaling to Quaternary Catchment scale, the methodology of applying a threshold analysis to a climate change scenario and results obtained with the HadCM2-S GCM. Results indicate for the case of a 10% decrease in MAR that this could occur in the western third of South Africa by 2015 already, and progressively later as one moves eastwards. This finding, together with results from a sensitivity study of changes in MAR to changes in individual climate change driving variables (Chapter 6), indicates that the Western Cape Province appears to be the most vulnerable region in South Africa to hydrological impacts of climate change.

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14.1 THE POTENTIAL THREAT OF CLIMATE CHANGE TO HYDROLOGY

Southern Africa, defined in this study as the contiguous area covered by the Republic of South Africa together with Lesotho and Swaziland, is under present conditions already characterised by a scarcity of available water in many regions. This is exacerbated by a high temporal and spatial variability of rainfall and runoff (cf. Chapter 6), thus rendering it a high risk natural environment (Basson 1997; Schulze 1997a). Changes in climate are expected to add an extra dimension to the present vulnerability, especially since it has been shown in many studies that the hydrological system amplifies any changes in climate (cf.Chapter 6). Further to that, developing countries are considered more vulnerable to climate change owing to their socio-economic infrastructure and, in many cases, a high dependency on natural resources such as natural streamflows and rainfed agriculture (Downing *et al*., 1997). One technique of assessing the potential threat of climate change impacts is by threshold analysis.

14.2 WHAT IS A THRESHOLD ANALYSIS?

In climate change impact studies, thresholds represent those magnitudes of a response variable (e.g. runoff) to changes in driving variables (e.g. rainfall, temperature, carbon dioxide concentration) at which that response becomes 'significantly' different to that under present climatic conditions. The implication of 'significant' could be that a discrete discontinuity in the response appears, e.g. when a certain level of curvilinearity of the runoff : rainfall relationship is attained (steepening or flattening), or when a certain level of relative change has occurred that is considered critical, e.g. when mean annual runoff change has reached $\pm$ 10% or $\pm$ 20% or one standard derivation from the present, or when a certain level of absolute change has occurred, e.g. when mean annual runoff has changed by $\pm$ 50 mm (i.e. 50 000 m^3/km^2 of catchment area) or $\pm$ 100 mm (i.e. 100 000 m^3/km^2 of catchment area).

14.3 WHAT ARE THE OBJECTIVES OF THIS THRESHOLD ANALYSIS?

The objectives of this study were

- to identify when, over the next 60 years, a threshold 10% decrease or increase in mean annual runoff (MAR) and mean annual recharge of soil water into the vadose zone could potentially occur over different regions of South Africa under a credible GCM scenario of greenhouse gas forced global climate change,
- by simulating mean annual runoff and mean annual recharge of soil water into the vadose zone using the *ACRU* model for 'present' climatic conditions as well as for time slices over the next 60 years during which a 2 x CO_2 'future' climate scenario is hypothesised to set in.

If 'present' climate, represented by climate characteristics for the 1961-1990 baseline period, is set at the year 2000 and an effective doubling of atmospheric carbon dioxide (2 x CO_2) is a GCM scenario of a 'future' climate assumed to occur at 2060, then the time slices for a ¼ change in climate, ½ and ¾ changes in climate could be considered to be analogous to the climates by the years 2015, 2030 and 2045.

14.4 WHAT GENERAL CIRCULATION MODEL WAS USED IN THIS THRESHOLD ANALYSIS?

Many GCMs are available for climate change impact studies, and outputs from five GCMs were evaluated for South Africa in a recent study (Perks, Schulze, Kiker, Horan and Maharaj, 2000; Schulze and Perks, 2000). Climatic output from the now frequently used 1998 version of the Hadley Centre GCM, HadCM2-S, was selected for use in this threshold analysis. This GCM was developed by the UK Meteorological Office and the Hadley Centre (Murphy and Mitchell, 1995). The Hadley model is a transient GCM which includes a coupled dynamical ocean model and runs at a spatial resolution of 2.50° latitude and 3.75° longitude. In transient GCM simulations the ambient CO_2 level is increased at a fixed rate, for example at 1% per annum over time, and then compounded until doubling has occurred (Joubert and Tyson, 1996). Output from these simulations does not include the effect of sulphate forcing.

14.5 HOW IS PRESENT CLIMATE PERTURBED TO REPRESENT A FUTURE CLIMATE SCENARIO?

Monthly mean values of precipitation, maximum and minimum temperatures for two simulation periods from the HadCM2-S GCM were provided by Hewitson *et al*. (1998), *viz*. a control simulation representing baseline, or 'present' (1961-90) climatic conditions (1 x CO_2) and a second simulation which included greenhouse gas forcing through a 1% per year increase in atmospheric CO_2 concentrations until an effective doubling of atmospheric CO_2 is reached (2 x CO_2), representing a potential 'future' climate scenario.

In the case of temperatures (T), the *difference* between GCM predictions from 2 x CO_2 (future, f) and 1 x CO_2 (present, p) climate scenarios may be considered a plausible temperature scenario for assessments of relative change. This difference is designated by ΔT. Similarly, in the case of precipitation, it is argued that the *ratios* between GCM outputs for 'future' and 'present' climates may be used as an index of relative changes in precipitation. This ratio change in precipitation is designated by ΔP. The absolute change in temperatures and ratio change in precipitation are then used in conjunction with the baseline (b) monthly estimation of temperature (T_b) and precipitation (P_b), respectively, to obtain future climate scenarios. Hence, a future temperature climate would be represented by

$$T_f = T + (T_f - T_p)$$

while a future rainfall climate would be represented by

$$P_f = P_b \times P_f/P_p.$$

14.6 HOW ARE VALUES FROM COARSE G.C.M. GRIDS DOWNSCALED (INTERPOLATED) TO A QUATERNARY CATCHMENTS SCALE?

Although many complex downscaling techniques are available (as reviewed in Perks *et al*., 2000), a relatively simple inverse distance weighting (IDW) technique available in the ARC/INFO GIS was used for weighted bilinear interpolation of the GCM output to a quarter of a degree latitude/longitude (¼°) resolution. The IDW interpolation technique determines grid values using a linearly weighted combination of a set of sample points, with the weighting being a function of the inverse of the distance from control points. This gives the closest point the highest, and the furthest point the lowest, relative weighting. In this study, the inverse of the square of the distance was used, so as to give the closest point an even higher relative representation. Thus, IDW allows for the control of the significance of known input points upon the interpolated values, based on their distance from the output point (ESRI, 1991).

14.7 HOW IS PRESENT CLIMATE, WHICH NEEDS TO BE PERTURBED TO SIMULATE A FUTURE CLIMATE SCENARIO, REPRESENTED?

Month-by-month grid values of present baseline rainfall as well as maximum and minimum temperature values are available for the southern African study area at a resolution of 1' x 1' of a degree latitude/longitude (~ 1.6 km x 1.6 km) from the *South African Atlas of Agrohydrology and -Climatology* (Schulze, 1997b).

The detailed 1' x 1' grids of present climate parameters already reflect all the major physiographic determinants (such as altitude, distance from sea, lapse rates) in their derivation. Physiographic influences will, therefore, also reflect these physiographic influences proportionally at local scale in impact studies of climate change scenarios, on the assumption that on a local scale these invariate characteristics such as altitude or topographic valley index will act similarly on perturbed climates as they do on present ones.

The threshold analyses were performed at a Quaternary Catchment (QC) spatial scale and thus estimates of changes in temperature and precipitation, as simulated by the HadCM2-S GCM, were needed for each QC. When determining the predicted magnitude of change of temperature and precipitation for each QC, the centroid of each QC was first determined. The ¼° grid value of either temperature or precipitation closest to the centroid's point location was then the value which was used to estimate the change in climate for that QC.

14.8 WHAT REFINEMENTS WERE MADE TO THE *ACRU* MODEL TO SIMULATE CLIMATE CHANGED CONDITIONS?

The drivers of climate change from a hydrological perspective are, first, changes in precipitation (number of raindays, amounts, intensities, durations, persistencies in wet/wet, wet/dry, dry/wet and dry/dry sequences); secondly, changes in temperature (and its effect on evaporative demand; also, as a trigger for biological development); and thirdly, changes in atmospheric CO_2 concentrations (which induce a transpiration loss feedback through a change in stomatal conductance). Changes in precipitation and temperature, and their impacts, have always been an option in the *ACRU* model. Further refinements were as follows:

- The first was to accommodate the suppression of transpiration which is associated with increased stomatal conductance when atmospheric concentrations of CO_2 rise. Following recent research (IPCC, 1996), the maximum transpiration suppression for leaf area indices, LAI, $\geq$ 2.7 was set at 15% for C3 plants (e.g. wheat, soybean, most vegetables) and 22% for C4 plants (e.g. maize, sorghum, sugarcane, most natural vegetation in South Africa). This maximum suppression is reduced proportionately with a decrease in canopy cover, and thus LAI, and the corresponding increased exposure of soil to evaporation processes.
- The second refinement was to trigger the seasonal development of biomass indicators in *ACRU* (e.g. the month-by-month vegetation water use coefficient, canopy interception per rainday and root fraction in the topsoil) to be thermally driven by critical minimum temperatures (Perks *et al*., 2000). Thereby a dynamic growth development was enabled, dependent upon temperature. An example of this is illustrated in Figure 14.1.
- This dynamic biomass development was modulated in *ACRU* to account for soil water stress and the plant's gradual recovery from stress following the soil's wetting up again after rainfall - with the recovery rate again being temperature driven. An example of this is given in Figure 14.2.

These three refinements account, in a dynamic manner, for regional as well as inter- and intra-seasonal changes in temperature and precipitation, and also global changes in atmospheric CO_2 concentrations, which are associated with climate change. All equations for these various refinements, as well as graphical examples thereof, are given in Perks *et al*. (2000) and Schulze and Perks (2000).

14.9 WHAT METHODOLOGY WAS USED FOR THE THRESHOLD ANALYSIS?

Simulations can be carried out assuming scenarios of either present climatic conditions or those for effectively doubled atmospheric CO_2 climatic conditions. These two output time periods do not, however, allow for simulations to be carried out at time intervals between the two output points. Therefore, the following methodology was used in the threshold analyses in this study to perform simulations representing present climatic conditions plus those of a ¼, ½, ¾ and complete change in climate for the future climate scenario from the HadCM2-S GCM. The assumption is made of a linear change in temperature, precipitation and atmospheric CO_2 concentration from present climatic conditions to the time when effective doubling of atmospheric CO_2 conditions have taken place. This assumption was found by Parry *et al*. (1999) in a detailed study to be a reasonable one.

Mean annual runoff and mean annual recharge into the vadose zone were simulated for each of the 1946 QCs in South Africa, Lesotho and Swaziland. Each QC was considered an independent spatial unit on which the *ACRU* model was run with the following climatic input:

- present precipitation and temperature
- ¼ change in GCM predicted change in precipitation, temperature and CO_2
- ½ change in GCM predicted change in precipitation, temperature and CO_2
- ¾ change in GCM predicted change in precipitation, temperature and CO_2 and
- complete change in GCM predicted precipitation, temperature and CO_2.

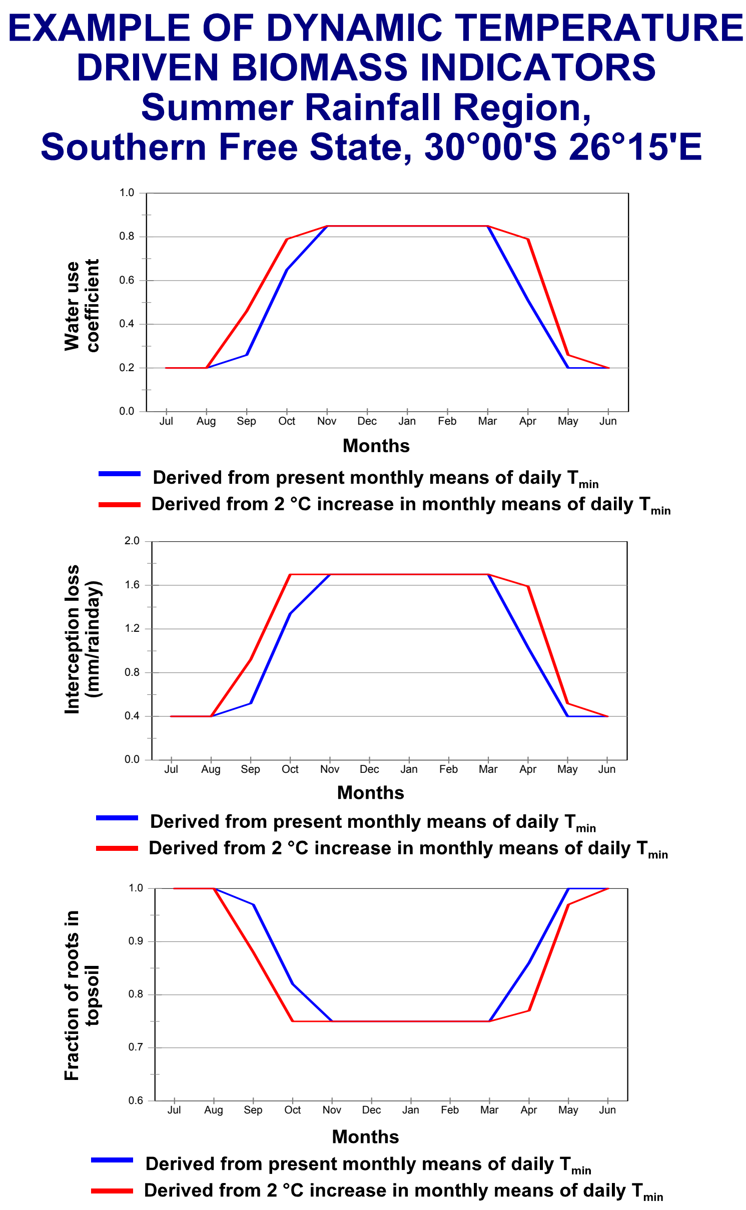

Figure 14.1 Example of dynamic temperature driven biomass indicators for present and future climate scenarios (after Schulze and Perks, 2000)

In the case of a ¼ change in GCM predicted change in climate,

¼ Δ P	=	[¼ (P_f / P_p - 1) + 1] x P_b for each month of the year
¼ Δ T	=	[¼ (T_f - T_p) + T_b] for each month of the year
¼ Δ CO_2	=	¼ (15%) suppression of transpiration in *ACRU* for C3 plants
	=	¼ (22%) suppression of transpiration in *ACRU* for C4 plants.

In the case of the other fractional changes in GCM predicted variables, the ¼ in the above equations was substituted by ½ and ¾ respectively. *ACRU* model runs were for C4 plants.

If estimated dates are assigned to the baseline, as well as to the ¼, ½, ¾ and completed climate change simulations, maps can be created showing when, in future, a critical change in response of a variable might occur, or alternatively, what the anticipated magnitude of change of a hydrological response would be by a certain date. If the assumption is made that the baseline climate is representative of the year 2000 and

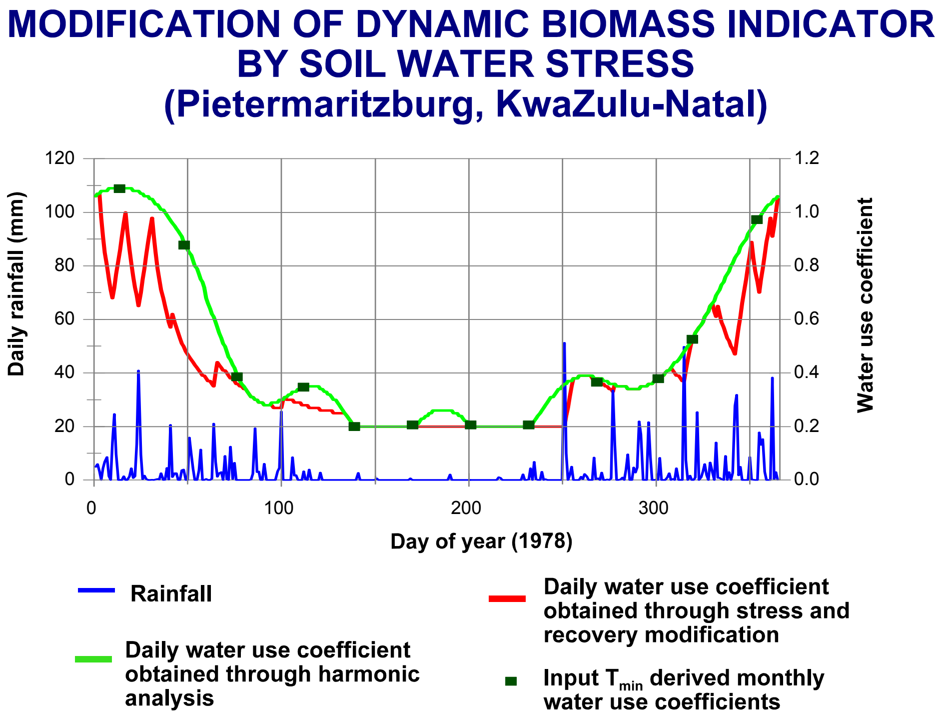

Figure 14.2 Modification of dynamic biomass indicator by soil water stress : An example (after Schulze and Perks, 2000)

that an effective doubling of CO_2 would occur in the year 2060, then ¼, ½ and ¾ changes in climate would be represented by the years 2015, 2030 and 2045 respectively.

14.10 BY WHEN COULD CLIMATE CHANGE IMPACTS ON HYDROLOGICAL RESPONSES BECOME SIGNIFICANT?

If the HadCM2-S GCM is assumed to simulate changes to climatic variables for 2 x CO_2 atmospheric concentrations realistically, and a 10% increase or decrease in mean annual runoff or mean annual recharge into the vadose zone is considered a significant change in hydrological response from a water resources perspective, then the threshold analysis described above produces the following results:

a) Threshold analysis of mean annual runoff

First, the year by which each QC in southern Africa was simulated to experience a 10% decrease or increase in mean annual runoff (MAR) was estimated. The western half of the study area may experience a 10% simulated decrease in MAR by the year 2015 already (Figure 14.3). This corresponds to a ¼ change in HadCM2-S GCM climate output. Moving from the western half of the study area towards the eastern coastline, the year by which a 10% decrease occurs is generally progressively later, with the central northern regions only expected to experience a 10% decrease in MAR by 2060, when climatic conditions are considered equivalent to those of a 2 x CO_2 atmosphere.

The northern and eastern regions of the study area experience increases in runoff in the future climate scenario as simulated by the 1998 version of the Hadley GCM. The areas that experience a 10% increase in runoff generally experience this increase only after 2030. There are, however, a number of QCs on the west coast which could experience a 10% increase in runoff by 2015 already.

b) Threshold analysis of mean annual recharge of soil water into the vadose zone

A more patchy image results from the threshold analysis of mean annual recharge into the vadose zone

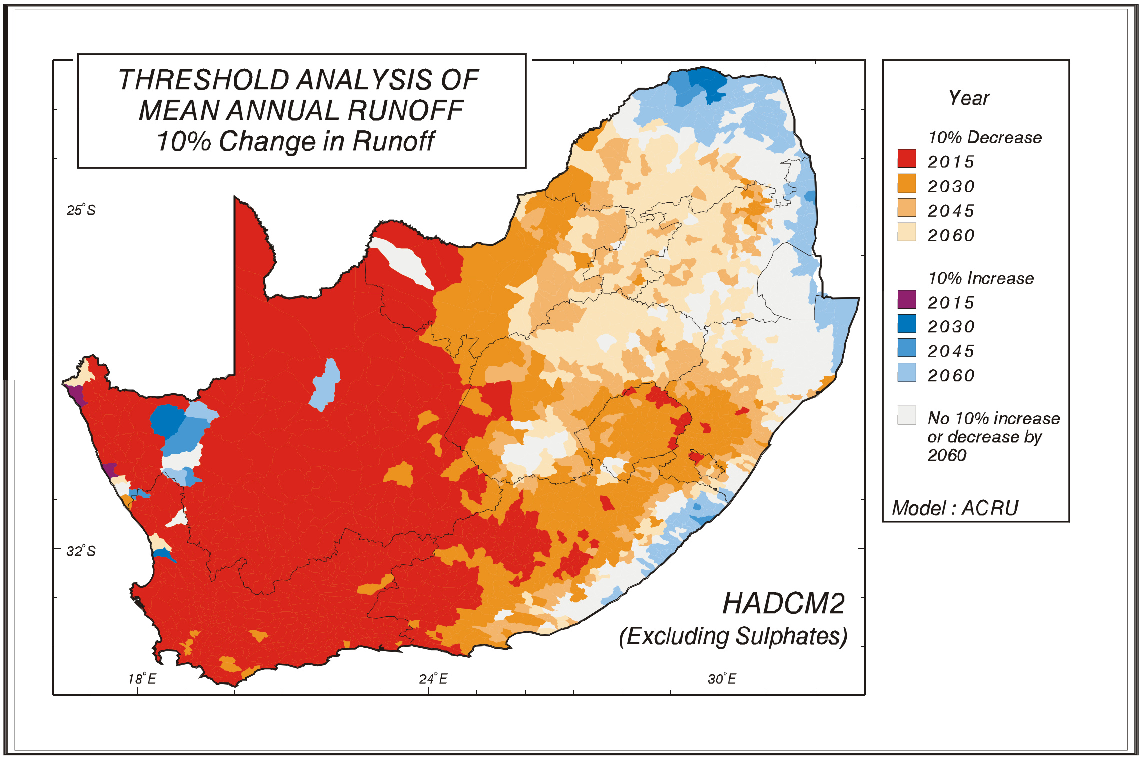

Figure 14.3 Threshold analysis of mean annual runoff, showing the year by which a 10% change in runoff is simulated to occur (after Schulze and Perks, 2000)

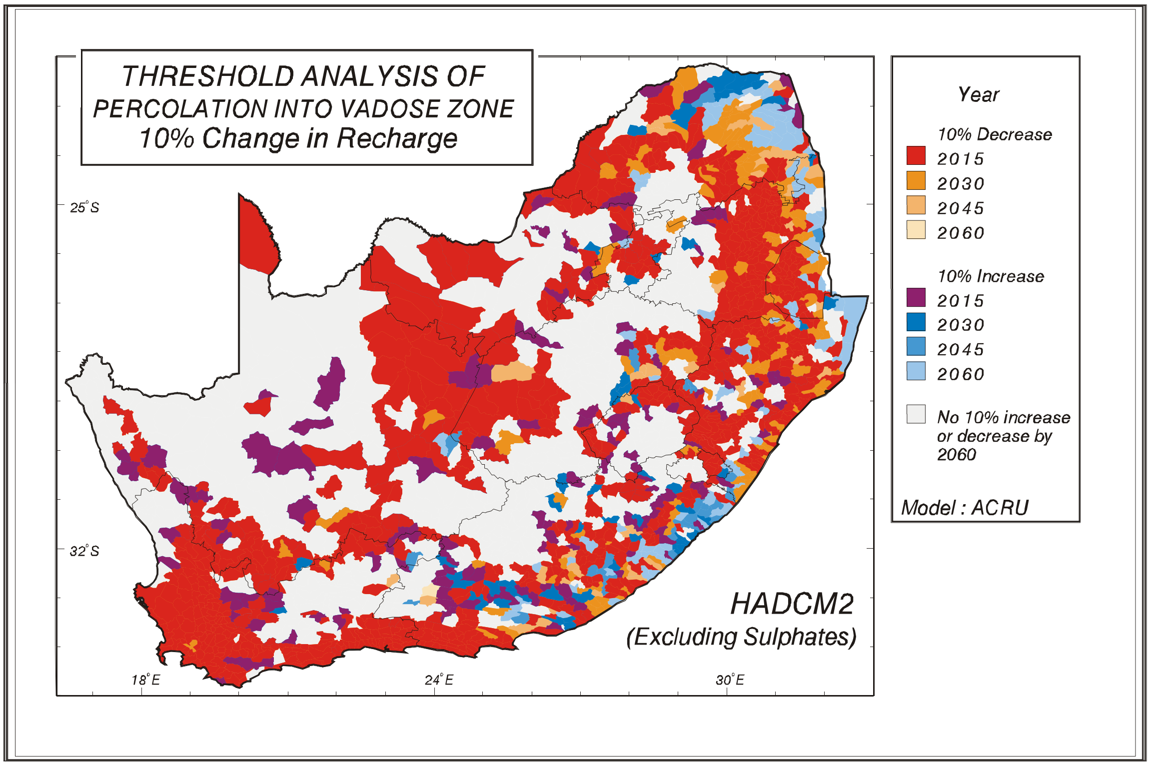

Figure 14.4 Threshold analysis of mean annual recharge of soil water into the vadose zone, showing the year by which a 10% change in mean annual recharge of soil water into the vadose zone is simulated to occur (after Schulze and Perks, 2000)

(Figure 14.4). The regions which experience a 10% decrease in mean annual recharge mostly experience this decrease by 2015 already, when only ¼ of a 2 x CO_2 climate change scenario is hypothesised to have occurred. There are a number of QCs which show a 10% increase in recharge by 2015. However, there does not appear to be any pattern to the changes using output from the 1998 version of the Hadley GCM. The 10% threshold response for recharge thus generally appears much earlier than that for runoff.

14.11 WHAT CONCLUSIONS MAY BE DRAWN FROM THIS STUDY?

Threshold analyses are useful to ascertain at what stage during a gradual change in climate the hydrological system's response will change significantly from that under present climatic conditions. The estimates of the threshold of mean annual runoff and recharge into the vadose zone were achieved by performing three *ACRU* simulations in addition to the simulations of present and estimated future climatic conditions. These additional simulations represented a ¼, ½ and ¾ change in climatic conditions between the present and a 2 x CO_2 scenario, using output from the 1998 version of the HadCM2-S GCM and assuming a linear change in climate with time.

Any assessment of potential impacts of changes in climate on hydrological systems is subject to a range of uncertainties. These uncertainties, described in detail in Schulze and Perks (2000), arise in part from an inadequate understanding of biophysical processes, such as the complex mechanisms involved in the responses of biological systems, and the uncertainties derived from inaccuracies of the GCM output through incomplete understanding of the behaviour of the physical climate system. In addition, there is the inability to accurately predict spontaneous and human induced adaptations to changes in climate.

If, however, the results shown in Chapter 6 on the sensitivity of individual drivers of climate change in hydrology, *viz*.

- increased concentrations of individual CO_2 (through changes in plants' stomatal resistances),
- increased temperatures (through increases in evaporative demand as well as regional and intra-seasonal changes in biomass development) and
- changes in precipitation characteristics (either up or down, varying day by day within a year and from place to place within southern Africa)

are viewed together with the threshold analysis depicting a potential 10% change in runoff by 2015, then the indicators are very strong that the southwestern parts of South Africa could be experiencing marked changes in their hydrological regime within the next two decades already.

This is considered an important finding which, despite all the uncertainties still surrounding climate change, should be borne in mind by water resources planners in South Africa.

14.12 ACKNOWLEDGEMENTS

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