CLIMATE CHANGE AND WATER RESOURCES IN SOUTHERN AFRICA

Studies on Scenarios, Impacts, Vulnerabilities and Adaptation

R.E. Schulze
(Editor)

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SECTION A

EXECUTIVE SUMMARY, TABLE OF CONTENTS AND GLOSSARY OF TERMS

The printed version of this report contains only Section A. The CD version attached to the back cover contains the full report.

EXECUTIVE SUMMARY

CLIMATE CHANGE AND WATER RESOURCES IN SOUTHERN AFRICA:
Studies on Scenarios, Impacts, Vulnerabilities and Adaptation

R.E. Schulze
(Editor)

WRC Project K5/1430 "Climate Change and Water Resources in South Africa: Potential Impacts of Climate Change and Mitigation Strategies"

This Executive Summary is presented under the following headings:

- Background
- Project Objectives
- Project Outcomes
- Summaries of Chapter Contents
- Take-Home Messages from the Project, in a Nutshell
- Acknowledgements
- Capacity Building
- Recommendations for Future Research

BACKGROUND

A focus on potential impacts of climate change on the water sector of southern Africa (in the context of this report, made up of the Republic of South Africa together with Lesotho and Swaziland) was triggered by a series of activities and events in the first three years of the new millennium which included the World Summit on Sustainable Development, the Intergovernmental Panel on Climate Change reports in 2001, the third World Water Forum, as well as active South African participation in the International Geosphere-Biosphere Programme and Dialogue on Water and Climate, among others. Additionally, there was the realisation that perturbations in climate parameters, particularly of rainfall, were largely amplified by the hydrological system and that if climate changes were to manifest themselves in the manner which international science was predicting, it would add a further layer of concern to the management of southern Africa's already high risk and stressed water sector, with potential implications to the entire region's socio-economic well-being, but particularly that of the poor.

These concerns culminated in the Water Research Commission's soliciting a two-year research project in mid-2002 titled

"Climate Change and Water Resources in South Africa: Potential Impacts of Climate Change and Mitigation Strategies"

The project was awarded to a consortium of four South African universities, *viz*. KwaZulu-Natal (lead organisation), Cape Town, Witwatersrand and Pretoria, within each of which specialist expertise and international experience existed in one or more of climate scenario development, impacts modelling and/or the human dimension and climate change.

PROJECT OBJECTIVES

This research project set out with five main objectives, some of them with sub-objectives. These are listed below with, in each case, a short reference to indicate in which chapter(s) of the project report the objective/sub-objective was addressed.

- **Objective 1: The Development of Plausible Climate Change Scenarios for Southern Africa**
  - Sub-Objective 1: Evaluating the Envelope of Future Climate Projections, Characterising the Uncertainty and Placing Quantifiable Error Bars on the Regional Projections
  - Sub-Objective 2: Investigating the Hemispheric-Scale Dynamical Responses to Greenhouse Gas Forcing in the Context of Southern Africa, as Simulated by Different GCMs
  - Sub-Objective 3: Analysis of Southern African Regional Dynamics and Feedbacks in the Context of Climate Change
  - Sub-Objective 4: Empirical vs RCM-Based Downscaling
  - Sub-Objective 5: Historical Trends and Variability.

  These sub-objectives are all addressed in *Chapters 2 - 4*, with sub-objective 5 further evaluated in *Chapters 15 - 19*, while *Chapter 5* synthesises the findings of the preceding three chapters.

- **Objective 2: Investigation of the Potential Impacts of Climate Change on Hydrological Responses and Associated Water Resources**

  - Sub-Objective 1: Design and Refinement of an Interlinked Quaternary Catchment Level Database for Southern Africa for Application with Daily Hydrological Modelling under Present and Future Climate Scenarios
  - Sub-Objective 2: Selection of a Suitable Daily Hydrological Modelling System
  - Sub-Objective 3: Assessment of a Range of Impacts of Climate Change on Hydrological Responses
  - Sub-Objective 4: Re-Application of Above Impact Studies to the Thukela Catchment, as a Detailed Study Area.

  Chapter 6 introduces the southern African hydrological “landscape” upon which climate change would be superimposed. *Chapters 7* and *8* cover the first 2 sub-objectives, while the impacts studies *per se* make up *Chapters 9 - 11*. In *Chapters 12 - 14* three additional case studies on potential impacts of hypothetical, but plausible, future climate scenarios on hydrological responses in southern Africa are presented.

- **Objective 3: Investigation of Possible Water Related Socio-Economic Impacts of Climate Change in the Thukela Catchment and Factors Contributing to Future Risk**

  This objective is covered in *Chapters 21 - 25* by first providing a conceptual framework on vulnerability, adaptive capacity, coping and adaptation (*Chapters 21* and 22), followed by three case studies (*Chapters 24* and *25*) with emphasis on research undertaken in the Thukela catchment. Beyond the contract obligations, a study on perceptions of climate change was carried out among different stakeholders in the water sector (*Chapter 23*).

- **Objective 4: Recommendations on Some Strategies to Adapt to, and Cope with, Water-Related Impacts of Potential Climate Change**

  While *Chapter 21* already addresses many aspects of coping and adaptation, a short overview of South African policy documents on climate change with respect to water resources (*Chapter 26*) prefaces a longer chapter, *Chapter 27*, which addresses broader issues of adaptation in the water sector and provides more specific conclusions of South African stakeholders with regard to policy/legal instruments, institutional/managerial issues and research/monitoring needs.

- **Objective 5: Detection of Effects of Climate Change and Recommendations on Appropriate Monitoring Systems for its Detection**

  - Sub-Objective 1: Changes Already Evident
  - Sub-Objective 2: Monitoring Systems for Detection.

  The first of these sub-objectives is reviewed and researched in depth in *Chapters 15 - 19* in a southern African context, while the second is evaluated in terms of southern Africa's rainfall network in *Chapter 20*.

All objectives set out at the commencement of the project, plus some additional ones, have been met and are reported upon, setting the scene for addressing more practical issues on how to cope with, legislate for and adapt to, issues related to climate change in the southern African water sector.

PROJECT OUTCOMES

The outcome of this project is this Report titled

"Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation".

The Report of 470 pages has been written as 29 chapters in 9 sections which reflect the major objectives of this study. The sections are as follows:

- **Section A: Executive Summary, Table of Contents and Glossary of Terms**
- **Section B: Background to the Project**
  This consists of a single chapter providing background concepts as well as the history of, and rationale behind, the project.
- **Section C: Development of Plausible Climate Change Scenarios for Southern Africa**
  Four chapters provide the conceptual foundation and uncertainties to the various downscaling approaches adopted, which provide the project with future climate scenarios.
- **Section D: An Investigation of the Potential Impacts of Climate Change on Hydrological Responses and Associated Water Resources over Southern Africa**
  This section is made up of nine chapters covering the current hydrological "landscape" in southern Africa, the hydrological model selected, the databases which are used as a framework for the impact studies, the impact studies *per se* at the scales of southern Africa and that of a designated Water Management Area, *viz*. the Thukela catchment, and some case studies.
- **Section E: Detection of Climate Change in Southern Africa**
  The six chapters making up this section consist first, of a review of, and a description of methods for, detecting climate change, followed by studies on detecting changes in temperature, hydrological responses and rainfall as well as an evaluation of the southern African rainfall station network in regard to detection.
- **Section F: Vulnerabilities and Sensitivities of Communities to Climate Risks**
  Five chapters make up this section, starting with two chapters on the conceptual framework on vulnerability, adaptive capacity, coping and adaptation, followed by a survey on perceptions of climate change held by different stakeholders in South Africa, a case study on climate change and water poverty and a chapter on case studies on climate and development with regard to farming communities - one operating at small-scale and the other at a large-scale.
- **Section G: Adapting to Climate Change in South Africa**
  The last technical section of two chapters focuses on policy in regard to climate change and the water sector in South Africa and on adaptations to climate change by the water sector.
- **Section H: Synthesis and Recommendations for Future Research**
  Take-home messages from the project are highlighted and, based on the outcomes of this project, some recommendations are made for future research.
- **Section I: Technology Transfer and Capacity Building**
  This section presents the activities of the project team in the fields of relevant publications, workshops attended, presentations made and students trained over the duration of the project from 2003 to mid-2005.

The various chapters, which are of different lengths and at different technical/conceptual levels, are presented as "independently interdependent" entities, with each chapter standing on its own, but forming an important component "link" in the "chain" that makes up the entity of this project. With each chapter "standing on its own", it goes without saying that certain issues are covered in more than one chapter.

What follows below are summaries of the chapter contents.

SUMMARIES OF CHAPTER CONTENTS

SECTION B : BACKGROUND TO THE PROJECT

CHAPTER 1 LOOKING INTO THE FUTURE: WHY RESEARCH IMPACTS OF POSSIBLE CLIMATE CHANGE ON HYDROLOGICAL RESPONSES IN SOUTHERN AFRICA?

Roland Schulze

(15 pages, 9 figures, 1 box)

1.1 Climate Change and Water Resources: Some Background
1.2 History of this Project
1.3 Rationale
1.4 Background Concepts 1: Why does the Hydrological System Amplify Changes in Climate?
1.5 Background Concepts 2: As a Consequence of Greenhouse Gas Forced Warming, the Natural Hydrological System Will Experience Major Repercussions
1.6 Background Concepts 3: These Changes in the Climatic Drivers of the Hydrological System (ΔCO_2, ΔT, ΔP) Take on Different Regional Significances in Southern Africa Because of Different Individual and Local Sensitivities to Change
1.7 Background Concepts 4: Previous Studies Already Show that Impacts of Climate Change may be Felt Sooner over Southern Africa than We Wish, with Impacts Not Spread Evenly Across the Region
1.8 Background Concepts 5: Water Resources Planners Cannot View Climate Change Impacts on Hydrological Responses in Isolation, without Considering Additional Impacts the Climate Change may have on Shifts in Baseline Land Cover and on Land Use Patterns
1.9 The Way Forward
1.10 References

Abstract

This chapter first provides a general background to the link between climate change and water resources, then gives a brief history of the project's coming into effect and its objectives, together with the rationale behind it. Thereafter, by way of background, it highlights reasons why the hydrological system can amplify/intensify changes in climate (especially of rainfall), how the "drivers" of climate change (*viz*. changes in CO_2 concentrations as well as in temperature and in rainfall patterns) can impact on hydrological responses and how these drivers can result in different sensitivities of runoff responses in different parts of southern Africa. The chapter furthermore illustrates that previous studies had already indicated that impacts of climate change on the region's water resources would probably be experienced earlier than expected in certain areas and how changes in land use and baseline land cover could affect hydrological responses in a future climate.

SECTION C: DEVELOPMENT OF PLAUSIBLE CLIMATE CHANGE SCENARIOS FOR SOUTHERN AFRICA

CHAPTER 2 CLIMATE CHANGE SCENARIOS: CONCEPTUAL FOUNDATIONS, LARGE SCALE FORCING, UNCERTAINTY AND THE CLIMATE CONTEXT

Bruce Hewitson, Mark Tadross and Chris Jack

(18 pages, 8 figures)

2.1 Preamble
2.2 Foundational Issues Underlying Regional Climate Change Scenarios
2.3 Large Scale Response to Greenhouse Gas Forcing
2.4 Southern Africa Regional Feedbacks and Dynamics
2.5 Downscaling Methodology
2.6 Concluding Thoughts
2.7 References

Abstract

The development of regional scenarios is an evolving, and maturing, research activity. Consequently, care needs to be taken in interpreting scenarios, particularly taking cognisance of the caveats and

limitations, as well as the sources of uncertainty involved. **Chapter 2** outlines the conceptual basis for regional scenarios, and explains the two primary downscaling tools employed, *viz*. empirical and dynamical models, and their limitations. Following this, the issues of uncertainty are explored, along with consideration of the sources of uncertainty and the impact on the credibility of regional climate projections. A key source of uncertainty, *viz.* feedback mechanisms, is discussed in greater detail.

CHAPTER 3 SCENARIOS DEVELOPED WITH EMPIRICAL AND REGIONAL CLIMATE MODEL-BASED DOWNSCALING

Bruce Hewitson, Mark Tadross and Chris Jack

(18 pages, 23 figures)

3.1 Introduction to Empirical Downscaling
3.2 Results from Empirical Downscaling
3.3 Summary Comments on the Empirical Downscaled Projections
3.4 Downscaling with Regional Climate Models
3.5 Concluding Thoughts
3.6 References

Abstract

The regional climate change scenarios for South Africa, as projected by empirical and RCM downscaling tools, are presented. The downscaling considers the regional response to large-scale circulation change as simulated by three GCMs. The downscaling shows notable regional agreement between the GCMs when following the empirical approach. The RCM-based approach has qualitative agreement with the empirical projections, but there are some notable regional differences. Nonetheless, there are common messages of consensus around precipitation; a wetter escarpment in the east, a shorter winter season in the southwest, a slight increase in intensity of precipitation, and drying in the far west of southern Africa. For temperature, the country as a whole is projected to experience an increase in temperature, with the maximum increase in the interior.

CHAPTER 4 SIMULATIONS OF CLIMATE AND CLIMATE CHANGE OVER SOUTHERN AND TROPICAL AFRICA WITH THE CONFORMAL-CUBIC ATMOSPHERIC MODEL

Francois Engelbrecht

(18 pages, 8 figures)

4.1 Introduction
4.2 The Conformal-Cubic Atmospheric Model
4.3 Experimental Design and Observed Data
4.4 Simulations of Present-Day Climate
4.5 Simulations of Climate Change
4.6 Discussion and Conclusions
4.7 References

Abstract

In this chapter, climate simulations by the Conformal-Cubic Atmospheric Model (C-CAM) for the period 2070-2100 are compared to simulations for the period 1975-2005. Lower boundary forcing was obtained from the CSIRO Mk3 OAGCM, which was integrated for the period 1961-2100 with increasing greenhouse gas concentrations. The simulation of present-day climate by C-CAM has been shown to capture the regional characteristics of minimum and maximum screen-height temperature well over southern and tropical Africa. The model simulation of present-day average monthly rainfall over a 31 year period, expressed as a percentage of the average total yearly rainfall of the model, shows a remarkable correspondence to the associated observed monthly CRU fields for a 30 year period. A realistic climate change scenario has been developed for the period 2070-2100 using C-CAM. The scenario is of high enough spatial resolution to be of use in impact studies. From the simulation it appears that the future Austral winter climate of southern and tropical Africa will be controlled by an intensification of the subtropical high-pressure belt. Frontal rain bands are simulated

to shift to the south in the future climate compared to the present-day average position. This leads to a general decrease in winter rainfall over the typical winter rainfall regions of South Africa in the model simulation. Much of the eastern subcontinent is simulated to experience an increase in rainfall in the early summer within the context of the future climate. This change appears to be a response to a simulated southeastward shift in the average position of the ITCZ. In late summer most of southern Africa is simulated to become drier, however, with some parts of Namibia and the western interior of South Africa experiencing significantly wetter conditions in the future climate. More intense subsidence under stronger mid-level high-pressure systems has been inferred as the reason for the above-mentioned drier conditions.

CHAPTER 5 GENERAL CONCLUSIONS ON DEVELOPMENT OF PLAUSIBLE CLIMATE CHANGE SCENARIOS FOR SOUTHERN AFRICA

Bruce Hewitson, Francois Engelbrecht, Mark Tadross and Chris Jack

(5 pages, 1 figure)

5.1 Context Review
5.2 Competency of Downscaling
5.3 Common Messages of Regional Change
5.4 Future Directions

Abstract

This chapter seeks to synthesise the messages of **Chapters 2** to **4**, discussing the key issues of context and credibility of the regional projections. It is concluded that the results obtained are, within limits, a significant advance in our understanding of the regional nature of future climate change, and that the methodologies have matured to the point where statements about the pattern changes at a regional scale can be made with some confidence. However, the confidence in the projections is weaker for the magnitude of change. The advances made are, nevertheless, a solid foundation for future development, and recommendations are made as to priorities for future work.

SECTION D: AN INVESTIGATION OF THE POTENTIAL IMPACTS OF CLIMATE CHANGE ON HYDROLOGICAL RESPONSES AND ASSOCIATED WATER RESOURCES OVER SOUTHERN AFRICA

CHAPTER 6 SETTING THE SCENE : THE CURRENT HYDROCLIMATIC "LANDSCAPE" IN SOUTHERN AFRICA

Roland Schulze

(12 pages, 7 figures, 1 table)

6.1 Introduction
6.2 Premise 1: Even when Considering Average Present Climatic Conditions, We Already Live in a High Risk Hydroclimatic Environment in Southern Africa
6.3 Premise 2: An Already High Inter-Annual Rainfall Variability is Amplified by the Natural Hydrological System
6.4 Premise 3: Intra-Annual Variabilities of Hydrological Responses are Even Higher than Inter-Annual Ones
6.5 Premise 4: Different Components of the Hydrological System Differ Markedly in their Responses to Rainfall Variability
6.6 Premise 5: Streamflow Variability is High in Individual External Subcatchments, but in a River System Becomes Attenuated in Internal and Mainstem Subcatchments
6.7 Premise 6: Land Use Change by Intensification or Extensification of Biomass Often Increases Flow Variability Because it Changes the Partitioning of Rainfall into Stormflow and Baseflow Components
6.8 Premise 7: Degradation of the Landscape can Amplify Further any Hydrological Responses, Especially Higher Order Responses
6.9 Concluding Thoughts
6.10 References

Abstract

The southern African hydroclimatic environment, even under present climatic conditions, is already a harsh one. As a backdrop to assessing potential impacts of climate change, a brief review is undertaken of present hydroclimatic conditions, upon which any perturbations of future climate will be superimposed. Amongst the basic premises made are that the hydrological system amplifies any variability in climate, that different components of the hydrological system differ markedly in their responses to rainfall variability, that streamflow variability is considerably higher in external than in internal (mainstem) subcatchments, that land use change often increases flow variability and that degradation of the landscape amplifies further any hydrological responses. Each premise is backed up with maps which clarify the points made.

CHAPTER 7 SELECTION OF A SUITABLE AGROHYDROLOGICAL MODEL FOR CLIMATE CHANGE IMPACT STUDIES OVER SOUTHERN AFRICA

Roland Schulze

(16 pages, 10 figures)

7.1 The Background Against which Management of the Hydrological System has to Operate
7.2 Considerations and Requirements when Modelling Impacts of Climate Change on the Hydrological System
7.3 The *ACRU* Agrohydrological Modelling System for Simulations of Climate Change Impacts on Hydrological Responses and Water Resources Assessments
7.4 Conclusions: Is *ACRU* a Suitable Model for Climate Change Impact Studies on Hydrological Processes and Water Resources?
7.5 References

Abstract

The background in which the hydrological system has to be managed is a complex one as it is essentially already a "damaged" ecosystem. This requires managers to take an holistic view of planning, as is embodied in the DPSIR (Drivers, Pressures, States, Impacts and Responses) approach, especially when climate change becomes an added stressor. The requirements, when modelling climate change impacts on the hydrological system, include the ability to explicitly model the dynamics of runoff generating mechanisms, to distinguish clearly between landscape-based and channel-based processes, and then modelling all those processes across a range of climatic regimes, land use practices and spatial scales. These requirements demand a physical-conceptual and process-based model to be selected which can account for non-linear dynamic responses. The daily timestep and multi-purpose *ACRU* model is evaluated according to the above criteria. Its advantages are highlighted, but shortcomings are also discussed. In conclusion the *ACRU* model is considered highly suitable for use in simulating impacts of climate change on hydrological responses

CHAPTER 8 THE SOUTHERN AFRICAN QUATERNARY CATCHMENTS DATABASE: REFINEMENTS TO, AND LINKS WITH, THE ACRU SYSTEM AS A FRAMEWORK FOR MODELLING IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

Roland Schulze, Michele Warburton, Trevor Lumsden and Mark Horan

(29 pages, 17 figures, 7 tables)

8.1 Overview and Objectives
8.2 Initial Structure of the *ACRU* Input Database
8.3 Revised Structure of the *ACRU* Input Database
8.4 The Pre-Populated Quaternary Catchments Input Database
8.5 Analyses on Climate Change Impacts with the Quaternary Catchments Database
8.6 Selections of Catchments from the Quaternary Catchments Input Database
8.7 Simulation of Agrohydrological Responses from Individual Catchments
8.8 Simulation of Agrohydrological Responses from Cascading Catchments
8.9 Extraction of Output from *ACRU* for Presentation
8.10 Further Refinements to the Quaternary Catchments Database
8.11 Conclusions

8.12 References

Abstract

Underpinning the entire assessment of climate change impacts on hydrological responses in southern Africa is the Quaternary Catchments Database (QCDB) which contains 1 946 Quaternary Catchments (QCs), each populated with a 50 year daily rainfall and temperature data file, as well as soils and land cover information. The QCs are linked hydrologically for streamflows generated with the *ACRU* model to flow from "external" to "internal" QCs and along mainstem rivers which eventually discharge either into the ocean or to neighbouring downstream countries. Additionally, the QCDB supports all the functionality of *ACRU* as a multi-purpose model which can simulate, *inter alia*, crop yields, irrigation requirements and sediment yield. This review of the QCDB supercedes a previous one by Hallowes *et al*. (2004) and highlights the refinements developed specifically for this project, i.e. primarily the introduction of the 50 year time series of *daily* temperatures for each QC and the totally revised, updated, quality controlled and intensively researched daily rainfall datasets for each QC.

CHAPTER 9 AN ASSESSMENT OF IMPACTS OF CLIMATE CHANGE ON AGROHYDROLOGICAL RESPONSES OVER SOUTHERN AFRICA

Roland Schulze, Trevor Lumsden, Mark Horan, Michele Warburton and Manjulla Maharaj

(49 pages, 32 figures, 1 table)

9.1 Setting the Scene
9.2 Baseline Climate
9.3 Baseline Land Cover
9.4 Terminology Used
9.5 Scenarios of Climate Change Using the C-CAM Regional Climate Model
9.6 Assessing Potential Impacts of Climate Change on Water Resources When Using Regional Climate Model Output: Problems Identified and the Approach Adopted
9.7 Comparison of Agrohydrological Model Drivers and Responses Between Future and Present Climate Scenarios
9.8 Agrohydrological Drivers 1: Rainfall Parameters
9.9 Agrohydrological Drivers 2: Temperature Parameters
9.10 Agrohydrological Drivers 3: Potential Evaporation, E_r
9.11 Agrohydrological Responses 1: Occurrences of Permanent Wilting Point in the Topsoil
9.12 Agrohydrological Responses 2: Stormflow
9.13 Agrohydrological Responses 3: Baseflow
9.14 Agrohydrological Responses 4: Accumulated Streamflows
9.15 Agrohydrological Responses 5: Net Irrigation Requirements
9.16 Agrohydrological Responses 6: Sediment Yields
9.17 Agrohydrological Responses 7: Partitioning of Rainfall into "Blue", "Green" and "White" Water Flows
9.18 Agrohydrological Responses 8: Design Rainfall and Extreme Events
9.19 Discussion and Conclusions
9.20 References

Abstract

In this chapter a brief history of climate change in relation to the water sector in South Africa precedes explanations and definitions of terms used, and a brief description of the regional climate model which is applied in subsequent sections on impacts on hydrological responses, *viz*. the C-CAM Regional Climate Model. After highlighting and illustrating problems which hydrological modellers typically encounter when using GCM or RCM climate input in their models, a "ratio of future to present" approach is opted to illustrate potential impacts of climate change on inputs into, and outputs from, the daily timestep conceptual-physical *ACRU* agrohydrological model. Future:present ratio changes between *inputs* of rainfall, temperature and potential evaporation are evaluated with respect to mean annual, as well as the 10th, 50th and 90th percentiles of annual values, and inter-annual coefficients of variation. Additionally, process-relevant and event-based ratios are calculated to explore potential impacts of climate perturbations on daily hydrological responses. Similarly, *output* from the *ACRU* model runs with present and future RCM daily climate input are analysed as ratio changes of parameters of soil water content, stormflows, baseflows, accumulated streamflows, net irrigation requirements, sediment yield, design hydrological values and so-called "blue", "green" and "white" water flows. The *ACRU* model, when using C-CAM daily output from its present and future climate

scenario runs, as input for agrohydrological simulations, illustrates that in some cases major ratio changes might in future result in "hotspots" of hydrological change, many of which may need to be acted upon by water resources managers. The present winter rainfall region in the Western Cape is one such "hotspot" of major concern. The credibility of the outcome of this study depends to a large extent on the downscaled output of daily climate values from one single regional climate model (RCM), *viz*. C-CAM. It is well appreciated that GCMs, from which the RCMs are developed, have known biases and that these are carried forward in the RCMs. More than one RCM, as well as proven empirical downscaled approaches, should therefore be used in subsequent hydrological impact studies in order to seek consistency in identifying "hotspots" of regional change. Finally, in interpreting the results of this study, it is important to bear in mind that the regional patterns of change and the sign of that change, rather than the magnitudes, are important.

CHAPTER 10 THE THUKELA CATCHMENT: PHYSICAL AND SOCIO-ECONOMIC BACKGROUND

Roland Schulze, Dennis Dlamini and Mark Horan

(19 pages, 18 figures, 13 tables)

10.1 Setting the Scene
10.2 Physiography
10.3 Climate
10.4 Soils
10.5 Land Cover and Land Use
10.6 Socio-Economic Profile

Abstract

The 29 062 km^2 Thukela catchment was selected as the case study Water Management Area for this climate change impacts study because of its diversity in physiography, climate, soils, land use and socio-economic profile. As a backdrop to chapters which follow on hydrological responses in the Thukela under present and future climate scenarios, the diverse elements of the catchment are described in this chapter by way of maps and accompanying descriptions on, *inter alia*, altitude, slopes, climatic variability, soil characteristics and land use patterns, as well as demography and its spatial distribution, education, income and household services, most of which highlight the underdevelopment of many areas within the catchment, which make them vulnerable to impacts of climate change.

CHAPTER 11 SENSITIVITY STUDIES OF HYDROLOGICAL RESPONSES IN THE THUKELA CATCHMENT TO SPATIAL AND TEMPORAL REPRESENTATIONS WHEN USING A BASELINE AND A PROJECTED FUTURE CLIMATE SCENARIO

Roland Schulze, Mark Horan and Ryan Gray

(22 pages, 16 figures)

11.1 Objectives
11.2 Why the Thukela Catchment?
11.3 Scaling Down from Southern Africa to the Thukela: What Remains and What Changes?
11.4 Shifts in Annual and Monthly Rainfall Patterns with Climate Change
11.5 Sensitivity of Runoff Parameters to Plausible Changes in Driver Variables of Climate Change
11.6 Shifts in Patterns of Reference Potential Evaporation with Climate Change
11.7 Baseline Hydrological Responses and Shifts in Patterns of Streamflows with Climate Change
11.8 Net Irrigation Requirements in the Thukela Catchment Under Baseline and Changed Climatic Conditions
11.9 Sediment Yields in the Thukela Catchment Under Baseline and Changed Climatic Conditions
11.10 Partitioning of Rainfall into "Blue", Green" and "White" Water Flows in the Thukela Catchment Under Baseline and Changed Climatic Conditions
11.11 Concluding Thoughts
11.12 References

Abstract

The underlying theme of this chapter is the concept of sensitivity of hydrological responses in the Thukela catchment to both baseline climate and to a projected future climate. Examples are provided of the sensitivity of hydrological model output to higher levels of spatial disaggregation of the Thukela catchment into 235 hydrologically homogeneous response zones (vs 86 Quaternary Catchments), of evaluating baseline and climate changed hydrological input and output at higher temporal resolutions (such as monthly vs annual), or the different sensitivities of individual components of runoff (i.e. stormflow and baseflow) or transpiration (i.e. transpiration from topsoil water vs transpiration from subsoil water), to climate change. It is illustrated that, while climate change may be a global phenomenon, its effects play themselves out at very local levels within operational catchments such as the Thukela, and at very specific times of the year.

CHAPTER 12 CASE STUDY 1: CHANGES IN HYDROCLIMATIC BASELINES UNDER DIFFERENT HYPOTHETICAL, BUT PLAUSIBLE, SCENARIOS OF CLIMATE CHANGE: INITIAL FINDINGS ON SENSITIVE AND ROBUST HYDROCLIMATIC ZONES IN SOUTHERN AFRICA

Roland Schulze

(8 pages, 3 figures, 2 tables)

12.1 Baselines of Climates and their Importance
12.2 Changes in Distributions of Köppen Climate Zones with Hypothetical, but Plausible, Climate Change Scenarios: Methods
12.3 Evaluation of Results from Climate Change Scenarios
12.4 Conclusions
12.5 References

Abstract

The importance of baselines of climate, climatic zones and of land cover in hydrological response studies is stressed, especially when the hydrological landscape may be in a state of flux as a result of perturbations in climate. In this chapter the changes in distributions of Köppen climate zones over southern Africa are evaluated for a number of hypothetical, but plausible, climate change scenarios. Major shifts in the zones are illustrated, with some zones shrinking significantly while others would enlarge. In particular the winter and all year rainfall regions are shown to be sensitive to changes in climate. The shifts are indicative of potential geographical shifts in baseline land cover in a future climate, with possible marked hydrological repercussions.

CHAPTER 13 CASE STUDY 2: POTENTIAL IMPACTS OF SHIFTS IN HYDROCLIMATIC ZONES ON DESIGN HYDROLOGY APPLICABLE TO SMALL CATCHMENTS IN SOUTHERN AFRICA

Roland Schulze

(7 pages, 2 figures, 2 tables)

13.1 Background
13.2 Hypotheses and Outline
13.3 The SCS Technique for Determining Design Flood Hydrographs
13.4 Hypothesis 1: Relationships Exist Between Antecedent Soil Moisture Conditions (ΔS) and Specific Köppen Climate Zones
13.5 Hypothesis 2: Spatial Changes in Köppen Zones over South Africa May Have Significant Consequences in Design Hydrology at a Location
13.6 Conclusions
13.7 References

Abstract

In this chapter two hypotheses are postulated. The first is that *within* spatially defined hydroclimatic

zones relatively consistent conditions of antecedent soil water status, which affect design hydrological responses, exist but that these conditions differ *between* hydroclimatic zones. Second, if the first hypothesis is correct, then shifts in hydroclimatic zones resulting from climate change may alter a location's design hydrology. In a test of the above, it was established that a close relationship existed between median ΔS and mean annual precipitation (*MAP*) *within* individual Köppen Climate Classes in southern Africa, but that these relationships differed *between* Köppen Climate Classes in the region. Using the SCS equations for determining design stormflows and peak discharges, it was shown by way of worked examples that marked changes in design floods are possible when Köppen climate zones shift geographically with climate change, with potentially serious repercussions in design hydrology.

CHAPTER 14 CASE STUDY 3: POTENTIAL IMPACTS OF A HYPOTHETICAL, BUT PLAUSIBLE, CLIMATE CHANGE SCENARIO ON WITHIN-COUNTRY RESERVOIR MANAGEMENT FOR IRRIGATION, AND OUT-OF-COUNTRY FLOW OBLIGATIONS IN THE MBULUZI CATCHMENT, SWAZILAND

Roland Schulze and Dennis Dlamini

(6 pages, 6 figures)

14.1 Introduction
14.2 The Mbuluzi Catchment: Where is it Located, What are its Climate Characteristics?
14.3 A Hypothetical, but Plausible, Climate Change Scenario and Methods of Analysis
14.4 Simulated Consequences of a Plausible Climate Change Scenario on Flows and Reservoir Performance
14.5 Conclusions
14.6 References

Abstract

With climate change likely to impact on the management of reservoir operations as well as on meeting international downstream water obligations, a case study is undertaken on Swaziland's 2 959 km^2 Mbuluzi catchment to assess possible impacts of a hypothetical, but plausible, climate change scenario on inflows into the Mnjoli Dam, the reservoir's performance, considering it to be the major supplier of water for all-year-round irrigation of sugarcane, and on outflows of the Mbuluzi river into downstream Mozambique. Impacts are particularly severe for 1:10 year dry hydrological conditions, with over 40% reductions to inflows into Mnjoli Dam as well as outflows to Mozambique, while in such dry years irrigation demand is simulated to draw down the dam to dead storage levels in 7 months of the year. Potential repercussions of such impacts are discussed.

SECTION E: DETECTION OF CLIMATE CHANGE IN SOUTHERN AFRICA

CHAPTER 15 DETECTION OF CLIMATE CHANGE: A REVIEW OF LITERATURE ON CHANGES IN TEMPERATURE, PRECIPITATION AND STREAMFLOW, ON DETECTION METHODS AND DATA PROBLEMS

Michele Warburton and Roland Schulze

(18 pages, 3 figures, 5 tables)

15.1 Introduction
15.2 A Review of Climate Change Detection Studies
15.3 Methods Used to Detect Climate Change
15.4 Problems Encountered in Detecting Climate Change
15.5 Discussion and Conclusions
15.6 References

Abstract

It has become accepted that long-term global mean temperatures have increased over the twentieth

century. To date, the warmest year on record is 1998. However, whether or not climate change can be detected at a local or regional scale is still questionable. The numerous new record highs and lows of temperatures recorded over South Africa for 2003, 2004 and 2005 provide reason to examine whether changes can already be detected in southern Africa's temperature record and modelled hydrological responses. As a preface to this, a literature review on detection of climate change, of methods used and data problems encountered, is undertaken. Temperatures have been shown to be increasing in the USA, Venezuela, Colombia, Europe and China. In particular, trends towards increasing minimum temperatures and decreasing cold spell frequencies have been found. Warming has also been shown over South Africa. However, the magnitude of change is variable, according to the literature. Increasing precipitation trends have been shown for the USA and UK, with a tendency for more heavy falls on rain days. Hulme (1992) shows decreases in rainfall for northern Africa and increases for Tunisia, Algeria and the Nile Basin. Over southern Africa the extremes of rainfall show intensification. Few hydrological detection studies have been undertaken, and the results are often inconclusive. Simple statistics, linear regression and the Mann-Kendall non-parametric test are the methods reviewed for detecting change. The Mann-Kendall test is chosen for this study as it is a simple statistical test of trend that is not affected by non-normally distributed data. Problems exist in the detection of climate change. Inhomogeneity in climatic datasets, as well as the lack of long-term, high quality daily datasets is problematic. Streamflow datasets, in particular, are a problem, as the network of gauges is relatively sparse in southern Africa and where they do exist, they are often poorly maintained and neglected. Thus, the advantage of generating streamflow estimates from physical conceptual models is explored. Detection of climate change at a regional level may indicate vulnerable areas and demonstrate to decision makers that climate change is a current reality.

CHAPTER 16 IS SOUTH AFRICA'S TEMPERATURE CHANGING? AN ANALYSIS OF TRENDS FROM DAILY RECORDS, 1950 - 2000

Michele Warburton, Roland Schulze and Manjulla Maharaj

(21 pages, 28 figures)

16.1 Introduction
16.2 Analyses to be Undertaken
16.3 Temperature Data Used in this Study
16.4 Results 1: Trends Over Time in Annual and Seasonal Means of Temperatures
16.5 Results 2: Trends over Time in Occurrences of Temperatures Above and Below Selected Percentiles
16.6 Results 3: Trends over Time in the Number of Days Above and Below Predefined Thresholds
16.7 Results 4: Trends in Occurrences of Frost and the Length of the Frost Season
16.8 Results 5: Trends in Heat and Chill Units
16.9 Results 6: A Comparison of Means and Variabilities of Temperature for 1950 - 1970 vs 1980 - 2000
16.10 Overall Conclusions: Is South Africa's Temperature Changing? A Summary of Findings
16.11 References

Abstract

With changes in global temperature evident and regional changes over various northern hemisphere countries evident, southern Africa's temperature record is examined for changes. The Mann-Kendall non-parametric test is applied to time series of annual means of minimum and maximum temperature, summer means of maximum temperature and winter means of minimum temperature. Furthermore, changes in the upper and lower ends of the temperature distribution are examined by applying the Mann-Kendall test to numbers of days and numbers of 3 consecutive days above/below thresholds of 10th and 90th percentiles of minimum and maximum temperatures, as well as threshold values of minimum (i.e. 0°) and maximum (i.e. 40°C) temperatures. A second analysis, using the split sample technique for the periods 1950 - 1970 vs 1980 - 2000, was performed for annual means of daily maximum and minimum temperatures, summer means of daily maximum temperatures, winter means of daily minimum temperatures and coefficients of variability of daily maximum and minimum temperatures. Two clear clusters of warming emerge from almost every analysis, *viz*. a cluster of stations in the Western Cape and a cluster of stations around the midlands of KwaZulu-Natal, along with a band of stations along the KwaZulu-Natal coast. Another finding is a less severe frost season over the Free State and Northern Cape. While certain changes are evident in temperature parameters, the changes are not uniform across southern Africa.

CHAPTER 17 DETECTION OF TRENDS OVER TIME IN HYDROLOGICAL DRIVERS AND RESPONSES OVER SOUTHERN AFRICA

Michele Warburton and Roland Schulze

(22 pages, 22 figures)

17.1 Hypotheses on Changes in Hydrological Drivers and Responses with Global Warming
17.2 Analyses Undertaken to Determine Whether Changes in Hydrological Drivers and Responses are Evident Yet
17.3 Modelling Assumptions Made
17.4 Analysis of Median Annual Reference Potential Evaporation
17.5 Analysis of Median Annual Soil Water Content of the Topsoil Horizon
17.6 Trends over Time in Annual Accumulated Streamflows
17.7 Accumulated Streamflows in Median, Dry and Wet Years
17.8 Ranges of Streamflows Between Wet and Dry Years
17.9 Analysis of Baseflows
17.10 Changes in the Seasonality of Streamflows
17.11 Changes in the Concentrations of Streamflows
17.12 Analysis of Changes in Gross Irrigation Demand
17.13 Conclusions
17.14 References

Abstract

Precipitation and evaporation are the primary drivers of the hydrological cycle, with temperature an important driver of evaporation. Thus, with changes in various temperature parameters having been identified over many parts of southern Africa, the question arises whether any changes can be seen as yet in hydrological responses. The *ACRU* model is used to generate daily streamflow values and associated hydrological responses from a baseline land cover, thus eliminating all possible human influences on the catchment and channel. A split-sample analysis of the simulated hydrological responses for the 1950 - 1969 vs 1980 - 1999 periods is undertaken. Trends over time in streamflow are examined for medians, dry and wet years, as well as the range between wet and dry years. The seasonality and concentration of streamflows between the periods 1950 - 1969 and 1980 - 1999 are examined to determine if changes may be identified. Potential evaporation, soil water content of the topsoil horizon, baseflow and irrigation demand are other hydrological variables examined to determine if changes may already be noted. Potential evaporation, computed as a function of temperature parameters, appears to have increased over the interior of southern Africa. Streamflows in the 'driest' year in 10 have increased in the Northern Cape, Eastern Cape and eastern Free State. Streamflow in the 'wettest' year in 10 has increased markedly over KwaZulu-Natal, as has the range of flows between dry and wet years. Some trends found were marked over large parts of Primary Catchments, and certainly require consideration in future water resources planning.

CHAPTER 18 HISTORICAL PRECIPITATION TRENDS OVER SOUTHERN AFRICA: A CLIMATOLOGY PERSPECTIVE

Bruce Hewitson, Mark Tadross and Chris Jack

(6 pages, 5 figures)

18.1 Historical Precipitation Trends
18.2 The Climate Context
18.3 Precipitation Trend Analysis
18.4 Concluding Thoughts
18.5 References

Abstract

This chapter assesses the historical climate change over southern Africa, focusing on circulation changes and changes in the totals as well as attributes of rainfall. The results show clear historical regional trends per decade of mean monthly precipitation totals, mean monthly number of raindays and mean monthly dry spell durations. These historical trends have notable regional implications in hydrological responses.

CHAPTER 19 HISTORICAL PRECIPITATION TRENDS OVER SOUTHERN AFRICA: A HYDROLOGY PERSPECTIVE

Michele Warburton and Roland Schulze

(14 pages, 16 figures)

19.1 Introduction
19.2 Data and Methods Used
19.3 Analysis of Median, Lowest and Highest Annual, Summer and Winter Season Rainfalls
19.4 Ranges of Rainfall Between Years with Low and High Rainfalls
19.5 Analysis of the Number of Rainfall Events Above Predefined Threshold Amounts
19.6 Can the Changes Evident in Hydrological Responses be Explained be Changes in the Rainfall Regime? A Discussion
19.7 References

Abstract

With strong changes over time in simulated hydrological responses already evident in certain Primary Catchments of South Africa using daily rainfall input data from 1950 - 1999 (**Chapter 17**), it became necessary to examine the rainfall regimes of the Quaternary Catchments' "driver" rainfall stations in order to determine if these hydrological response changes were supported by changes in rainfall patterns over time. A split-sample analysis was, therefore, performed on the rainfall input of each Quaternary Catchment. Not only medians were considered, but the higher and lower ends of the rainfall distribution were also analysed, as were the number of rainfall events above pre-defined daily thresholds. The changes evident over time in rainfall patterns over southern Africa vary from relatively unsubstantial increases or decreases to significant increase and decreases. The winter rainfall region of southern Africa is shown to be experiencing more rainfall in the later 1980 - 1999 period compared to the earlier 1950 - 1969 period. The southeastern Free State consistently indicates a decrease in rainfall in the later period for almost all rainfall parameters analysed. The Limpopo and North-West Provinces, along the borders of South Africa with Botswana and Zimbabwe, and an area stretching into the Northern Cape, represents another region consistently displaying a decrease in rainfall in the later period for the various parameters analysed. The changes evident in rainfall thresholds of 10 mm and 25 mm per day varied spatially across the country, and "hotspot" areas of change in the Western Cape, southeastern Free State, Limpopo and North-West provinces were identified.

CHAPTER 20 ON THE SOUTHERN AFRICAN RAINFALL STATION NETWORK AND ITS DATA FOR CLIMATE CHANGE DETECTION AND OTHER HYDROLOGICAL STUDIES

Michele Warburton and Roland Schulze

(10 pages, 6 figures, 2 tables)

20.1 Some Basic Rainfall Network Requirements for Detection and Other Studies
20.2 Objectives of this Research
20.3 The Rainfall Station Network over Southern Africa
20.4 Method of Analysis for Selecting Quaternary Catchment "Driver" Rainfall Stations
20.5 An Evaluation of the Re-Selected "Driver" Rainfall Stations
20.6 Conclusions
20.7 References

Abstract

Basic requirements for rainfall networks, the data from which are to be used in climate change detection and other hydrological studies, include at minimum one station per Quaternary Catchment (QC) with an already long, uninterrupted daily rainfall record of high reliability. In this chapter the latest comprehensive rainfall station network for southern Africa is first described, before a multiple criterion method is outlined for re-selection of QC "driver" rainfall stations. The re-selection procedures are then evaluated and a lack of stations with reliable long records is identified, *inter alia*, in the hydrologically sensitive mountain areas of the Drakensberg and Western Cape. It is concluded that the selected rainfall stations for the QCs in southern Africa generally have good rainfall records,

except for the regions already mentioned. A set of monitoring principles is presented, which should be followed if rainfall stations which are selected are to be considered suitable for climate change detection and other hydrological studies.

SECTION F: VULNERABILITIES AND SENSITIVITIES OF COMMUNITIES TO CLIMATE RISKS

CHAPTER 21 VULNERABILITY, ADAPTATIVE CAPACITY, COPING AND ADAPTATION: A CONCEPTUAL FRAMEWORK

Coleen Vogel and Paul Reid

(8 pages, 2 figures, 1 table)

21.1 Preamble
21.2 Introduction
21.3 Vulnerability and Adaptive Capacity
21.4 Determinants of Adaptive Capacity
21.5 Vulnerability, Coping and Adaptation: A Broader Perspective
21.6 From Concept to Case Study
21.7 References

Abstract

Global environmental change (GEC) poses several challenges for society. GEC includes a variety of multiple stresses that ultimately shape and configure various risks to society such as climate change and climate variability. Effective management of environmental risk requires a better understanding of two components of the risk profile, *viz*. vulnerability (which includes coping and adaptive capacities) and hazards (e.g. drought and floods). Technocratic approaches to risk management, with a strong focus on hazard detection, sensitivity and risks only provides one dimension of global environmental change risk management. Increasingly a more nuanced approach, that has strong relevance for southern African countries, focuses on a better understanding of vulnerability to climate risks. A framework for assessing vulnerability and adaptive response to climate variability is traced in this chapter.

CHAPTER 22 WHY ADOPT A VULNERABILITY APPROACH?

Samantha Boardley and Roland Schulze

(5 pages, 1 table)

22.1 Vulnerability and Adaptive Capacity
22.2 What is the Vulnerability Approach?
22.3 Conclusions
22.4 References

Abstract

Vulnerability is considered to be a function of exposure, sensitivity and adaptive capacity, with the latter, in turn, dependent on wealth, technology, education, information, skills, infrastructure, access to resources and stability as well as management capabilities. Adaptive capacity, therefore, reflects the resilience, stability, robustness and flexibility of a system, such as a farm or a community. The vulnerability approach is not so much a matter of considering only scientific accuracy, as it is of taking an approach of effective communication with affected stakeholders and considering local community needs. A vulnerability approach enables adaptive management options to be linked to decision-making processes already in place, thus starting with the system (e.g. a community) and not with the hazard *per se*. Vulnerability assessments, while difficult to quantify do, however, tailor adaptive assistance to local needs.

CHAPTER 23 PERCEPTIONS HELD BY DIFFERENT STAKEHOLDERS ON THE VULNERABILITY OF WATER RESOURCES IN SOUTH AFRICA TO CLIMATE CHANGE

Samantha Boardley and Roland Schulze

(**21 pages including appendices, 12 figures)**

23.1 Climate Change and Water Resources: Some Background
23.2 Perceptions of Previously Disadvantaged Rural, Urban and Township Domestic Water Users
23.3 Perceptions of Water Resources Managers, Decision-Makers and Stakeholders
23.4 Comparative Study: How do Managers Concerns Compare with Those Concerns of Domestic Water Users?
23.5 Overall Conclusions and Recommendations
23.6 References
Appendix A: Questionnaire on Perceptions of Climate Change: Domestic Water Users
Appendix B: Questionnaire on Perceptions of Climate Change: Water Resources Managers

Abstract

Following a brief review on vulnerability assessment and stakeholder perception studies, this chapter outlines two questionnaire surveys of stakeholder perceptions on climate change and the water sector. The first was with 187 university students from previously disadvantaged schools, representing rural, urbanised and township domestic water users, and the second with a group of 17 managers and technocrats from the water and agriculture sectors. Results from the domestic water users show a much higher awareness of climate change among urban compared with rural users, with most having heard of climate change at school. However, their concerns focused on HIV/AIDS and unemployment (53%) rather than on climate change (10%), but with a heightened concern for water in the future. Water resources technocrats, on the other hand, perceived the impacts of climate change on the water sector to date as moderate to high. A major concern of theirs was a lack of understanding of the National Water Resource Strategy. Both groups highlighted the need for more education and awareness-raising on issues of climate change and its potential impacts on the water sector.

CHAPTER 24 WATER POVERTY WITHIN A CONTEXT OF CLIMATE CHANGE: A CASE STUDY AT MESO-SCALE IN THE THUKELA CATCHMENT

Dennis Dlamini and Roland Schulze

(8 pages, 5 figures, 2 tables)

24.1 The Link Between Water Scarcity and Poverty
24.2 The Water Poverty Index
24.3 Superimposing a Hypothetical, but Plausible, Climate Change Scenario on the Resource Component of the Water Poverty Index
24.4 Changes in Meso-Scale Hydrological Responses
24.5 Changes in Reductions in Both the Water Resources Component of the Water Poverty Index and the Net Index
24.6 Conclusions
24.7 References

Abstract

The link between access to water and socio-economic wellbeing having been established by way of introduction, the multi-disciplinary, multi-level, framework-based and composite Water Poverty Index (WPI) is described with reference to its application at meso-catchment scale in the Thukela catchment for a hypothetical, but plausible, climate change scenario. Spatial differences to changes in absolute and relative reductions (i.e. a worsening) of the resources component of the WPI are shown for the Thukela, which then manifest themselves in the net WPI. The results highlight the possibility of a worsening situation in areas within the Thukela catchment which are experiencing severe water poverty already, should the climate change as postulated in the scenario used.

CHAPTER 25 CLIMATE AND DEVELOPMENT: EXPERIENCES OF FARMERS IN KWAZULU-NATAL, SOUTH AFRICA

Paul Reid, Ruth Massey and Coleen Vogel

(20 pages, 4 figures, 8 boxes, 1 table)

25.1 Background
25.2 Coping with Environmental Change? The Case of the Müden Community Irrigation Scheme, KwaZulu-Natal
25.3 Vulnerability Assessment in the Müden Area
25.4 Perceptions of Climate Change in the Müden Area
25.5 Building Resilience to Change in Müden: The Possible Role of Institutions
25.6 Living with Climate and Other Risks in the Midlands of KwaZulu-Natal: The Case of Large-Scale Commercial Farmers
25.7 Identification of Risks by Sector and Farming Group that Heighten Vulnerability to Periods of Climate Stress and Change in the Midlands of KwaZulu-Natal
25.8 Results from Questionnaire Surveys in the Midlands
25.9 Adaptive Capacity and Adaptation Strategies Identified by Small-, Medium- and Large-Scale Farmers
25.10 Possible Recommendations
25.11 Discussion
25.12 Conclusions
25.13 References

Abstract

A conceptual framework on climate-related stress, vulnerability, adaptive capacity and coping has been outlined in a previous chapter (**Chapter 21**). In this chapter, results from two case studies are presented which identify vulnerabilities and adaptive capacities of, first, a small-scale community of irrigation farmers at Müden and, second, large-scale commercial farmers, both in the Midlands of KwaZulu-Natal. In both case studies the Sustainable Livelihoods Framework approach is used. In the case of the small-scale farmers, several multiple stressors that enhance vulnerability and constrain adaptive capacity are given. These include lack of institutional organisation, lack of access to information and broader governance issues associated with relevant authorities. For commercial farmers, macro-economic and related factors, including the low price of sugar, the strong local currency (at the time of writing), legislation, land redistribution, high input costs and labour issues, including HIV/AIDS, are all shown to enhance vulnerabilities to climate variability. Broad common themes affecting both small- and large-scale farmers are identified. Finally, the need for more research on adaptive capacity to climate risks, linked to issues of sustainable development, is recommended.

SECTION G: ADAPTING TO CLIMATE CHANGE IN SOUTH AFRICA

CHAPTER 26 POLICY IN REGARD TO POTENTIAL IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES IN SOUTH AFRICA: AN OVERVIEW

Samantha Boardley and Roland Schulze

(5 pages)

26.1 Climate Change and Related Policies in South Africa
26.2 The National Climate Change Response Strategy for South Africa
26.3 The National Water Resource Strategy (NWRS): Some General Comments
26.4 The National Water Resource Strategy and Climate Change
26.5 Conclusions
26.6 References

Abstract

Two key documents of national level policy importance are reviewed in regard to climate change and water resources in South Africa. The National Climate Change Response Strategy for South Africa (NCCRS) highlights 10 general issues on climate change, most of which deal implicitly or explicitly with the water sector, but the document's emphasis is more on adaptation, with relatively little direct

focus on climate change and water resources. The National Water Resource Strategy (NWRS) takes a cautious line in regard to climate change, appreciating the vulnerability of the water sector to climate change, but emphasizing uncertainties which still exist. The view is held that future updates of the two documents will benefit from findings contained in this Report.

CHAPTER 27 ADAPTING TO CLIMATE CHANGE IN THE WATER RESOURCES SECTOR IN SOUTH AFRICA

Roland Schulze

(28 pages, 7 figures, 5 tables, 1 box)

27.1 Introduction
27.2 Water Management and Adaptation
27.3 Challenges to Adaptation in the Water Sector
27.4 Reasons to Adapt to Climate Change in Any Event: An IPCC View
27.5 Views Held by Experts on Adaptation to Climate Change in the Water Sector
27.6 Recommendations by International Agencies on Adaptation Strategies for Water Resource Management
27.7 Integrated Water Resources Management (IWRM) as a Pre-Requisite for Coping and Adaptation
27.8 Lessons Learned from the "Thukela Dialogue" on Climate Change and the Broader Water-Related Sector
27.9 An Adaptation Matrix Based on Feedback from the South African Water Sector
27.10 Concluding Thoughts
27.11 References

Abstract

This chapter presents an overview of thoughts, concepts and practical issues on adaptation to climate change in South Africa's water sector by first outlining who water managers are and what they manage. The focus thereafter shifts to challenges faced by water managers in adapting to climate change, including having to deal with many uncertainties which remain, to arguing for the adoption of a "no regrets" approach to managing for predicted climate change. Views of international institutions and experts on adaptation in the water sector are then presented. A plea is made for an integrated approach to water management as a pre-requisite to coping with, and adapting to, the hydrological manifestations of climate change.

Moving from a more generic/international view of adaptation to climate change in the water sector, to a South African perspective, the "lessons learnt" from the "Thukela Dialogue", a workshop on managing water resources related issues on climate variability and climate change in South Africa, are presented. These "lessons", summarising stakeholders' experiences and thoughts on legal/policy aspects, surface and groundwater, design hydrology, monitoring/data, agricultural, environmental, rural community and vulnerability aspects of the climate change:water link, forms the basis of a proposed framework of adaptation needs in South Africa. Together with feedback from three further workshops on climate change, the perceived adaptation needs and requirements identified by the South African water sector are presented under the three major themes of legal/policy, institutional/management and monitoring/research/information issues. The chapter concludes with some thoughts on the adaptation process and limits to adaptation.

SECTION H: SYNTHESIS AND RECOMMENDATIONS FOR FUTURE RESEARCH

CHAPTER 28 SYNTHESIS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Roland Schulze, Bruce Hewitson, Coleen Vogel and Francois Engelbrecht

(2 pages)

28.1 Take-Home Messages from the Project, in a Nutshell
28.2 Recommendations for Further Research

SECTION I TECHNOLOGY TRANSFER AND CAPACITY BUILDING

CHAPTER 29 TECHNOLOGY TRANSFER AND CAPACITY BUILDING

Roland Schulze, Coleen Vogel, Bruce Hewitson and Francois Engelbrecht

(10 pages)

29.1 Publications Related to This Project, 2003 - 2005
29.2 Publications in Press, as of June 2005
29.3 Attendance and/or Presentations at Symposia and Workshops, 2003 - June 2005
29.4 Climate Change Related Committees/Organising Duties
29.5 Visits to Scientific Institutions
29.6 Capacity Building
29.7 Research Teams, as of June 2005
29.8 Reference Group

TAKE-HOME MESSAGES FROM THE PROJECT, IN A NUTSHELL

While many "messages" have emanated from the research results presented in this report, the following points synthesise some of the key findings:

- Climate scenarios derived from various GCMs and downscaled temporally and spatially by different approaches, are displaying an ever-increasing consistency in patterns of anticipated climate change over southern Africa. This implies that they can now be used with increasing confidence by the impacts modelling community to make more definitive statements on potential impacts of climate change on the water sector.

- Southern African hydroclimatic databases on baseline conditions, as well as South African hydrological modelling systems have been developed/refined to the extent that wide-ranging and innovative agrohydrological and water resources studies can now be undertaken for both present and future climate scenarios. The tools developed are seen as powerful decision-making aids to water resources policy-makers, strategists and operators.

- The hydrological impact studies undertaken in this project for a 1975 - 2005 "present" and a 2070 - 2100 "future" climate scenario, using downscaled output from only one of the available global:regional climate modelling approaches, have identified several potential *hotspots* where anticipated climate change could have wide-ranging water resource (as well as agricultural and other) management implications. This, it is argued, requires the attention of planners *now*. One notable *hotspot* is the present winter rainfall region which covers largely the Western Cape province. Other areas' water resources stand to benefit from predicted climate change. For different components of the hydrological cycle certain areas in southern Africa have also been identified as more sensitive in their responses than others. More in-depth interpretation of results is still required of the various climate change impacts which were simulated.

- From climate records of the past 50 years, elements of climate change can already be clearly detected in certain regions within southern Africa, be it for derivatives of rainfall, temperature or for hydrological responses. Not all areas display equal change, and in some areas no change can as yet be detected.

- Vulnerable communities in southern Africa already have to cope with multiple stresses, of which climate variability is but one. Climate change will add an additional layer of stress, to which adaptive strategies and adaptation policies will have to be directed.

- In adaptation strategies for the region's water-related sector (including both small- and large-scale agriculture and the environment), emphasis will need to be on the "uniquely South African" situation, with its juxtapositioning of the developed vs the underdeveloped sectors of the population and economy. Strategies will need to take cognisance of specific *local* situational contexts, on the one hand, and *national* level policy and institutional issues, on the other. The latter are ideally implemented through effective Integrated Water Resources

Management.

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Dr Heather MacKay (WRC)	Mr Clive Turner (ESKOM)
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CAPACITY BUILDING

The following postgraduate students either contributed directly or indirectly to, or alternatively benefited materially from, this project and its products for their dissertations/theses:

Post-Doctoral
Tadross, M. (UCT)

PhD

Dlamini, D. (UKZN)	Taylor, V. (UKZN)	Walewege, R. (UCT)	Mpandelie, S. (UW)
Walker, N. (UKZN)	MacKellar, N. (UCT)	Jack, C. (UCT)	

MSc

Warburton, M. (UKZN)	Gray, R. (UKZN)	Mdoka, M. (UCT)
Reid, P. (UW)	Massey, R. (UW)	Van den Beek, R. (UCT)

Additionally, a significant amount of invaluable individual and institutional capacity was built amongst the research and supervising staff involved in this project - capacity of a technical and conceptual nature that will benefit not only future WRC-funded projects, but the southern African climate and hydrological (as well as other) sectors as a whole. It is vital that this acquired expertise not be lost to South Africa.

RECOMMENDATIONS FOR FUTURE RESEARCH

- It is vital that the momentum gained in climate scenario modelling be maintained and strengthened, in order to further reduce the many uncertainties still surrounding the outputs from regional climate models which are interpreted/used by the impacts and vulnerability research communities.

- The hydrological impacts modellers need to apply other empirical downscaling and Regional Climate Model output in a manner similar to that by which C-CAM RCM daily output was used in this project, in order to be able to identify *hotspots* of climate change impacts with consistency and greater certainty.

- For the hydrological community spatial downscaling of climate model output should, ideally, be to the level of a typical Quaternary Catchment in potentially climate-sensitive areas, i.e. approximately 100 - 500 km^2.

- Impact studies of potential climate change on the water sector need to move from baseline hydrological conditions of catchments to actual catchment conditions, which include present land uses, dams, irrigated areas, inter-basin transfers, return flows etc.

- The hydrological research community needs to focus in more depth on second order and third order consequences of possible climate change, e.g. on water quality responses, impacts on terrestrial and aquatic environments, the water/agriculture linkage, extreme events and potential international (downstream) impacts.

- Adaptation strategies to climate change in the water resource sector of southern Africa need to be placed on a “higher plane”, regarding both policy and implementation.

- Outcomes of a major research project such as this one, with potential impacts on many resource sectors in southern Africa, *inter alia*, need to be published in layman’s language and summarised for policy-makers and the public at large, in order to
  - *sensitise* relevant stakeholders to the potential consequences and challenges which are likely to arise out of a changed future climate in the already high risk natural environment of southern Africa and to
  - *maximise* the benefits of this type of research funding to the Water Research Commission (WRC), the researchers themselves and future collaborators.

- In regard to all of the above, it is significant that the WRC has seen fit to fund a policy makers’ summary/guide on climate change and water resources in South Africa and a further 3-year solicited research project on climate change and water resources, with emphasis not only on improved climate modelling, but also on water-related environmental and policy issues for southern Africa.

R.E. Schlulze
August 2005

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GLOSSARY OF TERMS

Selected from the IPCC WGII Third Assessment Report (2001), with adaptations to this Project

Acclimatisation
The physiological adaptation to climatic variations.

Adaptation
Adjustment in natural or human systems in response to actual or expected climatic *stimuli* or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation:
– ***Anticipatory Adaptation:*** Adaptation that takes place before impacts of climate change are observed. Also referred to as proactive adaptation.
– ***Autonomous Adaptation:*** Adaptation that does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems.
Also referred to as spontaneous adaptation.
– ***Planned Adaptation:*** Adaptation that is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state.
– ***Private Adaptation***: Adaptation that is initiated and implemented by individuals, households or private companies. Private adaptation is usually in the actor's rational self-interest.
– ***Public Adaptation***: Adaptation that is initiated and implemented by governments at all levels. Public adaptation is usually directed at collective needs.
– ***Reactive Adaptation:*** Adaptation that takes place after impacts of climate change have been observed. See also *adaptation assessment*, *adaptation benefits*, *adaptation costs*, *adaptive capacity*, and *maladaptation*.

Adaptation Assessment
The practice of identifying options to adapt to climate change and evaluating them in terms of criteria such as availability, benefits, costs, effectiveness, efficiency, and feasibility.

Adaptation Benefits
The avoided damage costs or the accrued benefits following the adoption and implementation of *adaptation* measures.

Adaptation Costs
Costs of planning, preparing for, facilitating, and implementing *adaptation* measures, including transition costs.

Adaptive Capacity
The ability of a system to adjust to *climate change* (including *climate variability* and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

Afforestation
Planting of new forests on lands that historically have not contained forests. For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation*, and *deforestation*, see the IPCC *Special Report on Land Use, Land-Use Change, and Forestry* (IPCC, 2000).

Aggregate Impacts
Total impacts summed up across sectors and/or regions. The aggregation of impacts requires knowledge of (or assumptions about) the relative importance of impacts in different sectors and regions. Measures of aggregate impacts include, for example, the total number of people affected, change in net primary productivity, number of systems undergoing change, or total economic costs.

Albedo
The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo; the albedo of soils ranges from high to low; vegetation-covered surfaces and oceans have a low albedo. The Earth's albedo varies mainly through varying cloudiness, snow, ice, leaf area, and land-cover changes.

Alkalinity
A measure of the capacity of water to neutralize acids.

Alpine
The *biogeographic* zone made up of slopes above timberline and characterized by the presence of rosette-forming herbaceous plants and low shrubby slow-growing woody plants.

Anoxia
A deficiency of oxygen, especially of such severity as to result in permanent damage.

Anthropogenic
Resulting from or produced by human beings.

Aquifer
Astratum of permeable rock that bears water. An unconfined aquifer is recharged directly by local rainfall, rivers, and lakes , and the rate of recharge will be influenced by the permeability of the overlying rocks and soils. A confined aquifer is characterized by an overlying bed that is impermeable and the local rainfall does not influence the aquifer.

Arid Regions
Ecosystems with <250 mm precipitation per year.

Baseflow
Sustained flow in a river or stream that is primarily produced by groundwater runoff, delayed subsurface runoff, and/or lake outflow.

Baseline/Reference
The baseline (or reference) is any datum against which change is measured. It might be a "current baseline," in which case it represents observable, present-day conditions. It might also be a "future baseline," which is a projected future set of conditions excluding the driving factor of interest. Alternative interpretations of the reference conditions can give rise to multiple baselines.

Basin
The drainage area of a stream, river, or lake, also termed catchment or watershed.

Biodiversity
The numbers and relative abundances of different genes (genetic diversity), species, and ecosystems (communities) in a particular area.

Biodiversity Hot Spots
Areas with high concentrations of *endemic* species facing extraordinary habitat destruction.

Biome
A grouping of similar plant and animal communities into broad landscape units that occur under similar environmental conditions.

Biosphere
The part of the Earth system comprising all ecosystems and living organisms in the atmosphere, on land (terrestrial biosphere), or in the oceans (marine biosphere), including derived dead organic matter, such as litter, soil organic matter, and oceanic detritus.

Biota
All living organisms of an area; the flora and fauna considered as a unit.

C_3 Plants
Plants that produce a three-carbon compound during photosynthesis, including most trees and agricultural crops such as rice, wheat, soybeans, potatoes, and vegetables.

C_4 Plants
Plants that produce a four-carbon compound during photosynthesis (mainly of tropical origin), including grasses and the agriculturally important crops maize, sugar cane, millet, and sorghum.

Carbon Dioxide (CO_2)
A naturally occurring gas, also a by-product of burning fossil fuels and *biomass*, as well as from land-use changes and other industrial processes. It is the principal *anthropogenic greenhouse gas* that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1.

Carbon Dioxide Fertilization
The enhancement of the growth of plants as a result of increased atmospheric *carbon dioxide* concentration. Depending on their mechanism of *photosynthesis*, certain types of plants are more sensitive to changes in atmospheric CO2 concentration. In particular, *C3 plants* generally show a larger response to CO2 than *C4 plants*.

Carrying Capacity
The number of individuals in a population that the resources of a *habitat* can support.

Catchment
An area that collects and drains rainwater.

Cholera
An intestinal infection that results in frequent watery stools, cramping abdominal pain, and eventual collapse from dehydration.

Climate
Climate in a narrow sense is usually defined as the "average weather," or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands of years. The classical period is 3 decades, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate Change
Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the *United Nations Framework Convention on Climate Change (UNFCCC)*, which defines "climate change" as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." See also *climate variability*.

Climate Model (Hierarchy)
A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity (i.e., for any one component or combination of components a hierarchy of models can be identified, diff e ring in such aspects as the number of spatial dimensions; the extent to which physical, chemical, or biological processes are explicitly represented; or the level at which empirical parameterizations are involved. Coupled atmosphere/ocean/ sea-ice General Circulation Models (AOGCMs) provide a comprehensive representation of the climate system. There is an evolution towards more complex models with active chemistry and biology. Climate models are applied, as a research tool, to study and simulate the climate, but also for operational purposes, including monthly, seasonal, and interannual climate predictions.

Climate Prediction
A climate prediction or climate forecast is the result of an attempt to produce a most likely description or estimate of the actual evolution of the climate in the future (e.g., at seasonal, interannual, or long-term time scales. See also *climate projection* and *climate scenario*.

Climate Projection
A projection of the response of the climate system to emission or concentration scenarios of *greenhouse gases* and *aerosols*, or *radiative forcing* scenarios, often based upon simulations by climate models. Climate projections are distinguished from *climate predictions* in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions, concerning, for example, future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty.

Climate Scenario
A plausible and often simplified representation of the future *climate*, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A “climate change scenario” is the difference between a climate scenario and the current climate.

Climate System
The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the *cryosphere*, the land surface, and the *biosphere*, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and human-induced forcings such as the changing composition of the
atmosphere and *land use*.

Climate Variability
Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability). See also *Climate Change*.

Desert
An ecosystem with <100 mm precipitation per year.

Desertification
Land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities. Further, the United Nations Convention to Combat Desertification (UNCCD) defines land degradation as a reduction or loss in arid, semi-arid, and dry sub-humid areas of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, forest, and woodlands resulting from land uses or from a process or combination of processes, including those arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical, and biological or economic properties of soil; and (iii) long-term loss of natural vegetation.

Disturbance Regime
Frequency, intensity, and types of disturbances, such as fires, inspect or pest outbreaks, floods, and *droughts*.

Diurnal Temperature Range
The difference between the maximum and minimum temperature during a day.

Downscaling
Reducing the scale of a model from a global to regional level.

Drought
The phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems.

Ecosystem
A distinct system of interacting living organisms, together with their physical environment. The boundaries of what could be called an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus the extent of an ecosystem may range from very small spatial scales to, ultimately, the entire Earth.

Ecosystem Services
Ecological processes or functions which have value to individuals or society.

Edaphic
Of or relating to the soil; factors inherent in the soil.

Effective Rainfall
The portion of the total rainfall that becomes available for plant growth.

El Niño-Southern Oscillation (ENSO)
El Niño, in its original sense, is a warm water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. This oceanic event is associated with a fluctuation of the inter-tropical surface pressure pattern and circulation in the Indian and Pacific Oceans, called the *Southern Oscillation*. This coupled atmosphere-ocean phenomenon is collectively known as El Niño-Southern Oscillation. During an El Niño event, the prevailing trade winds weaken and the equatorial countercurrent strengthens, causing warm surface waters in the Indonesian area to flow eastward to overlie the cold waters of the Peru current. This event has great impact on the wind, sea surface temperature, and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world. The opposite of an El Niño event is called La Niña.

Emission Scenario
A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., *greenhouse gases*, *aerosols*), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships. In 1992, the IPCC presented a set of emission scenarios that were used as a basis for the climate projections in the Second Assessment Report (IPCC, 1996). These emission scenarios are referred to as the IS92 scenarios. In the IPCC *Special Report on Emission Scenarios* (Nakicenovic *et al*., 2000), new emission scenarios—the so -called SRES scenarios—were published.

Endemic
Restricted or peculiar to a locality or region. With regard to human health, endemic can refer to a disease or agent present or usually prevalent in a population or geographical area at all times.

Epidemic
Occurring suddenly in numbers clearly in excess of normal expectancy, said especially of infectious diseases but applied also to any disease, injury, or other health-related event occurring in such outbreaks.

Erosion
The process of removal and transport of soil and rock by weathering, mass wasting, and the action of streams, glaciers, waves, winds, and underground water.

Eutrophication
The process by which a body of water (often shallow) becomes (either naturally or by pollution) rich in dissolved nutrients with a seasonal deficiency in dissolved oxygen.

Evaporation
The process by which a liquid becomes a gas. The combined process of *evaporation* from the Earth's surface and *transpiration* from vegetation.

Exposure
The nature and degree to which a system is exposed to significant climatic variations.

Extreme Weather Event
An event that is rare within its statistical reference distribution at a particular place. Definitions of "rare" vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile. By definition, the characteristics of what is called "extreme weather" may vary from place to place. An "extreme climate event" is an average of a number of weather events over a certain period of time, an average which is itself extreme (e.g., rainfall over a season).

Feedback
A process that triggers changes in a second process that in turn influences the original one; a positive feedback intensifies the original process, and a negative feedback reduces it.

Greenhouse Effect
Greenhouse gases effectively absorb infrared radiation emitted by the Earth's surface, by the atmosphere itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth's surface. Thus greenhouse gases trap heat within the surface-troposphere system. This is called the "natural greenhouse effect." Atmospheric radiation is strongly coupled to the temperature of the level at which it is emitted. In the troposphere, the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of on average -19°C, in balance with the net incoming solar radiation, whereas the Earth's surface is kept at a much higher temperature of on average 14°C. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a radiative forcing, an imbalance that can only be compensated for by an increase of the temperature of the surface-troposphere system. This is called the "enhanced greenhouse effect."

Gross Primary Production
The amount of carbon fixed from the atmosphere through *photosynthesis*.

Groundwater Recharge
The process by which external water is added to the zone of saturation of an *aquifer*, either directly into a formation or indirectly by way of another formation. The particular environment or place where an organism or species tends to live; a more locally circumscribed portion of the total environment.

Human System
Any system in which human organizations play a major role. Often, but not always, the term is synonymous with “society” or “social system” (e.g., agricultural system, political system, technological system, economic system); all are human systems in the sense applied in the TAR.

(Climate) Impact Assessment
The practice of identifying and evaluating the detrimental and beneficial consequences of climate change on natural and human systems.

(Climate) Impacts
Consequences of climate change on natural and human systems. Depending on the consideration of adaptation, one can distinguish between potential impacts and residual impacts.
– ***Potential Impacts***: All impacts that may occur given a projected change in climate, without considering adaptation.
– ***Residual Impacts***: The impacts of climate change that would occur after adaptation. See also *aggregate impacts*, *market impacts*, and *non - market impacts*.

Indigenous Peoples
People whose ancestors inhabited a place or a country when persons from another culture or ethnic background arrived on the scene and dominated them through conquest, settlement, or other means and who today live more in conformity with their own social, economic, and cultural customs and traditions than those of the country of which they now form a part (also referred to as “native,” “aboriginal,” or “tribal” peoples).

Infrastructure
The basic equipment, utilities, productive enterprises, installations, and services essential for the development, operation, and growth of an organization, city, or nation.

Integrated Assessment
A method of analysis that combines results and models from the physical, biological, economic, and social sciences, and the interactions between these components, in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it.

Introduced Species
A species occurring in an area outside its historically known natural range as a result of accidental dispersal by humans (also referred to as “exotic species” or “alien species”).

Invasive Species
An introduced species that invades natural habitats.

Land Use
The total of arrangements, activities, and inputs undertaken in a certain land-cover type (a set of human actions). The social and economic purposes for which land is managed (e.g., grazing, timber extraction, conservation).

Local Agenda 21
Local Agenda 21s are the local plans for environment and development that each local authority is meant to develop through a consultative process with their populations, with particular attention paid to involving women and youth. Many local authorities have developed Local Agenda 21s through consultative processes as a means of reorienting their policies, plans, and operations towards the achievement of *sustainable development* goals. The term comes from Chapter 28 of Agenda 21—the document formally endorsed by all government representatives attending the UN Conference on Environment and Development (also known as the Earth Summit) in Rio de Janeiro in 1992.

Maladaptation
Any changes in natural or human systems that inadvertently increase vulnerability to climatic stimuli; an adaptation that does not succeed in reducing vulnerability but increases it instead.

Montane
The biogeographic zone made up of relatively moist, cool upland slopes below timberline and characterized by the presence of large evergreen trees as a dominant life form.

Net Primary Production (NPP)
The increase in plant biomass or carbon of a unit of a landscape. NPP is equal to *Gross Primary Production* minus carbon lost through autotrophic respiration.

Orography
The study of the physical geography of mountains and mountain systems.

Phenology
The study of natural phenomena that recur periodically (e.g., blooming, migrating) and their relation to climate and seasonal changes.

Photosynthate
The product of *photosynthesis*.

Photosynthesis
The process by which plants take carbon dioxide from the air (or bicarbonate in water) to build carbohydrates, releasing oxygen in the process. There are several pathways of photosynthesis with different responses to atmospheric CO2 concentrations. See also *CO2 fertilization*, *C3 plants*, and *C4 plants*.

Physiographic
Of, relating to, or employing a description of nature or natural phenomena.

Rangeland
Unimproved grasslands, shrublands, savannas, and tundra.

Regeneration
The renewal of a stand of trees through either natural means (seeded onsite or adjacent stands or deposited by wind, birds, or animals) or artificial means (by planting seedlings or direct seeding).

Reinsurance
The transfer of a portion of primary insurance risks to a secondary tier of insurers (reinsurers); essentially "insurance for insurers."

Reservoir
A component of the climate system, other than the atmosphere, that has the capacity to store, accumulate, or release a substance of concern (e.g., carbon, a *greenhouse gas*, or precursor). Oceans, soils, and *forests* are examples of reservoirs of carbon. "Pool" is an equivalent term (note that the definition of pool often includes the atmosphere). The absolute quantity of substances of concern held within a reservoir at a specified time is called the "stock." The term also means an artificial or natural storage place for water, such as a lake, pond, or *aquifer*, from which the water may be withdrawn for such purposes as irrigation, water supply, or irrigation.

Resilience
Amount of change a system can undergo without changing state
.

Respiration
The process whereby living organisms convert organic matter to carbon dioxide, releasing energy and consuming oxygen.

Riparian
Relating to or living or located on the bank of a natural watercourse (as a river) or sometimes of a lake or a tidewater.

Runoff
That part of precipitation that does not evaporate. In some countries, runoff implies *surface runoff* only. In this study, runoff is made up of stormflow plus baseflow from a specified catchment or subcatchment.

Salinisation
The accumulation of salts in soils.

Scenario (Generic)
A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a "narrative storyline." See also *Climate Scenario* and *emissions scenario*.

Sea-Level Rise
An increase in the mean level of the ocean. Eustatic sea-level rise is a change in global average sea level brought about by an alteration to the volume of the world ocean. Relative sea-level rise occurs where there is a net increase in the level of the ocean relative to local land movements. Climate modelers largely concentrate on estimating eustatic sea-level change. Impact researchers focus on relative sea-level change.

Semi-Arid Regions
Ecosystems that have >250 mm precipitation per year, but are not highly productive; usually classified as rangelands.

Sensitivity
Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate-related *stimuli*. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to *sea level rise*).

Southern Oscillation
A large-scale atmospheric and hydrospheric fluctuation centered in the equatorial Pacific Ocean, exhibiting a pressure anomaly, alternatively high over the Indian Ocean and high over the South Pacific. Its period is slightly variable, averaging 2.33 years. The variation in pressure is accompanied by variations in wind strengths, ocean currents, sea-surface temperatures, and precipitation in the surrounding areas.

Stakeholders
Person or entity holding grants, concessions, or any other type of value that would be affected by a particular action or policy.

Stimuli (Climate-Related)
All the elements of climate change, including mean climate characteristics, climate variability, and the frequency and magnitude of extremes.

Stochastic Events
Events involving a random variable, chance, or probability.

Streamflow
Water within a river channel, usually expressed in m^3/s or mm/day. In the context of this study, streamflow is made up of runoff accumulated from a specific subcatchment and all upstream contributions flowing into that subcatchment.

Succession
Transition in the composition of plant communities following disturbance.

Surface Runoff
The water that travels over the soil surface to the nearest surface stream; *runoff* of a drainage basin that has not passed beneath the surface since precipitation.

Sustainable Development
Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Synoptic
Relating to or displaying atmospheric and weather conditions as they exist simultaneously over a broad area.

Timberline
The upper limit of tree growth in mountains or high latitudes.

Transpiration
The emission of water vapor from the surfaces of leaves or other plant parts.

Uncertainty
An expression of the degree to which a value (e.g., the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures (e.g., a range of values calculated by various models) or by qualitative statements (e.g., reflecting the judgment of a team of experts).

Unique and Threatened Systems
Entities that are confined to a relatively narrow geographical range but can affect other, often larger entities beyond their range; narrow geographical range points to sensitivity to environmental variables, including climate, and therefore attests to potential vulnerability to *climate change*.

United Nations Framework Convention on Climate Change (UNFCCC)
The Convention was adopted on 9 May 1992, in New York, and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” It contains commitments for all Parties. Under the Convention, Parties included in Annex I aim to return greenhouse gas emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The Convention entered in force in March 1994.

Vector-Borne Diseases
Disease that is transmitted between hosts by a *vector* organism (such as a mosquito or tick— for example, malaria, dengue fever, and leishmaniasis).

Vernalization
The act or process of hastening the flowering and fruiting of plants by treating seeds, bulbs, or seedlings so as to induce a shortening of the vegetative period.

Vulnerability
The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Water Consumption
Amount of extracted water irretrievably lost at a given territory during its use (evaporation and goods production). Water consumption is equal to water withdrawal minus return flow.

Water Stress
A country is water stressed if the available freshwater sup ply relative to *water withdrawals* acts as an important constraint on development. Withdrawals exceeding 20% of renewable water supply has been used as an indicator of water stress.

Water Use Efficiency
Carbon gain in photosynthesis per unit water lost in evapotranspiration. It can be expressed on a short-term basis as the ratio of photosynthetic carbon gain per unit transpirational water loss, or on a seasonal basis as the ratio of *net primary production* or agricultural yield to the amount of available water.