DEVELOPMENT OF TECHNICAL AND FINANCIAL NORMS AND STANDARDS FOR DRAINAGE OF IRRIGATED LANDS

Volume 1

Research Report

Report to the

WATER RESEARCH COMMISSION

By

AGRICULTURAL RESEARCH COUNCIL
Institute for Agricultural Engineering

Private Bag X519, Silverton, 0127

Mr FB Reinders[1], Dr H Oosthuizen[2], Dr A Senzanje[3], Prof JC Smithers[3], Mr RJ van der Merwe[1], Ms I van der Stoep[4], Prof L van Rensburg[5]

[1]ARC-Institute for Agricultural Engineering
[2]OABS Development
[3]University of KwaZulu-Natal;
[4]Bioresources Consulting
[5]University of the Free State

WRC Report No. 2026/1/15
ISBN 978-1-4312-0759-6

January 2016

Obtainable from

Water Research Commission
Private Bag X03
Gezina, 0031
South Africa

orders@wrc.org.za or download from www.wrc.org.za

This report forms part of a series of three reports. The reports are:
Volume 1: Research Report.
Volume 2: Supporting Information Relating to the Updating of Technical Standards and Economic Feasibility of Drainage Projects in South Africa.
Volume 3: Guidance for the Implementation of Surface and Sub-surface Drainage Projects in South Africa

EXECUTIVE SUMMARY

This report concludes the directed Water Research Commission (WRC) Project "Development of technical and financial norms and standards for drainage of irrigated lands", which was undertaken during the period April 2010 to March 2015.

The main objective of the Project was to develop technical and financial norms and standards for the drainage of irrigated lands in Southern Africa that resulted in a report and manual for the design, installation, operation and maintenance of drainage systems.

BACKGROUND

In South Africa an area of 1 399 221 ha was irrigated and 1 675 822 ha registered for irrigation during 2008 (Van der Stoep & Tylcote, 2014). It is estimated that 241 630 ha (Scotney et al., 1995) is affected by rising water tables and salinisation and problems appear to be expanding. There are many causes of drainage problems in South Africa. Some typical causes of drainage problems are:

- inefficient and badly managed irrigation systems, specifically in the case of very shallow soils and insufficient natural drainage. Salts then start to accumulate and the end result is that the land has to be withdrawn from production,
- leaking earthen dams and irrigation furrows,
- in some areas terraces are designed and established in order to obtain the right slopes for flood irrigation but, unfortunately, sooner or later drainage problems start to occur at the bottom of these terraces, and
- where natural waterways are being cultivated, wet conditions are expected and therefore drainage problems.

The main centres where there are drainage problems in the country include:

- the areas along the Orange River, especially at Vaalharts, Douglas and Upington,
- winter rainfall area at Robertson, Worcester, Swellendam, Ceres and Wellington with undulating topography,
- KwaZulu-Natal Region – Pongola and Nkwalini in the sugar producing areas with very heavy clay soils,
- Eastern Cape – Gamtoos valley, Sundays River valley and Great Fish River valley,
- Mpumalanga, Limpopo and North West region – Loskop and Hartbeespoort Irrigation schemes, and
- mainly where there is irrigated agriculture.

Planning and design of sub-surface drains was undertaken up to 1965 by members of the Soil and Irrigation Institute, and the staff of the Directorate of Agricultural Engineering. Various approaches were tested and at present designs are carried out according to selected norms and formulas like the Borehole Method of "Van Beers" to determine the hydraulic permeability, the drain spacing formula of Hooghoudt, and the use of derived formulas from Manning for determining the pipe diameter. Various techniques are currently used to assist the engineering practitioners in the field to quickly determine the layout spacing, pipe diameter, drain slope, etc. from various inputs.

Good practices, approaches and design techniques do exist in soil conservation (surface drainage) and need to be revisited, upgraded and compiled in a comprehensive format.

With the extensive research internationally and locally, practical experience and testing of drainage techniques and materials by personnel of the Soil and Irrigation Research Institute, the Directorate of Agricultural Engineering and others, a sound foundation of knowledge has been established 25 years ago and the need to update knowledge in this regard is essential.

RATIONALE

The extent and severity of drainage problems in South Africa is estimated at 241 630 ha (Scotney et al., 1995) and the problem of rising water tables and salinisation appear to be expanding. There are indications that the costs of drainage installation have increase quite significantly.

Apart from isolated projects for specific reasons, there has been no comprehensive research on drainage in South Africa over the past 25 years. The existing drainage design, installation and maintenance norms and standards have been adjusted by means of ad hoc studies. Consequently there is a need to revise and publish up to date norms and standards for South Africa. The timing of these revisions is critical because there are only a handful of experts in the drainage field and there is an urgent need to train new practitioners. By extension, it is then expected that these revised standards should form the basis for training of students at tertiary level and guiding of practitioners. The demand for the design of drainage in the field by far exceeds the available capacity.

Research output and modelling approaches available internationally should be assessed for applicability in South Africa. Also new ways of managing drainage should be introduced instead of only a narrow focus on the current available solutions. Due to poor quality water, more water for leaching is required which increases the need for drainage under field condition. Leaching is required because yields are declining and economic returns are negatively affected. Old drainage systems are no longer functional or coping because of a lack of operation and maintenance. Unfortunately new drainage systems have not been introduced to cope with the excessive water. The technical lifespan of existing drainage systems has expired, and with new technology the systematic replacement of current drainage systems needs to take place.

It is essential (actually imperative) to assess the financial feasibility of replacing and installing new drainage systems and this requires decision making support.

For existing and new schemes surface runoff has to be realigned and aligned effectively with sub-surface drainage. In the case of revitalisation of irrigation schemes a big component of the funding is allocated to surface and sub-surface drainage. There is a need to justify financial incentives or grants and determine the financial feasibility of drainage at farm and scheme level. Reclamation of irrigation land through drainage will improve production on existing schemes and this will decrease the pressure or need to develop new areas.

Effective management of the operation and maintenance of drainage systems will increase water use efficiency and lead to water savings which will support food security in rural areas.

OBJECTIVES AND AIMS

Main Objectvie:

To develop technical and financial standards and guidelines for assessment of the feasibility of surface and sub-surface drainage systems under South African conditions.

Specific Aims:

1. To review internationally and nationally available norms and standards and to give an overview of current drainage systems, practices and technology;
2. To evaluate the interaction between irrigation, drainage practices and impact on the natural environment;
3. To describe technical/physical/biological/financial requirements for drainage;
4. To refine and develop technical standards for drainage with reference to soil types, crops, irrigation method, water tables, salinisation, water quality and management practices;
5. To refine and develop financial standards for drainage with reference to capital investment, financing methods, operation and maintenance expenditure and management practices;
6. To evaluate the technical and financial feasibility of drainage based on selected case studies;
7. To develop guidelines for design, installation, operation and maintenance of drainage systems.

METHOD

The research method followed in the research project was tailored to answer the specific aims. The specific method followed for the specific aims are summarised as follows:

Aims 1, 2 and 3

Literature reviews of local and international books, journal articles and internet publications were conducted, and from these sources the terminology, definitions, practices and technology of the various drainage approaches were identified and documented. The descriptions included engineering, soil science, environmental and economic approaches on drainage. The review of literature also provided an overview of current drainage systems, practices and technologies worldwide, and those suited to South African conditions.

Appropriate research study sites were identified based on available information, extent of drainage problems, and cropping enterprises being practiced where data collection, drainage system performance and modelling were undertaken. Eventually three study sites were selected; Vaalharts (Northern Cape), Pongola (KwaZulu-Natal), and Breede River (Western Cape) irrigation schemes. The sites provided a range of climatic, soil and crop data variations that ensured that the results from the study would be widely applicable to South Africa. At these sites on-going drainage practices were monitored and evaluated for their adequacy (or otherwise) to deal with the drainage problems. Data was collected ranging from climate, soils, hydrology, crops, drainage system characteristics and layout and the drainage problems in existence. This information was applied in analysing and modelling the most appropriate engineering, environmental and economical approaches to drainage planning, design and development.

Aims 4 and 5

Water balance studies, international and local technical models applied in drainage design and management were reviewed. For the technical aspects the following models were reviewed – Drainmod, WaSim and SaltMOD were reviewed. From this group the world renowned Drainmod model was selected for verification and validation for the Pongola (Impala) study site. For Breede River and Vaalharts study sites the Endrain model was applied.

For the determination of the financial feasibility of drainage at the farm level a suite of related financial models under the Armour et al. (2008) model were reviewed and applied. These are SMCEDs, BankMod, FinData and FinAnalysis and SMsim. The DRAINFRAME methodology was also reviewed.

Aim 6 and 7

Drainmod was applied to evaluate the technical feasibility of drainage in the Impala irrigation scheme case study. Endrain was applied in the case of Breede River and Vaalharts irrigation schemes. Evaluations were carried out on existing installed drainage systems focusing on the type of drainage system, soil type, irrigation method, operation and management practices. The main output of the technical aspects of the research was the development of the appropriate drainage design criteria.

The Armour et al. (2008) model was applied across all the three study areas for the financial feasibility assessments of drainage at the farm level. The financial evaluations focused on the capital management, financing methods, operation and maintenance expenditure, and financial parameters such as Net Present Value (NPV), Internal Rate of Return (IRR), Return on Capital Investment (RCI) and cost-benefit ratios (CBA) were used to select the best drainage alternatives.

MAIN FINDINGS AND CONCLUSIONS

The main objective of the Project was to develop technical and financial norms and standards for the drainage of irrigated lands in Southern Africa. Thus, through funding from the Water Research Commission, the project, "Development of technical and financial norms and standards for the drainage of irrigated lands", was initiated. As a result of thorough research, three comprehensive volumes were produced: Volume 1 consists of the research report; Volume 2 contains supporting information; while Volume 3 provides guidance on both the technical and financial aspects for the implementation of surface and sub-surface drainage.

Literature reviews of local and international books, journal articles and internet publications were conducted, and from these sources, the terminology, definitions, practices and technology of the various drainage approaches were identified and documented. The descriptions included engineering, soil science, environmental and economic approaches on drainage. The review of literature also provided an overview of current drainage systems, practices and technologies worldwide, and those suited to South African conditions.

Water balance studies, international and local technical models applied in drainage design and management were also reviewed. For the technical aspects, the following models were reviewed – Drainmod, WaSim, SaltMOD and Endrain. From this group the world renowned Drainmod model was selected for verification and validation for the Pongola (Impala) study site and for the Breede River and Vaalharts study sites, the Endrain model was applied. Evaluations were carried out on existing designed and installed drainage systems focusing on the type of drainage system, soil type, irrigation method, operation and management practices. Although Drainmod confirmed that present design approaches are correct, it is a cumbersome approach as the model need to be tested first for a specific area before it could be fully put into use as a design and evaluation technique. On the other hand the Endrain model was found to be a user-friendly model for design purposes. A spreadsheet with the basic formulas can also be utilised according to the input data that is obtained from the field and this report.

On the financial side the models in WRC Report TT 448/08 (Armour and Viljoen, 2008) were used as a starting point and from this the DrainFin model was developed and applied across all three the study areas for the financial feasibility assessments of drainage at the farm level. The DrainFin model and all its components are described and is on the CD included with Volume 3. It include a database, enterprise crop budgets, a drainage plan and capital budget, projected financial statements and scenario analysis that can be done to determine the economic and financial viability of a drainage project. The accurate composition of the projected cash flow-statement, income statement and balance sheet is essential for financial assessment and evaluation. The DrainFin model makes provision for the comparison of up to ten different scenarios. These scenarios can be evaluated and compared in terms of per-hectare analysis.

The effect of subsidies, grants, etc. can easily be accommodated in the model to discount the monetary effect of government intervention on the financial feasibility of sub-surface drainage.

In addition, examples are presented in the text which illustrates application of the underlying scientific and economic principles which are unique to the field of drainage.

Comprehensive guidance is provided on the subject for both the technical and financial aspects of surface and sub-surface drainage and will benefit the following persons in both the engineering and financial sectors:

- Engineering technicians in the country's provincial agricultural departments
- Financial and technical advisors at co-operatives and agri-businesses who offer financial and technical advice to farmers
- Banks who offer financial assistance to farmers
- Technical personnel at engineering consultancies
- Students in the field of agricultural or bio-resources engineering

The project focused on acquiring, synthesizing and transferring contemporary knowledge on drainage (surface and subsurface) in South Africa, as described in the specific objectives. The project was managed by a core team who was responsible for collating data and report-writing, backed up by a team of specialist consultants and Departments from the collaborating organisations that provided inputs. The gap in knowledge on drainage (surface and subsurface) has now been filled and efforts should be made that the guidelines are widely implemented.

ACKNOWLEDGEMENTS

The Water Research Commission (WRC) is sincerely thanked for initiating, funding and managing this very important project. The authors would like to thank the Reference Group of the WRC Project for their assistance, guidance and the constructive discussions during the duration of the project.

WRC Reference Group:

Dr GR Backeberg	Water Research Commission (Chairman)
Dr RJ Armour	Agri Free State
Mr HM du Plessis	Private Consultant
Dr S Mpandeli	Water Research Commission
Dr JP Nell	ARC-Institute for Soil, Climate and Water
Mr AS Roux	Department of Agriculture – Western Cape
Prof JC Smithers	University of KwaZulu-Natal
Mr AT van Coller	Department of Agriculture, Forestry and Fisheries

Advisors and administrative support:

Mr J van der Merwe	Department of Agriculture, KwaZulu-Natal.
Mr H King	Department of Agriculture, Western Cape
Ms T Moema	ARC – Institute for Agricultural Engineering (Secretary)

Project Team:

Mr FB Reinders	ARC-Institute for Agricultural Engineering (Project Leader)
Dr H Oosthuizen	OABS Development
Dr A Senzanje	University of KwaZulu-Natal
Prof JC Smithers	University of KwaZulu-Natal
Mr RJ van der Merwe	ARC – Institute for Agricultural Engineering
Ms I van der Stoep	Bioresources Consulting
Prof L van Rensburg	University of the Free State

Acknowledgement is also given to JM van der Merwe of the KZN Department of Agriculture, Environmental Affairs and Rural Development for his inputs regarding sub-surface drainage chapter and for the supplying of photographs from his personal collection

This page was left blank deliberately

TABLE OF CONTENTS

The report is a set of three reports.

Volume 1: Research Report

Volume 2: Supporting Information Relating to the Updating of Technical Standards and Economic Feasibility of Drainage Projects in South Africa

Volume 3: Guidance for the Implementation of Surface and Sub-surface Drainage Projects in South Africa

Each volume is a stand-alone with its own table of contents.

Volume 1:

Research Report

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ARC-IAE	Agricultural Research Council-Institute of Agricultural Engineering
ASAE	American Society of Agricultural Engineering
BankMod	Bank model for financial analysis (of drainage)
BCR	Benefit cost ratio
B/C	Benefit/cost
BS	Base saturation
CAN-CS	Canistero fine loamy soil
CARA	Conservation of Agricultural Resources Act (Act 43 of 1983)
CEC	Cation exchange capacity
CLIMWAT	Climatic database for use with CROPWAT model
CMA	Catchment Management Area
CMS	Catchment Management System
CRM	Coefficient of residual mass
DAFF	Department of Agriculture, Fisheries and Forestry
Dil	Depth to impermeable layer
DP	Drainage porosity
DR	Drainage rate
DRAIN-FIN	Drainage Financial model
DRAINFRAME	Drainage Integrated Analytical Framework
DRAIMOD	Drainage Model
DS	Deep seepage
DUL	Drained upper limit
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EC	Electrical conductivity
ESP	Exchangeable sodium percentage
ET	Evapotranspiration
FAO	Food and Agricultural Organisation
FinData	Financial analysis model
FinAnalysis	Financial analysis model
GM	Gross margin
GNW	Growth in net worth
GPS	Geographical positioning system
GPV	Gross production value
HDPE	High density polyethylene (pipe)

HYDRUS	Modelling software for analysis of water flow, heat and solute transport
ICID	International Commission on Irrigation and Drainage
IRR	Internal rate of return
ISO	International Standardisation Office
ISRIC	International Soil Reference and Information Centre
LWSR	Layer water supply rate
MAE	Mean absolute error
NCSU	North Carolina State University
NFI	Net farm income
NFP	Net farm profit
NPV	Net present value
OM	Operation and maintenance
PET	Potential evapotranspiration
PMAD	Production, marketing, administration costs and depreciation
PVC	Polyvinyl chloride (pipe)
PWSR	Profile water supply rate
RETC	Retention curve (computer code)
SABS	South African Bureau of Standards
SaltMOD	Salinity (salt) .model
SAR	Sodium adsorption ratio
SCS	Soil Conservation Service
SEPAC	South-eastern Purdue Agricultural Centre
SEW30	Summation of the daily occurrences of excess water within 30 cm of the soil surface
SMCEB	Direct profitability analysis model
SMsim	Micro-economic simulation model
SWAMP	Soil Water Management Program model
USEPA	United States Environmental Protection Agency
USA	United States of America
WaSim	Water Balance Simulation model
WEBS-CC	Webster clay soil
WMA	Water Management Area
WRC	Water Research Commission
WTD	Water table depth

1 INTRODUCTION

The main objective of this Water Research Commission Project is to develop technical and financial norms and standards for the drainage of irrigated lands in Southern Africa. One of the specific aims is to review and report on internationally and nationally available norms and standards. Solutions to drainage problems in agricultural land are typically approached from a surface or a sub-surface perspective, depending on the origins of the excess water.

In South Africa an area of 16 740 000 ha is been cultivated and 1 676 000 ha registered for irrigation (Van der Stoep & Tylcote, 2012). It is estimated that 241 630 ha (Scotney et al., 1995) is affected by rising water tables and salinisation and problems appear to be expanding.

There is also an indication that costs of drainage have increased quite significantly. Various approaches and techniques have been used and are still been used to drain agricultural fields in South Africa. Apart from isolated projects for specific reasons, no comprehensive research on drainage in South Africa over the past 30 years has been conducted and existing norms and standards have been adjusted by means of ad hoc studies to provide solutions

There is therefore a need to revise and publish up to date norms and standards for South Africa that could form the basis for training of students at tertiary level and provide guidance for practitioners. The timing is critical because only a handful of experts in the field are left and there is a need to provide documented information and to train new practitioners. At present the demand for design of drainage in the field by far exceeds the availability of capacity.

Internationally and locally available research output and modelling approaches have been assessed for applicability in South Africa. In the past drainage systems were designed for a long life based on the assumption that climatic conditions would not change that much in the future. This is not the case anymore as significant changes to the agricultural environment are expected due to climate change which necessitates a re-look at how drainage systems are designed to adequately meet these future changes.

One of the main motivations for this project is the fact that few projects have been undertaken which document the current status of drainage in terms of the knowledge that has been gained in the implementation of drainage projects in the past 30 years. Due to continuing drainage problems in South Africa, and with a decline in the number of experts working in this field, it has become imperative to record this information to ensure the continuing effective role of drainage in sustainable agricultural practices.

It is also important to note that the both the economic and natural environments that mankind interacts with are changing. Thus, the need for review is enhanced by global concerns regarding climate change whereby there is documented evidence worldwide of increased rainfall intensities and variations in seasonal rainfall patterns in recent time. From this perspective it is important to investigate whether or not current approaches to drainage problems are still relevant given the direct correlation between drainage and precipitation. Environmentally, there is a growing awareness of the impacts of drainage water on water quality that need to be addressed. On the economic front, increasing energy costs such as diesel, which increase the costs of land preparation and the construction and maintenance of drainage structures, drive the need to be review current drainage practices. Furthermore there is a growing awareness of the impacts of drainage water on water quality that need to be addressed.

1.1 Motivation

It is estimated that 241 630 ha (Scotney et al., 1995) is affected by rising water tables and salinisation and problems appear to be expanding.

There is also an indication that costs of drainage have increased quite significantly. Various approaches and techniques have been used and are still been used to drain agricultural fields in South Africa. Apart from isolated projects for specific reasons, no comprehensive research on drainage in South Africa over the past 25 years has been conducted and existing norms and standards have been adjusted by means of ad hoc studies to provide solutions

There was therefore a need to revise and publish up to date norms and standards for South Africa that could form the basis for training of students at tertiary level and provide guidance for practitioners. The timing is critical because only a handful of experts in the field are left and there is a need to provide documented information and to train new practitioners. At present the demand for design of drainage in the field by far exceeds the availability of capacity. Through funding from the Water Research Commission, the project, “Development of Technical and Financial Norms and Standards for the Drainage of Irrigated Lands”, was initiated and resulted through research three comprehensive volumes. Volume 3, provides a comprehensive text on the subject of both the technical and financial aspects of surface and sub-surface drainage

Because of poor quality water, more water for leaching is required which increases the need for drainage and leaching is required because yields are declining and economic returns are negatively affected.

It is also essential to assess the financial feasibility of replacing and installing new drainage systems which requires decision making support.

Revitalising of irrigation systems is high on the agenda of the government and the Irrigation Strategy is a response to the call for the sector to increase its contribution to agricultural production for ensuring food security, poverty alleviation, and job creation. In the case of revitalisation of irrigation schemes a big component of the funding is allocated to surface and sub-surface drainage. This strategy includes directives from recent policy changes and provides directions for institutional reform and guidelines on public investment in irrigation initiatives. In this regard there is also a need to justify financial incentives/grants by determining the financial feasibility of drainage at farm and scheme level.

Reclamation of irrigation land through drainage improve production on existing schemes and decreases the pressure to develop new areas and with effective management of operation and maintenance of drainage it will increase water use efficiency and lead to water savings which will support food security in rural areas.

1.2 Main Objective

The main objective of this project is to develop technical and financial standards and guidelines for assessment of the feasibility of surface and sub-surface drainage systems under South African conditions.

1.3 Specific Aims

The specific aims of this project are:

(i) To review internationally and nationally available norms and standards and to give an overview of current drainage systems, practices and technology;

(ii) To evaluate the interaction between irrigation, drainage practices and impact on the natural environment;

(iii) To describe technical/physical/biological/financial requirements for drainage;

(iv) To refine and develop technical standards for drainage with reference to soil types, crops, irrigation method, water tables, salinisation, water quality and management practices;

(v) To refine and develop financial standards for drainage with reference to capital investment, financing methods, operation and maintenance expenditure and management practices;

(vi) To evaluate the technical and financial feasibility of drainage based on selected case studies;

1.4 Organisation of content

Figure 1-1 shows the structure of the manual. The content is presented in three volumes with each volume as a standalone document with its own table of contents.

- The first volume is the main report.
- The second volume comprises of background theory, literature review of current practices in surface and sub-surface drainage and the results of case studies.
- The third volume is the user manual for evaluating and implementing surface and sub-surface drainage projects in South Africa, utilising developed technical and financial approaches.

"Development of technical and financial norms and standards for drainage of irrigated lands"

Volume 1

Research Report

Volume 1 is the main report with:

1. An overview of Surface and Sub-Surface Drainage
2. An overview of Applicable Financial Approaches
3. A Review of Current International Norms and Standards
4. A Review of Current Drainage Practices in South Africa
5. Technical and Economic Feasibility of Drainage Projects

Volume 2

Supporting Information Relating to the Updating of Technical Standards and Economic Feasibility of Drainage Projects in South Africa

Volume 2 comprise of the background, theory, literature review of current practices in surface and sub-surface drainage and the results of case studies with:

1. Identification, Motivation and Selection of Appropriate Sites for Drainage
2. Technical and Financial Requirements for Measurement and Modelling of Drainage
3. Physical Measurements of the Interaction between Irrigation, Drainage Practices and the Natural Environment
4. Modelling for Extrapolation of the Interaction between Irrigation, Drainage Practices and the Natural Environment
5. Refinement of Financial Standards for Drainage with Reference to Capital Investment, Financing Methods, Operation and Maintenance Expenditure and Management Practices
6. Evaluation of technical and financial feasibility of drainage

Volume 3

Guidance for the Implementation of Surface and Sub-surface Drainage Projects in South Africa

Volume 3 is the user manual for evaluating and implementing surface and sub-surface drainage projects in South Africa utilising developed technical and financial approaches with:

1. Surface Drainage with Planning, Design and Implementation.
2. Sub surface Drainage with Planning, Design and Implementation.
3. Technical Feasibility – Design Guidelines
4. Economic Feasibility

Figure 1-1: Structure of the report

2 PROJECT METHOD

The research method followed in the research project was tailored to answer the specific aims. These aims are summarised in the following sub-sections.

Aims 1, 2 and 3

Literature reviews of local and international books, journal articles and internet publications were conducted, and from these sources, the terminology, definitions, practices and technology of the various drainage approaches were identified and documented. The descriptions included engineering, soil science, environmental and economic approaches on drainage. The review of literature also provided an overview of current drainage systems, practices and technologies worldwide, and those suited to South African conditions.

Appropriate research study sites were identified based on available information, extent of drainage problems, and cropping enterprises being practiced where data collection, drainage system performance and modelling were undertaken. In the end three study sites were selected; Vaalharts (Northern Cape), Pongola (KwaZulu-Natal), and Breede River (Western Cape) irrigation schemes. The sites provided a range of climatic, soil and crop data variations that ensured that the results from the study would be widely applicable to South Africa. At these sites on-going drainage practices were monitored and evaluated for their adequacy (or otherwise) to deal with the drainage problems. Data was collected ranging from; climate, soils, hydrology, crops, drainage system characteristics and layout and the drainage problems in existence. This information was applied in analysing and modelling the most appropriate engineering, environmental and economical approaches to drainage planning, design and development. Assessments of whole farm data were undertaken at the three irrigation schemes that enabled the construction of typical farm models that simulated the demand for irrigation water which is a derived demand from the profitability of irrigation crops.

Aims 4 and 5

Water balance studies, international and local technical models applied in drainage design and management were reviewed. For the technical aspects, the following models were reviewed – Drainmod, WaSim and SaltMOD were reviewed. From this group the world renowned Drainmod model was selected for verification and validation for the Pongola (Impala) study site. For Breede River and Vaalharts study sites the Endrain model was applied.

For the determination of the financial feasibility of drainage at the farm level a suite of related financial models under the DRAIN-FIN model were reviewed and applied. These are SMCEDs, BankMod, FinData and FinAnalysis and SMsim. The DRAINFRAME methodology was also reviewed.

Aim 6 and 7

Drainmod was applied to evaluate the technical feasibility of drainage in the Impala irrigation scheme case study. Endrain was applied in the cases of Breede River and Vaalharts irrigation schemes. Evaluations were carried out on existing installed drainage systems focusing on the type of drainage system, soil type, irrigation method, operation and management practices. The main output of the technical aspects of the research was the development of the appropriate drainage design criteria.

The Armour and Viljoen (2008) models were used as a starting point and from this the DrainFin model was developed and applied across all the three study areas for the financial feasibility assessments of drainage at the farm level. The financial evaluations focused on the capital management, financing methods, operation and maintenance expenditure, and financial parameters such as Net Present Value (NPV), Internal Rate of Return (IRR), Return on Capital Investment (RCI) and cost-benefit ratios (CBR) were used to select the best drainage alternatives.

Based on work done in the above aims as well as the old drainage design manual, the updated guidelines for the design, installation, operation and maintenance of drainage systems were developed.

3 OVERVIEW OF SURFACE AND SUB-SURFACE DRAINAGE

The purpose of agricultural drainage is to remove excess water from the soil in order to enhance crop production. In some soils, the natural drainage processes are sufficient for growth and production of agricultural crops, but in many other soils, artificial drainage is needed for efficient agricultural production (US Environmental Protection Agency, 2012).

Surface drainage is the removal of water that collects on the land surface. Many fields have low spots or depressions where water ponds. Surface drainage techniques such as land levelling, constructing surface inlets to subsurface drains, and the construction of shallow ditches or waterways can allow the water to leave the field rather than causing prolonged wet areas.

Subsurface drainage can be defined as the removal of water from below the surface (Albertus et al., 2002). In arid to semi-arid areas, drainage systems are designed mainly for the control of waterlogging and salinisation (Kenneth and Neeltjie, 2002). Out of the 270 million ha of irrigated land in the world, about 110 million ha is located in arid to semi-arid areas. The remaining 150 million ha of the irrigation is practised under more humid climatic conditions with the rainfall on an annual basis providing enough leaching to prevent the harmful accumulation of salts (Lambert and Karim, 2002).

Most serious irrigation-induced land salinisation is almost always attributed with the occurrence of shallow water tables. The accumulated salts are generally partly brought in by the irrigation water, partly by capillary rise of the groundwater (Lambert and Karim, 2002). Irrigated agriculture requires drainage systems to prevent waterlogging and salinisation (Kenneth and Neeltjie, 2002). Waterlogging and salinisation are the result of shallow water table and subsurface drainage systems are designed to treat these conditions (Evan et al., 2001).

Subsurface drainage system consists of field drains, which can either be open ditches, or more commonly a network of drainpipes installed horizontally below the ground surface.

Subsurface drainage removes excess water from the soil profile, usually through a network of perforated tubes installed 0.6 m to 1.2 m below the soil surface. These tubes are commonly called "tiles" because they were originally made from short lengths of clay pipes known as tiles.

The most common type of "tile" is corrugated plastic tubing with small perforations to allow water entry. When the water table in the soil is higher than the tile, water flows into the tubing, either through holes in the plastic tube or through the small cracks between adjacent clay tiles. This lowers the water table to the depth of the tile over the course of several days. Drain tiles allow excess water to leave the field, but once the water table has been lowered to the elevation of the tiles, no more water flows through the tiles. In most years, drain tiles are not flowing between June and October (US Environmental Protection Agency, 2012).

These drainpipes used to be manufactured of clay tiles, with the water entering the drainpipes through the open joints (Albertus et al., 2002). The use of perforated plastics in the 1960s increased the effectiveness, efficiency and economics of installation (Stuyt et al., 2005).

Drainpipes are surrounded by an envelope material to prevent clogging and siltation in pipes. The main function of a drain envelope is to improve particle retention and hydraulic properties of the drain. Many types of envelope material exist, from thick gravel and organic fibre to synthetic envelopes (Wright and Sands, 2001).

Since the late 1800s, U.S. farmers have been using drainage methods to allow cultivation of poorly drained soils, once believed to be unproductive and unhealthy. Today, proper drainage is still recognized as a key to maximum crop yields.

Nationally (USA), 25 percent of all cropland is classed as "wet" soil. And corn is grown on a surprisingly large portion of that land, thanks to drainage improvements. Increasing the productivity of a poorly drained soil by installing drainage improvements, however, does not necessarily guarantee increased corn production profits. A farmer has to compare potential benefits with the expected costs of a drainage investment to know if it's going to be profitable or not (Nolte et al., 2010).

This chapter contains a review of drainage from a surface and subsurface perspective and the practice of surface and sub-surface drainage on irrigated lands is investigated. The information was determined through knowledge and literature reviews of local and international books, journal articles and internet publications.

From the information gained, the terminology, definitions, practices and technology of the various drainage approaches are summarised. The fields cover engineering, soil science, environmental and economic aspects of drainage.

3.1 Soil Conservation Act

Drainage is regulated by the Conservation of Agricultural Resources Act (CARA) No. 43 of 1983 and it states: "To provide for control over the utilization of the natural agricultural resources of the Republic in order to promote the conservation of the soil, the water sources and the vegetation and the combating of weeds and invader plants; and for matters connected therewith". Article 6 of CARA "Control measures" states, *inter alia*:

(i) "In order to achieve the objects of this Act the Minister may prescribe control measures which shall be complied with by land users to whom they apply.

(ii) Such control measures may relate to-

- (a) the cultivation of virgin soil;
- (b) the utilization and protection of land which is cultivated;
- (c) the irrigation of land;
- (d) the prevention or control of waterlogging or salination of land;
- (e) the utilization and protection of vleis, marshes, water sponges, water courses and water sources;
- (f) the regulating of the flow pattern of run-off water;
- (g) the utilization and protection of the vegetation;
- (h) the grazing capacity of veld, expressed as an area of veld per large stock unit;
- (i) the maximum number and the kind of animals which may be kept on veld.

3.1.1 Control measures as stated in the Act

3.1.1.1 Cultivation of virgin soil

- Except on authority of a written permission by the executive officer, no land user shall cultivate any virgin soil: Provided that such authority shall not be required in respect of virgin land for which an approval has been granted in terms of section 4A of the Forest Act, 1972 (Act 68 of 1972).
- An application for a permission referred to in sub-regulation (1) shall be made on a form obtainable from an extension office for this purpose.

- Such application form shall be completed by the land user of the farm unit on which such virgin soil is situated and shall be lodged at the extension office for the area within which the farm unit concerned is situated at least three months prior to the intended date of cultivation.
- An officer may, for the purposes of an investigation deemed necessary to consider such application, direct a land user to dig such soil profile pits as such officer may determine and to take such other steps as that officer may determine.

3.1.1.2 Cultivation of land with a slope

(i) Except on authority of a written permission by the executive officer, no land user shall cultivate any land if it:-

- has a slope of more than 20 per cent; or
- has a slope of more than 12 per cent,
- is situated in an area specified in column 1 of Figure 3-1,
- consists mainly of soil of a soil form and soil series respectively specified in columns 2 and 3 of Figure 3-1 opposite the area concerned and,
- if applicable, has such physical properties as may be specified in column 4 of Figure 3-1 opposite the soil series concerned.

Area to which restriction applies	Soil to which restriction applies		
	Soil form	Soil series	Physical properties
1	2	3	4
1. The Magisterial District of Eshowe	Cartref	Cartref, Gorvedale, Kusasa and Waterridge	(i) Effective soil depth less than 500 mm; and (ii) clay content of A-horizon less than 15%
	Estcourt	Uitvlugt	do.
	Fernwood	Fernwood and Sandveld	do.
	Glenrosa	Glenrosa and Williamson	do.
	Katspruit	Killarney	do.
	Kroonstad	Avoca, Katarra, Mkambati and Slangkop	do.
	Longlands	Waldene	do.
	Mispah	Mispah	do.
	Sterkspruit	Hartbees	do.
2. The Magisterial Districts of Alexandria, Albany, Bathurst and East London	Cartref	Amabele, Arrochor and Rutherglen	-
	Glenrosa	Williamson	Clay content of the A-horizon less than 20%
	Hutton	Lowlands, Maitengwe, Mangano and Roodepoort	-
	Longlands	Orkney, Waaisand and Waldene	-
	Mispah	Mispah and Muden	Effective soil depth less than 300 mm
	Swartland	Malakata, Reveille, Rosehill and Uitzicht	-

Figure 3-1: Areas within which the cultivation of certain soils with slopes are restricted

(ii) The prohibition (no land user shall cultivate any land if it has a slope of more than 20%) shall not apply in respect of land which is under cultivation on the date of commencement of these regulations, provided it is already protected effectively in terms of regulation 4 against excessive soil loss due to erosion through the action of water.

(iii) The provisions of regulations 2.1.1 shall apply mutatis mutandis with regard to an application for permission by the executive officer.

3.1.1.3 Protection of cultivated land against erosion through the action of water

(i) Every land user shall by means of as many of the following measures as are necessary in his situation, protect the cultivated land on his farm unit effectively against excessive soil loss as a result of erosion through the action of water:

- A suitable soil conservation work shall be constructed and thereafter be maintained in order to divert run-off water from other land or to restrict the run-off speed of run-off water.
- The land concerned shall be cultivated in accordance with such method or be laid out in such a manner that the run-off speed of run-off water is restricted.
- The land concerned shall be utilised in accordance with a crop rotation system.
- Alternate strips on which a cover crop occurs shall be left undisturbed annually.
- Crop residues and other plant material shall be left on the land concerned, or shall be utilised as grazing or otherwise be removed only to such an extent that the remaining portion thereof will be sufficient to form a mulch.
- A suitable grazing crop shall be established on the land concerned, where after it shall be permanently withdrawn from cultivation.

(ii) If the executive officer is satisfied that the measures applied by a land user in a particular case in terms of sub-regulation 2.1.2 are not sufficient to protect cultivated land effectively against excessive soil loss as a result of erosion through the action of water, he may direct such land user in writing to apply such additional measures as the executive officer may determine.

3.1.1.4 Protection of cultivated land against erosion through the action of wind

Every land user shall by means of as many of the following measures as are necessary in his situation, protect the cultivated land on his farm unit effectively against excessive soil loss as a result of erosion through the action of wind:

- The land concerned shall be cultivated in accordance with such method or be laid out in such manner that the surface movement of soil particles through the action of wind is restricted.
- Strips of natural vegetation shall be left at right angles to the prevailing wind direction, a suitable wind break shall be constructed or suitable vegetation shall be established to serve as a wind break.
- The land concerned shall be utilised in accordance with a crop rotation system.
- Alternate strips on which a cover crop occurs shall be left undisturbed annually.
- The land concerned shall not be left fallow.
- The cultivation and grazing of the land concerned during periods of high winds shall be avoided.

- The establishing of crops of which the harvesting causes the disturbance of the topsoil shall be avoided.
- Crop residues and other plant material shall be left on the land concerned, or shall be utilised as grazing or otherwise be removed only to such extent that the remaining portions thereof will be sufficient to form a mulch.

3.1.1.5 Prevention of waterlogging and salination of irrigated land

(i) Every land user shall by means of as many of the following measures as are necessary in his situation, protect the irrigated land on his farm unit effectively against waterlogging and salination:

- Feeder channels, irrigation furrows and storage and catchment dams for irrigation water shall be made impermeable.
- The land concerned shall not be irrigated excessively or with water with too high a salt content.
- A suitable soil conservation work shall be constructed and thereafter be maintained in order to draw off excess surface and subterranean water and to dispose thereof safely to prevent the waterlogging and salination of lower lying land.
- Fertilizer which could contribute towards salination shall not be applied.
- If the land concerned shows signs of salination, a suitable soil ameliorant shall be applied in order to improve the production potential of that land.

(ii) If the executive officer is satisfied that the measures applied by a land user in a particular case in terms of the slopes specified in Section 3.1.1.2 are not sufficient to protect irrigated land effectively against waterlogging or salination, he may direct such land user in writing to apply such addition measures as the executive officer may determine.

3.2 Agricultural Drainage Criteria

Agricultural drainage criteria can be defined as criteria specifying the highest permissible levels of the water table, on or in the soil, so that the agricultural benefits are not reduced by problems of waterlogging (Oosterbaan, 1994).

If the actual water levels are higher than specified by the criteria, an agricultural drainage system may have to be installed, or an already installed system may have

to be improved, so that the waterlogging is eliminated. If, on the other hand, a drainage system has lowered water levels to a depth greater than specified by the criteria, we speak of an over-designed system.
Besides employing agricultural drainage criteria, we also employ technical drainage criteria (to minimize the costs of installing and operating the system, while maintaining the agricultural criteria), environmental drainage criteria (to minimize the environmental damage), and economic drainage criteria (to maximize the net benefits).

A correct assessment of the agricultural drainage criteria requires (Oosterbaan, 1994):

- knowledge of the various possible types of drainage systems;
- an appropriate index for the state of waterlogging;
- an adequate description of the agricultural objectives;
- information on the relationship between index and objective.

3.3 Terminology and Definitions Relating to Drainage Practices

3.3.1 Defining Agricultural Drainage

"Agricultural drainage systems" are systems that make it easier for water to flow from the land, so that agriculture can benefit from the subsequently reduced water levels. The systems can be made to ease the flow of water over the soil surface or through the underground, which leads to a distinction between "surface drainage systems" and "subsurface drainage systems". Both types of systems need an internal or "field drainage system", which lowers the water level in the field, and an external or "main drainage system", which transports the water to the outlet.

A surface drainage system is applied when the waterlogging occurs on the soil surface, whereas a subsurface drainage system is applied when the waterlogging occurs in the soil. Although subsurface drainage systems are sometimes installed to reduce surface waterlogging and vice versa, this practice is not recommended. Under certain conditions, however, combined surface/subsurface drainage systems are quite feasible.

The purpose of subsurface drainage is to lower the water table in the soil. The water table is the level at which the soil is entirely saturated with water. The excess water must be removed to a level below the ground surface where it will not interfere with plant root growth and development. Root growth requires air to be present in the soil. Both water and air need to be present in the spaces between the soil particles, often in equal proportions. If water fills all of these spaces (saturated), there is no room for air.

Agricultural drainage systems do not necessarily lead to increased peak discharges. Although this may occur, especially with surface drainage, the reduced waterlogging can lead to an increase in the temporary storage of water on or in the soil during periods of peak rainfall, so that peak discharges are indeed reduced. A drainage engineer should see to it that the flow of water from the soil occurs as steadily as possible instead of suddenly.

Sometimes (e.g. in irrigated, submerged rice fields), a form of temporary drainage is required whereby the drainage system is only allowed to function on certain occasions (e.g. during the harvest period). If allowed to function continuously, excessive quantities of water would be lost. Such a system is therefore called a "checked drainage system". More usually, however, the drainage system should function as regularly as possible to prevent undue waterlogging at any time. We then speak of a "regular drainage system". (In literature, this is sometimes also called "relief drainage").

The above definition of agricultural drainage systems excludes drainage systems for cities, highways, sports fields, and other non-agricultural purposes. Further, it excludes natural drainage systems. Agricultural drainage systems are artificial and are only installed when the natural drainage is insufficient for a satisfactory form of agriculture. The definition also excludes such reclamation measures as "hydraulic erosion control" (which aims rather at reducing the flow of water from the soil than enhancing it) and "flood protection" (which does not enhance the flow of water from the soil, but aims rather at containing the water in watercourses). Nevertheless, flood protection and drainage systems are often simultaneous components of land reclamation projects. The reason is that installing drainage systems without flood protection in areas prone to inundation would be a waste of time and money. Areas with both flood protection and drainage systems are often called "polders". Sometimes, a flood-control project alone suffices to cure the waterlogging. Drainage systems are then not required.

In the literature, the term "interceptor drainage" is encountered. The interception and diversion of surface waters with catch canals is common practice in water-management projects, but it is a flood-protection measure rather than a drainage measure. The interception of groundwater flowing laterally through the soil is usually not effective, because of the low velocities of groundwater flow. In the presence of a shallow impermeable layer, subsurface interceptor drains catch very little water and generally do not relieve waterlogging in extensive agricultural areas. In the presence of a deep impermeable layer, the total flow of groundwater can be considerable, but then it passes almost entirely underneath the subsurface interceptor drain. A single interceptor drain cannot intercept the upward seepage of groundwater: here, one needs a regular drainage system (Oosterbaan, 1994).

In the following section, terms and definitions which are typically associated with the science and practice of both surface and sub-surface drainage are presented.

3.3.2 Terms and Definitions

Backfilling — Placement of excavated soil in the trench after blinding has been completed.

Bedding — The earth foundation of the trench together with the select material around and over the drain, including envelope and filter material where used.

Bedding — Has the following explanations depending on the context in which the term is used:

- A surface drainage method accomplished by ploughing land to form a series of narrow ridges separated by parallel dead furrows. The ridges are oriented in the direction of the greatest land slope (crowning or ridging).
- Preparation of furrow irrigated row cropped field with wide, flattened ridges between furrows on which one or more crop rows are planted.
- The process of laying a pipe or other conduit in a trench with the bottom shaped to the contour of the conduit or tamping earth around the conduit to form its bed. The manner of bedding may be specified to conform to the earth load and conduit strength.
- Material placed under a pipe or other conduit for mechanical support.

Berm	A strip or area of land, usually level, between the spoil bank and the edge of a channel or ditch.
Blind Drain	Type of drain consisting of an excavated trench, refilled with pervious materials (coarse sand, gravel, or crushed stones) through whose voids water percolates and flows toward an outlet (also called a trench drain).
Blind Inlet	Surface water inlet in which water enters by percolation rather than through open flow conduits.
Blinding	Material placed on top of and around a drain tile or conduit to improve the flow of water to the drain and to prevent displacement during backfilling of the trench
Capillary Fringe	A zone in the soil just above the water table that remains saturated or almost saturated, the extent of which depends on the size-distribution of pores.
Catchment	The area contributing surface water to a point on a drainage or river system, which may be divided in to sub-catchments.
Coefficient of Roughness	The factor which expresses the frictional resistance to flow of a channel or a drain interior
Compaction	The deterioration of soil structure (loss of soil features) by mechanistic pressure which resulting predominantly from agricultural practices.
Confined Aquifer	An aquifer whose upper, and perhaps lower, boundary is defined by a layer of natural material that does not readily transmit water
Controlled Drainage	Regulation of the water table by means of control dams, check drains, or a combination of these, for maintaining the water table at a desired depth.

Continuous pipe	An extended length of pipe which has no perforations or unsealed joints.
Connections	Fittings used to join two drain lines.
Deep Percolation	Water that moves downward through the soil profile below the root zone and is unavailable for use by vegetation.
Depression	Is a low area in a field where surface drainage away from the area does not occur.
Deflection	Decrease in vertical diameter of tubing, often influenced by loading.
Design criteria	A set of standards agreed by the developer, planners and regulators that the proposed drainage system should satisfy.
Design storm	A synthetic rainfall event of a given duration and return period, which is derived by statistically analysing an historical series of rainfall events for a specific location.
Detention basin	A vegetated depression which is normally dry, excepting post storm events, constructed to store water temporarily to attenuate flows. May allow infiltration of water in to the ground.
Ditch	Constructed open channel for conducting water.
Diversion	Channel constructed across the slope for the purpose of intercepting surface runoff.
Drain	Any closed conduit (perforated tubing or tile) or open channel used for removal of surplus ground or surface water.

Drainage	Process of removing surface or subsurface water from a soil or area.
Drainage area	The area from which drainage water is collected and then delivered to an outlet. This is sometimes referred to as the watershed area for a particular drain.
Drainage coefficient	The depth of water, in inches, to be removed from an area within 24 hours or flowrate per unit area.
Drainage Curves	Flow rate versus drainage area curves giving prescribed rates of runoff for different levels of crop protection.
Drainage Pumping Plant	Pumps, power units, and appurtenances for lifting drainage water from a collection basin to an outlet
Drainage system	Collection of surface ditches or subsurface drains, together with structures and pumps used to collect and dispose of excess surface or subsurface water.
Drainage work	Means a soil conservation work that is an open drainage furrow or underground drainage passage that has as its object to prevent, by means of the drainage and safe disposal of excess or underground water, the waterlogging and salinisation of land.
Drop Structure	Hydraulic structure for safely transferring water in a channel to a lower elevation without causing erosion.
Envelope, Drain	Generic name for materials placed on or around a drainage conduit, irrespective of whether used for structural support, improvement in flow, or to stabilize surrounding soil material.
Envelope, Hydraulic	Permeable material placed around a drainage conduit to improve flow conditions in the area immediately adjacent to the drain.

Envelope, Filter	Permeable material placed around a drainage conduit to enhance water entry and to stabilize the structure of the surrounding soil material.
Field ditch	A graded ditch generally crossable with field equipment for collecting excess water from a field. A shallow channel, usually constructed with relatively flat side slopes that collects surface water within a field.
Geotextile	A woven or non-woven fabric of synthetic polymer fibres used to enhance soil properties or to improve structural performance
Grade or grade line	The degree of slope of a channel or natural ground.
Grade Stabilisation Structure	Hydraulic structure used to control the grade and head cutting in natural or artificial channels.
Groundwater	Water occurring in the zone of saturation in an aquifer or soil.
Groundwater Table	The groundwater table is the upper limit of the zone of total saturation in an aquifer.
Hydraulic Conductivity	The ability of a porous medium to transmit a specific fluid under a unit hydraulic gradient; a function of both the characteristics of the medium and the properties of the fluid being transmitted (usually a laboratory measurement corrected to a standard temperature and expressed in units of length/time).
Hydraulic Gradient	Change in the hydraulic head per unit distance (water surface slope in an open channel).
Impermeable Barrier/layer	A soil stratum with a permeability less than ten percent of the soil permeability between the layer and the ground surface.

Infiltration	The flow or movement of water through the surface into the soil body or ground either when it falls as rain, or when applied as irrigation, or from a stream flowing over the ground
Infiltration Rate	The quantity of water that enters the soil surface in a specified time interval (often expressed in volume of water per unit of soil surface area per unit of time).
Inspection well	Opening to surface in drain line to permit observation of flow conditions.
Interceptor line or drain	Surface ditch or subsurface drain, or a combination of both, designed and installed to intercept flowing water. Also, a line used to intercept several lines to keep the number of crossings at highways and similar locations to a minimum (also called collector lines).
Irrigation and Water	Water management is the activity of planning, developing distributing
Management	and optimum use of water resources under defined water policies and regulations
Junction	Point of intersection of two or more surface ditches or subsurface drains.
Land Smoothing	Is the process of producing a plane land surface with a continuous slope. Shaping the land to remove irregular, uneven, mounded, broken, or jagged surfaces without the need for detailed survey information.
Land grading	The operation of shaping the land surface to predetermined elevations for improved surface drainage or erosion control (also known as precision land forming).

Lateral	Secondary or side channel, ditch, or conduit that conveys flow to a mainline.
Lateral ditch	Principal channel or ditch that conducts drainage water from the field ditches to an outlet channel.
Lateral drain	Secondary drain that collects excess water from a field
Main drain	A principal drain which conveys drainage water from lateral drains and sub-mains to an outlet.
Manning's equation	An equation developed by Manning to relate flows in conduits to their size, shape, the gradient and the conduit roughness.
Outlet channel	Channel constructed primarily to carry water from manmade structures such as drain lines, surface ditches, diversions, and terraces.
Peak discharge	The maximum flow rate at a point in time at a specific location resulting from a given storm condition.
Perched Water Table	A localized condition of saturated soil held in a previous soil stratum because of an underlying impervious layer that prevents percolation to a deeper aquifer.
Percolation Rate	The rate at which water moves through a porous media, such as soil.
Permeability	The ease at which gases, liquids, or plant roots penetrates or pass through a layer of soil or porous media (qualitative). The specific soil property designating the rate at which gases and liquids can flow through the soil or porous media (quantitative).
Permittivity	A measure of the ability of a geotextile to permit water flow perpendicular to its plane. (The volumetric flow rate of water per unit cross-sectional area per unit head.)

Pipe A continuous length of non-perforated conduit typically used to protect an outlet or to provide additional structural strength.

Pipe drop inlet Type of surface water inlet, fabricated from pipe materials, which lowers surface water to a ditch bottom.

Precipitation The total measurable supply of water of all forms of falling moisture, including dew, rain, mist, snow, hail and sleet; usually expressed as depth of liquid water on a horizontal surface in a day, month, or year.
The process by which atmospheric moisture in liquid or solid state is discharged onto a land or water surface.

Pumping plant One or more pumps, power units, and appurtenances for lifting drainage water from a collecting basin to a gravity outlet.

Rainfall Event Single occurrence of a rainfall period before and after which there is a sufficient dry period to define its effect on the drainage system.

Rainfall Intensity The rate at which rainfall occurs expressed in depth units per unit time (mm/h).

Rational method A simple method, used throughout the world, for calculating the peak discharge.

Recharge Process by which water is added to the zone of saturation to replenish an aquifer.

Relief Drainage System A system of subsurface drain lines, installed within an area having a high water table, to lower the water table or maintain it at a given level.

Root Zone Depth of soil that roots readily penetrate and in which the predominant root activity occurs.

Run-off water	Means excess surface water resulting from rain
Seepage	The movement of water into and through the soil from unlined canals. ditches, or water control facilities
Slope	In relation to a specified portion of land on a farm unit, means the vertical difference in height between the highest and the lowest points of that portion of land, expressed as a percentage of the horizontal distance between those two points
Slot	Perforations in plastic tubing. Also, the opening in the ground created by the trenchless plow, as it lays the tubing.
Soil Erosion	The process that describes the detachment and movement of soil particles from the land surface by wind or water.
Soil Pores	Air spaces in the soil
Soil profile	A vertical section through the soil is called as the soil profile. The various distinguishable layer of soil that occurs are called horizons.
Soil Structure	The arrangement of soil particles into aggregates which occur in a variety of recognized shapes and sizes.
Soil Texture	Soil texture is a term commonly used to designate the proportionate distribution of the different sizes of mineral particles in a soil.
Soil Structure	The arrangement of soil particles into aggregates which occur in a variety of recognized shapes and sizes.
Spoil bank	Soil excavated from channel, ditch, or other site and placed along the excavation site.

Steady Flow	Open channel flow in which the rate and cross-sectional area remain constant with time at a given station.
Stretch	The increase in length of the tubing caused by tension forces during installation. It is expressed as a percent increase of the length prior to installation.
Sub irrigation	Application of irrigation water below the ground surface by raising the water table to within or near the root zone.
Submain	Branch drain off the main drain which collects discharge water from laterals or from the field.
Subsurface Drain	Subsurface conduits used primarily to remove subsurface water from soil. Classifications of subsurface drains include pipe drains, tile drains, and blind drains.
Surface Drainage	The diversion or orderly removal of excess water from the land surface by means of improved natural or constructed channels, supplemented when necessary by shaping and grading the land surface to such channels.
Sustainable Agriculture	Sustainable agriculture can be define as the form of agriculture aimed at meeting the food and fuel needs of the present generation without endangering the resource base for the future generations. It includes the study of Sustainable Utilization of Water Resources, Enhancing the Sustainability of Dryland Agriculture and Enhancing the Sustainability of Irrigated Agriculture.

Surface drainage — The diversion or orderly removal of excess water from the surface of land by means of improved natural or constructed channels, supplemented when necessary by shaping and grading of land surfaces to such channels. Surface drainage can be classified into two categories, depending on the topography of the land: Where ground slopes are flat (slopes less than 2 per cent), surface drainage is required to remove excess water that may cause waterlogging of the surface. Where ground slopes are steeper (slopes greater than 2 per cent), surface drainage is required principally for erosion control.

Surface Inlet — Structure for diverting surface water into an open ditch, subsurface drain, or pipeline.

Tile — Drains made of burned clay, concrete, or similar material, in short lengths, usually laid with open joints to collect and carry excess water from the soil.

Time of concentration — Time between the start of a runoff event and the time when the entire catchment is contributing flow to a specific point in the network.

Topography — A term used to describe the surface configuration of the land.

Tubing — A flexible drain that gains part of its vertical soil load-carrying capacity by lateral support from the surrounding soil.

Unconfined Aquifer — An aquifer whose upper boundary consists of relatively porous natural material that transmits water readily and does not confine water. The water level in the aquifer is the water table.

Watercourse — A natural or artificial channel for the passage of water.

Waterlogging The state in which soil is when it is totally saturated.

Water Table The upper limit of a free water surface in a saturated soil or underlying material

Water Table Management The control of ground water levels by regulating the flow of water with a controlled drainage or sub-irrigation system.

Watershed Total land area above a given point on a stream or waterway that contributes runoff to that point.

Waterway An artificial flow path constructed on land in order to carry away run-off water without causing excessive soil loss

Wetland The land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil.

3.4 Agricultural Drainage Classification

Figure 3-2 contains a classification of the various types of drainage systems. It shows the field (or internal) drainage systems and the main (or external) systems. The function of the field drainage system is to control the water table, whereas the function of the main drainage system is to collect, transport, and dispose of the water through an outfall or outlet. In Figure 3-2, the field drainage systems are differentiated in surface and subsurface drainage systems.

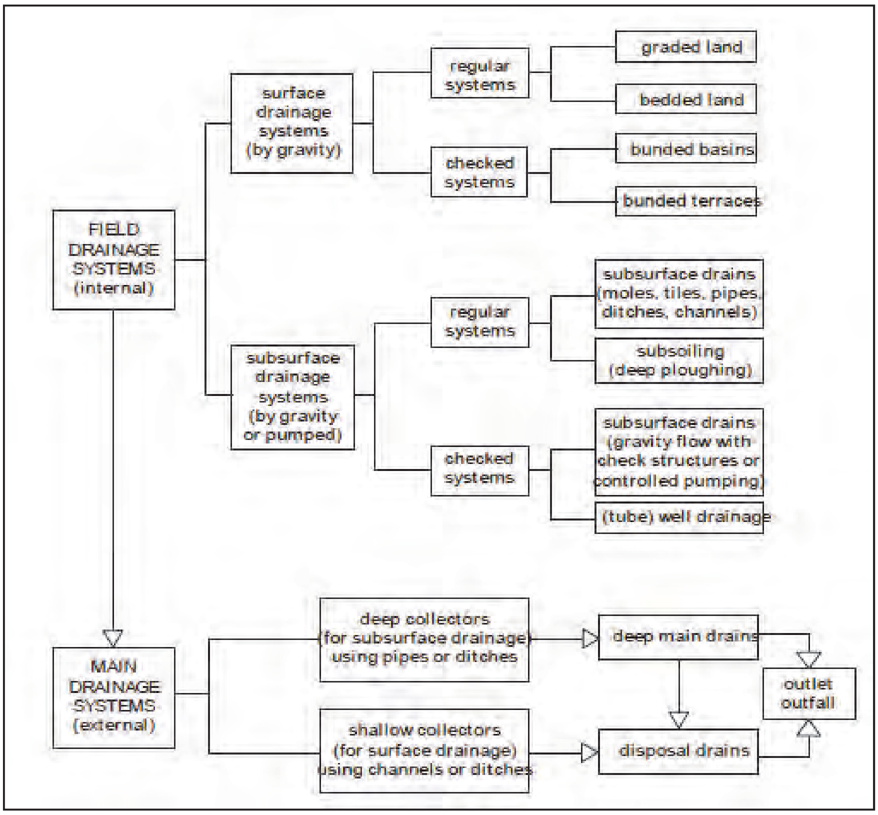


Figure 3-2: Classification of types of agricultural drainage systems (Oosterbaan, 1994)

The regular surface drainage systems, which start functioning as soon as there is an excess of rainfall or irrigation, operate entirely by gravity. They consist of reshaped or reformed land surfaces and can be divided into (Oosterbaan, 1994):

- Bedding systems, used in flat lands for crops other than rice;
- Graded systems, used in sloping land for crops other than rice.

The bedded and graded systems may or may not have ridges and furrows.

A checked surface drainage systems consist of check gates placed in the bunds surrounding flat basins, such as those used for rice fields in flat lands. These fields are usually submerged and only need to be drained on certain occasions (e.g. at harvest time). Checked surface drainage systems are also found in terraced lands used for rice (Oosterbaan et al., 1987, cited by Oosterbaan, 1994).

In literature, not much information can be found on the relations between the various regular surface field drainage systems, the reduction in the degree of waterlogging, and the agricultural or environmental effects. It is therefore difficult to develop sound agricultural criteria for the regular surface field drainage systems. Most of the known criteria for these systems concern the efficiency of the techniques of land levelling and earthmoving. Similarly, agricultural criteria for checked surface drainage systems are not very well known (Oosterbaan, 1994).

Like the surface field drainage systems, the subsurface field drainage systems can also be differentiated in regular systems and checked systems. When the drain discharge takes place entirely by gravity, both types of subsurface systems have much in common, except that the checked systems have control gates that can be opened and closed according to need. They can save much irrigation water (Qorani et al., 1990, cited by Oosterbaan, 1994). A checked drainage system also reduces the discharge through the main drainage system, thereby reducing construction costs.

When the discharge takes place by pumping, the drainage can be checked simply by not operating the pumps or by reducing the pumping time. In North-West India, this practice has increased the irrigation efficiency and reduced the quantity of irrigation water needed, and has not led to any undue salinisation (Rao et al., 1992, cited by Oosterbaan, 1994).

The subsurface field drainage systems consist of horizontal or slightly sloping channels made in the soil; they can be open ditches, buried pipe drains, or mole drains; they can also consist of a series of wells. The channels discharge their water into the collector or main system either by gravity or by pumping. The wells (which may be open dug wells or tube wells) have to be pumped, but sometimes they are connected to drains for discharge by gravity. In some instances, subsurface drainage can be achieved simply by breaking up slowly permeable soil layers by deep ploughing (sub-soiling), provided that the underground has sufficient natural drainage. In other instances, a combination of sub-soiling and subsurface drains may solve the problem.

Subsurface drainage by wells is often referred to as "vertical drainage", and drainage by channels as "horizontal drainage", but it is better to speak of "field drainage by wells", or "field drainage by ditches or pipes" (Oosterbaan, 1994).

The main drainage systems consist of deep or shallow collectors, and main drains or disposal drains (Figure 3-2). Deep collectors are required for subsurface field drainage systems, whereas shallow collectors are used for surface field drainage systems, but they can also be used for pumped subsurface systems. The terms deep and shallow collectors refer rather to the depth of the water level in the collector below the soil surface than to the depth of the bottom of the collector. The bottom depth is determined both by the depth of the water level and by the required discharge capacity.

The deep collectors may either discharge their water into deep main drains (which are drains that do not receive water directly from field drains, but only from collectors), or their water may be pumped into a "disposal drain". Disposal drains are main drains in which the depth of the water level below the soil surface is not bound to a minimum, and the water level may even be above the soil surface, provided that embankments are made to prevent inundations. Disposal drains can serve both subsurface and surface field drainage systems. Deep main drains can gradually become disposal drains if they are given a smaller gradient than the land slope along the drain. The final point of a main drainage system is the gravity outlet structure or the pumping station.

The technical criteria applicable to main drainage systems depend on the hydrological situation and on the type of system (Oosterbaan, 1994).

3.5 Application of agricultural drainage systems

Surface drainage systems are usually applied in relatively flat lands that have soils with a low or medium infiltration capacity, or in lands with high-intensity rainfalls that exceed the normal infiltration capacity, so that frequent waterlogging occurs on the soil surface (Oosterbaan, 1994).

Subsurface drainage systems are used when the drainage problem is mainly that of shallow water tables. When both surface and subsurface waterlogging occur, a combined surface/subsurface drainage system is required. Sometimes, a subsurface drainage system installed in soils with a low infiltration capacity and a surface drainage problem improves the soil structure and the infiltration capacity so greatly that a surface drainage system is no longer required (De Jong, 1979, cited Oosterbaan, 1994). On the other hand, it can also happen that a surface drainage system diminishes the recharge of the groundwater to such an extent that the subsurface drainage problem is considerably reduced or even eliminated.

The choice between a subsurface drainage system by pipes and ditches or by tube wells is more a matter of technical criteria and costs than of agricultural criteria, because both types of systems can be designed to meet the same agricultural criteria and achieve the same benefits. Usually, pipe drains or ditches are preferable to wells. However, when the soil consists of a poorly permeable top layer several metres thick, overlying a rapidly permeable and deep subsoil, wells may be a better option, because the drain spacing required for pipes or ditches would be very narrow whereas the well spacing can be very wide.

When the land needs a subsurface drainage system, but saline groundwater is present at great depth, it is better to employ a shallow, closely spaced system of pipes or ditches instead of a deep, widely spaced system. The reason is that the deeper systems produce a more salty effluent than the shallow systems. Environmental criteria may then prohibit the use of the deeper systems.

In some drainage projects, one may find that only main drainage systems are envisaged. The agricultural land is then still likely to suffer from field drainage problems. In other cases, one may find that field drainage systems are ineffective because there is no main drainage system. In either of these cases, the installation of drainage systems is not recommended (Oosterbaan, 1994).

3.6 Agro-Economic Effects of Drainage

Research dealing with the effects of soil drainage on corn yield levels, yield variation and date of planting is limited and results are frequently site-specific. Therefore, although the following studies indicate the likely benefits from drainage improvements, local experience and yield records should be used to verify these results (Nolte et al., 2010).

3.6.1 Effects on yield level and variability

Drainage improvements on poorly drained soils often result in substantially higher corn yields. Long-term experiments in north central Ohio on Toledo salty clay, a very poorly drained soil, have compared surface drainage only, tile drainage only, and a combination of surface and tile drainage on replicated plots (1). Average yields over 13 years were 92 (2.3 ton), 116 (2.9 ton) and 121 (3 ton) bushels per acre for the surface only, tile only and surface plus tile drainage systems, respectively, versus 60 bushels per acre (1.5 ton) on the undrained plots.

These same Ohio studies show that drainage improvements also tend to lessen variability in yields. Over the 13 years, there was 18 percent yield variation from year-to-year on the tile-drained and combination tile-and surface-drained plots compared to a 33% variation on the surface-drained plots and 46 percent on the undrained plots.

A 3-year experiment in southwest Ohio on Clermont silt loam, a "fragipan" soil, found that shallow (18 inches – 45 cm deep) subsurface drains together with good surface drainage can significantly improve corn yields. In fact, drainage improvements are essential to obtaining high yields with no-till practices on this poorly drained soil (2). In this experiment, average yields were 158 bushels (3.95 ton) per acre within 10 feet (3 meters) of the subsurface drains but only 140 bushels (3.5 ton) at a distance of 40 feet (12 meter) from the drains.

Drainage improvements are also likely to accentuate the yield benefits of irrigation on soils with low water-holding capacity in the root zone. A 5-year experiment in south central Illinois on the Cisne soil association, a claypan soil, showed that corn yields increased 15 bushels (0.375 ton) per acre in response to drainage improvements alone and 38 bushels (0.95 ton) per acre in response to irrigation alone (3). But where irrigation was applied to drainage-improved claypan, yields increased 78 bushels (1.95 ton) per acre-nearly double the no-treatment plot yields (Nolte et al., 2010).

3.6.2 Effects of timeliness of planting

Frequently, because of excess soil moisture planting must be delayed, which can significantly reduce corn yields. For example, long-term Ohio studies indicate that the optimum corn planting date is May 7 for Wooster and one day earlier each 10 miles south of Wooster which means April 23 for Portsmouth, Ohio. Date-of-planting studies at Columbus, Ohio, found that average yields decrease 0.2 percent per day for corn planted between April 8 and May 7, 0.6 percent per day when planted from May 7 to May 29, and 1.8 percent per day for May 29 to June 23. Similar North Carolina data suggest decreases of 0.87 percent per day for corn planted April 20 to May 30 and 1.86 percent per day after May 30 in that state.

Drainage improvements can speed up the drying rate for poorly drained soils, adding perhaps 2-3 field working days in May during wet years in Ohio. This would permit 4-9 calendar days earlier planting, since only about one-third of the month is suitable for field work in wet years (Nolte et al., 2010).

3.6.3 Predicting yield response to drainage improvements

Corn yield response to soil water stress can be predicted if one knows (a) the planting date and (b) the effects of both excessive and deficient soil moisture. The prediction (often called a yield index) is based on a stress-day index, certain crop susceptibility factors and soil water conditions. Yield indexes have, in turn, been used to predict the average annual net profit from corn production (Nolte et al., 2010).

3.7 Field drainage systems and crops production

To obtain a quantitative insight into the effects of drainage on agriculture, experiments can be performed with varying drainage designs and measure the corresponding crop production. The engineering factors depend on the type of drainage system involved and some of the engineering factors are specified in Volume 3.

Table 3-1: Examples of engineering factors by type of drainage system (after Oosterbaan, 1994)

Type of Drainage System	Engineering Factor
Subsurface drainage system	Depth, spacing and dimensions of ditches or pipe drains
Tubewell drainage system	Depth, spacing and dimensions of wells, pump capacity
Surface drainage system	Length and slope of fields, dimensions of furrows and bedding
Main drainage system	Depth, width, cross-section, and slope of drains, and spacing of the network

The effect of the engineering factors can be studied interactively (e.g. by using a range of drain spacings as shown in Figure 3-3), or by simply considering the "with and without" case (e.g. by comparing the crop production in drained and un-drained land as shown in Table 3-2).

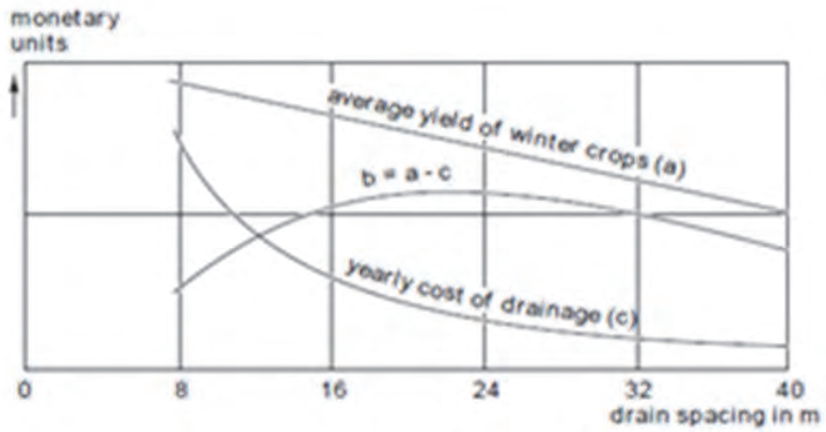


Figure 3-3: Example of Relation a showing net benefit (b) of winter crops as a function of drain spacing in a 60% clay soil in Sweden (Eriksson, 1979)

Table 3-2: Annual maize production (t/ha) with and without field drainage systems and different doses of N-fertilizer (after Schwab et al., 1966)

Type of drainage system	N fertilizer (kg/ha)		
	0	100	200
Subsurface field drainage system	3.7	5.9	7.0
Surface field drainage system	3.5	5.1	6.2
Without drainage system	2.5	3.0	4.0

Many results of the with/without comparison have been published by Trafford (1972), Baily (1979), and Irwin (1981). The first author reviewed data from literature and also quotes cases of unsuccessful drainage systems. Found et al. (1976) studied the economic impact of several drainage systems in Ontario, Canada. Some of their conclusions are (Oosterbaan, 1994):

- The Benefit/Cost (B/C) ratios of drains varied from 0.1 to 20, which indicates that some of the systems are uneconomical and other systems are highly beneficial;
- Influential factors on the B/C ratio were:
- The productivity of the environment: poor soils and adverse climatic conditions decreased B/C ratios;
- Local initiative to take advantage of the drainage facilities: some farmers did not make the necessary additional investments;
- Quality of engineering: some drains were too elaborate and costly for their purpose;

- Despite its significance, little analysis of the full effects of drainage systems has been undertaken.

When a relationship between the engineering factors (e.g. from Table 3-1) and crop production is established in a certain area, as shown by Relation A in Figure 3-4, it has no validity for application elsewhere, because it depends on the area's pedology, climate, hydrology, topography, agronomic, and socio-economic conditions.

A more universal relationship between engineering factors and crop production can be sought by introducing additional factors into Relation A. In Figure 3-4, for example, the water table regime is used as an additional intermediate factor, so that Relation A is divided into Relations B and C.

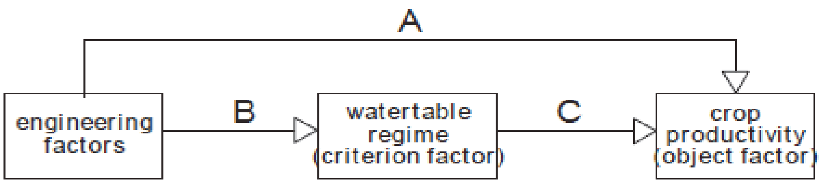


Figure 3-4: Relation A is divided into Relations B and C by means of the water table regime (Oosterbaan, 1994)

Relation B represents a direct effect of a drainage system. It is entirely a hydraulic function and lends itself to the development of generalized drainage formulas. These formulas have more than local value because they include parameters to represent natural conditions such as recharge and hydraulic conductivity explicitly in their formulation. A difficulty is still to survey and correctly assess these parameters, because of their wide variation in time and space.

Relation C represents an indirect effect of a drainage system. This relationship is very site-specific and is therefore not universally applicable. A more universal applicability can be obtained by dividing Relation C into other relationships with the help of the proper additional factors. This, however, leads to complicated interactions and therefore constrains practical application. Hence, the establishment of empirical relationships of the C-type remains a necessity in any region where a drainage project is proposed.

Implementing and operating a drainage system can have far-reaching effects, not only on the crop production but also on the total cropping system of an area. This is illustrated in Figure 3-5, which shows profound changes in the cropping pattern in England and Wales after drainage systems had been introduced.

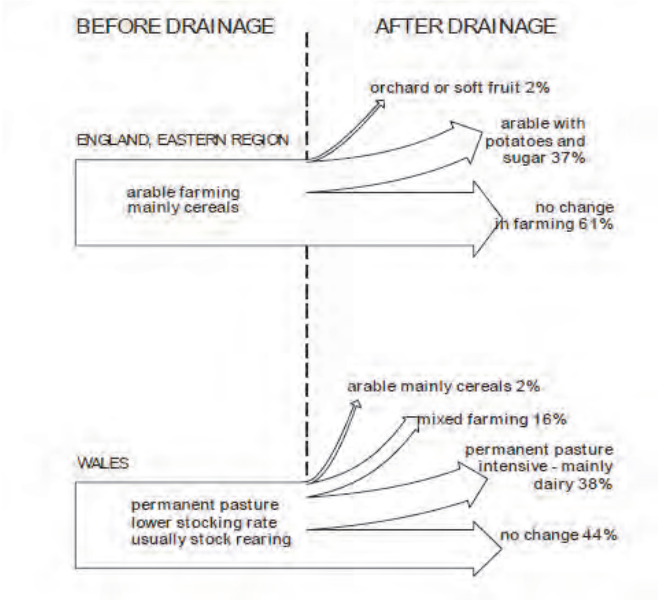


Figure 3-5: Changes in cropping pattern as a result of drainage (FDEU 1972)
(Source: Oosterbaan, 1994)

3.8 Potential environmental concerns

The major concerns related to drainage are (US Environmental Protection Agency, 2012):

- loss of wetlands, and
- increased loss of nitrate through tile drains.

3.8.1 Wetlands

Much of the Midwest landscape (USA) consisted of wetlands before large-scale drainage began in the 19th century. Although enormous public health and economic benefits have resulted from the draining of these wetlands over the last 150 years, there have also been negative impacts on the environment. Wetlands have an important hydrologic function in regulating water flow and maintaining water quality, as well as providing habitat for water-based wildlife. Recognition of their value has changed the way our society thinks about and protects wetlands.

Drainage improvements today are rarely for the purpose of converting existing wetlands to agricultural production. Improved drainage is usually aimed at making existing agricultural land more productive. Some fields have drain tiles that were installed 100 or more years ago, and are broken or plugged. In many fields, only a few of the wettest spots were originally drained, while the entire field would benefit from improved drainage. More tiles are often added to improve drainage efficiency, with the goal of increasing production (US Environmental Protection Agency, 2012).

3.8.2 Water quality

Drainage has both positive and negative effects on water quality. In general, less surface runoff, erosion, and phosphorus is lost from land that has good subsurface drainage than from land without drainage improvements or with only surface drainage.

Nitrate loss can be quite high from drained land. Because nitrate is very soluble, it flows easily through the soil and into tile lines. Nitrate flow from subsurface drains is one of the main sources of nitrate in streams and rivers in the Midwest. Concern about hypoxia, or low oxygen levels, in the Gulf of Mexico has increased concern about this nitrate source. Concentrations of nitrate in tile drains are usually quite high (10-40 mg/l).

Pesticides can also flow into subsurface drains, but usually only in very low concentrations. Pesticides move more easily in flow over the soil surface than through the soil, so the highest concentrations of pesticides in tiles are often in fields that have surface inlets into the drains. In fact, subsurface drainage may actually reduce pesticide loss to rivers and streams because it reduces surface runoff (US Environmental Protection Agency, 2012).

3.9 Analysis of Agricultural Drainage Systems

3.9.1 Objectives and effects

The objectives of agricultural drainage systems are to reclaim and conserve land for agriculture, to increase crop yields, to permit the cultivation of more valuable crops, to allow the cultivation of more than one crop a year, and/or to reduce the costs of crop production in otherwise waterlogged land. Such objectives are met through two direct effects and a large number of indirect effects (Oosterbaan, 1994).

The direct effects of installing a drainage system in waterlogged land are (Figure 3-6):

- A reduction in the average amount of water stored on or in the soil, inducing drier soil conditions and reducing waterlogging;

- A discharge of water through the system.

The direct effects are mainly determined by the hydrological conditions, the hydraulic properties of the soil, and the physical characteristics of the drainage system. The direct effects trigger a series of indirect effects. These are determined by climate, soil, crop, agricultural practices, and the social, economic, and environmental conditions. Assessing the indirect effects (including the extent to which the objectives are met) is therefore much more difficult, but not less important, than assessing the direct effects.

The indirect effects, which can be physical, chemical, biological, and/or hydrological, can be either positive or negative. Some examples are (Oosterbaan, 1994):

- Positive effects owing to the drier soil conditions: increased aeration of the soil; stabilized soil structure; higher availability of nitrogen in the soil; higher and more diversified crop production; better workability of the land; earlier planting dates; reduction of peak discharges by an increased temporary storage of water in the soil;
- Negative effects owing to the drier soil conditions: decomposition of organic matter; soil subsidence; acidification of potential acid sulphate soils; increased risk of drought; ecological damage;
- The indirect effects of drier soil conditions on weeds, pests, and plant diseases: these can be both positive and negative; the net result depends on the ecological conditions;
- Positive effects owing to the discharge: removal of salts or other harmful substances from the soil; availability of drainage water for various purposes;
- Negative effects owing to the discharge: downstream environmental damage by salty or otherwise polluted drainage water; the presence of ditches, canals, and structures impeding accessibility and interfering with other infrastructural elements of the land.

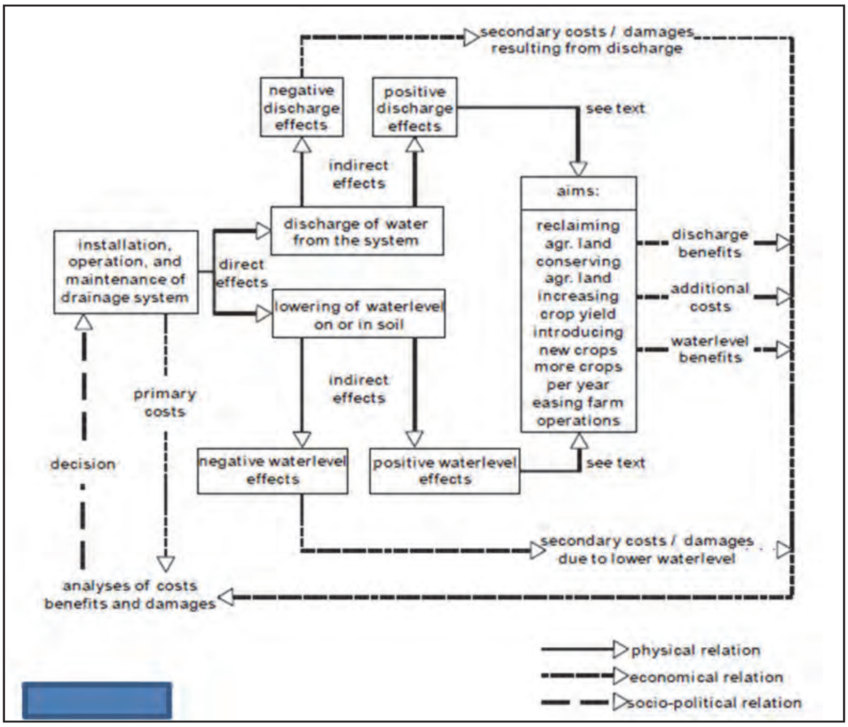


Figure 3-6: Diagram of the effects of drainage on agriculture and the economic evaluation (Oosterbaan, 1994)

Many of the indirect effects are mutually influenced and also exert their influence on the direct effects. For example, as a result of drainage, the following may happen:

- The more intensive agriculture increases the evapo-transpiration and consequently may reduce the discharge, unless this leads to an increased irrigation intensity;
- The more stable soil structure may increase the infiltration and the subsurface drain discharge, and decrease the surface runoff.

Both of the above effects sometimes neutralize each other so that the drain discharge is not appreciably affected.

The above considerations illustrate that, in developing agricultural drainage criteria, one needs a clear conceptual framework and a systems approach. Rules of thumb may be useful in the initial stages of reclaiming land by drainage, but subsequently a systematic monitoring program is required to validate or improve the criteria used with the aim, in the future, of avoiding ineffective and inefficient drainage systems and of mitigating negative effects (Oosterbaan, 1994).

3.10 Agricultural Criterion Factors and Object Functions

In agricultural drainage, agricultural, environmental, engineering, economic, and social aspects need to be considered.

The agricultural aspects concern "object factors" and "criterion factors". Object factors represent the agricultural aims (Figure 3-6) that are to be achieved to the highest possible degree (maximization) through a process of optimisation, yielding "agricultural targets" (see the insert in Figure 3-7). Optimising is done with criterion factors, which are factors that are affected by the drainage system and at the same time influence the object factors (Oosterbaan, 1994). Examples of criterion factors are the degree of waterlogging, the dryness or wetness of the soil, and the soil salinity.

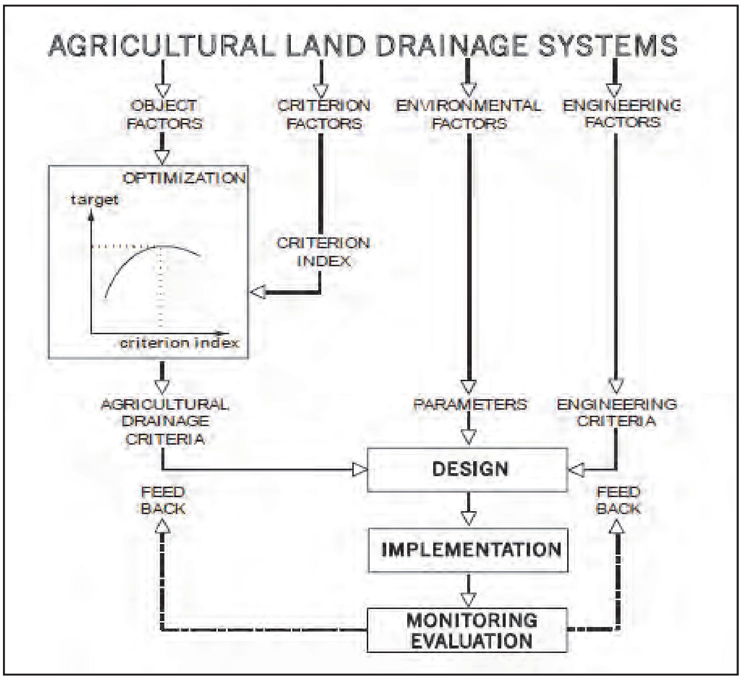


Figure 3-7: The role of agricultural, environmental, and engineering factors in the optimisation, design, and evaluation of drainage systems (Oosterbaan, 1994)

Owing to its variation in time and space, a criterion factor can be specified in different ways. A chosen specification can be called a "criterion index". Examples of such indices are (Oosterbaan, 1994):

- The average depth of the water table during the cropping season;
- The average depth of the water table during the off-season;

- The exceedance frequency of the water table over a critically high level;
- Seasonal average salinity of the root zone;
- Salinity of the topsoil at sowing time;
- Average, minimum, or maximum number of days that the soil is workable during a critical period.

The relationship between an object factor and an index can be called "object function of the index" and is also known as "response function" or "production function".

The optimisation procedure through the object function leads to a tolerance, or even an optimum, value of the index, which can be called an "agricultural drainage criterion". It serves as an instruction to the designer of the drainage system because it stipulates the agricultural condition the system must meet to be effective (i.e. to fulfil its purpose). Also, the instruction can prevent the design and implementation of a system that is unnecessarily intensive, expensive, and even detrimental (Oosterbaan, 1992).

"Environmental factors" are factors representing the given natural or hydrological conditions under which the system has to function. Examples of these factors are irrigation, rainfall, the soil's hydraulic conductivity, natural surface or subsurface drainage, topography, and aquifer conditions.

For design purposes, the environmental factors must be specified as "environmental indices", in the same way as the criterion factors are specified as criterion indices. Examples of environmental indices are the average seasonal rainfall, the extreme daily rainfall, the arithmetic or geometric mean of the hydraulic conductivity, and the variation in hydraulic conductivity with depth in the soil. Through a process of optimising the engineering aspects, the environmental indices yield "environmental parameters", which are fixed values of the indices, chosen as engineering or design criteria, in similarity to the agricultural criteria. Examples of such parameters are design values for rainfall, discharge, and hydraulic conductivity.

The engineering aspects include "engineering factors" and "engineering objectives". The objectives usually aim at minimizing the costs, and relate to the efficiency of the drainage system. A fully efficient drainage system fulfils the agricultural criteria at the lowest possible input level of materials and finances.

The engineering factors are factors representing the technical and material components of the drainage system (e.g. the layout, the longitudinal section and the cross-section of the drains, and the kind and quality of materials). The choice of the engineering factors is specified in the tender documents produced after the design has been completed.

Optimising the engineering aspects results not only in environmental parameters, but also in "engineering criteria". Both serve as instructions to the designer of the drainage system to secure an efficient design. The engineering criteria, which aim at minimizing costs can also be called "efficiency criteria", whereas the agricultural criteria, which aim at maximizing benefits can also be called "effectiveness criteria" (Oosterbaan, 1994).

After the design procedure has been completed, and before the drainage project can be offered for implementation, it has to be analysed on costs, benefits, and side effects. Through a survey of environmental factors, the agricultural criteria provide tools for an estimate of the drainage needs and the expected benefits. For example, with criteria specifying a minimum permissible depth of the water table and a depth-to-water table map, one can judge the extent of the drainage problems. With the response function, the expected benefits can also be estimated, assuming a drainage system is installed that meets the criteria.

Summarizing, one can say that the role of agricultural criterion factors and indices, and their object (production) functions, is threefold (Oosterbaan, 1994):

- They serve to assess the magnitude of drainage problems in hitherto un-drained lands and to predict the benefits of a drainage system;
- They serve to develop agricultural drainage criteria and instructions to the designer of the drainage system so that the system fulfils the agricultural objectives;
- They serve to check the (agricultural) effectiveness of a drainage system after its implementation and to assess the need for upgrading the system.

3.10.1 Soil Conditions and drainage

The process of drainage takes place by the movement of water over the land surface and through the soil profile. Therefore, the properties of the soil to transport water both horizontally and vertically are of major significance for drainage. Drainage is one of the possible crop-improvement or irrigation development practices and should not be considered in isolation. Other aspects of soil, such as soil texture, structural stability and salinity, strongly affect plant productivity, and need to be evaluated or studied in conjunction with drainage (Ritzema, 1994). According to Ritzema (1994), a soil survey is a prerequisite for planning and designing land-improvement projects, it provides a clear understanding of soil genesis, and of general and specific soil conditions that will be able to help an engineer in drainage planning process.

When a tract of land has a drainage problem and consideration is being given to improving that situation, a proper inventory and description of the existing drainage conditions first has to be made. The ways in which these conditions are affecting the present land use have to be understood. Subsequently, the factors that are causing the deficient drainage conditions have to be identified and understood properly (Ritzema, 1994). This section discusses the basic characteristics of soils and their related properties.

3.10.2 Soil Characteristics

This section discusses the basic soil characteristics, namely: soil texture, mineral compositions, physical and chemical characteristics of soil, and organic matter.

3.10.2.1 Soil texture

A soil consists of a skeleton of mineral particles with voids or pores, which contain air and water. Organic matter may be present as well, particularly in top soil layers. Mineral particles of soils vary widely in shape, size, mineral composition and surface-chemical characteristics (Stuyt et al., 2005). The particle size distribution of a soil, often referred to as soil texture, is an important indicator for soil structural stability. The classification of a soil is determined by the relative proportions of sand, silt, and clay in it. Textural classes of soils are as shown in Table 3-3. According to Ritzema (1994), this classification is in line with ISO (International Standardization Office).

Table 3-3: Particle size limits (after FAO-ISRIC, 1990; cited by Ritzema, 1994)

Soil particle size	**Size limits(diameter in mm)**
Clay	< 0.002
Fine silt	0.002-0.020
Coarse silt	0.020-0.063
Very fine sand	0.063-0.125
Fine sand	0.125-0.20
Medium sand	0.20-0.63
Coarse sand	0.63-1.25
Very coarse sand	I 1.25-2.00
Fine gravel	2.00-6.0
Medium gravel	6-20
Coarse gravel	20-60
Stones	60-200
Boulders	200-600
Large boulders	> 600

Soil texture is important because other properties, whether physical or chemical, are in many cases linked to it. For example, properties such as consistency, workability, water retention, permeability and fertility are related to soil texture. If the texture of the various layers of soil is known, some information on the soil’s physical properties and its agricultural qualities can be found (Ritzema, 1994). Texture alone cannot be used for indicating the structural stability of soils, this is because structural stability is not only dependent on the physical but also on the chemical properties of the soil (Stuyt et al., 2005).

3.10.2.2 Mineral compositions

There are two main groups of minerals: minerals in the sand and silt fraction, and minerals in the clay fraction. The mineral components which are present in the sand and silt fraction are determined by the soil's parent material and its state of weathering. Its composition determines the reserve of minerals available for plant use. Sand fraction is mostly composed of silica or quartz which is physically and chemically inert. The mineral components of the clay fraction consist of crystalline hydrous alumina silicates. In strongly-weathered tropical soils, crystalline and amorphous iron, aluminium oxides and hydroxides can be found. Hydrous alumino-silicates have a layered structure, they are composed of sheets of silicon oxide and sheets of aluminium hydroxide (Ritzema, 1994).

3.10.2.3 Physical and chemical characteristics of soil

Structural stability of a soil is affected by its salt and sodium content. In addition, cementing agents such as sands and silts are lime ($CaCO_3$) and sesquioxides (Al- and Fe-oxides). Lime precipitates around the contact points between soil particles. The binding capacity of Fe oxides is ill-defined, but Al-oxide is likely to be effective. Apart from these inorganic deposits, soil organisms and their organic by-products may also keep soil particles together. The chemical composition of a soil is quite relevant because of potential clogging of drainpipes and envelopes due to iron, lime and sulphate compounds (Stuyt et al., 2005).

Clays have pronounced physical and chemical properties because of two factors: a large specific surface area, and an electrical charge. The large specific surface area results from the platy or fibrous morphology of clay minerals whereas the electrical charge results from a process of isomorphic substitution when the clay minerals were being formed. During the isomorphic substitution, some of the silicon and aluminium ions in the crystal structure are replaced by cations of lower valency. Another factor that creates an electrical charge is the ionization of water on the aluminium sheets into hydroxyl (OH^-) groups. As a consequence, clay particles possess a negative charge at their surface, although some positive charges may occur at the edges of the sheets (Ritzema, 1994). Relative specific surface areas are as shown in Table 3-4.

Table 3-4: Specific surface area of various clay minerals (after Ritzema, 1994)

Clay mineral	Specific surface area (m^2/g)
Kaolinite	1-40
Illite	50-200
Smectite or montmorillonite	400-800

This negative surface charge is compensated by the adsorption of positively-charged cations like calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), hydrogen (H^+), ammonia (NH^{4+}), and aluminium (Al^{3+}). These cations are present in the so-called ‘diffuse double-layer between clay particles and their concentration is much higher near the surface of the clay particle than away from it (Ritzema, 1994). Evaluation of the risk of mineral clogging of drainpipes as a result of the chemical composition of the soil requires knowledge of the cation exchange capacity (CEC), salinity and sodicity of the soil (Stuyt et al., 2005).

3.10.2.4 Organic matter

Organic matter is that part of the soil that consists of organic carbon compounds or the material derived from the remains of living organisms (the remains of both plants and animals) (Ritzema, 1994). Organic matter has a stabilizing influence on the physical and chemical properties of soils, despite its generally modest quantity. It promotes the development and the stability of soil structure. The finer components of organic matter are converted into humus, as a result of their decomposition by micro-organisms. Like clays, humus is also a colloidal material. Its capacity to hold ions exceeds that of clay but clay is generally present in larger amounts. Hence, the contribution of clay to the chemical soil properties usually exceeds that of humus, except in very sandy soils (Stuyt et al., 2005).

Chemically, organic matter plays a role in extracting plant nutrients from minerals. The humus component of organic matter increases the CEC of the soil. In addition, there can be a fixation of nitrogen from the air by micro-organisms, which obtain their energy from decomposed plant tissue. In some cases, small amounts of organic matter can have a substantial effect on soil fertility, but it should be noted that a large amount of organic matter does not necessarily imply that the soil will have good characteristics. Peat is another form of organic matter. It is accumulated organic matter, and in most cases a large amount of it is not decomposed (Ritzema, 1994).

According to Ritzema (1994), a combined effect of a wet climate and poor natural drainage often results in the formation of peat because, under these conditions, the quantity of organic matter produced exceeds the quantity decomposed. By volume, peat soils have an organic-matter content of more than 0.50, muck soils have between 0.50 and 0.20, and organic soils between 0.20 and 0.15, and mineral soils less than 0.15 (organic matter as a fraction of dry solids) . Large organic-matter percentages are generally associated with a particular mode of soil formation. When organic matter has accumulated under conditions of poor drainage, the reclamation of such soils often creates problems, such as soil subsidence or a very low soil fertility (Ritzema, 1994).

3.11 Soil Properties

This section discusses the basic soil characteristics, namely: soil consistency, structural stability, soil colour, pore size distribution, cation exchange capacity, salinity and sodicity.

3.11.1 Soil consistency

Soil consistency refers to the behaviour of a soil at various moisture contents and largely depends on cohesion. Cohesion can be defined as the firmness of the bonds between soil particles (Stuyt et al., 2005). Consistency is related to the type of clay mineral and to the soil chemical status. The consistency is generally lower for coarse-textured soils than for fine-textured, lower for kaolinitic clays than illitic clays and lower for sodic than for non-sodic clays. Consistency may be useful in identifying sodicity (Ritzema, 1994).

There are two well-known plastic limits, the liguid and plastic limit. They are called atterbeg limits, their difference is called plastic Index. Plastic index indicates the firmness of the bonds between soil particles (Stuyt et al., 2005). The Plasticity Index (PI) represents the range of moisture content within which the soil exhibits the properties of a plastic solid. Also, it is a measure of the cohesive properties of the soil and indicates the degree of surface chemical activity and the bonding properties of the fine clay and colloidal fraction of the material (Vlotman et al., 2000). According to Ritzema (1994), the plastic index and soil texture are commonly used in engineering to characterize the soil. Sandy, clayey and silty soils are characterized as follows (Dierickx and Vlotman, 1995; cited by Vlotman et al., 2000):

For sandy soils: $PI < 15$

For silty soils: $5 \leq PI \leq 25$, and

For clayey soils: $PI > 15$.

The PI index can also be used to predict the sensitivity of a soil to mineral clogging of a drainpipe (Dieleman and Trafford, 1976; cited by Stuyt et al., 2005). The PI is interpreted as follows:

$PI < 6$: high tendency to siltation,

$6 \leq PI \leq 12$: limited tendency to siltation, and

$PI > 12$: no tendency to siltation.

3.11.2 Structural stability

The structure of a soil is the binding together of soil particles into aggregates or peds, which are separated from each other by cracks. Many wet soils and also all sandy soils, lack soil cracks and are thus structureless. Structural elements (i.e. the aggregates or peds) can vary in size from a few millimetres to tens of centimetres (Ritzema, 1994). Soil structure is conditioned by the soil texture, organic and other cementing substances, and the ratios between various cations that are present in the soil (Stuyt et al., 2005).

3.11.3 Soil colour

Soil colours are primarily due to coatings on the surface of soil particles. The colours can be described according to the Munsell Colour Chart or something similar. Colour depends on the nature of the parent material from which the soil was formed, on the drainage conditions and on the prevailing soil temperatures. Colour variation, whether between soils or within a soil profile, is a useful indicator in making a first assessment of general soil conditions. Well drained and poorly drained soils exhibit various colours. Well-drained soils are redder or browner than poorly-drained soils, which, under similar climatic conditions, are greyer. Black usually indicates that the soil possesses a substantial amount of organic matter, except in dark-coloured montmorillonite, which generally has low organic-matter content (Ritzema, 1994).

In tropical or subtropical regions, red indicates well-drained soils. Mottling, which is characterized by the presence of brownish/rusty and bluish/greyish spots is characteristic of soils in which the water table fluctuates. Brownish spots occur in the higher parts of layers that are alternately oxidized and reduced as a result of wetting and drying. Bluish/greyish spots occur in the lower part of the groundwater fluctuation zone. In the permanently wet zone, the mottles disappear and uniform grey colours prevail. Mottles are quite stable and often remain even when the drainage conditions have been improved. Therefore, care has to be exercised in interpreting mottles (Ritzema, 1994).

3.11.4 Pore size distribution

Big pore spaces between soils retain little or no water, but are very effective in conducting water under saturated or nearly saturated conditions (flooding or ponding rain). The opposite applies for small pore spaces, they retain water, and conduct water slowly. Part of the water in these pore spaces can be taken up by plant roots. When considering the size and the function of the pore spaces, a distinction can be made between micro-pores (3 to 30 pm diameter), meso-pores (30 to 100 pm diameter) and macro-pores (>100 pm diameter). A soil with an optimum pore-size distribution for plant growth has sufficient micro and meso-pores to retain water, and sufficient macro-pores to evacuate excess water (Ritzema, 1994).

Macro-pores are mainly created by soil fauna, so increasing the populations of soil fauna is one of the ways for improving the drainage conditions and aerating soils. The pore-size distribution is of great importance for the physical processes of transport in soil. It can be qualitatively assessed by visual observation in soil profiles. Macro-pores are visible to the naked eye, meso-pores are visible at a magnification, micro-pores are not visible, but their presence can sometimes be deduced from the faces of the aggregates (a rough surface indicating the presence of many micropores). No field methods are available for quantitative assessments of the pore distribution (Ritzema, 1994).

3.11.5 Cation exchange capacity

The cation exchange capacity (CEC) of a soil is defined as the amount of cations that can be adsorbed per unit mass (in cmol/kg or meq/l00 g). The higher the CEC, the more the soil solution is buffered against additions of particular cations, because an exchange of cations can occur between the soil solution and the exchange complex. A small CEC implies that small amounts of cations (e.g. hydrogen ions from plant roots) have a pronounced effect on the cation balance of the soil solution (Ritzema, 1994). The range in cation exchange capacity for three kinds of clays and organic matter is shown in Table 3-5.

Table 3-5: CEC of various clay minerals and organic matter (after Ritzema, 1994)

Component	CEC (meq/100 g)
Kaolinite	3-15
Illite	10-40
Montmorillonite	100-150
Organic matter	100-350

Kaolinite has a low CEC and organic matter a very high CEC, Soils that are characterized by kaolinite as the predominant clay mineral and the absence of appreciable amounts of organic matter, have a very low CEC. Such conditions are common in many tropical soils. Base Saturation (BS) refers to that part of the cation exchange capacity which is saturated with basic cations. The following equation is used to calculate BS.

$$BS=\frac{\gamma_{Ca}+\gamma_{Mg}+\gamma_{K}+\gamma_{Na}}{CEC}$$ Equation 3-1

where γ_{Ca}, γ_{Mg}, γ_{k}, γ_{Na}, refer to the amounts (in cmol/kg) of the exchangeable calcium, magnesium, potassium and sodium cations. Low values of the base saturation indicate intense leaching.

3.11.6 Salinity

The presence of soluble salts in the soil solution can affect plant growth, depending on the salt concentration and the susceptibility of the plant or crop. Except in cases of very high salinity where salt crystals can be readily seen, the presence of harmful amounts of salt in the soil is generally not observable to the eye (Ritzema, 1994). Various types of salts may be contained in the soil parent material (primary salinisation) or be transported dissolved in water and deposited after the soil has dried (Stuyt et al., 2005).

The major sources of secondary salinisation are salts added with the irrigation water and through capillary rise of groundwater, mainly if the ground water table is recharged by seepage. Salt contained in precipitation is negligible in comparison with the salt content of the irrigation water and the groundwater (Stuyt et al., 2005). In general, the accumulated salts in irrigated land are partly brought in by the irrigation water and partly by capillary rise of the groundwater (Lambert and Karim, 2002). Soil salinity is determined by measuring the electrical conductivity or salt concentration in soil-water extracts.

3.11.7 Sodicity

Sodicity refers to the presence of sodium (Na) ions on the exchange complex and in the soil solution. The soil aggregates become unstable when sodium ions are present and are likely to disperse. This unstable condition can cause open drains to collapse or cause siltation in the pipe drains. Other major effects are a reduction in soil permeability, a disturbance of nutrient equilibrium and toxicity to plants. Sodicity is usually expressed by the ‘exchangeable sodium percentage (ESP) or the sodium adsorption ratio (SAR) and is determined in the laboratory (Ritzema, 1994). SAR can be calculated by using the following formula (Stuyt et al., 2005):

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Ma^{2+}}{2}}}$$ Equation 3-2

ESP can be expressed in terms of SAR:

$$ESP(\%) = \frac{100(-0.0126\ + 0.01475SAR)}{1 + (-0.0126\ + 0.01475SAR)}$$ Equation 3-3

Within the range 2-30, SAR and ESP values are almost equal. Outside this limits, Equation 3-3 must be applied. High ESP or SAR values are usually an indication of poor physical soil conditions and high pH. Dispersion problems are generally more severe when the ESP or SAR values are greater. Dispersed material may be transported by groundwater and will enter the drainpipe. In general, under arid climates, problems are not experienced in soils with *ESP* values below 15 percent (Stuyt et al., 2005).

3.12 Water quality and soil salinity management

According to Volschenk et al. (2005), water quality is related to water quantity through leaching and should form a part of integrated water resource management. The national water quality management framework policy is therefore aligned with the National Water Act. Integrated water quality management comprises several facets, but water quality planning ultimately determines its principles of action. Catchment assessment studies continually serve to provide information regarding the physical and socio-economic cause-and-effect relationships underlying the principal water related problems in the WMA and its sub-catchments. Such studies enable the water quality manager to formulate a catchment water quality management strategy. The strategic management of water quality at the WMA and sub-catchment level is collectively governed through 19 Catchment Management Agencies (CMAs) now reduced to 9 CMAs. This is to facilitate alignment between Water Management Authority (WMA), or sub-catchments within a WMA, where water quality impacts on downstream-users. Such joint management of catchments is considered a necessity in the case of the Orange River which is the largest and most strategic water resource in South Africa.

Sub-surface outflow into the river systems contribute to the water quality and must be managed accordingly. Irrigation return flow constitutes an important part of the overall water balance of the Orange River and may be as high as 30% of water applied to the land (Volschenk, 2005). In comparison, urban and industrial return flows are minimal. Water quality of the return flow is generally poor. The magnitude and salinity of irrigation return flow to the river and canal systems, the extent and salt load of irrigation-induced recharge of groundwater, as well as the possible inflow of groundwater to surface water along the river are important factors dictating river salinisation, especially in arid areas. Both surface water degradation and salt retention are considered to be potential problems in the Lower Orange WMA which may impact on sustainability of agriculture.

In the study of Volschenk et al., 2005) they recommend that the management of water quality and salinisation in the lower Orange River area is achieved by determining the salinity status for soils that are being developed for the first time and deciding if installation of drainage is necessary. Installation of drainage can be recommended, but cannot be enforced. With regard to soil and land management, some soils are levelled by means of laser and restrictive layers removed during soil preparation. Irrigation efficiency varies and is influenced by irrigation scheduling (controlled and uncontrolled over irrigation) and use of different irrigation systems (flood, sprinkle and drip). Water quality is monitored at selected points in the river. Surface drainage from natural streamlets and disposal of subsurface drainage water (where, how, quality) were seen as specific problem areas. A drainage management plan for the area does not exist and surface and drainage water is canalized by means of the shortest and most economical route to the river.

3.13 Overview of Subsurface Drainage

The purpose of subsurface drainage is to lower the water table in the soil. The water table is the level at which the soil is entirely saturated with water. The excess water must be removed to a level below the ground surface where it will not interfere with plant root growth and development. Root growth requires air to be present in the soil. Both water and air need to be present in the spaces between the soil particles, often in equal proportions. If water fills all of these spaces (saturated), there is no room for air.

The consequences of irrigation development, which affect many irrigated lands worldwide, have not spared South Africa. The demand to feed South Africa's fast growing population, which has been projected at 54 million in the year 2014, has left The South Africa government with no choice but to increase crop production through irrigation. The total registered irrigated land in South Africa is 1.6 million ha. (Van der Stoep & Tylcote, 2014). Further to that, irrigation agriculture is the largest consumer of South Africa's surface water sources at 60% of total available water resources at an assurance level of 98% Department of Water and Sanitation in their National Water Resources Strategy (DWS, NWRS, 2013). This is because, 80% of the land in South Africa, lies within the semi-arid climate zone, which makes rain-fed crop production unfeasible in most areas.

Problems of rising water tables to the top soil (waterlogging) and the accumulation of salts within the upper soil layers (salinisation) are primarily irrigation induced in semi-arid climates, since the amount of precipitation received is not enough to provide for all the crop water requirements for the crop growing season. Freisem and Scheumann (2001) report that 500,000 ha of the total world‘s agricultural land are being lost out of production every year due to poor drainage. Thus, contributing to the reduced world food production level. Poor drainage problems in South Africa are reported to have reduced the crop production potential of about a quarter of the total 1.3 million ha of land under irrigation (Backeberg, 2000). Realizing the need for drainage systems in agricultural lands, the South African Government installed subsurface drainage systems on 54,000 ha of the total irrigated land and another 150,000 ha with surface drainage systems (Freisem and Scheumann, 2001). According to Singh et al*.* (2000) the need for subsurface drainage in irrigated lands cannot be over-emphasized as it has proved to be a sustainable and proven solution to both waterlogging and salinity problems. The ruin and demise of ancient Chaldea and the valley of the Tigris and Euphrates Rivers of Mesopotamia, which used to be fertile irrigated lands throughout history, are presently deserted lands. According to Luthin (1964), the demise of the two sites was a result of poor drainage, which leads to the accumulation of salts in the upper soil layers.

The design of drainage systems for agricultural lands could be considered tantamount to preventing salinity and waterlogging conditions. This would therefore mean that drainage requirements have to be predicted based on the excess water being supplied by the irrigation system. Skaggs (1990) describes the design of subsurface drainage systems in arid and semi-arid climates to be a highly complicated process due to the continuous variation in the behavior of the ground water table within a single irrigation season. The extensive research in drainage worldwide in the past years has led to the development of better means of designing and evaluating drainage systems in irrigated areas. Drainage models have been developed, e.g. DRAINMOD (Skaggs, 1978), WaSim (Oosterbaan, 2002), SaltMOD (Oosterbaan, 2002), to aid in the design of new drainage systems and evaluation of already installed drainage systems. The development of these hydrological models in drainage engineering has also lead to a better understanding of the soil system, which is regarded as one of the complex natural systems (Skaggs and Chestcheir, 1999; Bastiaanssen et al*.,* 2007).

Substantial improvement in the application of hydrological modeling in drainage design processes has occurred in other countries, where irrigation development has caused considerable degradation of agricultural land, e.g. Egypt and The Philippines (Freisem and Scheumann, 2001). The unavailability of literature in South Africa on the existence of drainage design criteria shows that drainage has not been fully addressed. Agricultural drainage is one of the viable water management techniques, which could make great improvements in the restoration of the productivity of agricultural lands. There is also lack of literature on the progress made in the application of hydrological models in drainage system management and design in South Africa, despite the successful stories these drainage models have had in countries where drainage problems were reported.

This document focuses on the need for drainage systems in agricultural lands to increase crop production on a sustainable basis. In volume 3, the theory of drainage in agriculture is reviewed to appreciate the need and benefits of improved drainage in agricultural lands. Hydrological simulation models, which aid in design and making timely decisions about the interaction of different water management systems, are presented in volume 3.

3.13.1 Theory of Agricultural Drainage

3.13.2 Drainage in agricultural lands

The extent of cultivated area worldwide is estimated at 1500 million ha, out of which about 390 million ha are said to be provided with sustainable water management systems, being irrigation, drainage, or both (Schultz et al*.,* 1999). They further report that even though drainage is perceived as a component of irrigation, only 22% of the 270 million ha irrigated worldwide is equipped with drainage systems despite notable improvements and successes in irrigation development in almost all countries. Frequently, irrigation technologies have been developed with an aim of increasing water productivity in irrigated agriculture, without considering drainage as one of the viable water management practices. There has been less emphasis made on the need to improve the drainage conditions in agricultural lands, especially in irrigated areas. Salinisation and waterlogging are still reducing the crop production potential of irrigated arid and semi-arid lands claiming 250,000-500,000 ha out of production every year (FAO, 2002). Agricultural drainage has the potential of contributing to crop production both under irrigated and rain-fed production (Martinez-Beltran et al*.,* 2007).

Optimum crop production from irrigated lands cannot be achieved on a sustainable basis due to the increasing salinity problems despite the need to increase the contribution irrigated agriculture makes to world food production. According to FAO (2006), irrigation currently contributes 40% of the total world food production and there is a need to increase its contribution to 50% by the year 2030. FAO (1997) and Urama (2004) report that environmental problems and the reduced crop yield being experienced in large scale irrigated areas is a result of lack of proper drainage. Installation and continuous evaluation of drainage systems would be a requirement in the revitalization of the already affected land and reduce further losses of agricultural land due to salinisation and waterlogging. Hirekhan et al*.* (2007) argue that if the world food production is to increase through irrigation to feed the ever growing world population, which is projected at 8 billion by the year 2025, drainage and irrigation improvement should be treated as single entity and inseparable water management systems.

Smedema and Rycroft (1983) and Luthin (1964) point out some of the adverse effects of poor drainage in agricultural lands to include: Impaired crop growth due to the imbalance on plant-air-soil-water relationship, which is caused by the rising water table to the crop root-zone; delays in performing essential farm operations, e.g. nursery bed preparation, weeding, spraying and harvesting; rising of soil salinity levels, which are toxic to crop growth; enhancing the prevalence of crop pests and diseases; poor germination rates as a result of lower soil temperature levels; and difficulties in accessing pasture lands. In order to prevent the above stated effects of poor drainage it is necessary to have a properly designed drainage system, based on site specific, developed drainage design criteria.

3.13.2.1 Need for drainage in agricultural lands

Water by itself is not harmful to crop growth. It forms one of the raw materials for photosynthesis and constitutes a substantial percentage to the plant biomass. The process of soil aeration forms one of the important determinants of plant growth and crop production (Evans and Fausey, 1999). Plant roots and soil micro-organisms require oxygen for respiration. In soils, where water table is within the top soil layers, the voids are filled with water. Thus, plant roots and soil micro-organisms can no longer respire aerobically. A prolonged deficient of oxygen in the soil leads to root rot and death of soil micro-organisms, which are essential in decomposition of crop residues.

Evans and Fausey (1999) define drainage as the practice of removing excess water from the land. They further describe drainage to have been an important water management practice for centuries, despite the slow adoption in agricultural areas. Drainage in agricultural land is aimed at improving crop production by providing favorable soil conditions for crop growth especially in areas where natural drainage is not capable of draining the excess water from the root zone, before the crop gets affected.

3.13.2.2 Status of drainage development in South Africa

South Africa lies in the semi-arid climatic zone and receives an average annual rainfall of 500 mm, which means that on average, farmers in South Africa cannot rely on rainfall alone as a sole source of water for crop production. In order to increase crop production to feed South Africa’s fast growing population, which has been estimated to reach 50 million by the year 2010 (Backeberg, 2000), the Government has, through the Department of Water Affairs, embarked on improving and promoting crop production through irrigation agriculture. The selection criteria for suitable land for irrigation in South Africa is said to be based on the potential of salinity hazard, i.e. if soils are of marine origin they are regarded as not suitable for irrigation development (DWAF, 2004; Freisem and Scheumann, 2001).

In South Africa, irrigation is the biggest single user of runoff (DWAF, 1993) in addition to being the biggest non-point pollution source, due to substantial return flows from irrigated lands into rivers. It is further reported that out of 1.3 million ha, irrigated in South Africa, 260,000 ha are affected by waterlogging and salinisation (DWAF, 2004). Though this is the case, DWAF (2004) further reports that the Government, through the Accelerated Shared Growth Initiatives for South Africa (AsgiSA) is aiming at increasing the current crop production tonnage from irrigated agriculture by 50% through the application of the following modalities; (i) increasing the water use efficiency of the irrigation systems, (ii) revitalization of the underused irrigation schemes/areas based on a sustainable and area wide planning approach, (iii) promoting small-scale irrigated agriculture for households and community-level food security through efficient irrigation technologies, and (iv) identifying new areas where irrigation development could be established.

The application of the above stated modalities does not guarantee increased crop production in South Africa through irrigation without sustainable preventive measures to waterlogging and salinity.

3.13.2.3 Causes of poor drainage

The objectives of drainage in humid and semi-arid climates vary considerably as has been explained in the previous section. Crop production in semi-arid climates is mainly through irrigation, while in humid climates is dependent on precipitation. Poor irrigation water management greatly affects the capability of the already existing subsurface drainage systems. Large volumes of water seeping through irrigation canals percolate down the root zone to recharge the groundwater. In a study which was conducted along the Breede River in South Africa, to investigate the effect of irrigation management on the control of potential irrigation losses and the resultant salinisation on the Breede River, Murray et al. (1993) found out that large volumes of drainage water occurred due to poor practices on irrigation scheduling. Table 3-6 shows the results of the study in which the high drainage losses were attributed to the low level of theoretical knowledge of the farmers about irrigation scheduling, which lead to over-irrigation and an increase in return flows. Increasing the irrigation efficiency can greatly reduce the return flows while at the same time increasing the water productivity of the whole irrigation system (Smedema and Rycroft, 1983).

Table 3-6: Observed irrigation efficiency as calculated for a 12 months period for an irrigation field along the Breede River in South Africa (Murray et al., 1993).

Crop/irrigation method combination	Irrigation depth (mm)	Actual depth of water drained		Water use efficiency (%)
		(mm)	% of irrig	
Vines/drip	435	181	41.6	56.8
Vines/micro	665	260	39.1	66.5
Vines/splrinkler	699	313	44.8	67.8
Vines/flood	507	371	73.2	64.1

It is believed that attention given to drainage improvement is less in South Africa and India (Table 3-7), despite the reported effects of poor drainage in irrigated lands. Currently the quality of irrigation water is continuously declining as opposed to the good quality water which was available through-out South African history. The emphasis has been on the proper selection of areas suitable for irrigation and the physiographical location of most irrigation schemes (DAWF, 2004). Though this is the case, further irrigation area expansion will not be possible in the near future in South Africa (Freisem and Scheumann, 2001), because the area has almost reached its maximum potential of 1.5 million ha.

Table 3-7: Irrigated and drained areas in some of the countries affected by salinity and waterlogging (Freisem and Scheumann, 2001)

Country	Area irrigated (ha)	Area drained (surface drainage) (ha)	Drainage % of total irrigated area (%)
Egypt	3,246,000	3,024,000	93
India	90,000,000	5,800,000	12
The Philippines	1,530,000	1,500,000	96
South Africa	1,500,000	150,000	10

3.13.2.4 Benefits of improved drainage in agricultural lands

Backeberg (2000) suggests that when planning to install a drainage system for an agricultural land, the designer should consider the benefits and costs the intended drainage system will have on the agricultural system. In the agricultural sector the benefits are normally reflected in the increase in yield which is a result of improved drainage conditions, improved field working conditions, decrease in the crop disease infection, which mostly comes due to the high water table conditions, and the improved workability of the soil.

Smedema and Rycroft (1983) indicate that drainage is one of the factors that determine the returns for a cropping system; the other factors being; cropping pattern, fertilizer application, irrigation, machinery use, management skills, etc. Conrad et al. (1999) estimate that soybean yield increases by half the normal harvest in a poorly drained area if the drainage condition is improved through the provision of subsurface drainage in irrigated areas. They further recommend a thorough assessment on the drainage needs so that the proposed drainage system should both be economically sound while at the same time optimizing the water table control for optimum crop production.

3.13.2.5 Drainage for salinity and water table control

FAO (2007) and Young (1999) indicate that drainage systems in arid and semi-arid irrigated climates should be capable of draining away the water percolating below the crop root zone. This ensures maintaining ground water levels which are not harmful to the crop while at the same time minimizing capillary salinisation to the crop root zone.

According to FAO (2007) drainage systems for irrigated areas should also be capable of lowering the ground water table within the shortest time possible in which the plant will not be negatively affected by the rising water table as a result of an irrigation application. At the same time, the drainage system in irrigated lands should be capable of maintaining suitable ground water levels in the rainy season when much of the recharge to the ground water is from the rainfall (Durnford and Hoffman, 1999). To make matters worse, rainfall in arid and semi-arid regions is in the form of intense storms of short duration. This result in the water table rising to its peak when the recharge to the ground water has already ceased (Skaggs, 1980; Gupa et al., 1993), a situation known as *unsteady state*. According to Smedema and Rycroft (1983) unsteady-state drainage conditions require many years of study of the ground water variation in response to rainfall or an irrigation application if the use of simulation models in the design and evaluation of the drainage system is to be avoided.

In humid climate zones, crop production is mostly done in spring, with winter being the off-season for crop production. Smedema and Rycroft (1983) mention that precipitation reaches 900 mm/year in winter season with insignificant evapotranspiration. They further state that the season with the most critical groundwater condition determines the criteria to be used in the drainage design presents one of basic drainage design criteria, which was developed and is commonly employed in the humid North West Europe. A criterion (Table 3-8) with a low hydraulic head to drainage discharge ratio (h/q) drains the soil much faster, since it results in a high water table drawdown per day. Thus, the criteria in Table 3-8 represent both water table-discharge and water table-drawdown criteria, consequently taking care of both steady and unsteady state conditions. Smedema and Rycroft (1983) report that under conditions of North West Europe, drainage systems with h/q = 55 to 100 generally ensure safe groundwater levels for crop production. Thus, preventing severe adverse effects on soil structure, nutrient availability and delays in agricultural operations in late winter/early spring.

Table 3-8: Basic design criteria for groundwater drainage in humid climate zone of North West Europe (Smedema and Rycroft, 1983)

Condition	**Drain discharge q (m/day)**	**Design water table depth z (m)**	**Hydraulic head h (m)**	**h/q (day)**
Low value crops (most grasslands)	0.007	0.30-0.40	0.60-0.70	85-100
Sensitive and high value crops	0.007	0.50-0.60	0.40-0.50	55-70
Average conditions	0.007	0.5	0.5	70

According to Horton and Kirkham (1999), it is necessary to maintain optimal physical conditions in the root zone during all growth stages of a crop, i.e. a good balance of air, water and temperature. With a well-designed subsurface drainage system, an attempt is made to avoid such periods of waterlogging and salinisation, in which the drainage system is designed so that at critical growing stages of the crop, the root zone is kept free of water logged conditions for most of the time. Ideally this would mean increasing the drain depth and hence increasing the construction costs and making the whole drainage project financially unsound. For this reason, Horton and Kirkham (1999) state that in irrigated areas, there is a close relationship between irrigation and drainage. It is necessary to determine the amount of drainage water to be removed by the subsurface drainage drains and how this is related to the irrigation amounts. In order to determine this relationship, it would demand a series of ground water monitoring (ASAE, 1999), which is expensive in terms of time and setting the observational field experiment under different drain depths and spacing. To overcome such a drawback, Skaggs and Chescheir (1999) point out that hydrological simulation models are reliable both in developing drainage design criteria and designing drainage systems (drain discharge, spacing and depth).

3.13.3 Drainage system design parameters

The success of a drainage system would be primarily based on how well the drainage system is maintaining suitable water table levels both in the crop growing and fallowing seasons, which according to ASAE (2003), is dependent on drain depth, spacing and the design water table depth of the drainage system.

The relationship which exists among the subsurface drainage design parameters could be well described using Figure 3-8, in which the drain depth (W), drain spacing (L), hydraulic head (h) at mid-point between two drain laterals, design water table depth (z) below the soil surface, depth to the impermeable layer (D), and daily drain discharge (q) from the drain lateral are all inter-related. Drain depth (W) is dependent on the crop root zone, soil properties and available installation equipment (ASAE 1999; 2003). For semiarid irrigated lands 1.5 m drain depth and a drain spacing of 50-80 m is suitable to provide for a good balance of plant-water-soil-air for most crops (Smedema and Rycroft, 1983; ASAE, 1999, 2003; FAO, 2007).

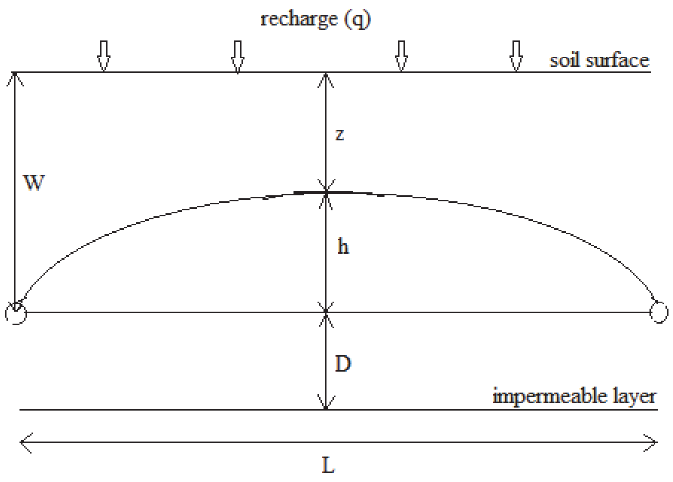


Figure 3-8: Main variables in groundwater drainage design (Smedema and Rycroft, 1983)

3.13.3.1 Drain depth

Determination of the drain depth (W) in the drainage design process of an irrigated land would have a direct effect on both the design water table level and drainage discharge. Depending on the soil type, shallow ground water levels would be expected where the drains are placed in shallow depths and wider apart, while deeper ground water levels are maintained when the drains are placed deeper and closer to each other. According to Skaggs (1980, 1999) the choice of the right drain depth and spacing is a function of severity of the drainage problem and the type of crop grown under such conditions. It is therefore necessary to realize the need for the optimization of the drainage system design parameters, i.e. design water table depth, drain depth and drain spacing both from the economic and technical point of views.

3.13.3.2 Drain spacing

ASAE (1999) recommends Donnan's steady-state equation (Equation 1) for application in determining drain spacing for humid climates, which does not truly reflect the ground water table variations in irrigated lands, which are more transient than steady-state ASAE (1999) recommends the US Bureau of Reclamation's transient flow method of determining drain spacing for unsteady-state conditions. It further points out the need for a thorough study of ground water level fluctuations in arid and semi-arid irrigated lands to be a requirement in order to establish the relationship of drainage discharge (q) and time (day), and water table depth (z) and time (day). Such relationships aid in determining suitable water table depth and daily drainage discharges to be met by the drainage system to maintaining lower water table levels suitable for crop grown.

$$L^2 = \frac{4K\left(b^2 + D^2\right)}{q} \qquad \text{Equation 3-4}$$

where: *L* is drain spacing, m; *K* is hydraulic conductivity, m/day; *D* is distance from drain depth to barrier layer, m; *b* is (D + h) as it is shown in Figure 3-8, which is the distance from maximum allowable water table height to the barrier layer, m; and *q* is recharge rate, m/day (precipitation or irrigation rate).

Derivation of Equation 3-4 is based on an assumption that only head losses due to radial flow to the drains are considered (Smedema and Rycroft, 1983). Head losses due to vertical flow are considered to be insignificant. Thus, a drainage system with parallel drainages ditches reaching the impermeable layer could generate the same discharge (q) for the same water table head (h). The soil hydraulic conductivity (k) and hydraulic head (h) determine the drainage discharge (q). Thus, for soils with lower hydraulic conductivities, the drain spacing (L) is in many cases smaller than drain spacing in soils with higher hydraulic conductivities at the same drain depth. Since (h) decreases towards the drain, (Figure 3-8), groundwater flow also decreases near the drain. Then it follows that, by reducing the drain spacing (L), a high drainage discharge (q) is expected with the same hydraulic head (h) between two drains.

Some hydrological simulation models which have been successful in the evaluation of existing drainage systems and the design of new drainage systems will be presented in the following chapter. Their data requirement and applicability to conditions similar to those of South Africa will also be assessed.

3.13.4 Drainage decision support tools

3.13.4.1 Hydrological modeling

The soil system is one of the highly complex natural systems due to greater variations and non-linear processes occurring within it (Wang et al*.,* 2006). Interestingly, crop production both under rain fed and irrigation is dependent on these processes, which require a good understanding of such processes in order to make effective decisions on water management systems. The soil exist both as saturated and unsaturated system at different times of the season, due to the variation of ground water table depth at different times of the season. According to Bastiaanssen et al*.* (2007) such complex systems can be well understood by the application of physical-mathematical models, which can be used to simulate the response of the soil system to changing parameters, e.g. recharge to the soil system and their effect on crop growth performance.

According to Bobba et al. (1995) the need for drainage guidelines and drainage design criteria for effective drainage operation under different site specific conditions, e.g. soil types, weather and management levels has driven intensive simulation model improvements. Presently, computer based simulation models are available and can effectively simulate the effect, which naturally occurring systems, e.g. rain fall and natural underground water flows would have on the performance of drainage systems. The models can also be used as design tools in determining subsurface drainage flows (q), design water table depth (z), optimum drain depth (*W*) and spacing (*L*). According to Haan and Skaggs (2003) and Wang et al. (2006) these hydrological models have enabled agricultural planners in making timely decisions about soil water systems which require many years of ground water monitoring, when at the same time it is extremely expensive to get such information through experiments. Bobba et al. (1995) and Wang et al*.* (2006) agree that drainage simulation models provide a better understanding of natural inter-related systems and help in making effective management decisions and planning of an agricultural production system. They further stress on the need for calibration and validation of the models under site specific conditions before the model can be fully applied as a support decision making tool.

3.13.4.2 Drainage modeling

Draining water from the soil profile is an important hydrologic component in most agricultural soils as it has already been cited from the previous chapters. Natural drainage process according to Wang et al. (2003), include; ground water flow to streams or other surface outlets; vertical seepage to underlying aquifers; or lateral flow (interflow), which may reappear at the surface at some other points in the landscape. Noria et al*.* (2007) states that artificial or improved drainage may be provided by installing drainage ditches or drain tubes in soils, where natural drainage seems not to be effective enough to enable crop production. One of the challenges in both irrigated and rain fed agriculture has been on how to answer the question: *how much to drain in order to sustain optimum crop yield?* The following sections will explain how such a question can be answered through the application of simulation modeling in drainage design process.

3.13.4.3 Drainage modelling in agriculture

The development of hydrological simulation models has increased quite significantly, since the 1970s, when researchers, drainage engineers and technicians recognized the need to optimize crop production with a better understanding of soil systems (Skaggs, 1999; Bastiaanssen, 2007). Since then, there has been an improvement in hydrological models and recent models can relate the effect of drainage on yield, nitrogen losses, etc. (Skaggs, 1999; Sarwar and Feddes, 2000; Feddes et al., 2004).

Despite the promising progress made and the steady growth in simulation model development, Bastiaanssen et al. (2007), suggests that the application drainage simulation models as water management decision support tools has not reached its optimum level in agricultural systems. They point some of the reasons, which have contributed to the slow adoption of simulation models in irrigation and drainage to be; (i) low education levels for most agricultural water managers and planners in using computer simulation models as decision support tools, (ii) the unavailability of the decision support tools to most middle level agricultural water managers, (iii) The natural belief in actual field measurement as opposed simulated results, and (iv) the absence of model calibration and validation agencies so that simulation models can be tested under local conditions before they can fully be used as decision support tools.

Having discussed some of the reasons which have contributed to simulation models not to be fully adopted in most agricultural lands despite their notable successes in predicting the drainage needs and its interaction with other water management systems, the following section will discuss further how simulation models have been applied in development of drainage design criteria for irrigated and rain fed agriculture.

3.13.4.4 Drainage design criteria and guideline development

SCS (1971) defines drainage design criteria as “the essential specifications for conditions which must exist in a particular area for a drainage system to have an optimum level of water table control, required by the agricultural system to be practiced either under irrigation or rain-fed.”

In view of the urgent need in drainage criteria development, Worksman and Skaggs (1989); Gupta et al. (1993); Breve et al. (1995, 1997) state that under such conditions, where timely decisions and cheaper means are required, drainage simulation provides for solutions as long as calibration and validation data are available. Skaggs (1990) points out that, simulation methods have been readily accepted and applied in other areas in the analysis and design of subsurface drainage systems, both in the humid and semi-arid conditions. He further argues that though traditionally the efforts of drainage researchers, engineers, technicians, and contractors have been aimed at one goal, which is to have a drainage system at a lowest cost possible. This has not materialized, because the design of subsurface drainage system is more of art and experience of the designer in handling similar problems. In arid and semi-arid regions, this may mean modification of the design and management of both drainage and irrigation systems at different times to consequently reduce both the drainage discharge and salt load in the drainage effluent.

Different simulation models which have been developed to simulate changes in soil water regime both under humid and arid/semi-arid conditions will be presented in the following sections. Though most of the models have already been calibrated and validated, it is emphasized to test the applicability of the models before they can be fully applied under specific conditions.

3.13.5 DRAINMOD model

DRAINMOD (Skaggs, 1978) is a hydrological model developed at the North Carolina State University (NCSU) in the department of Biological and Agricultural Engineering. The model is reported (Skaggs, 1980) to have been initially developed for analyzing field scale watershed management scenarios for poorly drained soils, but it has now been updated and used on both field- and watershed-scale management sites.

DRAINMOD model is one of the most widely applied of the water balance models in subsurface drainage system design (Skaggs, 1976, 1978, 1999; FAO, 2007), which uses functional algorithms to approximate the hydrological components of shallow water table soils. The model, according to Skaggs (1999), is capable of predicting hourly ground water fluctuations (h), drainage discharges (q) and drainage water salinity levels. He further reports that the model is based on the water balance of a unit soil sectional area, which extends from the impermeable layer to the surface and is located midway between parallel drains. The change in water pore space at any time increment (Δt) is a function of how much water is flowing into the unit soil as infiltration and flowing out of it through drainage, evapotranspiration and seepage. According to Skaggs (1999), the water balance for a time increment (Δt) may then be expressed as:

$$\Delta V_a = D + ET + DS - F \qquad \text{Equation 3-5}$$

where: ΔV_a is the change in the water free pore space or air volume, cm; D is the drainage from the section, cm; ET is the evapotranspiration, cm; DS is the deep seepage, cm; F is the infiltration entering the soil section, cm.

Skaggs (1999) gave the following discussion on the derivation of water balance models, which are based on conservation of mass. Precipitation (P) recharges the soil system and the soil is assumed to undergo no change in volume. Thus, the difference between water leaving and entering the system must be zero. Drainage (cm) from the soil is computed from the water table drawdown, which according to Skaggs (1999) constitutes the increase in free water pore space (ΔV), hence the water table drawdown. He further describes the computation of deep seepage to be based on the Darcy's empirical law, which states that "the volume of water flowing per unit time (q) is proportional to the cross-sectional area (A) corresponding to the flow and the hydraulic gradient (h)." Thus, deep seepage (DS) in equation 2 can be computed, knowing the coefficient of permeability (k) of the soil, which forms the proportionality constant in the Darcy's empirical law. Evapotranspiration (ET) being a function of weather conditions and the type crop can be estimated from crop coefficients and evaporation as recorded in weather stations (Smedema and Rycroft, 1983). Skaggs (1999) states that DRAINMOD estimates cumulative infiltration (F) from the Green Ampt model, a sub-model, which is incorporated in DRAINMOD model. He further states that cumulative infiltration is a function of soil infiltration rate (cm/hr) and precipitation duration (hours).

DRAINMOD model was primarily developed to simulate drainage performance and design in humid areas, where steady-state drainage conditions are quite common. Skaggs (1990) stresses that the model still gives simulated results which are agreeable with the observed results even in irrigated areas. However, Zaoh et al. (2000); Luo et al. (2001); Borin et al. (2000); Northcott et al. (2001); Helwig et al. (2002) pointed out that though DRAINMOD model have had successful stories in most of the areas as a drainage design supporting tool, the model can yield better results, if more site specific data is available.

3.13.5.1 DRAINMOD conceptual basics

According to Skaggs (1978) DRAINMOD assumes a one dimensional water balance or conservation of mass (whose derivation is described in section 4.3.2 and equation 2) in the soil profile, and uses long duration of weather data to simulate the performance of drainage systems. He further describe the model to have been developed to avoid complex numerical methods by using approximate methods in quantifying the hydrological components, e.g. subsurface drainage, sub irrigation, infiltration, evaporation (ET) and surface runoff. Subsurface drainage is computed using the one dimensional Hooghoudt's equation (Equation 3-6), which assumes an elliptical water table shape as measured at midway between two drain laterals. The soil profile above the water table is assumed to be drained to equilibrium with the water table (Smedema and Rycroft, 1983), so that recharge rate is equal to discharge rate from the soil system. Thus, a safe water table depth (z) to crop growth is maintained.

$$q=\frac{8\,k_2\,d\,h+4\,k_1\,h^2}{L^2} \qquad \text{Equation 3-6}$$

where: q is the drain discharge, m/day; L is the drain spacing, m; h is the head of water table midway between two drain laterals, m; k_1 and k_2 are the soil hydraulic conductivities for soil layers above and below the impermeable layer, respectively, m/day; d is the depth from the drain base to the impermeable layer, m.

The derivation of Equation 3-6 is similar to that of Equation 3-4, except that Equation 3-6 also assumes an equilibrium drainage discharge and recharge rate of the system. Flow of water to the drains is due to the available hydraulic head (h), in addition to the zero water potential at the drains *(sinks)*. Skaggs (1978) states that water movement below and above the water table is a function of soil hydraulic conductivity (k) as has been explained in Section 3.13.3.2. Thus, the flow of water to the drains in a soil with two layers of soil having different hydraulic conductivities will be different to the flow of water to the drains in a homogeneous soil. Equation 3-6 considers a drainage flow in a soil profile with different soil hydraulic conductivities below and above the drains.

3.13.5.2 Model data input requirements

In order to predict water table fluctuations (h) on hourly basis, subsurface drainage discharges (q), and the quality of the drained discharge, Skaggs (1978, 1980) report that the model requires data inputs such as; (1) weather data; hourly precipitation (or irrigation), minimum and maximum daily temperatures and the potential evapotranspiration, (2) soil data; the soil hydraulic conductivities (k) for the soil profile layers, the thickness of the soil horizons above the restricting layer; and (3) drainage system parameters; the drain spacing and depth for the existing drainage system.

The applicability of DRAINMOD model was tested in Iowa (Singh et al., 2006) for its suitability as a decision making tool in designing a subsurface drainage system in the area in which the model was calibrated and validated under site specific conditions. The model was tested under two soils; clay soils in Webster (WEBS-CC), where the whole field was grown with corn and on fine loamy soils in Canistero (CAN-CS), where corn-soybean were grown in rotation with other crops. The results of the experiment (Figure 3-9 a and b), showed a close agreement between the predicted and the observed results with coefficients of correlation of 0.88 and 0.89 for CANI-CS and WEBS-CC, respectively. The model was further used in simulating the impacts of varying drain depth and spacing on drainage discharge in the same area. It was found that a daily drainage discharge of 0.46 cm/day was sufficient enough to maintain suitable water table depth for most crops with drain depth and spacing of 1.05 and 25 m, respectively.

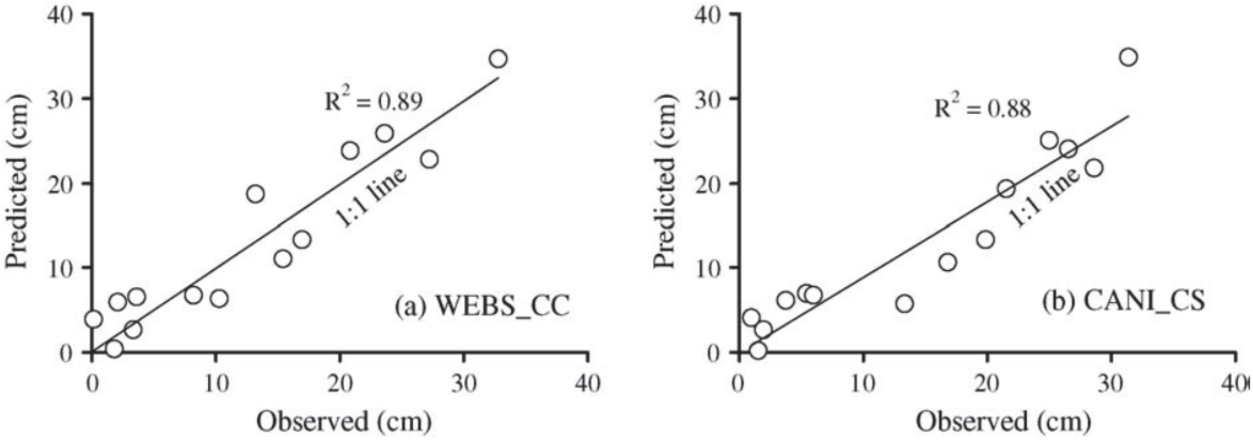


Figure 3-9: Observed and predicted subsurface drainage (cm) for WEBS and CANI in Iowa during the calibration and validation years of DRAINMOD model (Singh et al., 2006)

DRAINMOD was also applied in South-eastern Purdue Agricultural Center (SEPAC), USA, (Wang et al*.,* 2006) to optimize crop production in loamy-clay soil, by optimizing the subsurface drainage design parameters, i.e. drain spacing and depth. The model was simulated for drain spacing ranging from 5 m to 40 m. The results showed that a drain spacing of 25 m was ideal for the area to accommodate lower ground water levels with a minimum drain depth of 0.75 m. However Wang et al*.* (2006) concluded that though the predicted and observed results of the experiment showed a good agreement, there is a need to have long-term simulation runs of the model to yield suitable mean yield predictions with suitable mean drain depth and spacing which could guide in the whole subsurface drainage system design process.

3.13.5.3 Limitations on the use of DRAINMOD model

Skaggs (1980) stresses the importance of applying the model to conditions which are similar to those of the area to which the model was calibrated, i.e. humid conditions. They further points out that if the model is to be applied in performance evaluation of drainage systems in irrigated arid or semi-arid regions then the model has to be tested under such conditions before it can be fully put into use.

3.13.6 WaSim model

The WaSim model is also based on water balance model (Equation 3-5) and was developed by Cranfield University and HR Wallington to simulate changes in root zone soil water content and water table position in response to weather and water management. The model, according to Hess et al. (2000), uses a three layer soil water balance model to estimate the changes in soil water content on a daily basis taking into account inputs of rainfall (and irrigation) and out-put being evaporation and deep percolation (Equation 2). The deep percolation forms an input into a water table model, which then estimates the possible drainage needs under given rainfall or irrigation conditions.

3.13.6.1 Data input requirements

In order to successfully run the WaSim model, it requires a time series of daily rainfall and reference evapotranspiration data in addition to the crop, soil and the drainage system design parameters (drain depth, spacing and filter material).

3.13.6.2 Strength of WaSim model

WaSim model was tested, calibrated and validated in India and it gave satisfactory results in which the predicted and the observed results agreed quite well (Hirekhan et al., 2007). Figure 3-10 shows a comparison of observed to simulated results from the experiment in which WaSim model was tested for its applicability in designing of subsurface drainage system under semi-arid irrigated conditions of India. Hirekhan et al. (2007) concluded that the model appeared to be a simple and user friendly drainage design and management tool for semi-arid climates. Though the predicted and the observed results of the experiment conducted in India showed such a good agreement, Hirekhan et al. (2007) recommended to test the model for its suitability in conditions where it is to be applied. Thus, the need for calibration and validation of the model under site specific conditions due to great variation in site specific conditions, i.e. soil, weather, crop and drainage parameters

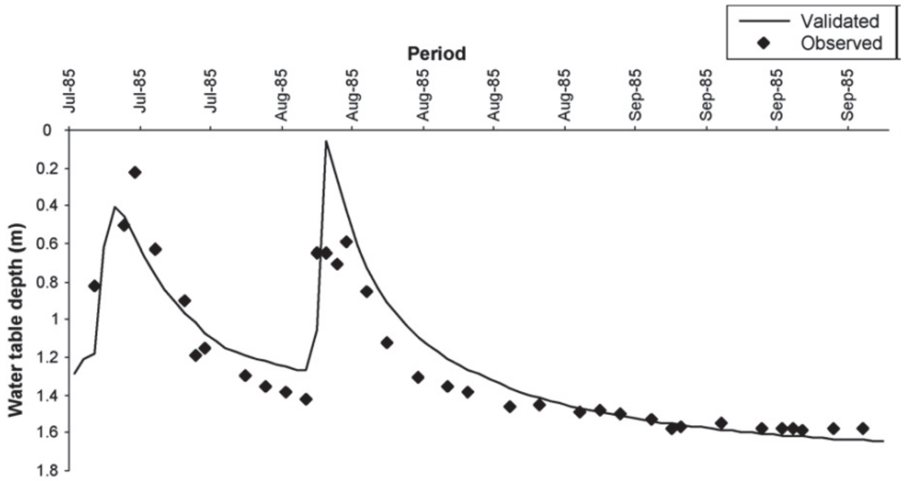


Figure 3-10: Observed and validated water table depth at Sampla in India during the validation runs of WaSim model (Hirekhan et al., 2007)

3.13.7 SaltMOD model

SaltMOD is a computer based model which was developed in The Netherlands to simulate ground water table variation, drain discharge and effluent quality for arid and semi-arid climates (Oosterbaan, 1998; Bahceci et al*.,* 2006). According to Bahceci et al*.* (2006) the model was developed to make long term predictions on effects of changing water management systems (including drainage) on ground water response.

3.13.7.1 Data input requirements

According to Oosterbaan (2002) SaltMOD model requires data inputs such as; duration of the crop season, soil properties, irrigation or rainfall, drainage criteria and system parameters, and the initial boundary conditions, i.e. water table depths at the beginning of the season and the salinity level of the irrigation/rainfall water. Unlike other models, e.g. WaSim and DRAINMOD models, which require scarce data inputs like the soil hydraulic conductivity, unsaturated soil moisture content and water tension which are highly site specific, the SaltMOD model, according to Oosterbaan (2002) requires a simpler data structure, which makes it relatively easier to be understood operated by agricultural water management planners.

3.13.7.2 Conceptual basics of SaltMOD model

The SaltMOD model is based on a water balance or conservation of mass approach (explained in Section 3.13.5 and Equation 3-5) whose principle is illustrated in

Figure 3-11 (Oosterbaan, 2002, Bahceci et al*.,* 2006), where four reservoirs representing the soil system are shown on which the model is built on, namely; surface reservoir, root zone, transition zone and the aquifer zone.

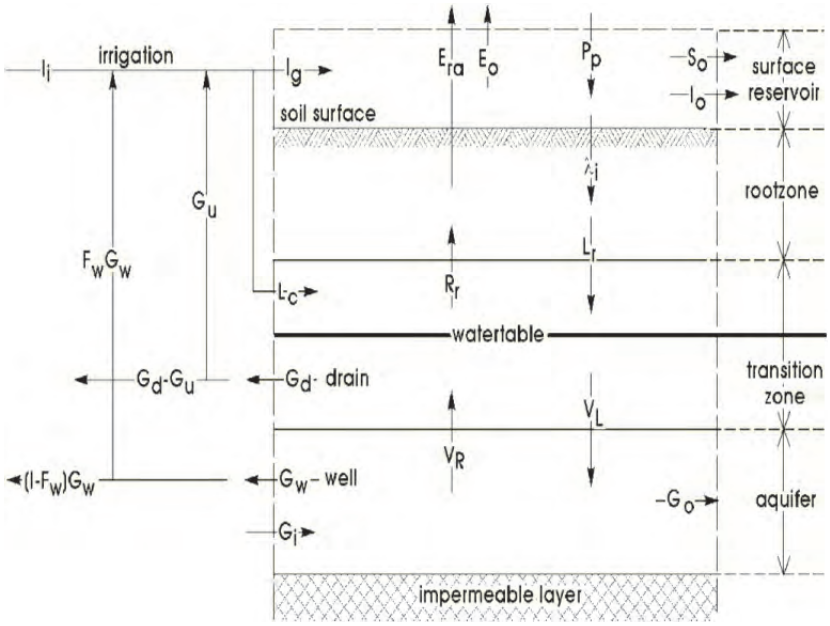


Figure 3-11: The concept of four reservoirs of SaltMOD model with the hydrological inflow and out flow component (Oosterbaan, 2002)

For each of the four reservoirs in Figure 3-11, a water balance or conservation of mass as described in Section 3.13.5 and Equation 3-5, can be made for each zone, which are then expressed as seasonal volumes per unit surface area to give a seasonal depth of water with dimension (L). Where: P_P is recharge due to precipitation mm/day, λ_i is the recharge due to infiltration (mm/day), L_c is the recharge due to irrigation (mm/day), L_r is the deep percolation from the root zone (mm/day), V_L the ground water contribution to the aquifer (mm/day), G_i is the lateral contribution to the aquifer (mm/day), E_o is the evaporation from surface water (mm/day), E_{ra} is the evaporation from the root zone (mm/day), S_o is the surface runoff (mm/day), G_d is the ground water drainage (mm/day), G_w is the aquifer contribution to a well (mm/day), V_R is the aquifer contribution to the ground water (mm/day), and G_o is the lateral outflow from the aquifer (mm/day).

3.13.7.3 Application of SaltMOD model

The model was applied in a variety of areas, e.g. in the coastal fields of Andra Pradesh, India (Sarangi et al*.,* 2006) and Konya-Cumra Plain in Turkey (Bahceci et al., 2006). SaltMOD model was used to simulate the effect of varying drain spacing and depths on the amount of drainage water, root zone salinity and depth of water table in the Konya-Cumra Plains. The simulation results of the experiment showed that the problem of salinity was not severe in the tested area as compared to problem of high water table levels. It was concluded that drain depth and spacing of 1.2 m and 100 m respectively were ideal in controlling high water table levels due to irrigation as compared to the previous drain spacing and depth of 100 m and 1.5 m respectively.

3.14 Overview of Surface Drainage

3.14.1 Introduction

Agricultural surface drainage may be defined as the removal of excess water from the surface of a cultivated field or from the root zone of the crops in that field and in particular it can be best described as:
"The diversion or orderly removal of excess water from the surface of the land by means of improved natural or constructed channels, supplemented when necessary by shaping and grading of the land surface to such channels" (ICID 1982)

Surface drainage applies primarily on flat land where in combination with any of the factors such as slow infiltration, low permeability, restricting layers in the soil profile or shallow soil covering rock or deep clays, prevent the ready percolation of rainfall, runoff, seepage from uplands, or overflow from streams through the soil to deep stratum.
A surface drainage system needs to be designed to remove excess water at a rate which will prevent long periods of standing water so that crops with have optimum conditions for growth and minimise the risk of flooding without excessive soil erosion. The design capacity of drainage systems therefore depends on several interrelated factors including rainfall patterns, soil characteristics and the type of crop grown.

3.14.2 The need for drainage

The two main reasons ensuring the effective drainage of cultivated lands are for soil conservation and for the improvement and safe guarding of crop yields. In particular a key element of surface drainage improvements is to reduce crop damage in the growing season from water ponding on the surface of the field from excess rainfall. Excess rainfall is that portion of the rainfall that is in excess of what the agricultural plants can use for growth. This excess rainfall, if it remains on the crop field, will first damage, then destroy, the agricultural crop, by severely reducing the amount of free air oxygen that is absorbed by the roots of the crop plants. Artificial agricultural drainage provides for the draining away of the excess rainfall which ponds on the crop fields. Secondary agricultural benefits which occur when the water table is lowered by some desirable amount include increasing the depth of the root zone and making a greater percentage of the soil nutrients available to the plant. The growth of beneficial soil bacteria is promoted and soil temperatures are increased. Proper drainage also produces soil conditions more favourable for conducting farming operations. An example of how poor drainage can impact on a farming operation is shown in Figure 3-12.

Figure 3-12: An example of poor drainage in an agricultural context (http://www.extension.umn.edu/agriculture/water/agricultural-drainage-publication-series/)

3.14.3 Reasons for poor natural drainage

Excessive surface water natural drainage can occur for two main reasons:

(i) The land is so flat that the rainfall runoff occurs very slowly.

(ii) There are no natural streams capable of removing the runoff from a rainfall event in a timely manner.

In addition to the above, any of the following factors may contribute to the excessive accumulation of water on the surface of the land as outlined below: fine soil texture, massive soil structure, low soil permeability, topography, soil compaction, restrictive geologic layer, excess precipitation are the various factors which may in part or in combination contribute to poor drainage.

Soil Texture – The sand, silt and clay composition of the solid mineral particles of a soil is referred to as soil texture. Soil texture has a dramatic effect on how well the soil retains water and the ease with which water can move through the soil. Fine textured soils have a large percentage of clay and silt particles which generally hold water well but drain poorly. On the other hand coarse textured soils have a large percentage of sand or gravel particles which generally drain well but have a poor water holding capacity.

Soil Structure – The physical arrangement of the solid mineral particles of a soil is referred to as the soil structure. A soil with a granular structure will promote the movement of water whereas a structure that is massive (lacking any distinct arrangement of soil particles) will impede the movement of water.

Permeability – The relative ease with which water can move through a block of soil is described as soil permeability.

Topography – The shape and slope of the land surface can cause wet soil conditions, especially around depressions where water tends to accumulate. If there is no natural outlet the water will drain away very slowly.

Geological Formation – The geological formation underlying a soil can dramatically impact the drainage of water from the land even the soil possesses textural and structural properties that are beneficial to the movement of water. If the geologic formation underlying such a soil consists of dense clay or solid rock, it could restrict the downward movement of water, causing the soil above the formation to remain saturated during certain times of the year.

Compaction – Human activities also contribute to excessive soil water problems. For example, operating equipment on a wet soil can compact the soil and destroy its structure. A soil layer that is compacted will generally have no structure since most of the voids in this layer will have been eliminated. Voids are open spaces between soil particles that can be filled with air, water or a combination of both. Soil water will tend to accumulate above the compacted layer because movement of water through the compacted layer is severely restricted. If the compacted layer is located at the soil surface, very little water will enter the soil and much of the water will runoff, potentially creating a flooding and/or erosion hazard.

Precipitation – Excessive rainfall events often cause ponding of water on the soil surface especially if the soil is saturated prior to rainfall occurring. The nature of the rainfall event also has an effect since intense rainfall associated with thunderstorm activity will frequently result in runoff because the rainfall intensity is greater than the infiltration rate of the soil.

In order to better understand the science and practices of drainage the terminology and definitions relating to drainage are examined in the next section before an overview to the solutions are explored in the following sections.

3.14.4 Components of a typical surface drainage

The components of a typical surface drainage system consist of a series of inter leading channels.

3.14.5 Types of channels

Field Ditches

Field ditches are shallow graded channels usually having flat side slopes that collect water in a field and convey the water to a channel. Cross sections are typically “V” or trapezoidal and may be farmed or vegetated. The steepest side slope for a farmed field ditch is 8H: 1V. If not farmed or crossed by equipment, the steepest recommended side slope for a field ditch in a cropped field is 4H: 1V and 3H:1V in a pasture.

Field ditches may require cleanout following tillage operations. When field ditches are not cropped, weed growth must be controlled by mowing or spraying.

Lateral Ditches

Field ditches convey water to lateral ditches. The lateral receives this water and sometimes water from the filled surface and conveys it to the main ditch. Lateral ditches require periodic maintenance to control vegetation on the bottom and side slopes. Sides slopes of 3H : 1V or flatter are recommended for ease of mowing. Where excessive sediment deposition occurs in a lateral, occasional cleanout will be required.

Main Ditches

The main ditch is the outlet for the drainage system. It receives flow from lateral ditches and sometimes other mains.

3.14.6 Types of open drain systems

Drains should be located to fit the farm or other land use operations and should have capacity to handle the runoff and not cause harmful erosion. ((Bureau of Reclamation, 1978). The drain system should cause excess water to flow readily from the land to the disposal drain. Five common drain systems are described in this section.

Random Drain System

This type system is adapted to drainage systems on undulating land where only scattered wet areas require drainage. The ditches should be located so they intercept depressions and provide the least interference with farming operations. (Figure 3-13) The ditches should be shallow and have side slopes flat enough for farm equipment to cross. Precision land forming and smoothing maybe required to ensure the removal of surface water from less permeable soil.

Where the topography is irregular, but so flat or gently sloping as to have wet depressions scattered over the cultivated area, a random drainage system is used.

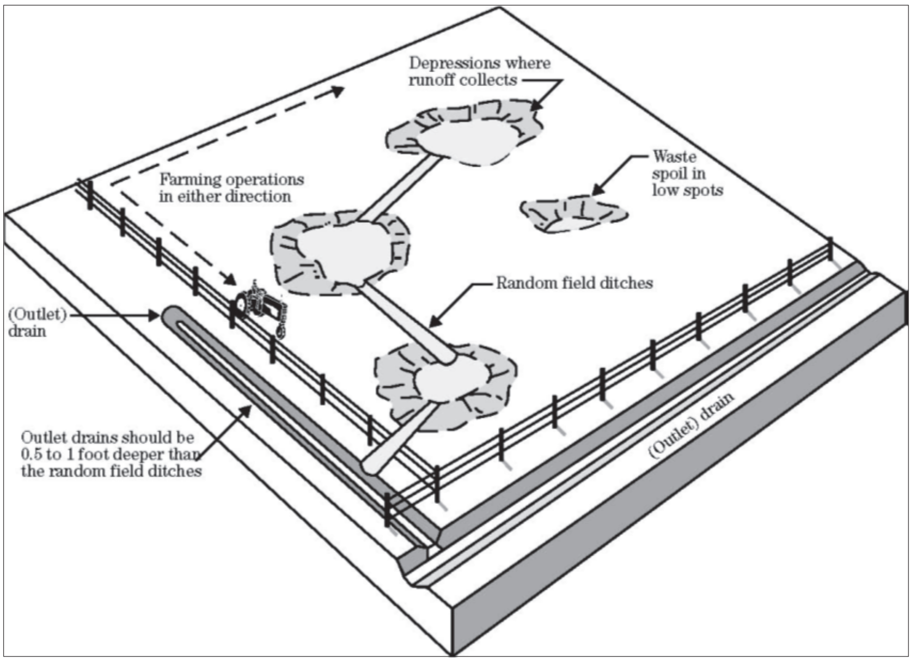


Figure 3-13: Random Drainage System (Bureau of Reclamation, 1978)

Parallel Drain System

This type system is applicable to land where the topography is flat and regular and where uniform drainage is needed. The ditches are established parallel but not necessarily equidistant, as shown in Figure 3-14. The direction of the land slope generally determines the direction of the ditches. Field ditches are generally perpendicular to the slope, and laterals run in the direction of the slope. The location of diversions, cross slope ditches, and access roads for farming equipment can also influence the drain location. Spacing of the field ditches depends upon the water tolerance of crops, the soil hydraulic conductivity, and the uniformity of the topography. Land forming can reduce the number of ditches required by making the topography more uniform. Where possible, spacing should be adjusted to fit the number of passes of tillage and harvesting equipment.

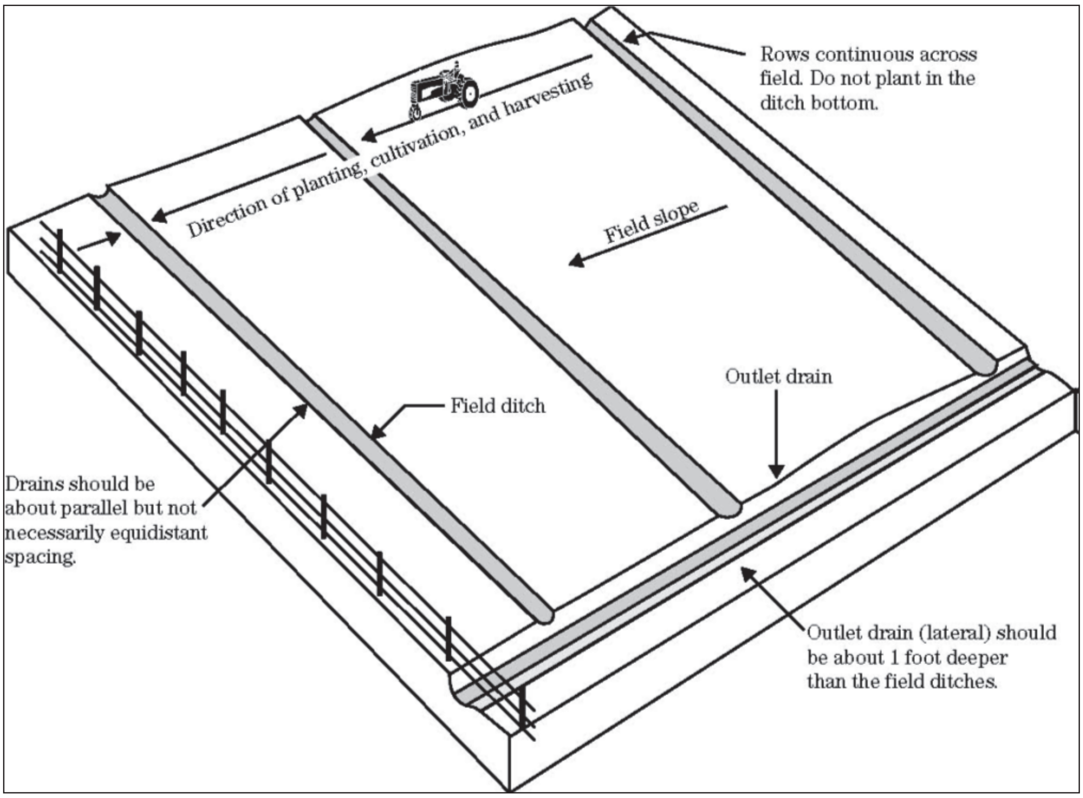


Figure 3-14: Parallel Drainage System (Bureau of Reclamation, 1978)

Cross Slope Drain System

A cross slope drain system is used to drain sloping land, to prevent the accumulation of water from higher land, and to prevent the concentration of water within a field. The field ditches work best on slopes of less than 2 percent. The drain is located across the slope as straight as topography will permit, as shown in Figure 3-15. The spacing of these ditches varies with the land slope and should be based on recommendations contained in this guide. The excavated material should be placed in low areas or on the downhill side of the drain. Land forming or smoothing between the ditches improves operation of the system by preventing the concentration of flow and the occurrence of ponding.

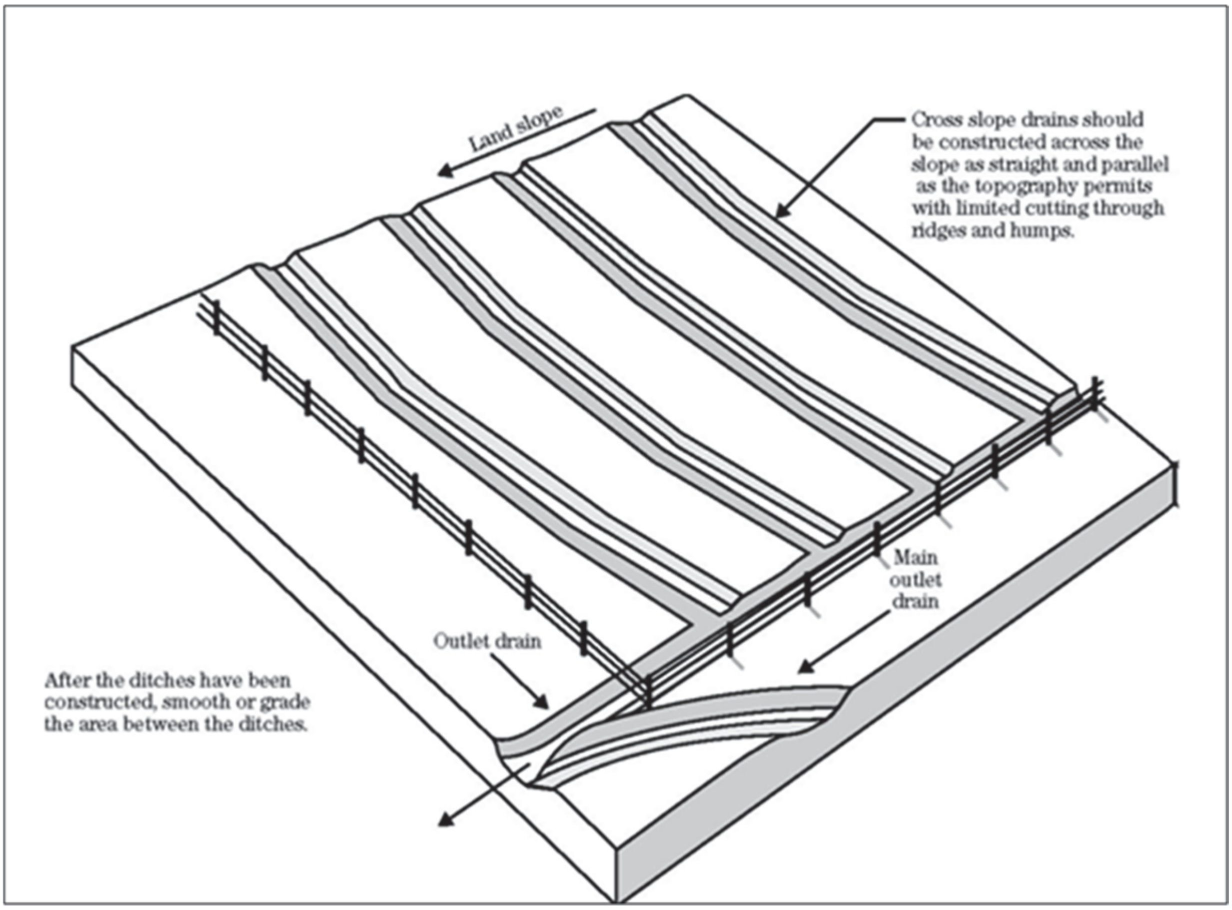


Figure 3-15: Cross Slope Drainage System (Bureau of Reclamation, 1978)

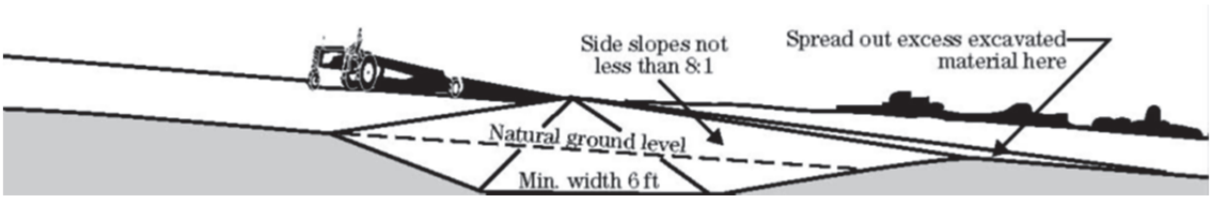


Figure 3-16: Typical Flat Bottomed Section (Bureau of Reclamation, 1978)

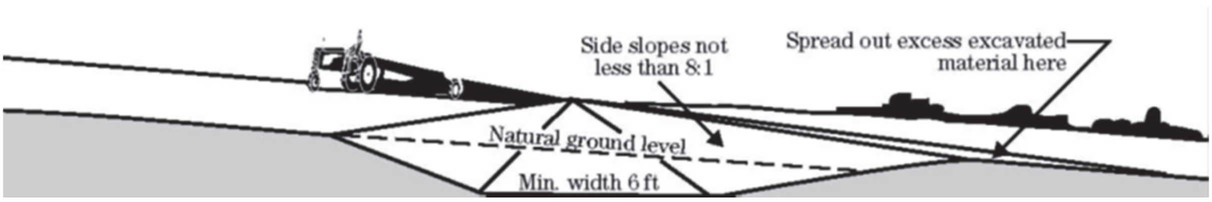
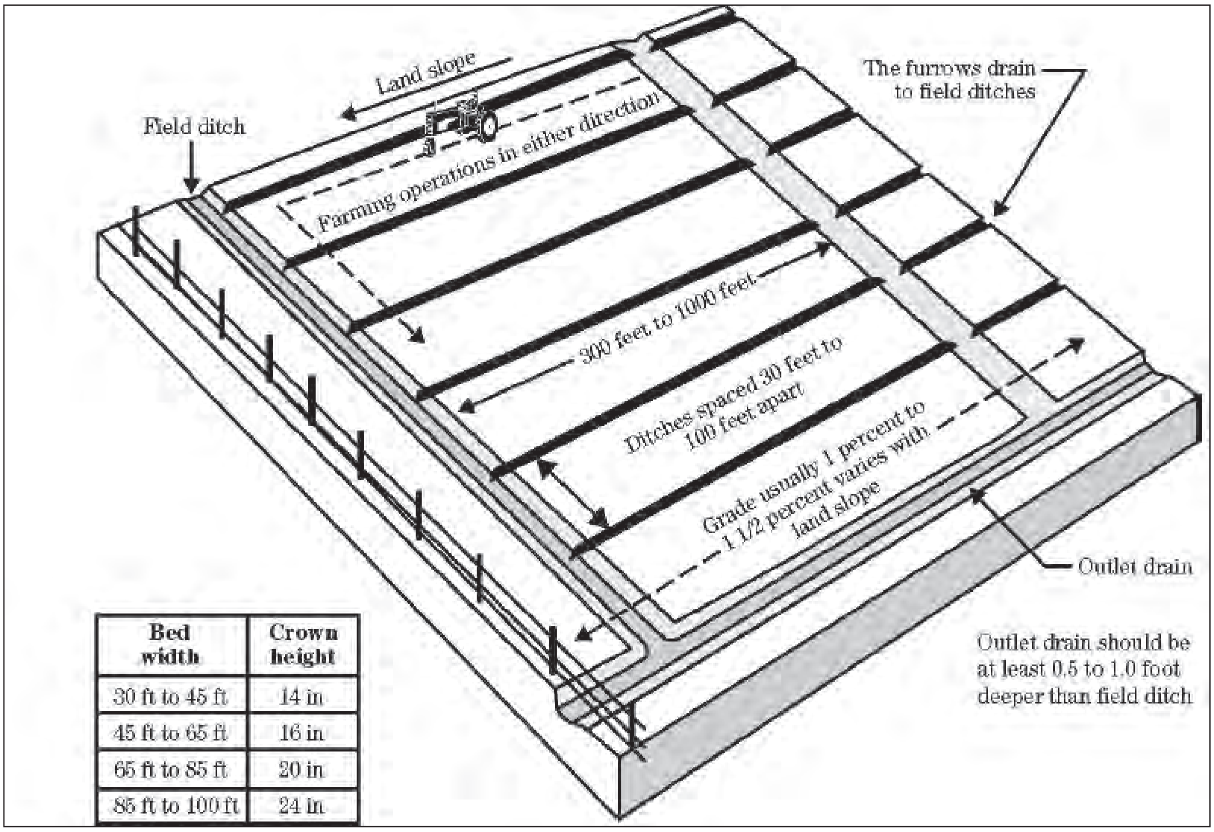


Figure 3-17: Typical V-Channel Section (Bureau of Reclamation, 1978)

3.14.7 Bedding

Bedding resembles a system of parallel field ditches with the intervening land shaped to a raised, rounded surface, as shown in Figure 3-18. This drainage system generally is used where slopes are flat and the soil is slowly permeable and where other types of drainage are not economically feasible. A bedding system generally is in small land areas and is installed using farm equipment. Beds are established to run with the land slope or in the direction of the most desirable outlet. Local information should be used to determine the width of beds, the crown height, construction method and maintenance.



Bed width	Crown height
30 ft to 45 ft	14 in
45 ft to 65 ft	16 in
65 ft to 85 ft	20 in
85 ft to 100 ft	24 in

Figure 3-18: Bedding Drainage System (Bureau of Reclamation, 1978)

Narrow Raised Beds

A narrow bed system has a raised bed wide enough for single or double cropping rows to provide an aerated surface profile. This system facilitates surface water movement and aeration of the shallow root zone. When used with plastic covers for weed control, evaporation control, and nutrient management, the narrow bed system can be extremely effective for some cropping systems.

3.14.8 Land Forming

Land forming refers to the reshaping of the land surface to facilitate the movement of surface water. Land smoothing and precision land forming are used in surface drainage to improve the effectiveness of the drainage system.

3.14.8.1 Land Smoothing

Land smoothing is the elimination of minor depressions and irregularities without changing the general topography. Equipment needed is usually a land plane or land leveller. The purpose is to provide a more uniform surface for runoff to move toward field ditches. The operation of land smoothing on land with more than 0.1 percent grade can usually be accomplished without a detailed survey or plan. However, in critical portions of a field where visual observations do not provide the accuracy required, a survey is necessary.

3.14.8.2 Precision Land Forming

Precision land forming is the process of reshaping the land surface to predetermined grades, such that each point on the field has positive drainage. Precision land forming, by carefully designed cutting and filling operations, can provide excellent surface drainage. Areas to be graded are planned with a minimum number of field ditches, with ditches located, if possible, perpendicular to the laterals and to the field rows.

Minimum grade limits should include a tolerance for construction that will permit elimination of depressions. For most fields, a 0.2 percent grade will readily accomplish this goal. A grade of 0.1 percent or flatter will require unusual precision in the maximum allowable depth of cut will depend on the soil and economics. Soil borings are necessary for determining the maximum depth of cut. The degree of compaction imparted in fill areas should be sufficient to avoid future settlement problems but not exceed densities restrictive to root growth, especially in the rooting construction. The recommended grades range from 0.1 percent to 0.5 percent with grades being uniform or varied.

The maximum allowable depth of cut will depend on the soil and economics. Soil borings are necessary for determining the maximum depth of cut. The degree of compaction imparted in fill areas should be sufficient to avoid future settlement problems but not exceed densities restrictive to root growth, especially in the rooting zone of the planned crop or vegetation. Fields must not be graded when soil moisture levels are high, as this will impair the physical structure of the soil. Topsoil should be salvaged from areas of deep cuts or fills for spreading on areas where deep cuts expose the subsoil.

3.14.9 Surface drainage design approaches

3.14.10 Drainage Channel Design

Main and lateral ditches are open channels that serve as outlets for drainage systems. These ditches can serve as outlets for other conservation practices as well as for the disposal of excess surface and subsurface drainage water.

3.14.10.1 Considerations

For new systems, the location of mains and laterals must be carefully planned because they will define field size and restrict farm traffic patterns. Culverts or bridges will usually be required for access across mains and laterals, so their number should be minimized to reduce installation and maintenance costs. Channel depth is important where surface drains are to serve as outlets for other practices such as subsurface drainage conduits. All systems require an adequate outlet whether discharge will be by gravity flow or pumping.

In the rehabilitation of existing mains and laterals, restoration is usually to re-establish the historic cross section and profile by removal of sediments. This can be accomplished through identification of control points, such as existing culvert inverts and subsurface drain outlets, along with probing to determine sediment depths. Consideration should be given to preserving existing stabilizing vegetation, especially along the channel side slopes. Where banks must be disturbed, excavation should be limited as much as practical to one side of the channel. Tree canopy that provides shading to the ditch should also be preserved. Whether new construction or restoration is planned, consideration must be given to the environmental impacts including effects on wetlands, fisheries, wildlife habitat, water quality, and aesthetics.

3.14.10.2 Velocity estimation

The velocity in a channel must be high enough to prevent sediment deposition (at least 0.4 m/s), yet low enough to avoid erosion.

Table 3-9 provides the allowable velocity at design flow depth for various soils and materials. The most critical soil type, or that having the lowest allowable velocity, is usually selected as the maximum allowable velocity for design.

Table 3-9: Allowable velocity for various soils and materials

Soil Texture or Material	Velocity (m/s)
Sand, sandy loam	0.76
Silt Loam, Loam	0.91
Sandy Clay Loam	1.07
Clay Loam	1.22
Clay, fine gravel, graded loam to gravel	1.52
Gravel silt to cobbles	1,68
Shale, hard pan and coarse gravel	1,83

Velocity for design of surface drains is commonly determined using Manning's formula as in Equation3-7:

$$v = \frac{1}{n} \times R^{\frac{2}{3}} \times s^{0.5}$$ Equation 3-7

where:

V = velocity (m/s)

n = roughness coefficient

R = hydraulic radius, A/P

S = slope of hydraulic grade line (m/m)

A = cross sectional flow area (m^2)

P = wetted perimeter (m)

3.14.10.3 Roughness coefficient

The roughness coefficient, n, is a factor that accounts for the retarding influences on channel flow such as surface irregularities, vegetation, meander, obstructions, and variation in cross section. For most ditch designs where good maintenance is expected, an n value of 0.04 is commonly used to determine capacity. For newly constructed channels, it is recommended that a value of 0.025 (bare earth condition) be used to check velocity to avoid erosion.

Table 3-10 provides guidance for determining the n value of a channel with good alignment and grassed vegetation based on hydraulic radius.

Table 3-10: Value of Manning's n for drainage ditch design

Hydraulic Radius	n
< 2.5	0.04-0.045
2.5-4.0	0.035-0.04
4.0-5.0	0.03-0.035
>5.0	0.025-0.030

3.14.10.4 Hydraulic Grade Line

The slope of the hydraulic grade line (water surface) is important in determining flow velocity. In the design of most small unobstructed ditches in uniform topography, the hydraulic grade line is assumed parallel to the ditch bottom. Proper location of the grade line is more important as drain flows become greater. The profile of the channel should be plotted showing the location and elevation of control points. The control points help to select the maximum elevation of the hydraulic grade line desired for the drain. They may include, but are not limited to, the following:

- Natural ground elevations along the route of the proposed drain.
- Location, size, and elevation of critical low areas to be drained. These are obtained from the topographic data.
- Hydraulic grade line for side ditches or laterals established from the critical areas to the design drain. Plot the elevation where the side drain hydraulic grade line meets the design drain as a control point.
- Where laterals or natural streams enter the design drain, use the same procedure as that for hydraulic grade line for side ditches.
- Bridges across drainage ditches should not reduce the area of the design cross section. Where feasible to do so, the hydraulic grade line should be placed 0, 30 m below the stringers of the bridge. The allowable head loss on culverts should be kept low. On agricultural drainage the allowable head loss generally should not exceed 0, 15 m.
- Elevations of buildings or other property within the area to be protected from overflow.
- If the drain being designed is to outlet into an existing drain or natural stream, the elevation of the water in the outlet drain or stream against which the designed drain must discharge should be used as a control point. The water surface elevation in the outlet ditch may be determined from recorded data, historic observation, or high water marks. Another method of obtaining this elevation is to

determine the depth of flow in the outlet ditch by applying the same flow design basis as that used for the proposed ditch. For small outlet ditches in rather flat topography, the water elevation may be estimated at the bankfull stage.

Control points should be connected with a line on the profile. The hydraulic grade line is drawn through or below the control points. The grades should be as long as possible and should be broken only where necessary to stay close to the control points. If the hydraulic grade line has been well established, it will not be altered except at structures that have head losses. At these control points, the head loss will be shown upstream from the structure as a backwater curve. This will change the hydraulic gradient, although generally for only a short distance.

3.14.10.5 Cross section, depth and side slopes

The most economical ditch cross-section approaches that of a semicircle. A deep, narrow ditch generally carries more water than a wide, shallow ditch of the same cross-sectional area. An excessively wide, shallow ditch tends to develop sand or silt bars, which cause ditch meandering and bank cutting, and a fairly deep, narrow ditch tends to increase velocities and reduce sediment deposition and meandering. Because the cross-section selected is a matter of judgment, all factors involved should be considered. Ditches shall be designed to be stable. In some cases economy and hydraulic efficiency must be sacrificed in the interest of ditch stability and maintenance.

Factors that must be considered in establishing the depth of a ditch are:

- Depth to provide the capacity for removing the surface runoff plus freeboard.
- Depth to provide outlet for subsurface drainage.
- Depth to clear bridges.
- Depth to allow for sufficient capacity after subsidence in organic soils.
- Depth to trap sediment below the elevation of a design flow line.

The machinery used for construction of the ditch should be considered in the selection of ditch bottom width. A bulldozer or blade equipment is used to construct V-shaped ditches. Flat bottom ditches frequently are designed if scrapers, hydraulic hoes, or draglines are to be used to construct the ditch. Depth of ditch and soil conditions affects the type of equipment used. Specified minimum bottom widths are often based on the available equipment.

The side slope selected for design must be stable, meet maintenance requirements, and be designed according to site conditions. Special investigations and stability analysis may be required when seepage is present in the channel banks from high water table conditions, low strength soils are encountered, or where channel soils are erosive and could lead to undermining of the banks.

3.14.10.6 Calculation of Ditch Capacity

The capacity of a ditch can be determined from the Continuity Equation:

$$Q = VA \quad \text{Equation 3-8}$$

where:

Q = capacity (m^3/s)

V = velocity (m/s)

A = cross sectional flow area (m^2)

3.14.10.7 Culverts and Bridges

Culverts and bridges should be designed for the expected loads from farm equipment, construction equipment, or vehicles that will use the crossing. The hydraulic capacity of the culvert or bridge should be large enough to avoid a reduction in the channel capacity. Wet crossings, or fords, may also be considered for livestock or for farm equipment where infrequent use is expected.

When a culvert or bridge is installed in a channel, it has the effect of backing up water or increasing head at the inlet. The amount of this rise in water level is determined by the entrance losses, friction losses, and exit losses. The amount of head loss needs to be considered in the design to insure that the upstream water surface is not as high as to prevent good drainage or to cause an increase in flood levels on adjacent properties. The velocity through a bridge and at the outlet of a culvert should be checked to determine if scour protection is needed. Riprap may be required when allowable velocities are exceeded. Preformed scour holes may be used to stabilize conduit outlets.

Culverts and bridges for farm field access lanes should have a design capacity consistent with that of the channel.

3.14.10.8 Junctions

The bottom grades of ditches having about the same depth and capacity should be designed to meet at or near the same elevation. The bottom of a shallow, small capacity ditch may be designed to meet a larger ditch at or near the normal or low flow elevation of the larger ditch. A transition is designed where a shallow ditch enters a much deeper ditch. Before beginning a transition, the grade of the shallow ditch generally is designed 10 to 100 feet upstream on a zero grade at the elevation of the deeper ditch. The transition should be on a non-erosive grade not to exceed 1 percent. Where the difference in the elevation of the ditch grade lines is considerable and transition grades seem impractical, a structure should be used to control the drop from the shallow ditch to the deeper ditch.

3.14.10.9 Surface Water Entry

Provisions should be made to control surface water entering into a ditch to avoid erosion of the banks. Ideally, surface water enters a ditch only through lateral ditches graded to the bottom of the channel, or through structures including chutes, drop spillways, or pipe conduits. Collection ditches can be used to reduce the number of necessary structures. Excavated spoil can be spread or left in spoil banks along the channel with openings spaced to control surface water entry. A minimum berm width, or set-back, of eight feet should be provided between the spoil pile and the ditch bank to low for maintenance and erosion control, and to prevent overloading of the bank slope.

3.14.10.10 Channel Vegetation and Maintenance

Field ditches that will not be cropped and the banks of all mains and laterals should be stabilized with a good vegetative cover of appropriate grasses. Channel beds may also be stabilized with vegetation where prolonged flows are not expected. The area adjacent to the channel should also be vegetated including spoil banks, berms, and buffer strips. Surface drains have an estimated service life of 15 years. This can be achieved and prolonged through proper maintenance.

4 OVERVIEW OF APPLICABLE FINANCIAL APPROACHES

4.1 Introduction

The economic viability of drainage refers to the per hectare ability of the direct increase in profitability as a result of drainage to repay the capital required to drain, whereas financial feasibility refers to the ability of the farming unit to access sufficient additional funds to pay for the drainage required and maintain an overall increasing cash flow in the long term or positive Net Present Value (NPV). Economic viability is a prerequisite for financial feasibility (Armour & Viljoen, 2008).

Two sets of financial criteria needs to be assessed, viz.:

- **Economic** Benefit Cost analysis (per hectare)
- **Financial** Whole-farm analysis

The economic analysis is an academic exercise to determine whether sub-surface drainage installation makes economic sense. The financial analysis, on the other hand, determines if the installation will be financially feasible, taking into account general accepted financing norms, etc.

4.2 Economic Benefit Cost analysis (per hectare)

A decision-making tool used by Backeberg (1981), to evaluate capital investment on irrigation drainage is benefit cost analysis which includes:

- Internal Rate of Return (IRR),
- Net Present Value (NPV),
- Benefit Cost Ratio (B/C ratio)
- Payback period (average).

The Net Present Value (NPV) is the difference between the present value of income and present value of the capital and other expenditure. The Benefit Cost Ratio (B/C Ratio) is obtained by dividing the present value of the income by the present value of capital and other expenditure. The Internal Rate of Return (IRR) is the breakeven discount rate at which the B/C ratio equals 1, or alternatively where the NPV equals zero. The average payback period is the time that it will take to repay the investment based on the average incremental benefit of the investment decision over a twenty year period.

4.3 Financial Whole-farm analysis

Financial Whole-farm analysis ratios and norms, includes:

- Projected Production Cost ratios,
- Projected Cash flow ratios,
- Projected Debt ratios, and
- Projected Bank balance

The above ratios are derived from the 20-year projected financial statements, i.e. Whole-farm Cash flow-, Income Statement and Balance Sheet.

4.3.1 Projected financial statements

The financial statements for the farm business are compiled from farm records. A full set of financial statements for a farm business would consist of a balance sheet, an income statement and a cash flow statement. The balance sheet is often linked to a photo on a specific date. It is a picture of the farm's financial situation at a specific point in time, showing that the famers owes and owns. If the balance sheet is a photo, then the income statement may be compared to a video that shows us what has occurred from one balance sheet to the next. The cash flow statement shows all of the cash flowing into and out of the farm business for a specific period (Standard Bank, 2013). For future planning projected cash flow statement, income statement and balance sheet are of paramount importance.

4.3.1.1 Cash flow statement projection

Most of the information needed for financial analysis of the farm business is contained in the balance sheet and income statement. Most financial decisions can generally be based on information and analysis of this nature. An important shortcoming of balance sheets and income statements is that they do not take account of the cash flow or flow of funds in the farm business for the period under preview.

At first this might not seem important, but these days cash flow is probably the most important component of the financial management of the farm business. The large number of farm businesses currently experiencing cash flow and cash flow-related problems prove this point.

The income statement reflects the income and expenditure of the farm business. To realise the projected profit, large amounts of money need to be spent initially on items such as seed, fertiliser, herbicides, pesticides, fuel, stock-feed and licks. Because income is only realised after these expenses have been incurred, a farm business could show a profit during a financial year but have an overdrawn bank account for the best part of that year. Only once the income is realised will the overdraft be reduced or converted to a positive balance. This is currently the rule rather than the exception. Thus, as far as financing and financial management are concerned, cash flow analysis is of significant importance.

The most important feature of the cash flow statement is that only cash expenses and cash income are indicated at the time of payment or receipt. The cash flow statement is based on the cash analysis book. The cash flow statement reflects the sources from which funds were generated during the accounting period as well as the purposes for which these funds were used. The accounting period is divided into individual months so that the flow of funds can easily be traced during the period under review.

Because cash flow is an important consideration when it comes to financing the farm business, the bank and the monthly bank balance are important elements of the cash flow statement. The cash flow statement consists of three components, namely income, expenditure and the bank balance, in that order:

- Income consists of operating income (income from products, for example, wool, maize and milk), capital income (sales of livestock and machinery) and non-farming income. Only actual cash income is regarded as income, and only in the month of the actual receipt.
- Expenditure is classified as operating expenditure (seed, fertilizer and purchased stock-feed), capital expenditure (purchasing of livestock and machinery), debt repayments (interest and capital redemption) and non-farming expenditure. As in the case of income, only actual payments are recorded in the cash flow statement, and then only in the month of payment.

Two aspects are especially important: Firstly, non-cash flow items, such as depreciation, are not recorded in the cash flow statement. Secondly, items such as seed and fertiliser are often bought on credit at cooperatives. These items are only recorded in the cash flow statement in the month that account is paid. If the account is partially paid, only the portion that has been paid should be recorded. Amounts in arrears are not reflected on the cash flow statement.

The surplus or shortfall for a specific month can be calculated by deducting the total expenditure from total income. The sum total of the surplus/shortfall and the opening bank balance give a new balance, which could be either negative or positive. If this balance is negative, the interest that has to be paid on the farm business' bank overdraft is added to calculate the closing balance. If the balance is positive, the amount is directly carried over to the closing balance because no interest is payable in this case. It should be borne in mind that interest on overdrawn balances is calculated on that month's balance only, that is, the interest charges will differ from month to month as the overdrawn balance fluctuates. The closing balance for one month is the opening balance for the next month.

A schematic presentation of how to calculate the net disposable income is given in Figure 4-1, illustrating the relationship between the income statement and the cash flow statement.

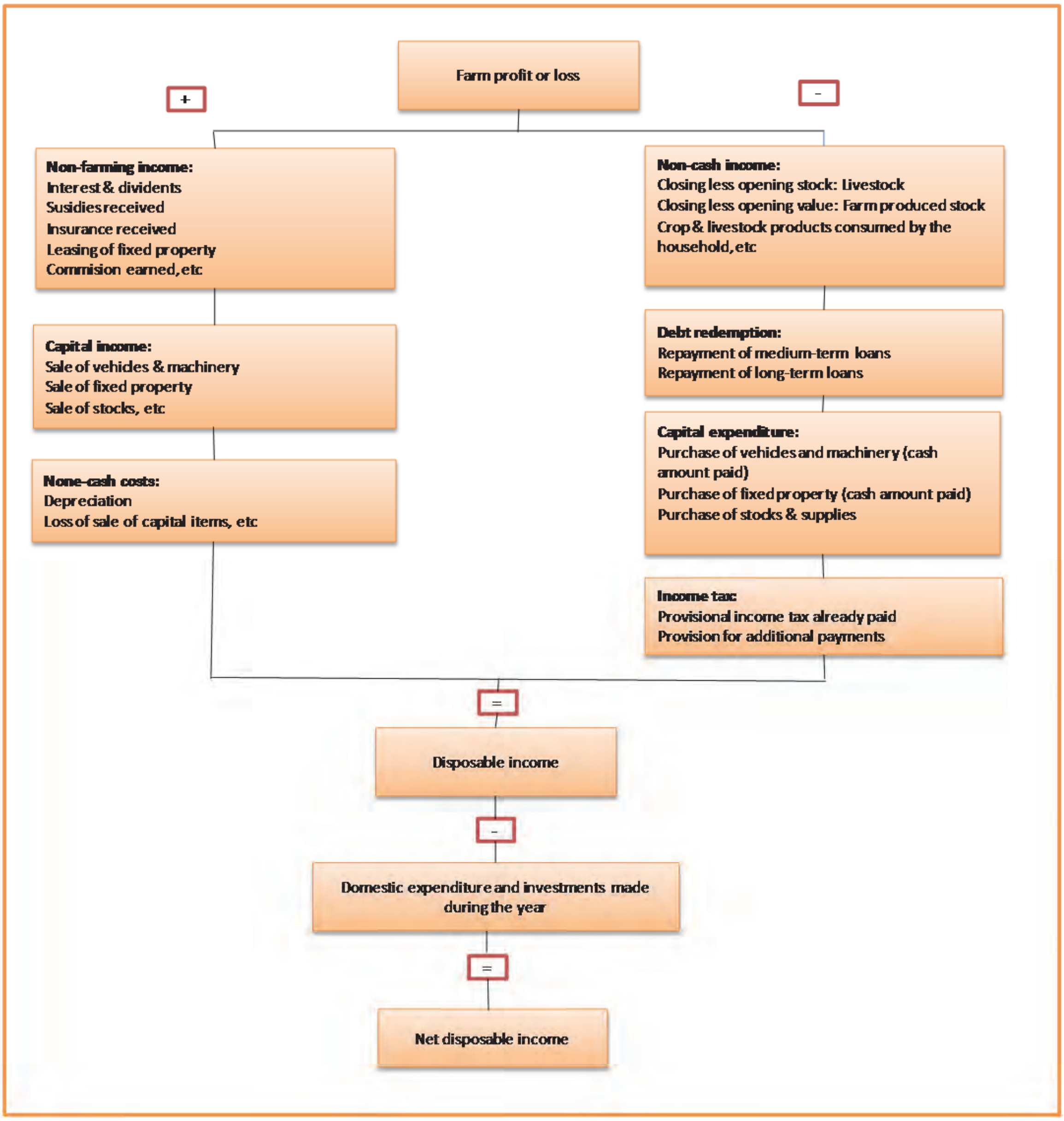


Figure 4-1**:** Schematic presentation of how to calculate the net disposable income *(Source: Standard Bank, 2013)*

4.3.1.1.1 Mathematical specification of the Cash flow statement projection

In mathematical terms the Cash flow statement projection objective is as follows:

$$\text{Net cash flow} = \sum_{i=a}^{d} Ii - \sum_{o=l}^{q} Io$$

Where:

- I_a Total crop production income
- I_b Total Livestock income

- I_c Total Capital income
- I_d Total Non-farm income
- I_i Interest rate on positive bank balance
- O_l Total Direct allocated production costs
- O_m Total Livestock production costs
- O_n Total Non-allocated production costs
- O_o Total Capital expenditure
- O_p Total Debt redemption
- O_q Total other expenditure
- O_i Interest rate on negative bank balance

4.3.1.2 Income statement projection

Based on the financial information contained in the forgoing farming information system (that is, records of accounts receivable and accounts payable, records of income and expenditure) the farmer can summarise the financial results of the farm business on the income statement. Whereas the balance sheet reflects the financial status of a business at a specific date, the income statement indicates how this financial status was achieved. It therefore indicates how the assets were used during a certain period. The income statement is a summary of the income and expenditure of the farm business for a specific period, financial year, production year or tax year (Standard Bank, 2013).

Because opening and closing balance sheets have been compiled for the opening and closing dates of the period covered by the income statement, a link can be drawn between the income statement and the balance sheet. This is known as the reconciliation of the net worth according to the opening and closing balance sheets.

The information contained in the income statement is schematically summarised in Figure 4-2. A discussion of the most important components of the income statement follows in the paragraphs below.

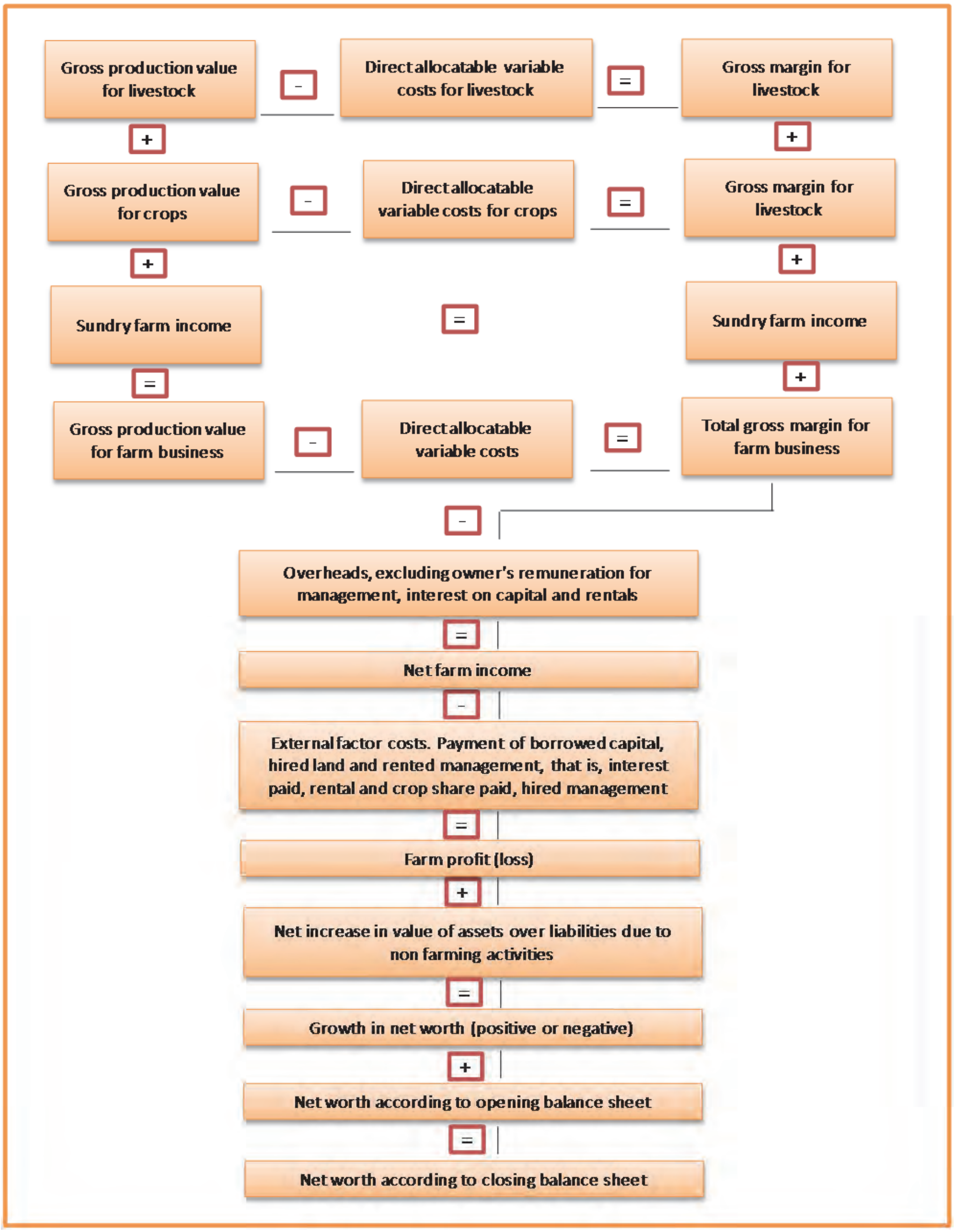


Figure 4-2: Schematic summary of information contained in the income statement *(Source: Standard bank, 2013)*

Gross production value

The gross production value of the farm business consists of the gross production value for crop and livestock enterprises as well as sundry farm income:

- The gross production value for a livestock enterprise is the total value of livestock products plus any change in inventory. It is calculated as follows:

- Trade income = Livestock sales + livestock slaughtered for household and labourers (including donations) + insurance received on livestock losses + other direct expenses – livestock purchases.
- Plus change in inventory = Closing value of livestock + internal transfers (transfers to other livestock enterprises) – opening value of livestock – internal transfers (transfers in from other livestock enterprises).

- The gross production value of a cash crop enterprise is the total value of the products produced by the enterprise. It consists of the marketable yield, which represents the following:
  - Gross sales (including advances and interim and deferred payments) + insurance payments received due to crop losses + consumption by household and labourers (including donations) + crops used on the farm for stock-feed and seed (internal transfers) + stock adjustment (closing and stock less opening stock).
  - The gross production value of fodder and pasture crops is reflected by output figures for livestock enterprises that uses these crops.
- Sundry farm income is income generated by farming activities, but which cannot be directly allocated to a specific enterprise. Examples include income derived from contract work by using existing surplus capacity, bonus on turnover, casual income from renting out pasture, and selling hay and crops suitable for stock feed.

Gross production value is the sum total of the gross production value for all the enterprises plus sundry farm income, while gross farm income is equal to the gross production value less internal transfers for the accounting period.

Directly allocated variable costs

Variable costs are that part of the total cost components that could vary within the framework of a specific production structure as the size of the enterprise varies and/or the intensity of production per unit changes. In other words, variable costs are those costs that can be controlled in the short-term.

Directly allocated variable costs are those variable costs that can be readily allocated to an enterprise. For crop enterprises these include seed (bought and produced on the farm), fertiliser, herbicides, pesticides, specific contract work, casual labour, marketing costs, hired transport, crop insurance and packaging material. For livestock enterprises these would include items such as bought feed and licks, fodder produced on the farm, veterinary costs and remedies, contract work packaging material, marketing costs, hired transport and insurance.

Gross margin

The gross margin (GM) of an enterprise is the gross production value for that enterprise less directly allocated variable costs. The total gross margin is calculated by adding together the gross margins of all enterprises in the farm business. Should further deductions be made from the gross margin, the margin over directly allocated costs would be obtained. All comparisons between enterprises are based on the gross margin.

Net farm income

The net farm income (NFI) is the total gross margin less overhead costs (excluding remuneration and interest on capital and rentals). Overheads consists of all non-directly allocated variable costs (fuel oil, lubricants, repairs and spare parts for vehicles, and implements and electricity) and fixed costs (depreciation, insurance on buildings and implements, licenses, regular labour, bookkeeping fees, bank charges and telephone and mailing costs). Net farm income does not imply profit as it is generally understood because management remuneration, interest on capital and rentals are excluded. The reason is that the NFI is solely used as a criterion for comparison between farm businesses. To prevent apples from being compared to pears, all external factor costs (management, interest and rental) are excluded. In this way a farmer can compare the NFI of the farm business – especially if it is expressed per capital investment or per area unit – to those of other businesses, regardless of whether the farm has been inherited, is being rented or has been bought on credit.

Farm profit

Farm profit (FP) is the NFI less remuneration of hired management, rentals and interest on capital, that is, the return to external factor costs. The farm profit is not the amount that is available for spending at the end of the year since compulsory redemption of capital and income tax must still be paid from this amount. During the course of the year amounts have been spent on items such as a voluntary redemption of capital, household expenses and machinery and equipment.

Non-farming activities

The net increase of the value of assets over liabilities as a result of non-farming activities is calculated as follows:

Non-farm income plus capital redemption plus capital profits plus own-capital inflow less capital losses less own-capital outflow les income tax less private and household imbursements less farm products consumed.

Net worth

The growth in net worth is calculated by adding the farm profit/loss to the net increase/decrease in the value of assets over liabilities as a result of non-farming activities. The growth in net worth is not an amount that is in the bank at the end of the year, but an amount that can be spend without reducing the initial own capital in the farm business. This could, for example, be tied up in products still to be sold or in payments still to be received.

4.3.1.2.1 Mathematical specification of the Income statement

In mathematical terms the Income statement projection objective is as follows:

$$[GNW] \quad = [GPV] \sum_{i=a}^{c} - \ [PMAD] \sum_{e=h}^{i} = [NFI] + \sum_{l=m}^{n} = \ [NFP] + \sum_{o=p}^{s} - \sum_{o=t}^{y}$$

Where:

- GNW Growth in Net Worth
- GPV Gross Production Value
- PMAD Production, Marketing, Admin costs and Depreciation
- NFI Net Farm Income
- NFP Net Farm Profit
- I_a Total farm produce sales
- I_b Total consumption
- I_c Total stock adjustment
- E_h Total Production, Marketing and admin costs
- E_i Depreciation
- L_m Interest received
- L_n Interest paid

- O_p Non farm income
- O_q Capital appreciation
- O_r Capital profits
- O_s Own capital inflow
- O_t Capital loss
- O_u Own capital outflow
- O_v Dividends
- O_w Income tax provision
- O_x Private expenses
- O_y Farm produce consumed

4.3.1.3 Projected Balance sheet

The balance sheet is a financial statement that reflects the financial position of a farm business on a specific date. This date is usually the first and/or the last day of the financial year or at the end of a production season. The financial status of a farm business is determined by three aspects, namely assets, liabilities and net worth (ownership interest or own capital). The balance sheet is the systematic presentation of these three aspects for a specific date, with each item being identified and linked to a money value. The balance sheet is a representation of historical information that reflects the cumulative effect of finalised transactions without indicating how the current financial position was reached (Standard Bank, 2013).

The assets recorded on the balance sheet represent everything the farm business owns, for example, land, fixed improvements, machinery and equipment, stocks and supplies, and cash. The asset side of the balance sheet is always based on the inventory. The liabilities recorded on the balance sheet represent all the liabilities of the farm business as at the date of the balance sheet. The difference between the assets and the liabilities recorded on the balance sheet indicates the net worth of the farm business on that date.

The net worth is also called ownership interest or own capital and represents the amount the farmer would retain if all assets were sold and all debts paid. If the net worth is negative, the farmer would be insolvent or bankrupt. The net worth is entered on the liability side of the balance sheet and represents the amount that the farm business owes the owner. The asset side of the balance sheet indicates all the assets of the business as at the date of the balance sheet, while the liability side indicates how these assets were financed.

There are a variety of balance sheet forms and formats. There is however a common link among them all. The balance sheet is organised by the basic accounting as in equation 4-1:

$$\text{Total assets} = \text{Total liabilities} + \text{Net worth/equity} \qquad \text{Equation 4-1}$$
$$A = L + E$$

In other words, the value of assets must equal the value of the liabilities against those assets plus the value of the farm's equity. The equation balances because the assets must be funded by either debt or equity.

As the words 'balance sheet' imply, the two sides of the equation should always be equal. A transaction that affects one side of the equation must result in an identical change on the other side.

The ration between the various types of assets and liabilities is important when the financial position of a farm business is examined. For this reason assets and liabilities with similar features are grouped together and systematically recorded on the balance sheet.

Assets

Assets are classified according to their liquidity or ability to be converted to cash. Accordingly, there are three categories of assets, namely current assets, medium-term assets and fixed assets.

I. Current assets (also known as short-term assets) are the most liquid assets and consist of items such as cash on hand, cash in the bank, stocks and supplies, debtors, finished and semi-finished products, short-term investments and prepaid accounts. These assets can easily be converted to cash in a 12-month cycle without disrupting the farm business.

II. Medium-term assets (also called movable assets) are used in the production process to produce saleable items over a period of time, but are usually depleted in the medium-term (normally 2-10 years). Moveable assets include items such as vehicles, machinery implements, tools, equipment, orchards, breeding stock, plantations and medium-term investments. Most of these assets are subject to depreciation.

III. Fixed assets are also used in the production process, but have a longer serviceable lifetime (usually longer than 10 years). Fixed improvements and land are examples of fixed assets.

Liabilities

Liabilities of the farm business are classified according to the period available for redeeming the debt or liability. Just like assets, liabilities can be classified into three categories, namely current liabilities, medium-term liabilities and long-term liabilities. The order in which liabilities are recorded on the balance sheet is once again based on the duration of the repayment period.

I. Current liabilities (or short-term liabilities) are debt commitments payable within 12 months and include items such as bank overdrafts, unpaid cheques, accounts in arrears, accounts at the cooperative, trade creditors and provision for instalments on medium- and long-term loans.

II. Medium-term liabilities are debt commitments that have to be repaid within one to 10 years and include instalment sale credit, leasing and medium-term loans (private or at the Land Bank).

III. Long-term liabilities represent all debt commitments that have to be discharged over 10 years or longer. Mortgage bonds and other long-term loans are examples of long-term liabilities.

Net worth

Net worth, or owner's equity, represents the owner's claims against the business. Net worth is classified as contributed capital, which reflects the financial resources provided by the owner and retained earnings, which are claims generated by retaining the business' profits.

Contributed capital is that money that was invested in the business by the owner. It includes capital the owner in the farm business when it started as well as additional capital contributed at a later stage. Retained earnings are earnings that have been generated by the farm business in the course of its operations that have been reinvested in the business and not have been distributed to the owner.

A Balance sheet is drawn up on a specific date and can be completed for any chosen calendar day. If, however, the farmer wants to make a meaningful and informed financial analysis of the farm business, the period covered by the balance sheet should correlate with the period for which the income and expenditure (income statement) are summarised. An accounting period or financial year should therefore be chosen and all financial statements should be based on this period. The balance sheet should be completed at the end of this period, whether it is a calendar year, tax year or production year. Thus the closing balance sheet for one period would serve as the opening balance sheet for the following period.

It should once again be stressed that the inventory is the basis of the valuation and recording of assets on the balance sheet. The relevant items are carried over from the inventory to the balance sheet. The balance sheet reflects the financial position of the business on a specific date (in this case, the beginning and/or the end of the production year) and presents a static image of the business.

Two aspects of the balance sheet warrant further explanation:

- The value of hired items is not an asset and should therefore not be included in the balance sheet. For practical purposes the value of leased items is included under medium-term assets. Rented land and buildings are not included in the balance sheet, but for the sake of consistency and for comparative and analytical purposes these are included as a type of ‘addendum’ under the total assets of the business. The sum total of the total assets of the farm business and value of rented land represent the total capital employed in the farm business.
- Long- and medium-term loans are repaid in periodic instalments. If such an instalment is payable within the following 12 months, it is represents a short-term liability. The total instalment is brought into account under short-term liabilities. Instalments usually consist of two components, that is, an interest component and a capital component. Although the total instalment is included as short-term liability, the existing long- or medium-term loan is decreased by the capital component of the payment only. This aspect will be explained in more detail in the example at the end of this chapter.

4.3.1.3.1 Mathematical specification of the Projected balance sheet

In mathematical terms the Balance sheet statement projection objective is as follows:

$$[Equity] \quad = [Assets] \sum_{a=b}^{d} - \ [Liabilities] \sum_{l=e}^{g}$$

Where:

- A_b Current assets
- A_c Medium term assets
- A_d Fixed assets
- L_e Current liabilities
- L_f Medium term liabilities
- L_g Long term liabilities

4.4 Drainage and crop yield

The decision to drain agricultural land will be guided by the estimated seed yields of crops grown in water table soils, as influenced by waterlogging and soil salinity under specific rainfall and soil conditions, in the presence or absence of artificial drainage, due to irrigation with a specific water quality.

To determine expected crop yields with and without drainage is essential in calculating the economic and financial viability of the drainage investment decision.

4.5 Capital budget and annual maintenance cost

The capital and maintenance costs for different sub-surface systems and different locations differ. To determine the optimal sub-surface drainage system from an economic and financial point of view, it is necessary to analyse different drainage systems (cost and effect on yields) with different scenarios.

4.6 General accepted Financing Criteria and Norms

Traditionally, lenders apply the five C's of credit when determining the credit-worthiness of agricultural borrowers (Wilson et al., 2006):

- The borrowers **Capacity** to repay the loan obligation and bear the associated financial risks, calculated by analysing both past and projected profitability and cash flow of the farm business. If a farmer has previously installed drainage, increased return as a result of drainage records will be useful; otherwise data from a close neighbour with similar conditions who has installed drainage, or verified simulation models can also be used.

- The borrowers **Capital** available for farm operations, assessed from balance sheets with liquidity and solvency calculations to gauge equity investment in the farm and how effectively it generates cash flows. Without sufficient capital (and managerial expertise) to optimise the returns from the investment in drainage (e.g. planting more capital intensive higher value long term crops), the investment may be underutilised.
- The borrowers‟ security **Collateral** as a final source of repayment if the borrower defaults on the terms of the loan agreement or dies. The higher the risk of the operation for which the loan is requested, the higher level of Collateral required. As drainage has no salvage value, the full costs of the drains often needs to be covered by some form of collateral. The higher the percentage of a farmers' total land that needs to be drained, the less likely that the land itself can cover the collateral obligations.
- The **Conditions** for use of the funds, or the intended purpose of the funds required by the borrower are considered in terms of general economic conditions, interest rates, inflation and the demand for money in order to come up with a discount rate with which to calculate the net present value (NPV), benefit cost ratio (B/C) and internal rate of return (IRR), all useful in comparing funding alternatives.
- The **Character** of the borrower, i.e. the attitude of the borrower towards risk and financial track record available from credit bureaus, is also a very important factor for commercial lenders considering a loan application. In the case of subsidised state funding and grants the potential recipients character in terms of "money grabbing" and not applying the funds productively also needs to be evaluated to ensure efficient use of public funds.

"Capacity" and "Capital" can be addressed by means of quantitative assessment by using the following ratios:

- Production cost ratio (to ensure that production costs projections is in line with industry norms)
- Cash flow ratio (an indicator of repayment ability and the enterprise's ability to survive financial setbacks)
- Debt ratio (an indicator of solvency)

"Collateral", "Conditions" and "Character" cannot be calculated using quantitative inputs only and will differ for each analysis and also for different financiers.

4.7 Summary

Chapter 4 is an overview of applicable financial approaches to appraise the economic and financial viability of the sub-surface drainage investment decision. These approaches include the Economic Benefit Cost analysis (per hectare) and Financial Whole-farm analysis and its components, viz. database, crop enterprise budgets, drainage plan and capital budget, expected yield curves (with and without drainage) and projected financial statements.

The capital and maintenance costs varies for different sub-surface systems and different locations. To determine the optimal sub-surface drainage system from an economic and financial point of view, it is necessary to analyse different drainage systems (cost and effect on yields) with different scenarios. The accurate composition of the projected Cash flow-, Income statement and Balance sheet is essential for financial assessment and evaluation.

5 REVIEW OF CURRENT INTERNATIONAL NORMS AND STANDARDS

In order to model and document the correct approaches to drainage system management, the status of drainage performance based on sound scientific principals needs to be evaluated, measured and analysed. The technical requirements will be adapted or new ones formulated after the interaction between irrigation, drainage practices and the environment have been observed, measured, modelled and documented.

A number of tools will be employed to assess, measure, simulate, model and evaluate the various factors that guides drainage approaches for the correct design of efficient drainage systems with reference to soil types, crops, irrigation methods, water tables, salinisation, water quality and management practices.

A water balance approach will be taken to assess and evaluate drainage systems, as this provides the most suitable work method to determine how water moves at a field, farm or catchment level.

The water balance in a drained system for a time increment (Δt) may be expressed as:

$$\Delta V_a = D + ET + DS – F$$

where: ΔV_a is the change in the water free pore space or air volume (cm); D is the drainage from the section (cm); ET is the evapotranspiration (cm); DS is the deep seepage (cm); and F is the infiltration entering the soil section (cm).

Presently, computer based simulation models are available and can effectively simulate the effect, which naturally occurring systems, e.g. rain fall and natural underground water flows would have on the performance of drainage systems. The models can also be used as design tools in determining subsurface drainage flows (q), design water table depth (z), optimum drain depth (W) and spacing (L).

Drainage simulation models provide a better understanding of natural interrelated systems and help in making effective management decisions and planning of an agricultural production system. However, there is a need for calibration and validation of the models under site specific conditions before the model can be fully applied as a support decision making tool.

Natural drainage process according include; ground water flow to streams or other surface outlets; vertical seepage to underlying aquifers; or lateral flow (interflow), which may reappear at the surface at some other points in the landscape. Artificial or improved drainage may be provided by installing drainage ditches or drain tubes in soils, where natural drainage seems not to be effective enough to enable crop production.

With the available technical and financial data from the literature and the schemes together with the models (DRAINMOD, Linear Programme Routines) the technical and financial standards for drainage will be refined and developed.

DRAINMOD assumes a one dimensional water balance or conservation of mass in the soil profile, and uses long duration of weather data to simulate the performance of drainage systems. The model have been developed to avoid complex numerical methods by using approximate methods in quantifying the hydrological components, e.g. subsurface drainage, sub irrigation, infiltration, evaporation (ET) and surface runoff.

Subsurface drainage is computed using the one dimensional Hooghoudt's equation which assumes an elliptical water table shape as measured at midway between two drain laterals. The soil profile above the water table is assumed to be drained to equilibrium with the water table, so that recharge rate is equal to discharge rate from the soil system. Thus, a safe water table depth (z) to crop growth is maintained.

In order to predict water table fluctuations (h) on an hourly basis, subsurface drainage discharges (q), and the quality of the drained discharge, the model requires data inputs such as; (1) weather data; hourly precipitation (or irrigation), minimum and maximum daily temperatures and the potential evapotranspiration, (2) soil data; the soil hydraulic conductivities (k) for the soil profile layers, the thickness of the soil horizons above the restricting layer; and (3) drainage system parameters; the drain spacing and depth for the existing drainage system. These are the type of measurements that will be required during the field work.

In order to verify the outcomes, there is a need to have long-term simulation runs of the model to yield suitable mean yield predictions with suitable mean drain depth and spacing which could guide in the whole subsurface drainage system design process.

It is envisaged that the project procedure will consist of an appraisal process with field visits, direct measurement and interviews at the scheme to gather the data. The evaluation will be implemented at the sites identified. Data to be collected and used in the research will predominantly be soil, crops and climatic data. Some of the measurements and data to be collected include: rainfall and irrigation events, rainfall and irrigation water amounts applied, crop evapotranspiration, soil profiling, depth to the impermeable layer, soil internal drainage, soil deep drainage, saturated hydraulic conductivity, field water table level fluctuations, daily drain discharge in affected areas, periodic salinity (EC) measurement, seasonal groundwater hydrographs, and general water balance in the field, Also collected will be relevant weather data from nearby weather stations that includes temperature, relative humidity, solar radiation, and wind speed. Such data will be used in the Penman-Monteith equation to determine crop evapotranspiration as part of the general water balance calculations in drainage affected cropped lands. Most of the collected information will be used as inputs into the modelling efforts, both for, but separately, calibration and verification of drainage models and then to simulate various scenarios applicable to drainage problems in South Africa so as to come up with drainage design criteria.

Although in the initial stages, DRAINMOD has been identified as the most suitable model to be used in the research, other possible models include WASIM and SaltMOD. These models have capabilities to simulate drainage problems and derive best management practices through development of design guidelines or framework. DRAINMOD is particularly preferred for this research because it is one of the most widely applied of the water balance models in subsurface drainage system design and is well documented. The model is based on the water balance of a unit soil sectional area, which extends from the impermeable layer to the surface and is located midway between parallel drains. The change in water pore space at any time increment is a function of how much water is flowing into the unit soil as infiltration and flowing out of it through drainage, evapotranspiration and seepage.

The linear programming models will give an indication of the affordability of alternative drainage systems and will embed the efficiency of these drainage systems. The models will be structured in such a way as to select the optimal drainage alternatives by considering efficiency, costs and the benefits of the alternative drainage systems in the long-run.

5.1 Drainage Modelling

Drainage design attempts to space and place drains such that the water table depth is maintained at a level that is suitable for the growth of given crops under a set of given conditions. Drainage conditions could be considered steady state (non-transient) as found in areas of long duration rainfall like Europe, or non-steady state (transient) as is found under irrigated conditions in semi-arid areas of the world. Water table depth is influenced by several key input variables. Water table depth monitoring is important in drainage systems management but it is found that physical measurement and monitoring of water table depth for optimal drainage design is expensive and time consuming. Drainage simulation models provide simple and cost-effective ways of determining or predicting water table behaviour for given conditions leading on to proper drainage system design. DRAINMOD is a world renowned model for drainage modelling and has many capabilities. One of its greatest merits is the ability to predict the crop response to changes in drainage system design. One or more design parameters can be changed without affecting others. It will be used in this study because it has already been calibrated for Pongola, which is one of the case study areas.

5.2 The DRAINMOD model

5.2.1 Model background

Drainage is provided by parallel drain tubes or parallel open ditches at a distance d, above the soil profile's impermeable layer and spaced a distance L, apart. When rainfall occurs or irrigation takes place, water infiltrates and percolates through the soil profile raising the water table and increasing the subsurface drainage rate. If the rainfall or irrigation rate is greater than the capacity of the soil to infiltrate, water begins to collect on the surface. When good surface drainage is provided so that the surface is smooth, most of the surface water will be available for runoff. However, if surface drainage is poor, a certain amount of water must be stored in depressions before runoff can begin as shown in Figure 5-1.

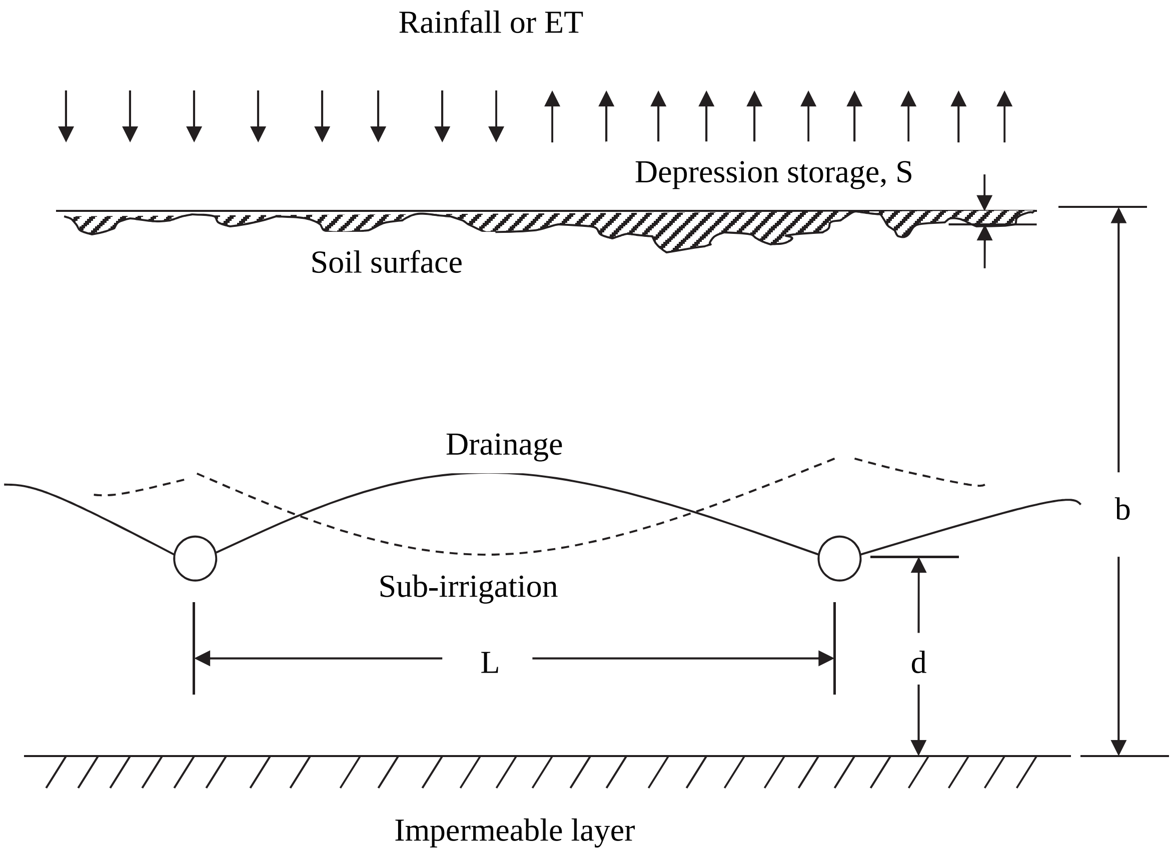


Figure 5-1: Schematic representation of water movement system with subsurface drains (Skaggs, 1978)

After rainfall or irrigation stops, infiltration continues until the water stored in surface depressions is infiltrated into the soil. Thus, poor surface drainage effectively lengthens the infiltration event for a given storm or irrigation event permitting more water to infiltrate and a larger rise in the water table than would occur if depression storage did not exist.

The rate at which water is drained from the soil profile depends on the hydraulic conductivity of the soil, the drain depth and spacing, the effective profile depth, and the depth of water in the drains. When the water level is raised in the drainage ditches, for purposes of supplying water to the root zone of the crop, the drainage rate will be reduced and water may move from the drains into the soil profile giving the shape shown by the broken curve in Figure 5-1. A high water table reduces the amount of storage available for infiltrating rainfall irrigation water and may result in frequent conditions of excessive soil water if the system is not properly designed and managed. Water may also be removed from the profile by ET, and by deep seepage, both of which must be considered in the calculations if the soil water regime is to be modeled successfully.

5.2.2 Model development

DRAINMOD is capable of describing all aspects of water movement and storage in the profile so as to characterize, as accurately as possible, the soil water regime and drainage rates with time. The model was developed such that the computer time necessary to simulate long term events is not prohibitive. The guiding principle in the model development was assembling the linkage between various components of the system, allowing the specifics to be incorporated as subroutines, so that they can readily be modified when better methods are developed. The potential of the model to be modified makes it the ideal model to use in assessing the status of drainage in South Africa.

The basis for the model is a water balance for the soil profile as shown in Figure 5-2. Approximate methods are used to characterize the water movement processes. To ensure that the approximate methods provided reliable estimates, they were compared to exactly the same methods for a range of soils and boundary conditions. Further, the reliability of the model can easily be tested using field experiments.

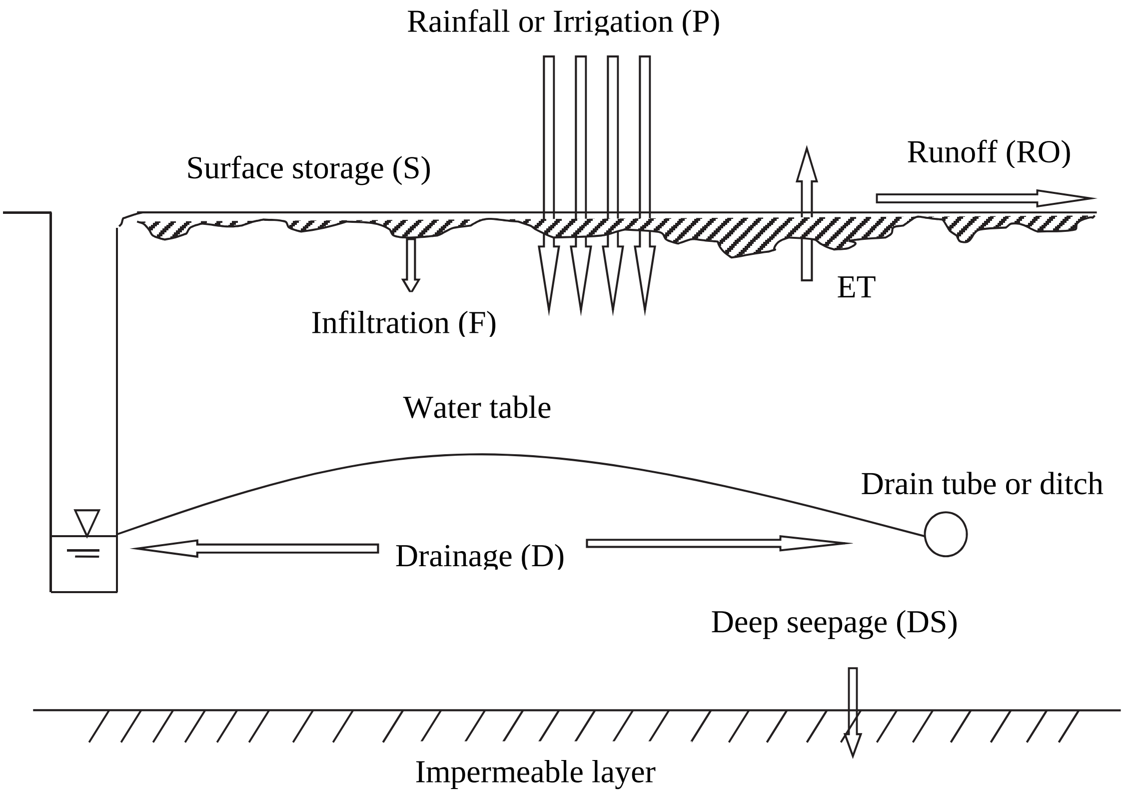


Figure 5-2: Water balance system with drainage to ditches or drain tubes (Skaggs, 1978)

The basic relationship in the model is a water balance for a thin section of soil of unit surface area which extends from the impermeable layer to the surface and is located midway between adjacent drains. The water balance for a time increment of Δt may be expressed as:

$$\Delta V = D + ET + DS - F$$

where ΔV, is the change in the water free pore space or air volume, cm; D is the drainage, cm; from the section; ET is the evapotranspiration, cm; DS is the deep seepage, cm; and F is the infiltration, cm, entering the section in Δt. DRAINMOD uses functional algorithms to approximate the hydrological components of shallow water table soils, and is capable of predicting hourly ground water fluctuations (h), drainage discharges (q) and drainage water salinity levels.

5.2.3 Model components

5.2.3.1 Precipitation

Precipitation records are one of the major inputs of DRAINMOD. The accuracy of the mode1 prediction for infiltration, runoff and surface storage is dependent on the complete description of rainfall or irrigation events. Therefore, a short time increment for rainfall or irrigation input data will allow better estimates of these model components than will less frequent data. Hourly rainfall data are readily available for many locations in South Africa even though shorter duration rainfall records may be available for other locations.

5.2.3.2 Infiltration

Infiltration is affected by soil factors such as hydraulic conductivity, initial water content, surface compaction, depth of soil profile, and water table depth; plant factors such as extent of cover and depth of root zone; and rainfall and/or irrigation factors such as intensity, duration, and temporal distribution of rainfall.

Methods for characterizing the infiltration process have concentrated on the effects of soil factors and have generally assumed the soil system to be a fixed or undeformable matrix with well-defined hydraulic conductivity and soil water characteristic functions. Under these assumptions and the additional assumption that there is negligible resistance to the movement of displaced air, the Richards equation maybe taken as the governing relationship for the process. For vertical water movement, the Richards equation may be written as:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] - \frac{\partial K(h)}{\partial z}$$

where h is the soil water pressure head, cm; z is the distance below the soil surface, cm; t is time, hr; K(h) is the hydraulic conductivity function and C(h) is the water capacity function which is obtained from the soil water characteristics. The effects of rainfall rate and time distribution, initial soil water conditions, and water table depth are incorporated as boundary and initial conditions in the solution of the above equation.

Although the Richards equation provides a rather comprehensive method of determining the effects of many interactive factors on infiltration, input and computational requirements prohibit its use in DRAINMOD. This is because it is nonlinear and must be solved by numerical methods requiring time increments in the order of a few seconds. The computer time required by such solutions would clearly be prohibitive for long term simulations covering several years of record. Nevertheless, these solutions can be used to evaluate approximate methods and, in some cases, to determine parameter values required in these methods.

5.2.3.3 Surface drainage

Surface drainage is characterized by the average depth of depression storage that must be satisfied before runoff can begin. Surface storage could be considered as a time dependent function or to be dependent on other events such as rainfall and the time sequence of ti1lage operations. Therefore, the variation in the depression storage during the year can be simulated. However, it is assumed to be constant in the DRAINMOD model.

5.2.3.4 Subsurface drainage

The rate of subsurface water movement into drain tubes or ditches depends on the hydraulic conductivity of the soil, drain spacing and depth, soil profile depth and water table elevation. Water moves toward drains in both the saturated and unsaturated zones and can best be quantified by solving the Richards equation for two-dimensional flow.

DRAINMOD calculates drainage rates based on the assumption that lateral water movement occurs mainly in the saturated region. The effective horizontal saturated hydraulic conductivity is used and the flux is evaluated in terms of the water table elevation midway between the drains and the water level or hydraulic head in the drains. Several methods are available for estimating the drain flux. However, Hooghoudt's steady state equation is selected for use in DRAINMOD. Because this equation is used for both, drainage and sub-irrigation flux, a brief derivation is given below.

Consider steady drainage due to constant rainfall or irrigation at rate, R, as shown schematically in Figure 5-3. Considering flow in the saturated zone only, flux per unit width can be expressed as:

$$Q = -Kh\frac{dh}{dx}$$

where K is the horizontal or lateral saturated hydraulic conductivity and h is the height of the water table above the impermeable layer. From conservation of mass we know that the flux at any point x is equal to the total rainfall between x and the midpoint, x = L/2**.**

$$-Kh\frac{dh}{dx} = -R\left(\frac{L}{2} - X\right)$$

where the negative sign on the right hand side of the equation is due to the fact that flow to the drain at x = 0 is in the negative x-direction. Separating variables and integrating the equation subject to the boundary conditions h = d at x = 0 and h = d + m at x = L/2 yields and expression for R in terms of the water table elevation at the midpoint as:

$$R = \frac{4K(2md + m^2)}{L^2}$$

Although drainage is not a steady state process in most cases, a good approximation of the drainage flux can be obtained from the above equation. The equation for drainage flux may therefore be written as:

$$q = \frac{8Kd_e m + 4Km^2}{CL^2}$$

where q is the discharge flux, $cm.hr^{-1}$; m is the midpoint water table height above the drain, m; K is the effective lateral hydraulic conductivity, m/day; and L is the distance between the drains, m; C to be equal to the ratio of the average flux between the drains to the flux midway between the drains, (-).

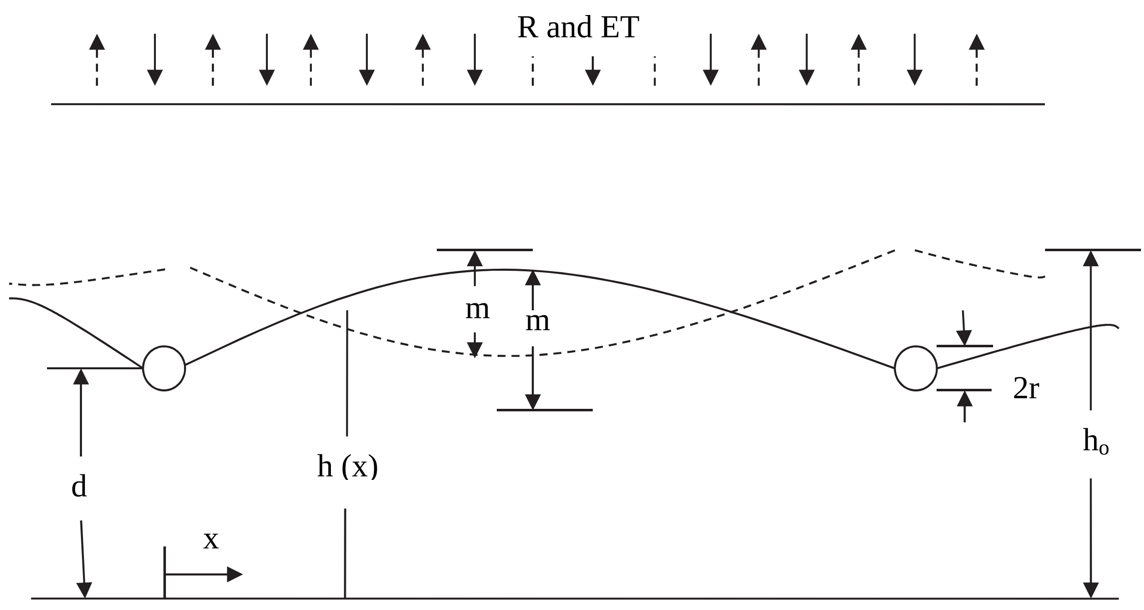


Figure 5-3: Water table drawdown to and sub-irrigation from parallel drain tubes (Skaggs, 1978)

5.2.3.5 Sub-irrigation

When sub-irrigation is used, water is raised in the drainage outlet so as to maintain a pressure head at the drain of h_0 (refer to the broken curve in Figure 5-3). If the boundary condition $h = h_0$ at $x = 0$ is used in solving the equation above, the equation corresponding to that for flux is:

$$q = \frac{4K}{L^2}(2h_0m + m^2)$$

where m is always defined as water table elevation midway between the drains minus the equivalent water table elevation at the drain, h_0, in this case. Therefore, for sub-irrigation m is negative as is the flux.

5.2.3.6 Evapotranspiration

The determination of evapotranspiration (ET) is a two-step process in DRAINMOD. First the daily potential evapotranspiration (PET) is calculated in terms of atmospheric data and is distributed on an hourly basis. The PET represents the maximum amount of water that will leave the soil system by evapotranspiration when there is a sufficient supply of soil water. The DRAINMOD model distributes the PET at a uniform rate for 12 hours. In case of rainfall, hourly PET is set equal to zero for any hour in which rainfall occurs. After PET is calculated, checks are made to determine if ET is limited by soil water conditions. If soil water conditions are not limiting, ET is set equal to PET. When PET is higher than the amount of water that can be supplied from the soil system, ET is set equal to the smaller amount. Methods used for determining PET and the rate that water can be supplied from the soil water system are discussed be1ow.

Potential ET depends on climatological factors which include net radiation, temperature, humidity and wind velocity. Evapotranspiration can be directly measured with lysimeters or from water balance-soil water depletion methods. However, such measurements are rarely available for a given time and location and most PET values are obtained from climatological data using one of the many estimation methods. The method selected for use in the DRAINMOD model is the empirical method developed by Thornthwaite (1948). The PET is computed in the main program of DRAINMOD from recorded daily maximum and minimum temperature values.

5.2.3.7 Soil water distribution

Methods used to evaluate the individual components such as drainage and ET depend on the position of the water table and the soil water distribution in the unsaturated zone. One of the key variables determined at the end of every water balance calculation in DRAINMOD is the water table depth. The soil water content below the water table is assumed to be essentially saturated; actually it is slightly less than the saturated value due to residual entrapped air in soils with fluctuating water tables.

Water is removed from the profile by ET which results in water table drawdown and changes in the water content of the unsaturated zone. In this case the vertical hydraulic gradient in the unsaturated zone is in the upward direction. However when the water table is near the surface, the vertical gradient will be small and the water content distribution still close to the equilibrium distribution.

For purposes of calculation in DRAINMOD, the soil water is assumed to be distributed in two zones – a wet zone extending from the water table up to the root zone and possibly through the root zone to the surface, and a dry zone. The water content distribution in the wet zone is assumed to be that of a drained to equilibrium profile. When the maximum rate of upward water movement, determined as a function of the water table depth, is not sufficient to supply the ET demand, water is removed from root zone storage creating a dry zone.

5.2.3.8 Rooting depth

The effective rooting depth is used in the DRAINMOD model to define the zone from which water can be removed as is necessary to meet ET demands. Rooting depth is read in to the model as a function of Julian date. Since the simulation process is usually continuous for several years, an effective depth is defined for all periods. When the soil is fallow the effective depth is defined as the depth of the thin layer that will dry out at the surface. When a second crop or a cover crop is grown its respective rooting depth function is also included.

The depth and distribution of plant roots is affected by many factors in addition to crop species and date after planting. These factors include physical barriers such as hardpans and plow pans, chemical barriers, fertilizer distribution, tillage treatments and others. One of the most important factors influencing root growth and distribution is soil water. This includes both depth and fluctuation of the water table as well as the distribution of soil water during dry periods. Since the purpose of the model is to predict the water table position and soil water content, DRAINMOD includes the complex plant growth processes.

5.2.4 Simulation model inputs required

5.2.4.1 Drainage design parameters

Design water table depth (z), hydraulic head (h) and drain discharge (q) are the three drainage design parameters that are generally considered in assessing the extent to which a subsurface drainage system achieves its design objectives as shown in Figure 5-4.

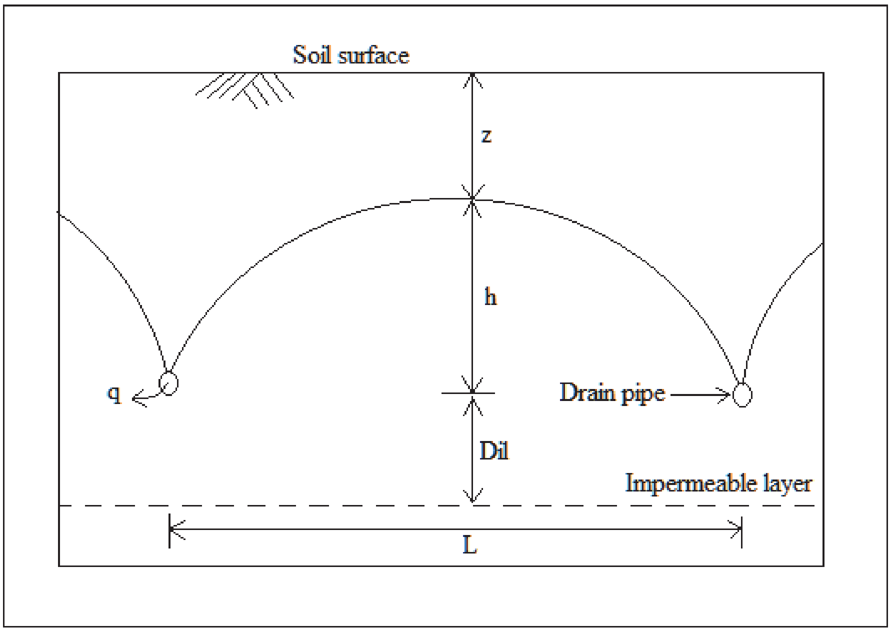


Figure 5-4: Subsurface drainage design parameters (after Smedema and Rycroft, 1983)

(a) Drain depth (z + h)

This is the depth of placement of drain pipes from the soil surface. The drain depth is limited by soil conditions (unfavourable soil hydrological/mechanical conditions may occur at some soil depth), the available machinery (few machines go beyond 2.5 m) or the cost/benefit ratio.

(b) Drain spacing (L)

The horizontal distance between the drain pipes. Since L depends on h and h in turn depends on L, Hooghoudt formula is not explicit in L and can be solved through trial and error, graphically from a nomograph or by the DRAINMOD model.

(c) Depth to impermeable layer (Dil)

This is the depth of the impermeable layer from the drain pipe depth. Depth to the impermeable layer is defined differently by different authors but generally if the (vertical) hydraulic conductivity of the soil layer decreases by about 10x that of the layer above, then an impermeable layer is taken as to be in existence.

(d) Drain discharge (q)

This defines the water flux that enters and exits the drain pipe. Under steady state conditions, the discharge q equates to the water input into the system by rainfall (R) and the water table remains in a fairly stable position, whereas under none steady state (transient) conditions q and R do not equate (except maybe for very brief periods) thus the water table is always fluctuating – rising or falling.

(e) Drain pipe type and radius (r)

Drain pipe radius defines the cross-sectional area of the drain pipe. Drain pipe radius is derived from the drain discharge. Drain pipes should be designed to carry safely the peak discharge which usually occurs for a short duration after each rainfall or irrigation event. This is determined as the discharge of the drainage system under its maximum water table.

(f) Water table depth (z)

Water table is the surface where the water pressure head is the atmospheric pressure. Its position is the shallowest depth to a wet soil layer (water table) at any time during the year from the soil surface. For design and operational purposes, the important water table depth is that which exists halfway between any two drains because it is highest at this point. If crop drainage conditions are satisfied at this point, then elsewhere in the system drainage requirements will have been met. Thus in most modelling exercises, a key output of the model is the water table height between any two drains in a given drainage system.

5.2.4.2 Weather data parameters

The weather parameters for Drainmod comprise the rainfall (precipitation) (P), irrigation (I), daily temperature (T) and potential evapotranspiration (PET).

(a) Rainfall (precipitation)

Rainfall is a major input into Drainmod as it represents water input into the system that is being modelled. It is this water input (recharge) in a cropped land system that results in high water tables if not removed fast enough. For most modelling exercises, long term rainfall data from nearby weather stations will be used. Measured rainfall from rain gauges at the study site will be used for the direct seasonal water table fluctuation monitoring.

(b) Irrigation (I)

Irrigation, just like rainfall, is also taken as a key input into any system to be modelled as it represents another form of recharge into the cropped land system. Historical records from farmers' irrigation activities will be used for long term modelling, and actual irrigation amounts will be measured using rain gauges at the study sites for the seasonal water table fluctuation modelling.

(c) Temperature (T)

Temperature data in Drainmod is required for the calculation of the potential evapotranspiration (PET) which is a major measure of water output from a cropped land system that is being modelled. Typically, maximum and minimum daily temperatures are required for Drainmod. Temperature data will be obtained, at the right temporal scale, from local weather stations. South Africa has a wide network of weather stations that have good quality data for use in Drainmod. If required for the seasonal modelling exercise, temperature data can be measured directly at the study sites, but this could limit the scope and scale of Drainmod modelling.

(d) Evapotranspiration (ET)

Evapotranspiration is a measure of the amount of water lost from a system through the combined processes of direct evaporation (from the soil, open water surfaces and crop foliage) and transpiration (from crop). ET is normally obtained from calculated values of PET combined with a crop factor for a given crop and crop growth stage. For modelling purposes, crop information like crop type, planting dates, and crop growth stages will be used to obtain the appropriate Kc values that will then be combined with PET to determine ET. Data from farmer operations, local weather stations as well as FAO CLIMWAT files will be used.

5.2.4.3 Soil input parameters

For Drainmod, the soils data required consist of soil water characteristics (0h), soil saturated hydraulic conductivity (K_{sat}) and the thickness of the soil layers (in a layered soil).

(a) Soil water characteristics (θ(h))

Soil water characteristics data (soil moisture characteristic curve) for the top soil layer are required for Drainmod as these are used in the soil water balance calculations. The typical soil water characteristics data are approximated by Soil Physics equations like the Brooks and Corey or the Van Genuchten (1992).

(b) Saturated hydraulic conductivity (K_{sat})

The hydraulic conductivity of the soil depends mainly on the geometry and distribution of the water-filled pores. The hydraulic conductivity of a soil may vary across an area as well as in depth due to variations in soil texture and soil structure. The saturated hydraulic conductivities of the main layers of the soil profile are very important in Drainmod because they are key components of the one-dimensional Hooghoudt's steady state drainage equation used in Drainmod. Saturated hydraulic conductivity determines to a large extent the rate of soil water movement in both the vertical and horizontal directions – flow above and below the drains.

(c) Soil layer thickness

Soil layering and soil layer(s) thickness is required in the determination of rate of water movement in the soil for input into the Hooghoudt's equation that is central to Drainmod. For layered soil, Hooghoudt's equation requires different K_{sat} values per soil layer for soil layers above and below the drains. If the soil is homogenous, then only a single K_{sat} value is required. Soil layering will be measured by digging soil pits and observing any significant layering, then measuring the thickness of each of these layers and collecting soil cores to determine K_{sat} or permeability.

5.2.5 Model inputs measurement

5.2.5.1 Study approach

The study approach is as shown in Figure 5-5.

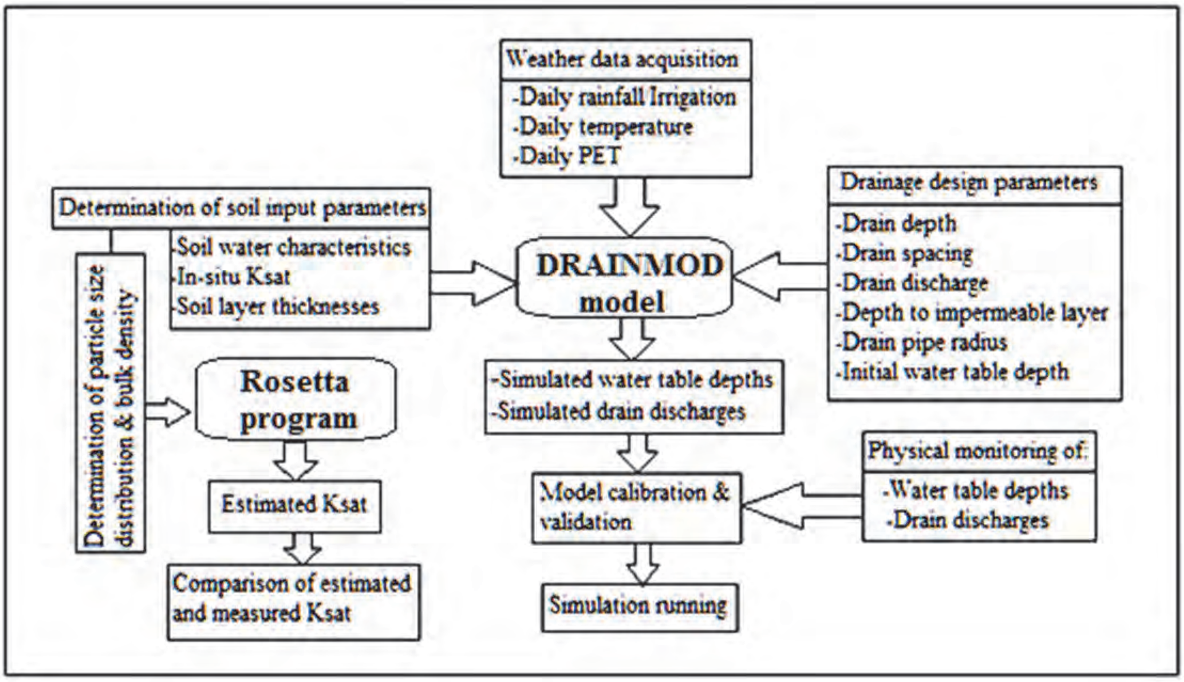


Figure 5-5: Flow diagram of the study approach (adapted from Malota, 2012)

5.2.5.2 Measurement of water table depths and drain discharges

Coming up withan appropriate sampling density that will give a true representation of a parameter under study is the first step towards obtaining reliable results. For water table mapping in agricultural lands, FAO (1999) recommends a sampling density of four piezometers per 50 ha to be adequate. However, recent studies by FAO (2007) indicate that such a sampling density is still not adequate in water table mapping, considering the spatial variation in the soil physical and chemical properties within a given area. FAO (2007) therefore recommends 5-10 piezometers per 50 ha to be adequate. In this study, for the Pongola area, a total of 36 piezometers, installed at 54 x 54 m grid nodes on a 32 ha field shall be used. This translates to 55 piezometers per 50 ha, which is far more than the minimum sampling density suggested by FAO (2007).

The piezometers will be manually augured using a 70 mm outside diameter auger to a depth of 1.7 m from the soil surface. A 50 mm internal diameter, class 4 PVC pipe with perforations, will be lowered in each piezometer to a depth of 1.7 m, while ensuring that a 30 cm length is above the ground level to prevent runoff water from flowing in. End caps will be fitted to both ends of the pipe to prevent the intrusion of materials into the piezometer. To prevent clogging of the perforations, coarse sand will be backfilled throughout the whole perforated section of pipe.

Water table depths at each piezometer will be determined by gradually lowering an electronic dip meter in the piezometer until a beep sound is heard. Figure 5-6 below is a detailed cross-section of one of the piezometers.

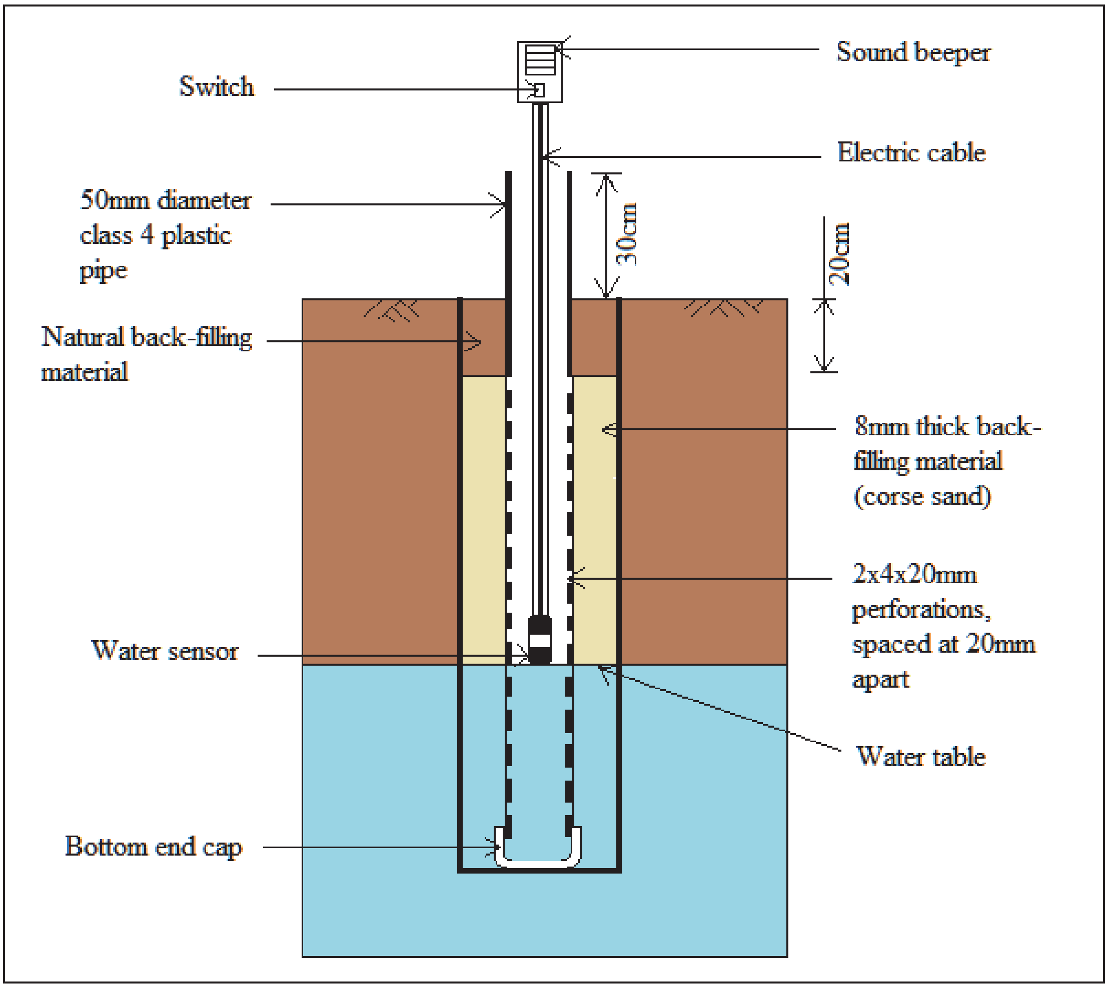


Figure 5-6: Piezometer cross-section equipped with electronic dip meter (adapted from Malota, 2012)

Water table depths shall be monitored every day for, but may be adjusted depending on rainfall frequency in the area.

The latitudes and longitudes of all the locations of the piezometers will be determined using a GPS. Average WTDs at each piezometer will be calculated and recorded.

Surfer8 software will be used to generate a water table map for the site. Shallow water table affected areas shall be classified based on the design water table depth which the subsurface drainage system at the site was designed to maintain. Using this design water table depth, areas with WTD shallower than the design water table depth shall be considered to be affected, while those with greater from the soil surface will be considered not to be affected.

To determine the effect of drainage conditions on water table depth (i.e. subsurface drainage system maintenance level and presence and absence of artificial subsurface drainage systems), out of the 36 piezometers installed in well maintained drainage systems, six will be installed mid-way between drainage laterals. Similarly, in field with poorly maintained drainage systems, six piezometers will also be installed mid-way between drainage laterals, while the same will be done with six piezometers being installed in no drainage system, since there is no subsurface drainage system on it. Figure 5-7 is a schematic view of the locations of the piezometers mid-way between drainage laterals.

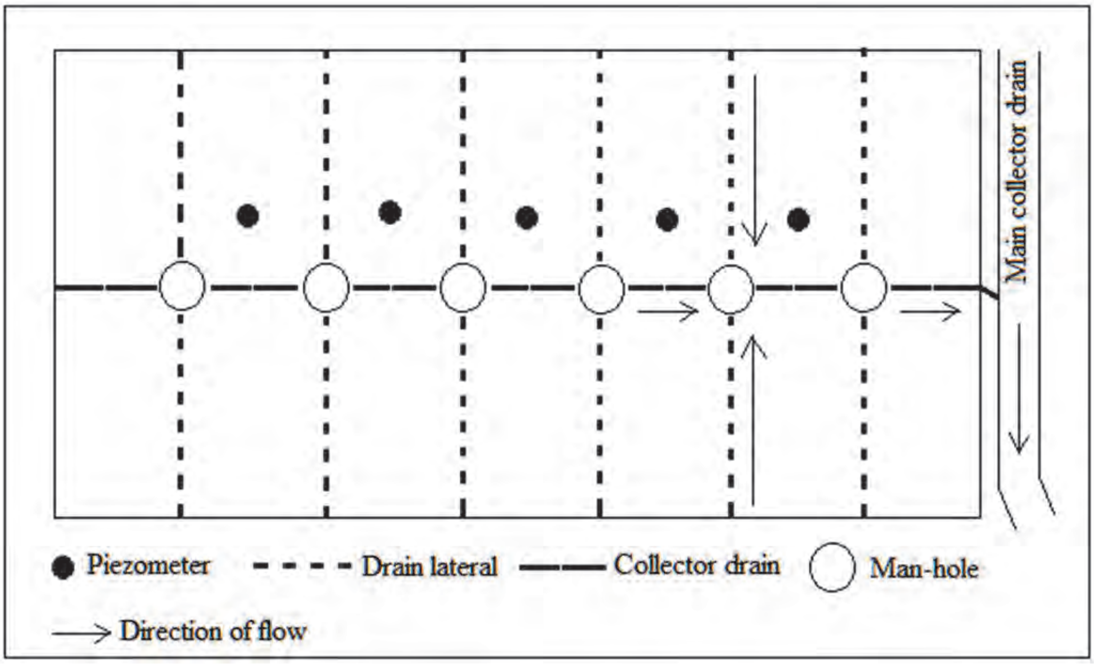


Figure 5-7: Layout of piezometers at mid-span spacing (adapted from Malota, 2012)

Drainage discharges (*q*) in mm.day^{-1} will be measured manually at three drainage outlet points (man-holes) in well maintained drainage system, using a bucket and clock.

Firstly, drainage discharges will be measured in $l.sec^{-1}$ and then converted to $mm.day^{-1}$ using:

$$q = \frac{86400l}{A} = \frac{86400l}{SL}$$

Where q is the drainage discharge ($mm.day^{-1}$); l is the measured discharge ($l.sec^{-1}$); A is the drained area (m^2);L is the drain spacing (m), and S is the drain length (m).

5.2.5.3 Measurement of saturated hydraulic conductivity (K_{sat})

Soil hydraulic conductivity (K_{sat}) values will be measured using the in situ method, i.e. the auger-hole method (Van Beers, 1983), which according to Oosterbaan and Nijland (1994), is the most accurate and yet the simplest method, as opposed to laboratory methods. Prior to carrying out K_{sat} tests, five trenches will be dug in the field (north, south, east, west and center). This is done to characterize any heterogeneities in soil layer boundaries and to determine the number and thicknesses of the soil profile layers from the soil surface. The field will then be divided into three sections (upper, middle and lower sections). Three 70 mm diameter auger-holes will be drilled in each of the upper and middle sections, while four auger-holes will be drilled in the lower section. This makes a total of 10 auger-holes drilled in the whole field and is done to determine the best possible mean K_{sat} value that could represent the whole field during model calibration, as recommended by Sobieraj et al*.* (2001).The measurement procedure to be followed during the K_{sat} test is given by Van Beers (1983).

About five readings will be taken successively at each auger-hole and average changes in water table depths (cm) per unit time (sec) will then be calculated and recorded. Saturated hydraulic conductivity values in $m.day^{-1}$ will be computed as (Ernest, 1950):

$$K_{sat} = \frac{400a}{(20 + h/a)(2 - y/h)y} \frac{\Delta y}{\Delta t}$$

where Δy is the rise in water level during the test, cm; Δt is the time taken for rise in water level measurement, sec; a is the radius of the auger-hole, cm; h is the depth of the water table to the bottom of the auger-hole (cm); y is the depth of water table to the beginning of the test reading, cm. Figure 5-8 below is a section of one of the auger-holes, during the K_{sat} measurement, using the auger-hole method.

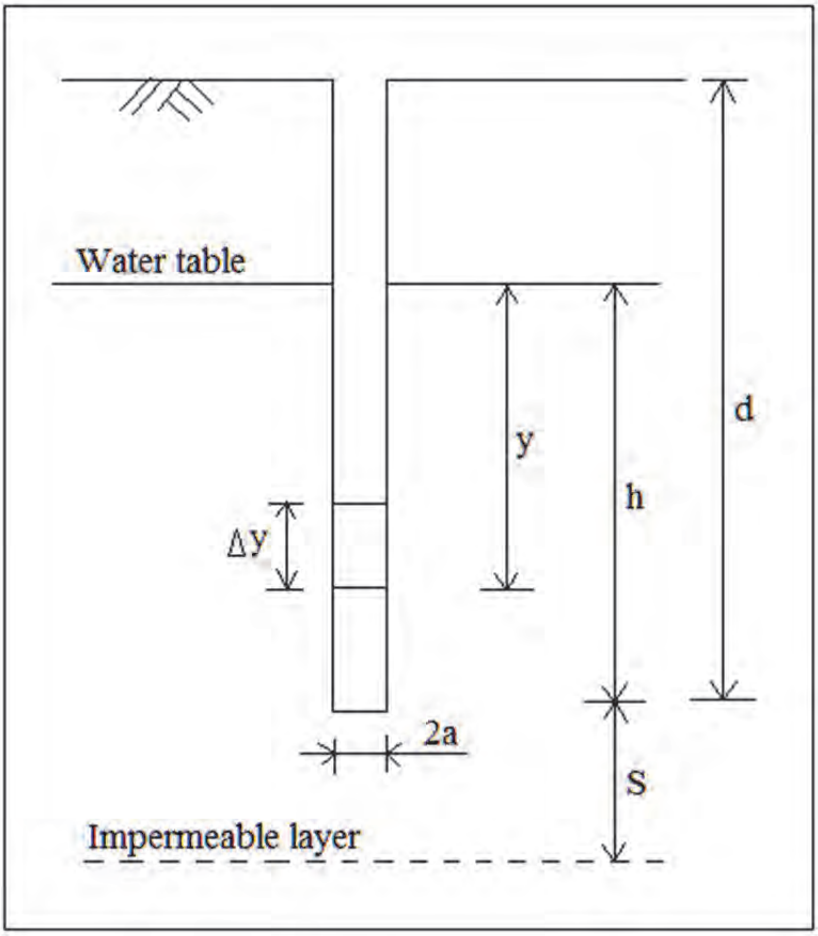


Figure 5-8: Section through an auger-hole

5.2.5.4 Soil particle distribution and estimation of K_{sat} values using the Rosetta program

Saturated hydraulic conductivity values will also be estimated using the Rosetta program, based on soil particle size distribution (% sand, silt and clay) and soil bulk density ($g.cm^3$).This program will be chosen because Schaap et al*.* (2001) and Salazar et al*.* (2008) found that it can effectively estimate K_{sat} values from the aforementioned easily accessed soil data. In addition to estimating K_{sat} values, the Rosetta program is also capable of predicting the Van Genuchten (1980) soil water retention ($\theta(h)$) and unsaturated hydraulic conductivities (K) (Schaap et al*.,* 2001). According to Schaap and Leij (1998) and Schaap et al*.* (2001), the Van Genuchten water retention model is given by:

$$\theta(h) = \frac{\theta_s + \theta_r}{[1+(\alpha h)^n]^{1-1/n}} \qquad h<0$$

$$\theta(h) = \theta_s \qquad h>0$$

Where θ_s and $\theta_r$are saturated and residual moisture content, $cm^3.cm^{-3}$, respectively; his the soil water pressure head, cm at a given soil moisture content; n (>1)is the measure of pore-size distribution and α (>0) is related to the inverse of air entry pressure, cm^{-1} (Van Genuchten, 1980).

Using the above equations, in juxtaposition with the Mualem (1976) pore-size distribution model yields the Van Genuchten-Mualem model, which according to Van Genuchten (1980) and Schaap et al. (2001), is then used to estimate the K_{sat}values. According to Schaap and Leij (1998) the Van Genuchten-Mualem model is given by:

$$K(S_e) = K_0 S_e^L \left\{1 - \left[1 - S_e^{n/(n-1)}\right]^{1-(1/n)}\right\}^2$$

where S_e is the effective saturation, $cm^3.cm^{-3}$ and is given as:

$$S_e = \frac{\theta(h) - \theta_r}{\theta_S - \theta_r} = [1 + (\alpha h)^n]^{1/(n-1)}$$

Where K_0 is the matching point at saturation, $m.day^{-1}$ and is comparable, but not entirely equal to K_{sat}; L (<0) is an empirical connectivity parameter in most cases assumed to be 0.5 (Mualem, 1976).

Undisturbed soil samples will be collected from the locations, where auger-hole tests will be conducted (Section 3.3.4). The samples will be collected within the same soil layer in which the water table rests during auger-hole tests. Soil bulk densities will be determined first followed by the soil particle size analysis, using the standard sieve-pipette method (Gee and Bauder, 1986).

The soil samples will be air-dried, crushed and sodium pyrophosphate added as a dispersing agent. The soil sample is passed through a 2 mm sieve to determine the sand fraction (>0.053 mm). The pipette method will be done then after to determine the silt (0.002-0.053 mm) and clay (<0.002 mm) fractions, based on the Stokes Law (Lamb, 1964). The soil particle size analysis will be done at the University of KwaZulu-Natal Soil Science laboratory.

The soil particle size distribution data and bulk densities, $g.cm^{-3}$ will be inputted into the Rosetta program to estimate K_{sat} values for each of the land units where the samples were collected. The in-situ measured K_{sat} values will be compared to the

Rosetta estimated K_{sat} values. Three statistical parameters will be used to characterize the K_{sat} estimation performance of the program, namely, the Mean Absolute Error (MAE) (Equation below) (El-Sadek, 2007), the Pearson's product-moment correlation (R^2) (equation below) (Wang et al*.,* 2006), also known as the Goodness of fit (Shahin et al*.,* 1993; Legates and McCabe, 1999; Vazquez et al*.,* 2002) and the Coefficient of Residual Mass (CRM) (Equation below) (El-Sadek, 2007). These three statistical parameters are chosen because, according to Anderson and Woessner (1992) and Vazquez et al*.* (2002), they provide both quantitative and objective justifications in assessing the performance of a model in estimating a particular soil property.

$$MAE = \frac{\sum_{i=1}^{N} \left|(O_i - P_i)\right|}{N}$$

$$R^2 = \left[\frac{\sum_{i=1}^{N} (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{N} (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^{N} (P_i - \bar{P})^2}} \right]^2$$

$$CRM = \frac{\sum_{i=1}^{N} O_i - \sum_{i=1}^{N} P_i}{\sum_{i=1}^{N} O_i}$$

where P_i is the simulated value, O_i is the observed value, and N is the number of data entries.

MAE describes the accuracy of a model in making right predictions by measuring the average magnitude of errors between the simulated and the observed values (Shahin et al*.,* 1993; Legates and McCabe, 1999; Vazquez et al*.,* 2002). According to Moraisi et al*.* (2007) and El-Sadek (2007), the MAE has a minimum value of 0.0, with values closer to 0.0 indicating a better agreement between measured and estimated values. The Goodness of fit measures how the estimated and measured data sets correlate and has minimum and maximum values of 0.0 and 1.0, respectively, with values closer to 1.0 indicating a better correlation between the two data sets (Shahin et al*.,* 1993; Legates and McCabe, 1999; Vazquez et al*.,* 2002). On the other hand, CRM characterizes the model's tendency to over-estimate (CRM<1) or under-estimate a property (CRM>1) (El-Sadek, 2007).

5.2.5.5 Measurement of soil water characteristics θ(h)

The DRAINMOD model requires the following relationships in order for it to establish a soil water balance: (i) water table depth and volume of water drained (ii) water table depth and upward flux and (iii) Green Ampt infiltration parameters and recharge (Singh et al., 2006). According to Skaggs (1978), the model calculates these parameters from the soil water characteristic data of the top soil layer, i.e. residual moisture content (θ) versus soil water pressure heads (*h*).

Soil water pressure heads, m, and their respective soil moisture contents, $cm^3.cm^{-3}$ will be measured using a pressure plate at the University of KwaZulu-Natal School of Engineering laboratory. Richards (1948) and Klute (1986) found out that the pressure plate laboratory method can reliably measure soil water characteristics, when undisturbed soil samples are used.

Undisturbed soil samples will be collected from the upper soil layer (0-40 cm) using 50 mm internal diameter and 50 mm long stainless steel rings. Refer to Figure 5-9 for the description of the laboratory set up.

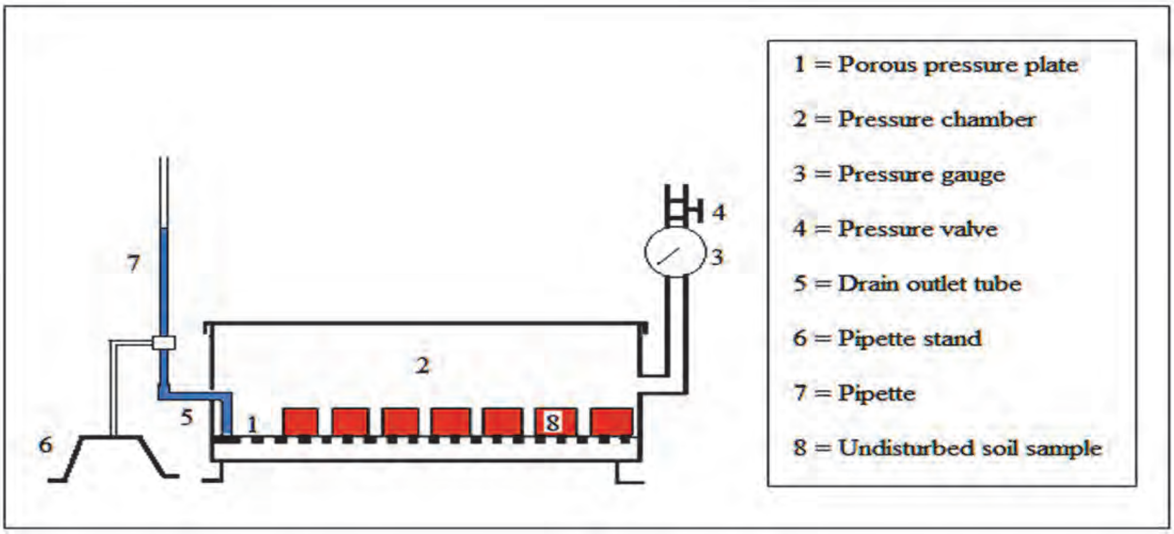


Figure 5-9: Schematic representation of pressure plate (after Warrick, 2000) (Malota, 2012)

Firstly, the soil cores and the porous pressure plate will be fully saturated in a vacuum chamber for two to three days, after which, the soil cores will be weighed without subjecting them to any pressure. The soil cores will then be placed on the porous plate in the pressure chamber and tightly closed. A 10 m pressure is set by loosening the pressure valve to increase the pressure in the pressure chamber to the set pressure, so that water can drain out of the soil sample, as a result of the applied pressure. The rise in water level draining from the soil samples through the pipette is left to stabilize, after which, the soil cores will then be removed from the pressure chamber, weighed and placed back in the pressure chamber. The applied pressure is then increased and the same procedure followed for increased pressures of 20, 40, 110 and 150 m. The 0 to 150 m pressure range will be chosen because Skaggs (1978) highlights that the DRAINMOD model requires the very last soil moisture content ($cm^3.cm^{-3}$) to be calculated, after subjecting a soil sample to a pressure of ≥10 m, while the rest of the soil water contents can be calculated after subjecting the soil samples to smaller pressures.

The soil cores will be oven-dried at 105°C for 24 hours and the soil water contents at each respective pressure setting will be calculated as:

$$\theta_v = W_i \frac{\rho_{soil}}{\rho_{water}}$$

Where θ_v is the volumetric soil water content $cm^3.cm^{-3}$; W_i is the soil water content by mass, $g.g^{-1}$ (wet basis); ρ_{soil} is the bulk density of the soil sample, $g.cm^{-3}$, ρ_{water} is the density of water, $g.cm^{-3}$ (Warrick, 2000).

The Van Genuchten soil water retention model will be fitted to the measured $\theta(h)$ data, using the RETC program (Van Genuchten et al*.,* 1992) – a HYDRUS-2D soil water retention optimization program. In addition, mean moisture contents, $cm^3.cm^{-3}$ and their respective pressure heads (0-150 m) will be calculated and imputed in DRAINMOD 6.1.

5.2.5.6 Weather data acquisition

Long period (say 15 years) weather data (daily rainfall, potential evapotranspiration, and minimum and maximum temperatures) shall be obtained from nearby weather stations having long period databases. DRAINMOD weather file requires the inclusion of the irrigation component, $mm.day^{-1}$, in the rainfall input file to account for any recharge to the soil system due to irrigation. Therefore, depths of irrigation water per irrigation event shall be measured using a rain gauge to be installed at the study sites. Were required historical irrigation data from farmers or irrigation managers will be acquired and used in the Drainmod model.

5.2.6 DRAINMOD model calibration and evaluation

Calibration is the process whereby default model input parameters are systematically adjusted to attain the best possible agreement between simulated and observed data sets, whereas validation is the process of testing the model's reliability in making appropriate predictions based on the calibrated parameters (Singh et al*.,* 2006). It is recommended that two independent data sets be used during the calibration and validation periods, in order to avoid ambiguities when making recommendations concerning the model's dependability (Schaap et al*.,* 2001; Dayyani et al*.,* 2009; Dayyani et al*.,* 2010).

Literature shows that the DRAINMOD model can be calibrated on a trial-and-error basis (Dayyani et al*.,* 2010), by adjusting any or a set of input parameters presented in Table 5-1, until an optimal agreement between observed and simulated data sets is attained.

Table 5-1: DRAINMOD model calibration parameters based on literature

Calibration parameter(s)	**Source(s)**
Lateral hydraulic conductivity, maximum soil surface storage depth, crop root depth	Zhao et al. (2000)
Monthly ET factors	Jin and Sands (2003)
Drainage coefficient, saturation soil water content, residual soil water content, lateral saturated hydraulic conductivity of soil layers	Haan and Skaggs (2003) Singh et al. (2006)
Vertical hydraulic conductivity of the bottom soil layers	Wang et al. (2006)

The lateral saturated hydraulic conductivity ($K_{L\text{-}sat}$) for the bottom soil layer will be set at twice the vertical saturated hydraulic conductivity (K_{sat}), while $K_{L\text{-}sat}$ for the top soil layer will be set equal to the K_{sat}, as suggested by Skaggs (1978).

Time series simulations of water table depths and drain depths will be run, using the DRAINMOD model after every alteration of an input parameter or set of parameters. Simulated water table depths and drain depths will then be compared to observed water table depths and drain depths. Initially, the agreement between the two data sets will be assessed by mere visual judgments from water table depth and drain depth hydrographs (Moraisi et al., 2007; Dayyani et al*.,* 2009), and later on, quantitative statistical model performance parameters (Equations above) will be employed, as suggested by Legates and McCabe (1999) and Vazquez et al. (2002).

5.3 SMsim Model

5.3.1 Background

The main objective of the SMsim model (SMsim – micro-economic simulation model) is to improve the financial sustainability of irrigated agriculture while at the same time ensuring social and environmental sustainability. The model holistically integrates the bio-physical components/processes (including the hydrology) involved in irrigation salinisation into a long term (dynamic) economic model. A further objective of the model is to achieve financial sustainability using existing hydrological and biophysical models as much as is possible and build on the salinity economics work already done in another model called SALMOD (Armour, 2007).

5.3.2 SMsim model data requirements

The Armour financial model to be used in this project is adequately described above and will not be repeated here.

5.4 SWAMP Model

5.4.1 Background and concepts

The **S**oil **W**ater **M**anagement **P**rogram, SWAMP (Bennie et al., 1998) was selected to assist in determining the drainage component of the soil water balance in selected plots located in the Vaalharts Irrigation Scheme. Swamp is a local model which was recently calibrated and validated for water uptake from shallow water tables under field crops such as maize, wheat, groundnuts and peas (Van Rensburg et al., 2012). The field-lysimeter validation results showed that the model is able to estimate the interaction between water drained from the unsaturated root zone to the water table (downwards drainage) and water table uptake through capillary (upwards drainage). Barnard (2012) also demonstrated with case studies from Vaalharts how the model can be used in real world situations to assess irrigation and drainage practices.

A detailed mathematical description of how the different soil water balance components of the SWAMP model are estimated is given by Bennie et al. (1998), Ehlers et al. (2003) and Van Rensburg et al. (2012). Accordingly, a flow diagram linking the different subroutines in SWAMP is presented in Figure 5-10. The gains (rainfall, irrigation and capillary rise) are directly coupled to the soil water content and also the processes that caused water losses (evaporation from the soil, runoff and transpiration). Rainfall and irrigation are input parameters from which runoff can be estimated if present. Estimation of evaporation from a bare soil surface is based on the principle that empirical coefficients, for the Rose and Ritchie equations, are calculated from soil water content and particle size distribution inputs. The evaporation rate or cumulative evaporation is calculated with these equations on a daily basis from the time it rained or when the soil was irrigated. Calculation of evaporation from covered soil surfaces initially follows the same procedure as described above. To reduce the calculated cumulative evaporation, a factor equal to one minus the fractional shading of the soil surface is used.

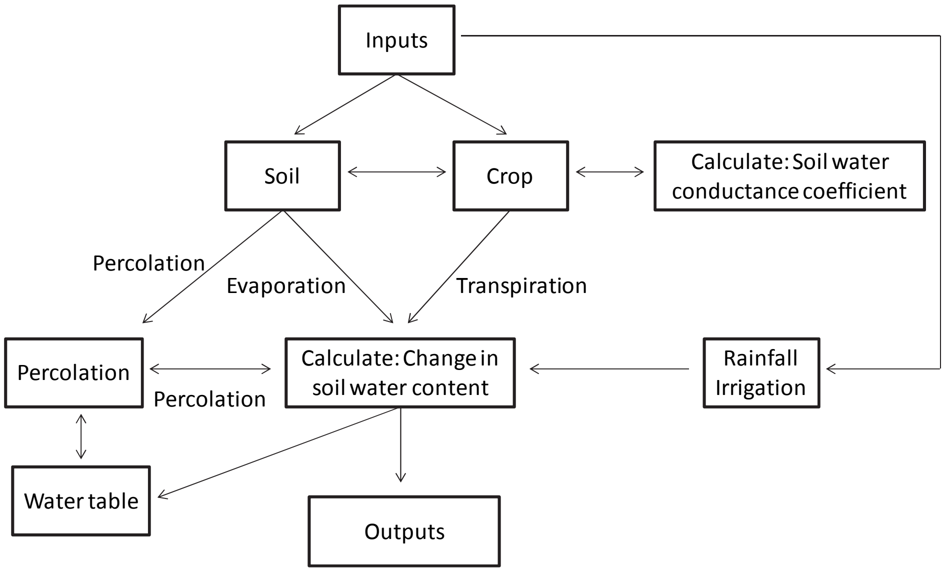


Figure 5-10: Flow diagram of the SWAMP model showing the interaction between the different subroutines

When present, the contribution of a water table to daily transpiration is simulated according to the upward cascading approach, where the maximum upward flux from the water table is related to a specific height above the water table. The sum of the daily water uptake from all the layers within the capillary zone is taken as the total contribution of the water table to the daily crop transpiration. This happens only when daily transpiration or root water uptake is less than the maximum upward flux rate through a layer. When daily transpiration or root water uptake is more than the maximum upward flux rate through a layer, daily water table uptake is equal to the maximum upward flux rate.

The infiltrated water through rain or irrigation is divided between the soil layers with the cascading principle, according to which the soil layers are wetted from the top to the drained upper limit (DUL). Excess water is transported downwards within the soil profile as percolation (Hillel, 1998), until the last soil layer is reached. Water that percolates beyond this depth is seen as deep percolation or deep drainage. In the absence of a water table and when the soil is wetter than the DUL, SWAMP uses a logarithmic drainage curve to calculate deep percolation:

$$\mathbf{DR = \frac{a}{exp^{\frac{(b-W)}{a}}}}$$

where DR = drainage rate (mm day^{-1})

W = soil water content of potential root zone (mm)

a and b = drainage coefficients, depending on soil texture.

Coefficients for the drainage curves are obtained from the mean silt-plus-clay content of the potential root zone. These coefficients were determined for soils with silt-plus-clay contents that ranged from 16 to 47%.

$$\mathbf{a = 45.72\text{-}1.334(Silt\text{+}Clay_{Root\ zone}\%)\text{+}0.011(Silt\text{+}Clay_{Root\ zone}\%)^2} \quad (R^2 = 0.88)$$

$$\mathbf{b' = 70.99\text{+}11.67(Silt\text{+}Clay_{Root\ zone})\text{-}0.117(Silt\text{+}Clay_{Root\ zone}\%)^2} \quad (R^2 = 0.91)$$

Soil water depletion with depth, is calculated using the profile water supply (PWSR) rate-approach of Van Rensburg (1998). The procedure is based on the principle that drying of a soil layer is proportional to the ratio between the layer water supply rate (LWSR) and the PWSR. The LWSR is a function of the soil-root conductance coefficient, rooting density, relative soil water content (actual volumetric soil water content relative to the water content where water uptake stopped), matric potential of the soil, critical leaf water potential and soil depth. When the profile water supply rate of a specific day is larger than the estimated daily transpiration, the daily soil water depletion will be equal to the transpiration or root water uptake. If the profile water supply rate is less than the required estimated daily transpiration, soil water depletion will be equal to the profile water supply rate. This will also indicate the onset of soil-induced crop water stress.

5.4.2 Inputs required

Site specific measurements with respect to:

***Soils*:**

(i) Depth of profile and the clay- plus-silt content of each 300 soil layer.

(ii) In situ measurements of the following soil water balance components: Rainfall (event), irrigation (event), soil water content (weekly), water table depth (weekly) and artificial drainage (weekly).

***Crops*:**

(i) Type and length of the four major growth stages and corresponding grain and above ground biomass.

***Atmosphere*:**

(I) Potential evapotranspiration on a daily basis.

6 REVIEW OF CURRENT DRAINAGE PRACTICES IN SOUTH AFRICA

This chapter is how designers currently (i.e. prior to this project) plan and design subsurface drainage systems, which will comply with the requirements of the Soil Conservation Act. The "Manual on the application of the Soil Conservation Act", Part C: Soil Conservation Works must therefore be used together with this chapter. All in field examinations are subject to a certain procedure and depending on the complexity of the problem, the examination, design, plans and specification will have to be more detailed. The designer must always keep in mind that all drainage works, small and large, have certain requirements accordance with the following, as basis for all:

- Identify the purpose of what is to be reached with the drainage works,
- Investigate all conditions and obtain design information in the field, and
- Make use of previous information and experience of a similar area.
- Do a proper financial costing of the project.

As soon as distinction is obtained on the above, the designer can proceed with:

- Design of a drainage system,
- Preparation of work drawings and plans, and
- Compiling of specifications.

6.1 Surveys and Field Examinations

During the field examination, all the relevant information that will be required for the design of the drainage system must be physically collected on the site. The scope of the examination will depend on the measure of waterlogging and/or salinity, the typical case with which the designer is involved and the choice of a system.

6.1.1 Aerial photographs and mosaics

Order aerial photographs from Mowbray in the prescribed manner, if they are not available at the local extension office. Identify the problem on the photographs and indicate the following information with coloured pencils and legends:

- Farm boundaries (black broken lines)
- Affected area (yellow)

- Possible origin of water (red)
- Existing water streams, open trenches and drains (blue with legends)
- Depositing site (depth available and name of river or drain)
- Any other information that is important, such as ridges, terrace walls, dams, farm buildings, etc. (legends)
- Final layout of drainage system (black solid lines with work numbers).
- Orientation direction (North arrow)

The above information is obviously completed during the planning phase and the completed mosaic is included with the report. Infrared aerial photographs may also be used, but these are for the account of the landowner.

6.1.2 Origin of water

First determine from the aerial photographs, if possible, where the origin of the water is that causes the waterlogging. Verify this in the field and with the particulars that the landowner has provided.

6.1.2.1 Irrigation efficiency

Obtain the application and cycle being used from the landowner and verify this with efficient irrigation practices. Make recommendations if it can be a solution to, or alleviate the waterlogging problem.

6.1.2.2 Leaking dams or canals

Give advice on sufficient sealing of dams and canals, rather than designing an expensive drainage system. A cost estimation will have to be done, since good sealing of large dams can often be expensive or impractical. A single, well-planned cut-off drain can be a solution.

6.1.2.3 Topography

Plan drainage where waterlogging occurs as a result of natural depressions, which includes storm-water drains, waterways and contours.

6.1.2.4 Standard case

Identify the waterlogged area according to the typical drainage cases, remove the above causes if it can be done economically and then continue, if necessary, with further inspections.

6.1.3 Drainage water outflow

Gravitational depositing sites:
Do a survey of all available outflow sites, measure the position and relevant depth and identify the river or drain in which the drainage water is to be deposited. A depositing site must be deep enough to ensure a suitable placing depth of the pipe drains, so that the drainage water can flow away under gravity.

Pump drainage:
Where gravitational outflow sites are not available, collection wells must be built to make pump drainage possible. In paragraph 5, directives are given for the planning of collection wells and pump stations.

6.1.4 Soil Survey

Determine the soil and soil-water depth with the aid of a soil auger and holes, to establish the scope, source and movement direction of the water upstream from and in the waterlogged area.

6.1.4.1 Drilling of holes

Measure and mark with numbered iron pegs, on a grid basis of 150 x 150 m to indicate the positions where drilling is to be done. Adapt the grid basis according to the area and site and drill holes to an impermeable layer or to a depth of 1,8 m. Draw profile sketches of each hole with an indication of the priority classes and the depth of consecutive layers. Also measure the water position after a period of two hours in sand, to twelve hours in clay and also indicate this on the sketch.

The position, number and relative height of the boreholes must also be measured during the survey in order to indicate them on the site plan.

6.1.4.2 Excavation of holes

Excavate holes of 1.8 m deep and 1.2 x 0.5 m in each soil type occurring in the waterlogged area and note the following information:

- soil form and series,
- effective depth of soil, suitable for crop cultivation,
- the limited layer and depth thereof,
- a seepage layer with depth and thickness, and
- depth of water table.

6.1.4.3 Taking of soil samples

Take samples only at observable brackish spots to have the brackishness status and type of brackishness determined. For a reliable analysis, it is necessary to make a profile hole in the brackish area and dig out, all along the wall, samples of at least 2 kg at depths of 0-300 mm (topsoil), 300-750 mm and 750-1 200 mm (subsurface soil) which are representative of the entire subsurface soil profile. Place the samples in clean containers that have been washed thoroughly. Provide each sample container with a short and clear number or symbol for identification purposes. Have the samples analysed by a soil laboratory and have the soil scientists interpret the results in order to suggest reclamation, soil improvement remedies and methods.

It is important to take an additional soil sample per soil type at the depth where the drains are to be placed, in order to do a screen analysis for use with filter design, as described in Section 6.2.12. Where orchards have to be drained, soil samples can also be analysed to determine the PH-status and fertility, so that lime and fertilizer requirements can be supplied to the farmer. A recommendation on sub-soiling (if necessary) can also be made according to all the information on the soil profile.

6.1.5 Site survey

Do a complete topographical survey of the site to enable you to draw accurate contours. Also measure the following that may have an influence on the layout, without too much detail, to still make the practical layout possible:

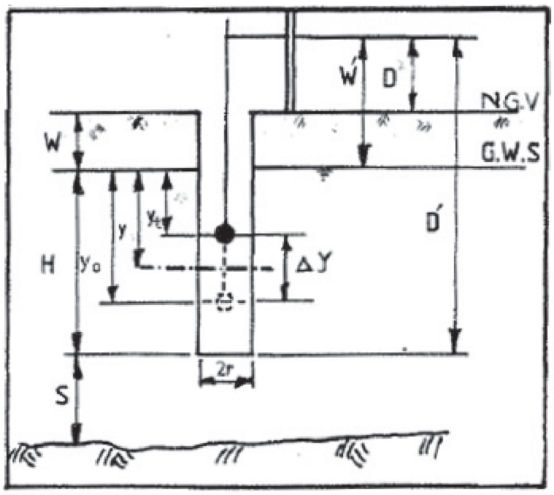
- Fixed reference points (at least two, for the later accurate pegging off of the system);

- Fixed improvements such as buildings and dams;
- Concrete canals, pipelines with hydrant positions;
- Existing drainage systems with depth of manholes and the layout, if it does not appear on the farm plan;
- Farm boundaries;
- Irrigation beds with their irrigation direction, terrace walls and irrigation ditches;
- Water sources;
- Depositing points with the depth available;
- Holes drilled during the oil survey;
- Orientation direction.

6.1.6 Determining permeability

Determine the permeability or hydraulic conductivity (K-value) of each type of soil in the problem area by means of the borehole method. At least three measurements per 10 ha is required, but own discretion can be used.

Drill a hole to 0,6 m below the water table and empty the borehole a few times. Wait until the original Soil Water Position is reached. (Two hours in sand to 12 hours in clay). Empty the hole quickly so that the drops approximately 0,3 m and take a few readings of the rise of the water level with time elapse. The following conditions must be complied with.



30 mm < r < 70 mm

200 mm < H < 2000 mm

0,2 H < Y

Δ Y ≤ 0,25%

Figure 6-1: Permeability measurement

where

k = hydraulic permeability in m/day

H = depth of hole below the water table in mm

r = radius of borehole in mm

Y = distance between water table and the average level of the water in the hole in mm for a time interval Δ T seconds.

ΔY = rise in water in the borehole in mm during the time interval of Δ T seconds

S = depth of the impermeable layer below the borehole's bottom in mm.

6.2 Planning and Design

Process all the information and particulars collected during the field survey, so that the correct conclusion and choice regarding a drainage system can be made, in order to do a rational design of an efficient drainage system. The following is required:

6.2.1 Topographic chart

Draw a topographic chart with complete details that can serve a s a basis for further charts and planning. Use the following contour intervals (Table 6-1) and scales (Table 6-2) in the compilation of the chart.

Table 6-1: Contour intervals

Average gradient of the land (%)	Vertical contour intervals in (m)
0-1	0,25
1-3	0,50
>3	1,00

Table 6-2: Scales

Relevant surface (ha)	Scale	Paper size
0-10	1: 000	A3
10-100	1:2000	A2
>100	1:5000	A1

Make adaptations depending on the design of the scheme. The following must also appear on the chart:

- Reference points,
- Date height,

- Scale,
- Legend – for explanation of symbols used,
- Boreholes with the relative heights and borehole numbers of the soil and soil water table appearing on the survey Form.
- Orientation direction (North arrow), and
- Title block with:
    - name of landowner,
    - site or farm name,
    - designer, and
    - date.

6.2.2 Water table depth chart

Make a transparency of the topographic chart and draw in the soil water contours. Identify these areas with the same water depth, circle it and indicate it with different coloured pens. Use the following colour coding as in Table 6-3.

Table 6-3: Soil water coloring code

Soil water position depth (m)	Colour
0.00-0.50	Red
0.50-0.75	Blue
0.75-1.00	Yellow
1.00-1.20	Green
>1.20	Brown

The water table depth chart will indicate the waterlogged area and will give more information on the movement of water through the area. It therefor gives a clearer reflection of the subsurface conditions in the area, so that a suitable solution can be obtained. This chart can therefore be used for planning the system layout and to drain the areas with a too high water table.

6.2.3 Permeability calculation

Apply Ernst's formulas to calculate the permeability using the prescribed Forms D5

$$If\ \ S => H:\quad K = \frac{400 r^2}{Y\,(H + 20\,r)\quad (2 - {}^{Y}/_{H})}\ \ \frac{\Delta Y}{\Delta T}\quad m/day$$

$$If\ \ S = \ 0\ :\quad K = \frac{360\ r^2}{Y\,(H + 10\,r)\quad (2 - {}^{Y}/_{H})}\ \ \frac{\Delta Y}{\Delta T}\quad m/day$$

and D6.

All lengths in mm and time in seconds.

Typical values of K are shown in Table 6-4.

Table 6-4: Typical K values

Soil Classification	**K (m/day)**
Sandy loam	1,25
Loamy soil	1,00
Clay loam	0,75
Clay	0,50
Heavy clay	0,25
Silt	0,10

6.2.4 Choice of drainage factor

The drainage factor is the amount of water in mm that must be removed from a field surface within a period of 24 hours by means of a successfully installed drainage system. It is one of the factors that determine the drain pipe spacing and capacity of a system. Use the factors in Table 6-5 and Equation 6-1, if necessary.

Table 6-5: Drainage factor

Soil type	Area type	
	Humid (f-factor)	Arid with regular irrigation
Sandy	0,8 x 10^{-3}	
Loam	0,7x10^{-3}	q = 5x10^{-3} m/day*
Clay and Silt	0,5x10^{-3}	

* Where the practice indicates that another q-value must be used, it may be used with motivation

In humid areas the drainage factor q is calculated using Equation 6-1 with the f-factor in Table 6-5:

$$q = f \times \frac{\text{Rainfall for normal wettest month}}{\text{number of days in month}} \times 2 \text{ m/day}$$ Equation 6-1

Apply the reduction factor (Table 6-6) when the collection pipe design must be done in large areas

Table 6-6: q reducing factor

Size of area (ha)	**Multiply with q**
10-30	0.7
30-200	0.5
>200	0.3

6.2.5 Drainage pipe spacing calculation

6.2.5.1 Spacing of grid systems

Apply Hooghoudt's (1940) formula to obtain the required drainage pipe spacing (see Figure 6-2). In the compilation of the formula, a horizontal flow assumption was used, but in the area of the drains there is radial flow.

To make provision therefor, an equivalent layer "d" is used in the equation. If the computer is used for the solution of the equation, the spacing comparison must be solved at the same time with the equivalent layer, or the nomograph shown in Figure 6-3 can be used. The Hooghoudt formula is as follows

$$L^2 = \frac{8\,K_2 h}{q}\ \ d + \frac{4\,K_1 h^2}{q} \quad \text{and}$$

the equivalentlayer formula is as follows :

$$d = \left(\frac{L}{8\left(\frac{\left(L - D\sqrt{2}\right)^2}{8DL} + \frac{1}{\Pi}\ln\left(\frac{D}{r_0\sqrt{2}} \right) \right)} \right)$$

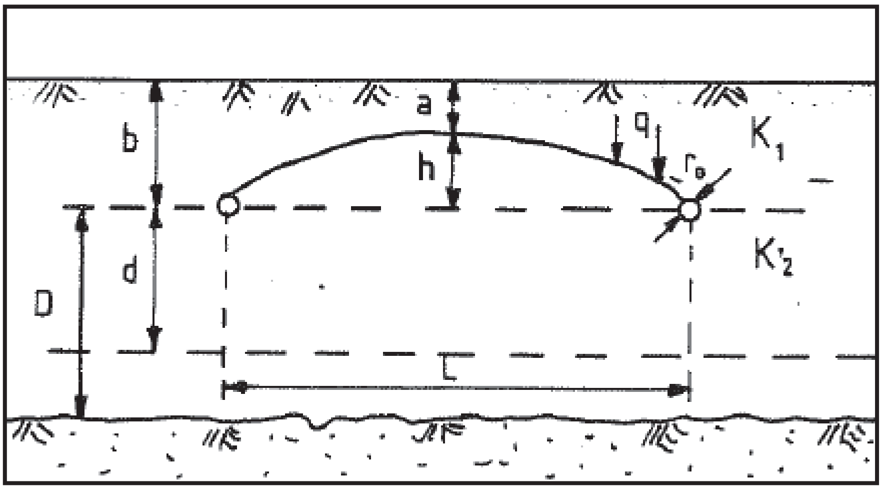


Figure 6-2: Hooghoudt’s drainage spacing

where

L	=	spacing between two drains (m)
d	=	thickness of equivalent layer (in m) below the drains
D	=	depth of impermeable layer below drains (m)
h	=	height of soil water condition between the drains to the level through the drains (m)
K_1	=	Hydraulic conductivity above the drains (m/day)
K_2	=	Hydraulic conductivity below the drains (m/day)
q	=	drainage factor (m/day)
r_o	=	drainage pipe radius (m)
ℓn	=	logarithm to the basis e

For application of the formulas or nomogram, the following must first be known or calculated:

Drainage pipe depth "b":

Calculate or select the drainpipe depth, **b**, taking into account:

(i) The type of crop to be cultivated, i.e. deep or shallow rooted crops (Keep in mind that the roots of perennial deep-rooted crops can block drains. Such drains are therefor laid deeper)

(ii) Depositing point depth

(iii) The ability of the drainage machine (if one is used)

(iv) The depth of a dense layer and

(v) What is practically feasible and

(vi) Take into account the farmer's requirements.

Aerated soil depth:

Select an aerated soil depth, **a**, which consists of the crop's root system depth as indicated in Table 6-7, plus the area of capillary line water level (hangwater) of 0.3 m. With **b** and **a** now known, calculate the height h = (b – a) and the values 8 K_2 h/q and 4K_1 h^2/q and read the required drainage pipe spacing from the nomogram in Figure 6-3 or apply the formula for a uniform soil, K_2 = K1 and if drains are to be laid on a dense layer, apply the following formula directly:

$$L = 2\,h \sqrt{\frac{K}{q}} \quad (m)$$

Example 1:

In an arid area of 5 ha, where cotton is cultivated as a crop, irrigation is applied every 21 days. The following was established during the inspection phase:

Soil profile	:	Loam to 2,1 m depth
	:	Clay loam to 2,75 m depth
	:	Clay deeper than 2,75 m
Permeability	:	K_1 = 0,9 m/day – loam (measured in 1,5 m deep borehole in the field)
		K_2 = 0,4 m/day clay loam (laboratory tests)
Depositing site	:	Collection canal of the Department of Water Affairs – Depth 2,2 m

For the calculation of the spacing, see the calculation sheet.

Example 2:

In a humid area of 3 ha with an average rainfall for the wettest month of 150 mm (July), citrus is cultivated as a crop.

The following was established during the inspection phase:

Soil profile : Clay loam to 1,3 m

Dense clay deeper than 1,3 m

Permeability : K_1 = 0,75 m/day (measured in the field)

Depositing site : Brackish stream with a collection depth of 2 m

See calculation sheet on next page.

DRAINAGE PIPE SPACING

LANDOWNER______________________

DISTRICT___________________________

NAME OF FARM____________________ FILE NUMBER_____________________

PORTION		
Area type (Table 6-5)	Arid	Humid
Irrigation frequency	21	-
Drainage factor from Table 6-5 m/day or q=	0,005	-
$q = f \ x \ \frac{Rainfall \ wettest \ month}{Number \ of \ days} \ x \ 2m/day$ $q =$		$0,6x10^{-3} \ x \ \frac{150}{31} \ x \ 2 = 0,006$
Conductivity K_1 m/day K_1=	0,9	0,75
K_2 m/day K_2=	0,4	-
Drainpipe depth (b) m b=	2,0	1,3
Root depth from Table 6-7 (W) m W=	0,9	0,5
Capillary water level (C) m C=	0,3	0,3
Aerated soil depth (a=W+C) m a=	1,2	0,8
height (h = b – a) m h=	0,8	0,5
Depth of impermeable layer below drainage tube(D)m D=	0,75	0,0
Factors: $\frac{8 \ K_2 h}{q}$ $\frac{4 \ Kh^2}{q}$	$\frac{8x0,4x0,8}{0,005}=512$ $\frac{4x0,9x(0,8)^2}{0,005}=460$	
Read spacing (L) in m from Nomogram L=	29	
$use \ L = 2h \sqrt{\frac{K}{q}} \ m$ $L =$ Where $K_2 = K$ and $D = 0$		$2x0,5 \sqrt{\frac{0,75}{0,006}} = 11$

Table 6-7: Root depths of different crops

Crop	Root depth (mm)	Crop	Root depth (mm)
Peas	600	Deciduous fruit and grapes	750
Cabbage crops	600	Avocados	900
Runner crops	600	Coffee	900
Beans	600	Litchis	900
Tomatoes	600	Macadamia nuts	900
Onions (transplanted)	450	Mangoes	900
Onions (directly sown)	450	Pecan nuts	1 200
Potatoes	600	Bananas	600
Groundnuts	900	Citrus	450
Cotton	900	Tea	900
Wheat	900		
Lucerne	900		
Maize	900		
Tobacco	600		

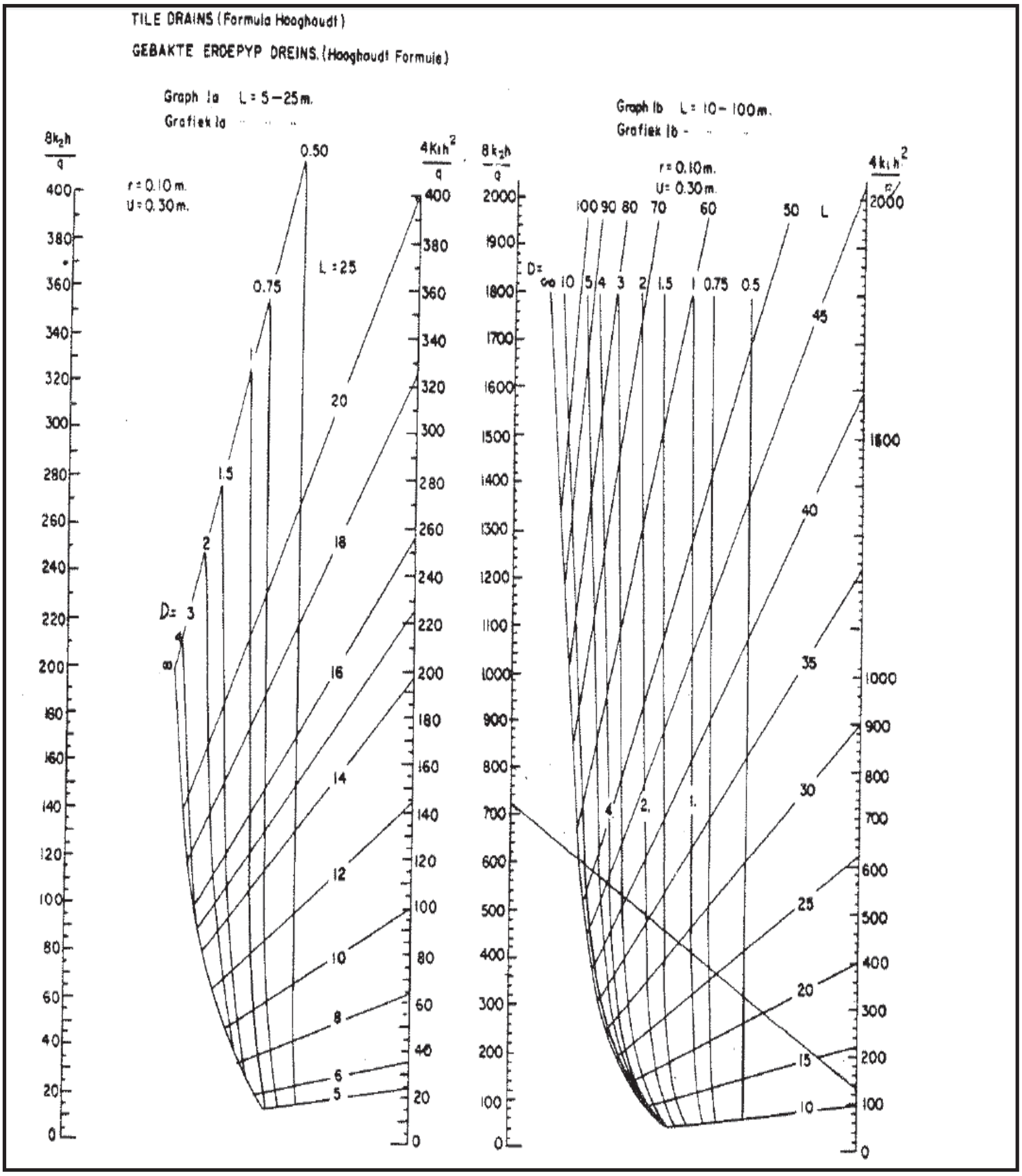


Figure 6-3: Nomograph for sub-surface drainage design

By linking the nomogram factor $\frac{8 K_2 h}{q}$ on the left side with the nomogram factor $\frac{4 K_1 h^2}{q}$ on the right side and obtaining the point of intersection of this line with the line D, the drainpipe spacing can be read.

6.2.5.2 Spacing cut-off drains

The calculation of a spacing for cut-off drains is often difficult because of the heterogeneity of the soils. The problem can be solved by using the equation below or by progressive construction. The equation is based on the assumption that all flow, sloping down from the drain is intercepted to the depth of the drain and that the distance down-slope on which it is effectively dependent on the depth of drainage required and the replenishment to the soil water in the area below the drain (Figure 6-4). In the figure, it is the distance L, i.e. from the drain to the point (m) where it is no longer effective.

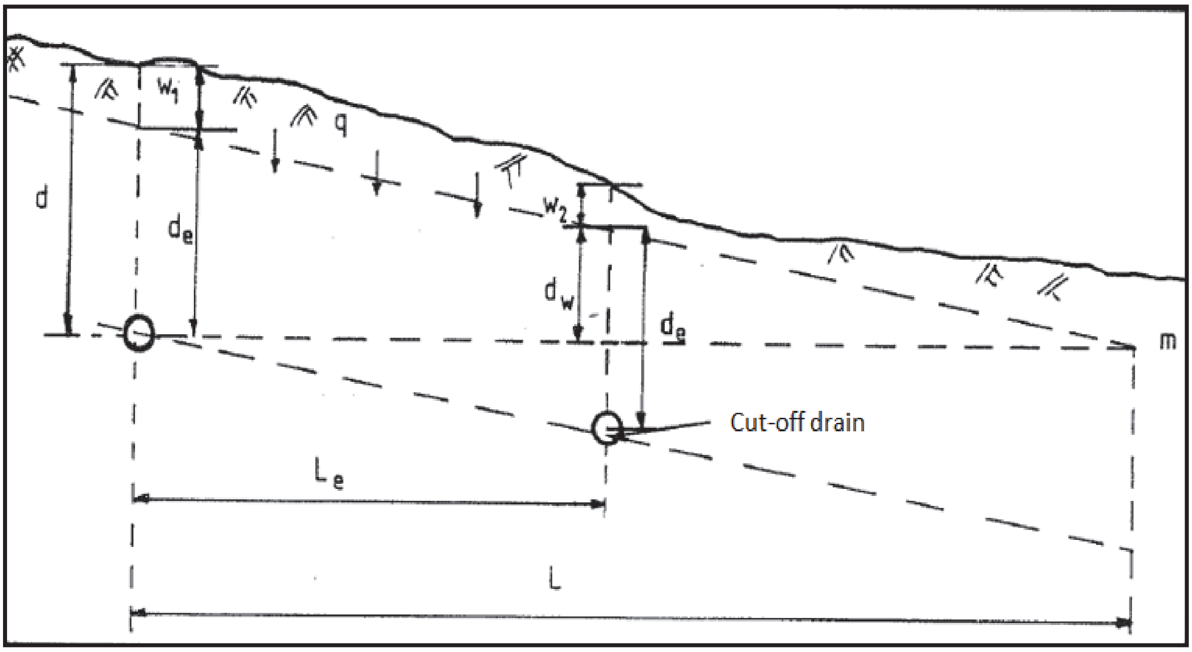


Figure 6-4: Spacing of cut-off drains

$$L_e = \frac{K\,i\,(de - dw + W2)}{q}$$

where:

L_e = the distance down-slope from the drain to the point where the water table is at the desired depth after drainage m;

K = average hydraulic conductivity of the soil to a depth "d" of the drain in m/day;

i = hydraulic gradient of the water table before drainage in m/m;

q = drainage coefficient in m/day

de = the effective depth of the drain in m;

dw = the desired minimum depth to the water table after drainage in m;

W_1 = the distance from the soil surface to the water table before drainage in m;

W_2 = the distance from the soil surface to the water table before drainage on the distance Le, m.

In the equation, Le and W_2 are mutually dependent on each other. In the solution of the equation, W_2 must be estimated in order to first make a preliminary calculation. If the measured value W_2 differs substantially on known distance Le, a second calculation must be done. Where i is uniform throughout the area, W_2 can be selected equal to W_1.

Example 3:

The following information was collected in the area:

W_1 = 0,46 m

K = 3 m/day (borehole tests)

i = 0,05 m/m

q = 5×10^{-3} m/day

The depth on which the drain is to be placed:

d = 2,5 m and

the depth to where the water table must be reduced

dw = 1,0 m

de = $d - W_1$

= 2,5-0,46

= 2,04 m

Assume W_2 = W_1 = 0,46 m

$$Le = \frac{K\,i}{q}(de - dw + W_2)$$

$$= \frac{3\ (0{,}05)\ (2{,}04-1+0{,}46)}{5 \times 10^{-3}}$$

$$= 45\ m$$

6.2.6 Drainage system layout

Plan the system such that the best economic and drainage benefit can be obtained. Take into account, the following:

(i) Obtain a suitable drop on the pipeline with the following in mind:
Minimum slope where sediment is not a threat:

Pipe diameter (mm)	% Slope
100	0,1
125	0,07
150	0,05
In sandy soils	0,2%

Maximum slopes of perforated pipes 5%

(ii) Place the collection drain along a road or fence to make inspection and maintenance at the access wells easier and to avoid cumbersome access wells in tillable fields.

(iii) Place the branch drains perpendicular on the direction of soil water flow.

(iv) Utilise the available field slope to the best advantage by aiming to keep the same excavation depth throughout.

(v) Type of crop: e.g. in an orchard or vineyard, the branch drains must be planned as much as possible between the rows to prevent loss of crops.

(vi) The landowner's ideas during the discussion of the proposed layout.

Layouts as described in Sections are possible

6.2.6.1 Cut-off drains

If strange water seeps into the area from outside, the first consideration in the choice of a drainage system is to effectuate a cut-off function. If this cannot be done successfully, fixed systems have to be planned. Cut-off drains are planned as single distributed drains or as a series of parallel drains. In the case of shallow soils ($D<1$ m) or stone, pot-clay or a limestone reef with a moderate slope of $S>1\%$ and if there are indications that the subsurface backwater collection is caused by this obstruction by the seepage of water from higher-lying land under irrigation or from leaking dams and canals, cut-off drains must be used. Figure 6-5, Figure 6-6 and Figure 6-7 only shows two variations, which may occur and no fixed norms can be laid down where exactly the cut-off drains must be placed for the handling of these problems.

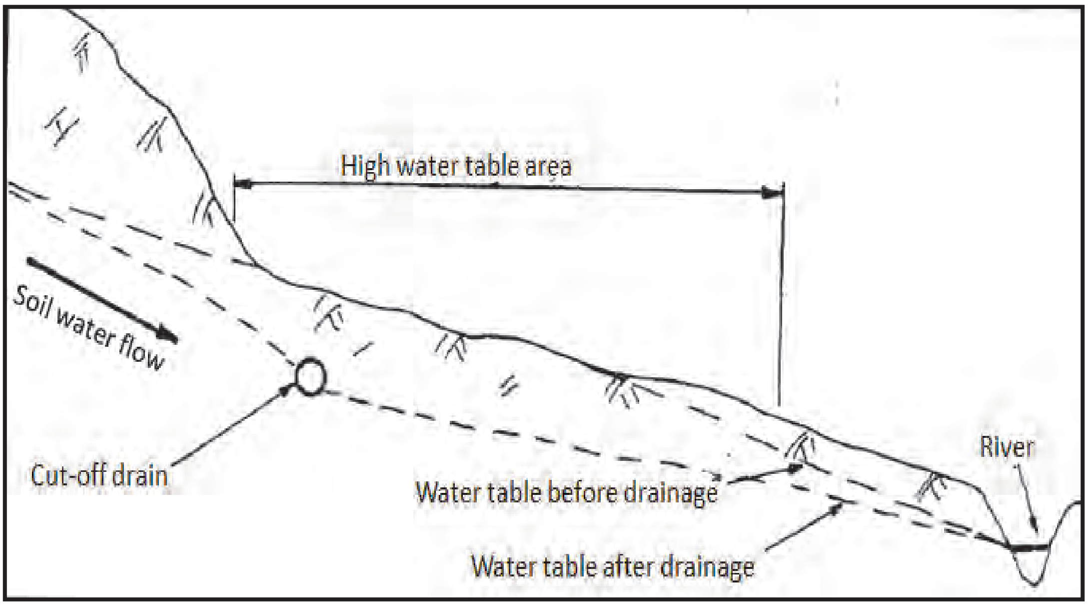


Figure 6-5: Cut-off drain in a valley region (Reinders, 1985)

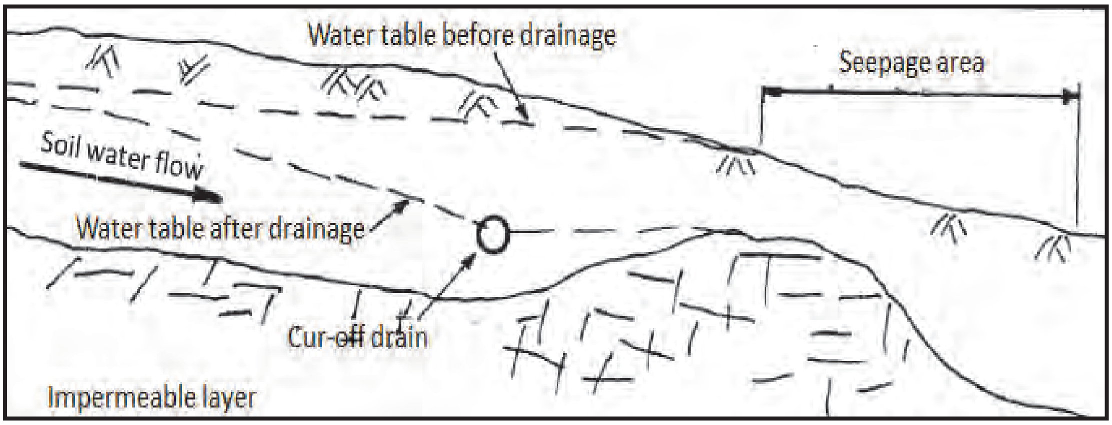


Figure 6-6: Cut-off drain where an impermeable layer occurs (Reinders, 1985)

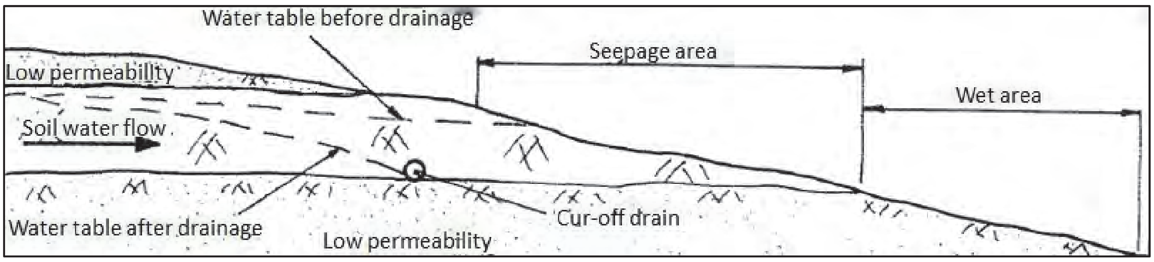


Figure 6-7: Cut-off drain at the base of a water carrier (Reinders, 1985)

In the design of a cut-off drain, it is usually necessary to estimate the down-slope effect of cut-off drains in order to determine if one or more drains are needed to reduce the water table in the wet area. The distance that the water table must be reduced with, is directly proportional to the depth of the drain. Spacing of drains can be calculated as indicated in Section 6.2.5.1. As a result of the heterogeneity of the soil, the construction must often be done progressively, rather than being unsure of calculated spacing. It may therefor mean, the construction of a drain above the wet area or below the source of origin and the evaluation of the effect of the drains before further drains are installed.

6.2.6.2 Local drains

When only single local problem spots occur, which are caused by topographic characteristics (Figure 6-8) or differences in layering of the subsoil, the planning is done to drain these wet spots by following the natural drainage pattern. By evaluating these, additional drains can later be placed.

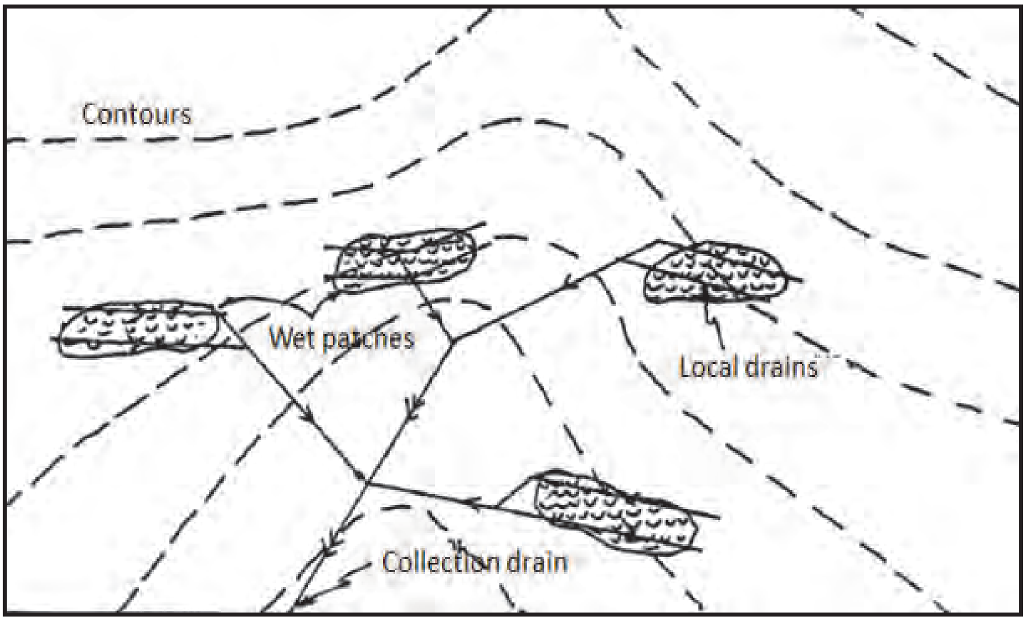


Figure 6-8: Drainage of local patches by means of local drains (Reinders, 1985).

6.2.6.3 Distributed drains

When drainage of extensive surfaces is required, a network of drains must be placed at regularly calculated drainage pipe spacing. A fishbone system can also be used, which is a series of parallel drains that lead to a collection pipe, placed in the centre where a clear depression is adjacent to the centre of a field surface (see Figure 6-9). A grid system can be used, which is a series of parallel drains lead to a collection pipe on one side (see Figure 6-10).

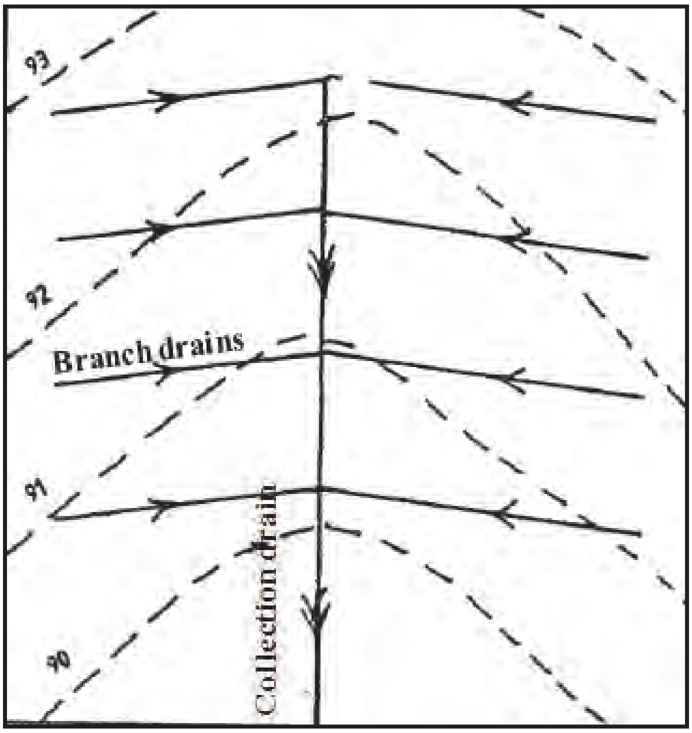


Figure 6-9: Fishbone system (Reinders, 1985)

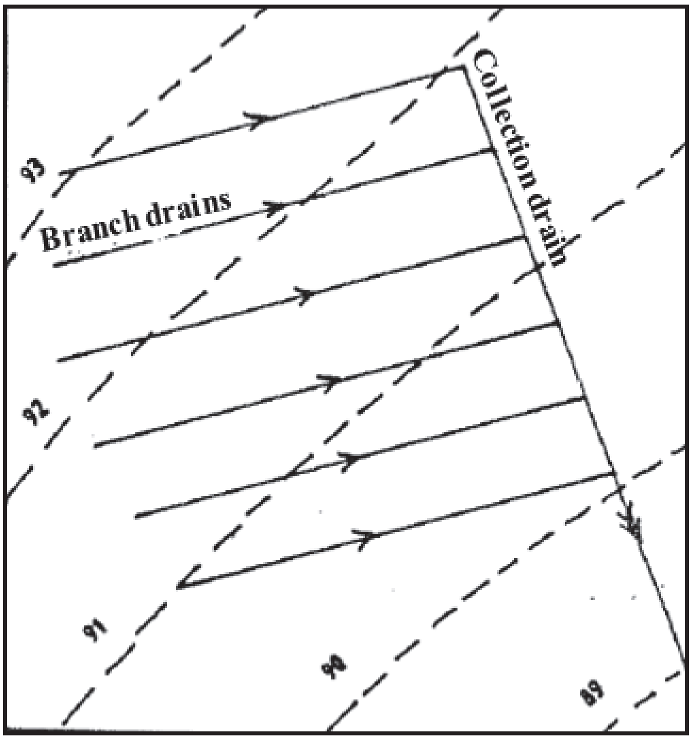


Figure 6-10: Grid System (Reinders, 1985)

6.2.7 Sketching of system

Sketch the system layout on a transparency of the topographic chart, with measurements to localise the exact placing and to peg out the works easily. Complete a page with a summary of the design information.

6.2.8 Longitudinal sections

Draw longitudinal sections of:

- all main lines,
- branch lines longer than 200 m, and
- each fifth branch line with grid and fishbone systems, laid out on a reasonably level slope.

The following information must be provided:

- Converted height of the soil surface and
- Excavation depth at the beginning and end point of the drain
- The slope at which the drain will be laid
- The length of the pipeline
- The diameter of the pipe – perforated or not perforated
- The position and placing of filter materials
- The vertical and horizontal scales, and
- Position of access points.

6.2.9 Access manholes

With the system layout and the slopes at which the pipes will be laid now known, place access manholes on the following positions:

- at all connections of two or more pipes,
- at direction changes of the pipeline,
- at slope changes of the pipeline, and
- at distances not further than 200 m apart.

The access manholes must comply with the following requirements:

- the opening size in round openings must be >750 mm,

- the opening size in oblong openings must not be smaller than 0,36 m², therefor plan measurements of not smaller than 0,6 x 0,6 m,
- it must provide 200 mm water depth for sediment storage, and
- a well must stretch with 100 mm to above the terrain height.

Where circumstances require it, the well may be covered with soil to outside the implements' working depths. The position of these wells must be clearly identified with pegs or marks for easy location during regular inspections or maintenance, and each well must be provided with a steel or concrete reinforced lid.

6.2.10 Calculation of the required drainage pipe diameter

Use the nomograph in Figure 6-11 to calculate the drainpipe diameter. In order to use the nomograph in Figure 6-11, the following information is required:

- The surface are (ha) drained by a pipe of a length X (m) and the spacing L (m) required to meet the design discharge (m³/h).
- The drainage factor q in m/day, derived from Table 6-5.
- The type of pipe – this determines the roughness constants n, as indicated Table 6-8
- The slope S of the pipe in %. For branch drain design, a slope of $S^1 = {}^3/_2$ S is used. Provision is made in the nomograph in Figure 6-11 for a slope 2/3 S^{-1}.

The following formula can also be used to determine the pipe diameter:

$$d = \left(\frac{A\,q\,n}{\sqrt{s}\;26{,}93x10^{-2}} \right)^{3/8} \quad m$$

or

$$d = \left(\frac{L.X.q.n}{\sqrt{s}\;26{,}93x10^{+2}} \right)^{3/8} \quad m$$

$$d = \left(\frac{Q.n}{\sqrt{s}\, 112{,}2} \right)^{3/8} \quad m$$

or

where	L	=	spacing of pipelines in m
	X	=	length of pipeline in m
	q	=	drainage factor in m/day as in Table 6-5
	n	=	roughness factor from Table 6-8
	S	=	slope of pipe in %
	A	=	area drained by pipe in ha
	Q	=	flow rate or discharge in m^3/h

Table 6-8: Values of manning's roughness constant n

Type of pipe	**n**
HDPE Draynex	0,007
Plastic, not perforated	0,009
Perforated PVC Ceramic pipes, extremely well laid	0,010
Concrete pipes	0,011
Ceramic pipes	0,012
Ribbed/Corrugated plastic pipes	0,025

To determine design strength of current Q in cut-off drains, an equation, which is linked to D'Arcy's law is used:

$$Q = \frac{K.i.de.X}{24} \quad m^3/h$$

where	Q	=	design flowrate in m^3/h
	K	=	hydraulic conductivity in m/day
	i	=	hydraulic gradient of the undisturbed water table in m/m
	X	=	Length of drain in m

D'Arcy's law, on which this equation is based, accepts a uniform soil profile, a uniform hydraulic conductivity and an accurate conclusion of the cross section area. It is more accurate and advisable to excavate a guiding trench and do measurements regarding the flow rate for the design purposes.

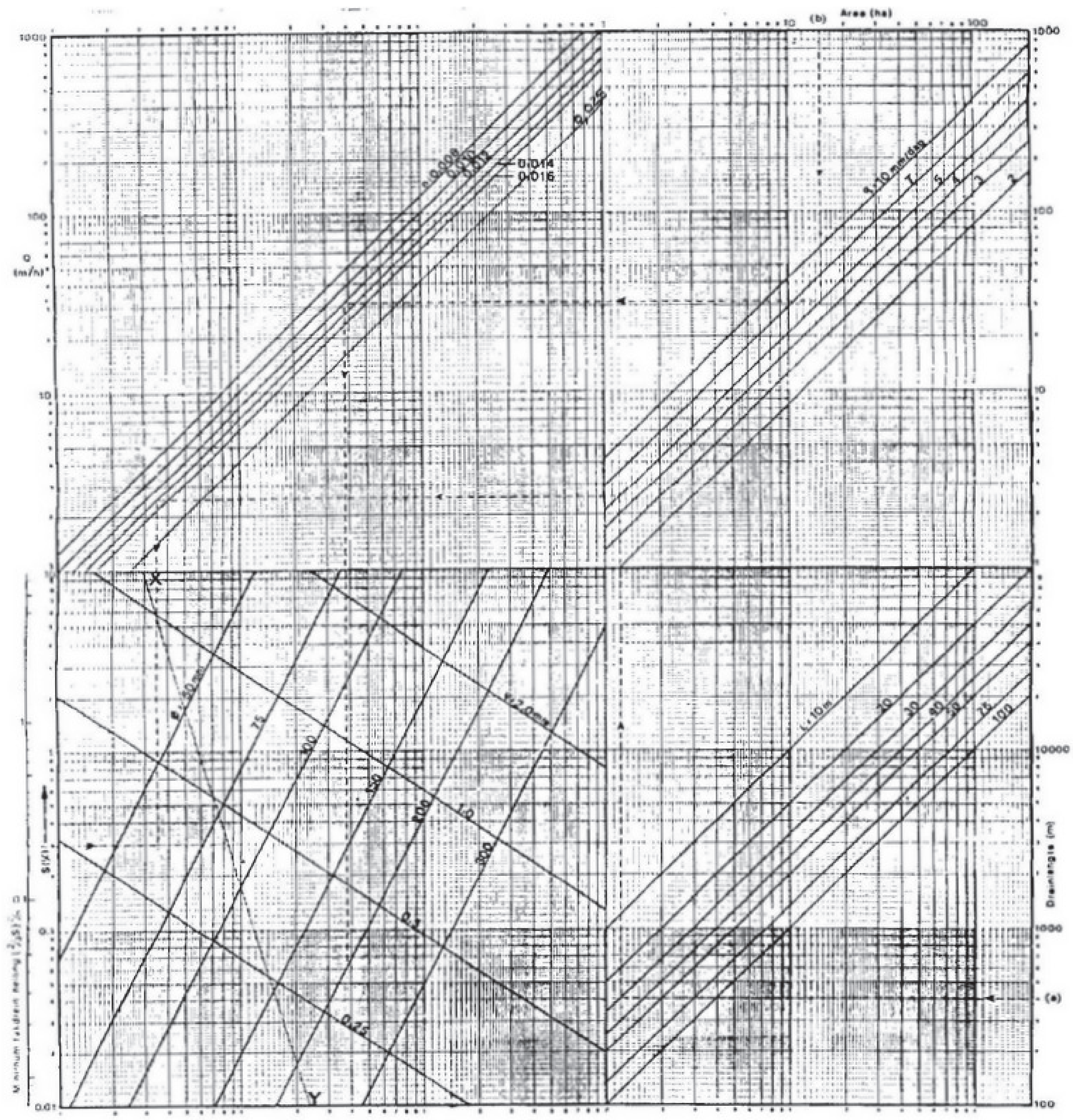


Figure 6-11: Nomograph 2 to calculate the drainpipe diameter

6.2.11 Examples of different applications of the nomogram

Design branch drains of 400 m long on a spacing L = 30 m of ribbed plastic pipes (n = 0,025) on a slope of 0,2% if the drainage factor = 5 x 10-3 m/day. Go into the right-bottom quadrant of Nomograph 2 on the height: drain tube length = 400 m. Now follow the dotted line by finding the following values consecutively: spacing L = 30 m, drainage factor q = 5x10-3 m/day, n = 0,025, and then straight down. Also go horizontally into left-bottom quadrant on the branch drainage slope = 0,2% (branch drain slope-scale) to get a crossing point. It seems that a 75 mm pipe will be able to handle the capacity.

Design a main drain that serves an area of 15 ha with a drainage factor of 5x10-3 m/day. The soil slope is 0.1% and short ceramic pipes are used. From Figure 6-11, it seems that an n = 0.012 can be used. Go into the top-right quadrant of Nomogram 2 on the 15 ha vertical line and find the 5x10-3 m/day drainage factor and then the n = 0.012 line. Study the vertical line through this last point. It seems that a 150 mm pipe on a 0.28% slope of a 200 mm pipe on a 0,6% slope will be able to drain the water. It can be considered to use a smaller pipe at the steeper energy slope, e.g. by placing the pipe steeper than the soil slope, if the length is short. It is however usually preferred to have the pipe slope steeper than the soil slope and a 200 mm pipe will then be necessary. From Nomogram 2, it seems as if a 200 mm pipe that flows full, will deliver a flow speed of 0,35 x 0,01/0,012 = 0,29 m/s.

Design a cut-off drain from perforated pitch fibre that has to handle a total flow of 10 m^3/h and which lies at an angle of 0.2%. The design may be done as for a branch drain, i.e. so that the last portion of the pipe may flow full. According to Table 6-8, a value of n = 0.01 applies. Go to the top-left quadrant on Nomogram 2 on the height Q = 10 m^3/h and find the n = 0.01 line (dotted lines were nor drawn in this case). Go down vertically and also go in horizontally with the minimum branch drain slope of 0,2%, to obtain a crossing point which lies between the 75 and 100 mm pipe diameter. A 100 mm pipe is therefore required.

Design a discharge pipe to serve a drained area of 60 ha with a drainage factor of 4×10^{-3} m/day, with a PVC pipe 500 m long. The soil slope is 0.2% and the pipe is 2 m deep.

6.2.12 Filtering and casing material

Use Form D9 to determine the filter specification. Filters are required in sandy soils that contain no cohesion and of which the particle size distribution is poor and contains very fine material.

Use a filter that complies to the following requirements:

$$\frac{D50\ (filter)}{D50\ (soil)} = 12 \text{ to } 58$$

$$\frac{D15\ (filter)}{D15\ (soil)} = 12 \text{ to } 40$$

or in the case of uniform graded materials:

$$\frac{D15\ (filter)}{D85\ (soil)} = <5$$

Where D15 is the particle size of which 15% of the material goes through the sieve with mesh size D, etc.

Taking of soil samples as described under 6.1.4.3, can be analysed at a soil laboratory and the results can be plotted on a sieve analysis graph. In soils with a moderate clay content and cohesion, the following casing material can be used:

- Crushed stone of 5 mm to 15 mm particle size, free of fine dust,
- Gravel or coarse sand, free of shale and dust, and
- Coal ash with minimum fine particles.

Diversions hereof are permissible if satisfactory practical results already occur in a region of a specific type of filtering material. It is required that a thickness of at least 75 mm should be placed around the pipe. The m^3/metre required for different pipe diameters plus 5% wastage, is as shown in Table 6-9.

Table 6-9: Volume of filter material required

Pipe diameter (mm)	**Volume (m^3 filter/metre pipe)**	**Pipe Length (m pipe/m^3 filter)**
50	0.040	25.0
75	0.049	20.5
100	0.057	17.5
150	0.076	13.0

Or m^3 filter required/metre pipe with a diameter d in mm.

$$= (23625 + 315d + 0{,}225d^2) \times 10^{-6}\ m^3/m\ pipe.$$

6.2.13 Drainage channels and drainage trenches

Use drainage channels when the flow is too great to be handled economically by pipes. System planning will be the same and where drainage channels must also handle surface water, the capacity must make provision for the runoff intensity for once every 10 years. The measurements are shown in Figure 6-12.

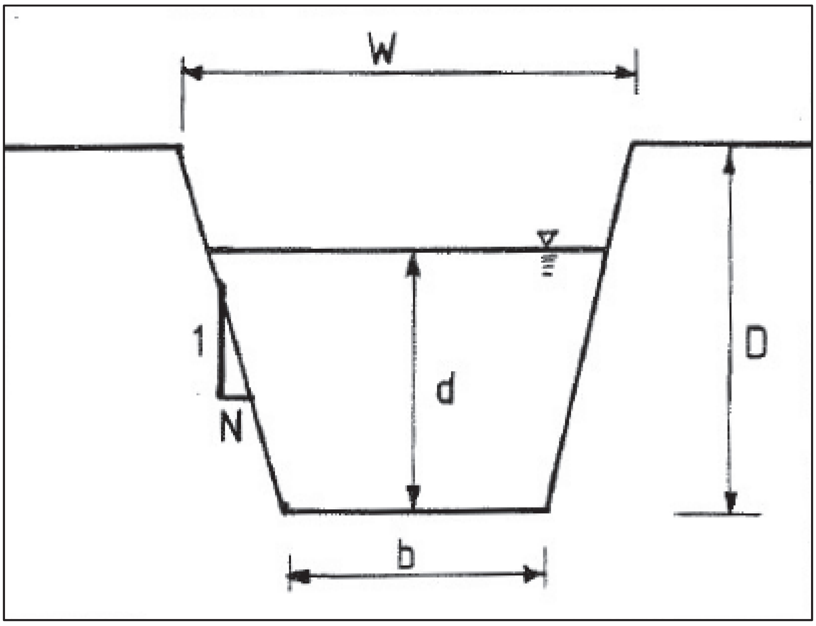


Figure 6-12: Measurements of drainage channels

The bottom width is selected after the depth and capacity is determined with the aid of Table 6-10, Table 6-11, Table 6-12 and Table 6-13.

Table 6-10: Side inclines

Soil characteristics	Side inclines 1 : n	
	Shallow channels 1,2 m	Deep channels 1.2 m
Rock	Vertical	Vertical
Peat	Vertical	1 : ¼
Stiff clay	1 : ½	1 : 1
Clayey loam and gravel	1 : 1	1 : 1½
Sandy loam	1 : 1 ½	1 : 2
Loose sandy soil	1 : 2	1 : 3

Table 6-11: Clay loam and gravel

Gradient (%)	Bottom width (m)											
	0,5		1,0		1,5		2,0		2,5		3,0	
	d	Q	d	Q	d	Q	d	Q	d	Q	d	q
0,2	1,4	2,81	1,2	2,80	1,0	2,58	1,0	3,26	0,8	2,66	0,8	3,14
0,3	1,0	1,61	0,8	1,52	0,8	2,09	0,6	1,60	0,6	1,97	0,6	2,35
0,5	0,6	0,70	0,5	0,81	0,4	0,78	0,4	1,03	0,4	1,28	0,4	1,50
1,0	0,3	0,25	0,2	0,23	0,2	0,34	0,2	0,45	0,2	0,57	0,2	0,68

Flow speed 1,0-1,1 m/s
Side inclines 1 : 1,
n = 0,03
d = flow depth in m;
Q = delivery in m^3/s

Table 6-12: Sandy loam

Gradient %	Bottom width in metre											
	0,5		1,0		1,5		2,0		2,5		3,0	
	d	Q	d	Q	d	Q	d	Q	d	Q	d	q
0.2	0.8	1.10	0.6	0.86	0.6	1.15	0.5	1.04	0.5	1.27	0.5	1.49
0.3	0.5	0.48	0.4	0.48	0.4	0.66	0.4	0.85	0.3	0.64	0.3	0.76
0.5	0.3	0.21	0.3	0.36	0.25	0.37	0.25	0.49	0.41	0.41	0.2	0.49
1.0	0.15	0.08	0.15	0.15	0.15	0.22	0.15	0.29	0.18	0.18	0.1	0.22

Flow speed 0,75-0,8 m/s;
Side inclines 1½ : 1
n = 0,03
d = flow depth in m;
Q = delivery in m^3/s

Table 6-13: Loose sandy soil

Gradient %	Bottom width in metre											
	0,5		1,0		1,5		2,0		2,5		3,0	
	d	Q	d	Q	d	Q	d	Q	d	Q	d	Q
0.1	0.6	0.50	0.06	0.70	0.6	0.91	0.5	0.79	0.4	0.63	0.4	0.75
0.2	0.3	0.16	0.3	0.25	0.3	0.34	0.3	0.44	0.3	0.54	0.2	0.32
0.3	0.2	0.08	0.2	0.14	0.2	0.20	0.2	0.26	0.2	0.33	0.2	0.39
0.5	0.15	0.06	0.1	0.05	0.1	0.08	0.1	0.10	0.1	0.13	0.1	0.15

Flow speed 0,4-0,6 m/s;
Side inclines 2 : 1
n = 0,03
d = flow depth (m)
Q = delivery (m^3/s)

For the purpose of calculation, Manning's defined formula can be used, namely:

$$Q = \frac{\left[d\ (b + (d\ x\ N))\right]^{5/3} S^{1/2}}{\left[b + 2d\ \sqrt{N^2 + 1}\right]^{2/3} n}$$

Where Q = capacity in m³/s
b = bottom width in m
d = flow depth in m
N = side inclines
S = Gradient in m/m
n = Manning's constants = 0,02 for coarse concrete or masonry
= 0,03 for earth canals
= 0,04 for vegetated canals

Depending on the type of canal bottom, there are maximum speeds that are still safe against flooding. By striving for the values in Table 6-14, silt deposits will be prevented without causing flooding.

Table 6-14: Maximum flow speeds that are safe against flooding

Type of canal bottom	Maximum flow speed (m/s)
Coarse or light sandy soil	0,4-0,6
Sandy loam	0,75-0,8
Loam	0,8-1,0
Clay loam	1,0-1,2
Stiff clay or gravel	1,2-1,5
Concrete	4,5-6,0

When other sections than trapezoidal sections are designed, use Manning's formula in the following form:

$$Q = VA$$

$$V = \frac{R^{2/3} S^{1/2}}{n}$$

Where

Q	=	Capacities in m^3/s
V	=	Flow speed in m/s
R	=	$^A/_P$ = hydraulic perimeter in m
A	=	cross section surface in m^2
P	=	wetted circumference in m
S	=	gradient in m/m
n	=	Manning's constants

6.2.14 Collection wells, pump and pump sizes required

Where gravitational drainage cannot be used, suitable collection wells must be constructed (See Figure 6-13) to lift the drainage water to a higher level by means of a pump, in order to make gravitational flow possible.

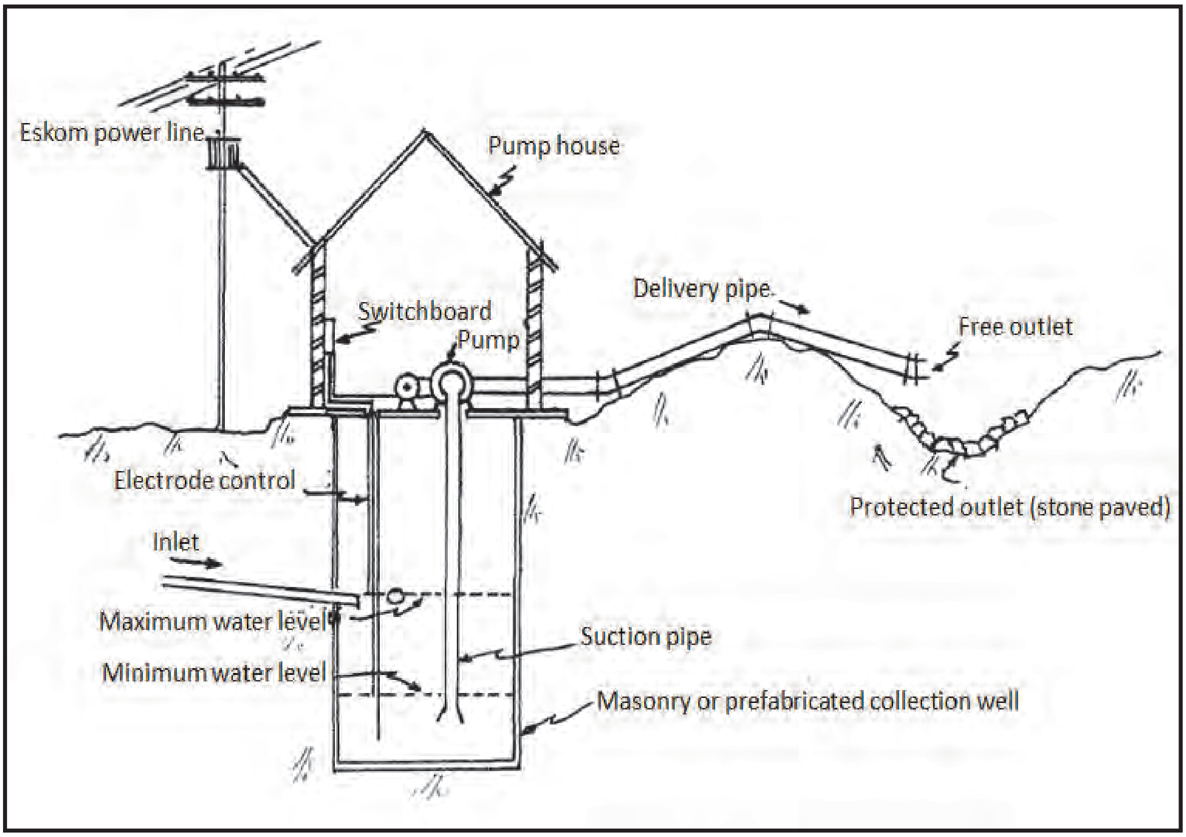


Figure 6-13: Typical set-up for pump drainage

The requirements for planning, design and construction of the pump facilities can differ from place to place and the following directives are given. These are important in the planning and design of a pump station. Determining of and points of importance in:

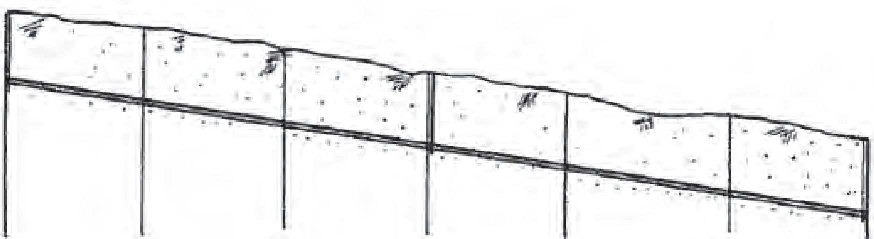
- The placing and type of collection point
  - The entire system must be served by one pump station if possible
  - The position of deposit sites
  - Accessibility to Eskom power lines and fuel access roads
  - Masonry collection wells or prefabricated cement wells
  - The required quantity of water that must be removed
  - Use Nomogram 2 for determining of the flowrate (with the area and drainage factor known, the flowrate Q in m^3/h can be read from the Nomogram.
- The total pump head
- Suction and delivery head

- The type, capacity and size of the pump
  - The manufacturers can make recommendations if the information is supplied
- Accessories
  - Switchgear and protection gear
  - Automatic water level control to activate switchgear to switch on and off at predetermined water levels
- Shelter
  - Pump house for protection against weather conditions and vandalism

6.2.15 Calculation of soil works

Calculate the average depth of excavation for each diameter pipe.

Example of calculation



Peg number.	1		2		3		4		5		6		7
Excavation depth	1,8		1,7		1,6		1,8		1,6		1,5		1,7
Distance between pegs		110		95		80		75		105		120	
Pipe Ø and gradient				100 mm; 0,3%						125 mm; 0,25%			

SOIL WORKS CALCULATION

LANDOWNER______________________

DISTRICT____________________

FARM______________________________ FILE NUMBER_________________

Peg NO.	Excavation depth m	Average excavation depth in m $\bar{D}$	Length in m L	$\bar{D}$ x L	Calculations $\frac{\Sigma(\bar{D} \; x \; L)}{\Sigma(L)}$	Summary
1	1,8	1,75	110	192,50		
2	1,7	1,65	95	156,75	485,25	L = 285 m
3	1,6	1,70	80	136,00	285	d = 100 mm
4	1,8		Σ = 285	Σ=485,25	= 170	D = 1,70 m
5	1.8	1,7	75	127,50	482,25	L = 300 m
6	1,6	1,55	105	162,75	300,00	D = 125 mm
7	1,5	1,60	120	192,00	= 1,61	D = 1,61 m
	1,7		Σ = 300	Σ= 482,25		

6.2.16 Submission of design for subsidy purposes

In the finalisation of a system design, the administrative work must be done in a prescribed manner and submitted for verification and finalisation as described in the Soil Conservation Manual, as described in the applicable chapters.

6.3 Construction Procedures

6.3.1 Pegging-out of works

Measure and mark al drainage works as specified on the plans, by following the procedure below:

Begin pegging-out at the outlet of the system and place pegs at a constant distance away from the centre-line outside the work area. The pegs must be placed at intervals of 30 m or less and also placed at slopes or direction changes. Keep in mind that at least 3 pegs are necessary to determine a slope accurately. It is also good practice to place pegs at control points such as maximum excavations, existing subsurface structures, centre of trenches, etc. Pen heights and soil heights at the centre-line are measured in and a list of the depths (‘d’ in Figure 6-14) is provided to the landowner or foreman, who must use it with the work plans. Staff angles can be erected at the pegs at a comfortable height above the trench bottom (“D” in Figure 6-15). By placing a staff angle in the trench and aiming over the aim correctors, the excavation depths can be verified.

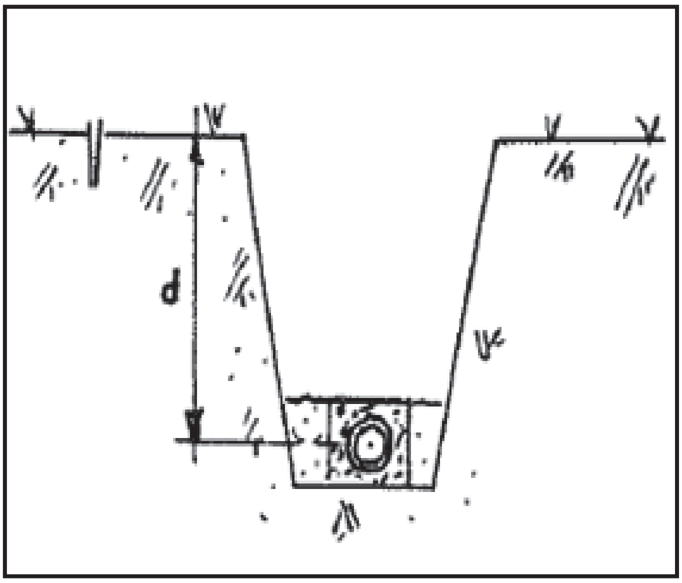


Figure 6-14: Profile dimensions

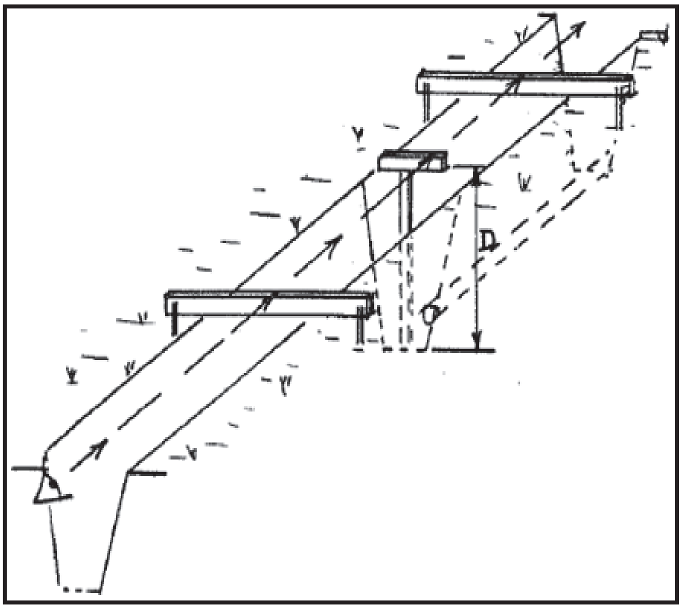


Figure 6-15: Trench layout

When installation is done by machine with hydraulic or laser beam accuracy control, only the centre line and two or more depths have to be measured out.

6.3.2 Installation of a drainage system

A few points of interest that the foreman must take note of regarding the installation of the system are the following:

- If possible, do the excavation and installation when the soil water position is deep.
- Begin the installation at the outlet side.
- Limit the width of the trench to save on costs, without hampering the installation
- Prevent the excavation from getting deeper than the measured bottom
- Verify the slope of the pipe continuously at regular distances with an instrument or staff angle.
- Carefully place the filter material with the correct prescribed thickness around the pipe. For a saving on filter material, a filter box can be used for installing the material (See Figure 6-16).

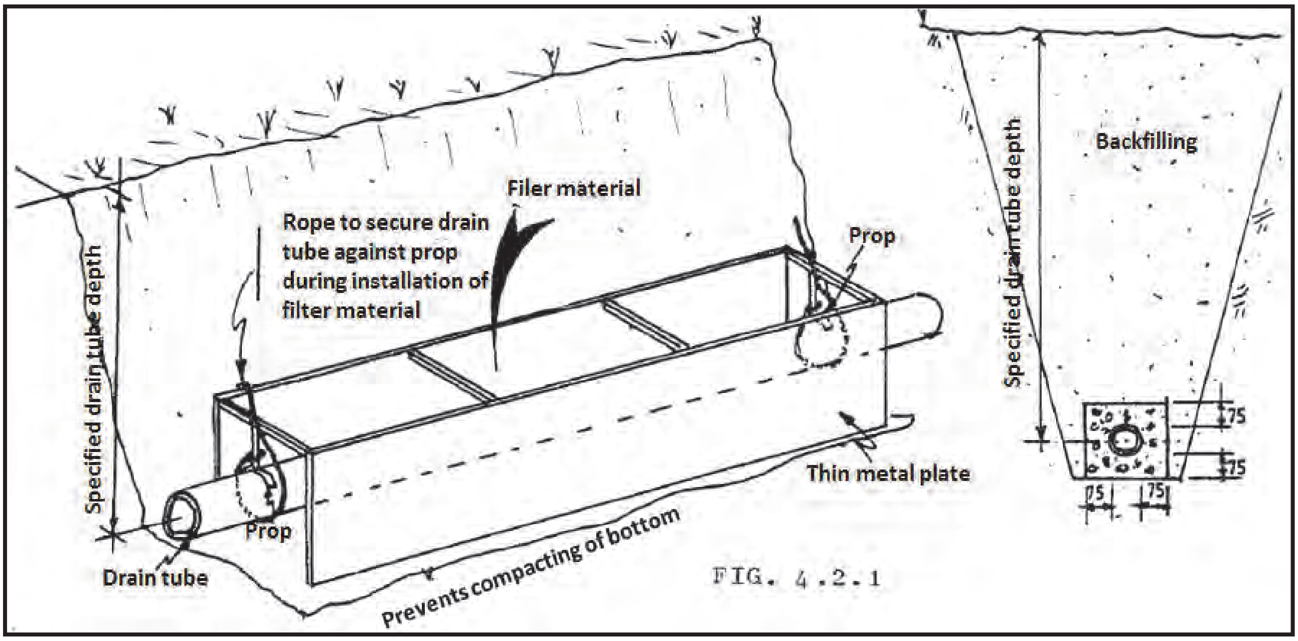


Figure 6-16: Filter box for envelope placing

6.3.3 Construction inspections

The purpose of inspections during and after completion of works ensures that installation is done according to plans and specifications.

6.3.3.1 Interim Inspections

Do interim inspections to ensure that the plans and specifications are interpreted correctly and that the drain installation is done accordingly. Make certain of:

- the quality of drainpipes,
- filter and other materials,
- the outlining,
- depth and slope of the drains,
- connection to and type of inspection wells,
- thickness placing and, and
- deposit point construction.

Any deviation from the specifications and the reasons therefor must be clearly indicated and if necessary, a report must be compiled.

6.3.3.2 Final inspection

Do a final inspection as soon as notification of completion is received:

- Compare the work plan and layout with the locality, routes, spacing and work numbers and verify these aspects with the fixed reference marks,
- Inspect all the inspection points, compare the measurements, material used, type of insulating lid and positions of the in- and outlet pipes in the inspection well,
- Verify the depth, slope and cross sections of the pipes and ensure that the filter material around the pipes is placed at the correct thickness, and
- Observe the flow of drainage water. This will indicate whether the system is functioning efficiently.

With machine installation, where everything is done is one process, the following method can be used to observe the depth and locality of the pipes:

- Pegs are installed on the surface above the pipes at the following positions:
- At terraces, direction changes, slope changes and at distances not further than 100 m apart. A steel staff measuring ±2 m, with a diameter of 13 mm is then used to insert at the marks. The top of the gravel and pipe, height and depth readings can be taken and verification done according to the work plan can be

distinguished without much experience. The other inspection points are still handled as mentioned above.

6.3.3.3 Permissible deviation norms

- Spacing-not further away from centre line than 0,5 m
- Slope – no negative slope is allowed and no portion longer than 10 m may be level
- Depth-Deviation ± 50 mm
- Filter – a cover of less than 50 mm is disapproved
- Inspection wells – opening for access in the case of round openings – minimum 750 mm diameter and in the case of oblong openings, an opening of 0,36 m^2. All wells must be provided with an insulation lid.

6.3.4 Final report

When a final inspection is completed and completed to the satisfaction of the inspecting officer, the final report must be completed. The procedures of the Soil Conservation Manual must be followed.

6.4 Maintenance

A well-designed and thoroughly-installed subsurface drainage system needs very little aftercare. Regular inspection of the system will indicate whether maintenance is necessary.

6.4.1 The outlet

- Keep the outflow area clear of weeds
- Maintain the stabilised side inclines at the outlet
- Ensure uninterrupted flow from the outlet
- If vermin creates a problem at the outlet, install a grid or hinge flap

6.4.2 Inspection manholes

- Ensure that insulating lids are still in position

- Remove sediment and other deposits from the bottom of the manholes
- Ensure free through-flow in inlet and outlet pipes

6.4.3 System

- Verify flow tempo before and after a heavy rain shower. It gives an indication whether blockages occur in the pipes.
- Inspect sediment dross and do maintenance if necessary.

When a blockage occurs in a pipe, holes must be drilled in a line perpendicular to the direction of the pipeline to correlate the soil water position with the drain depth. A too high soil water position will indicate a blockage and the following methods may be followed:

- Obtain a flushing action by pumping water into the pipeline under high pressure, from the downstream side, by using a water hose with a special nozzle.
- Pull a wire to and fro through the pipes in an effort to remove the plant roots. Special apparatus is also available for cutting and removing the roots from inside the pipes.
- Iron and manganese oxide deposits can be removed chemically with a solution of sulphur dioxide and water. It can be injected at a tempo so that a 2% solution is maintained (i.e. 50 gram per 2,5 litre of water). Use Table 6-15 for determining the amounts:

Table 6-15: Amount for treatment with SO_2

Drainage pipe size mm	75	100	125	150	200	250
Gram SO_2 per metre	88	157	245	353	628	982
Litre water per metre	4,42	7,85	12,27	17,67	31,42	49,08

If these and other methods do not work:

- Localise the position of the blockage by excavating in the potential wetter spots and do maintenance.

6.5 Equipment and Apparatus required for a Drainage Inspection

Field equipment required when a drainage inspection must be done, are the following:

- Iron pegs for placing reference marks in
- Wire pegs with numbered tags to mark out the grid on which measuring and soil inspection is to be done
- Tacheometer or surveyor's rod with a tripod
- Staff or staffs
- Measuring tape
- Surveyor's book
- Soil auger with a drill bit of a diameter 80-100 mm and extension pieces to 2,5 m
- Bailer with extension pieces to 2,5 m. (See Figure 6-17)
- Measuring apparatus to observe the rate of water swell in the borehole (See Figure 6-18)

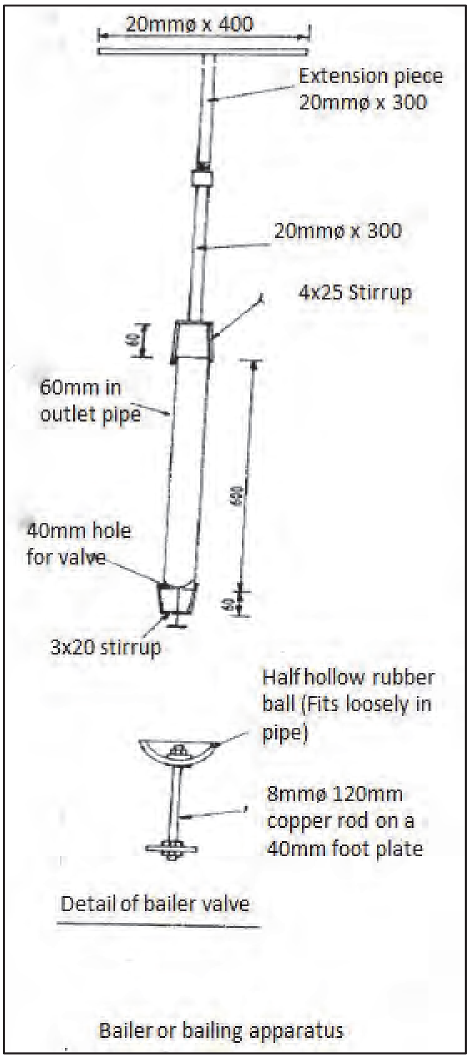


Figure 6-17: Bailer (Reinders, 1985)

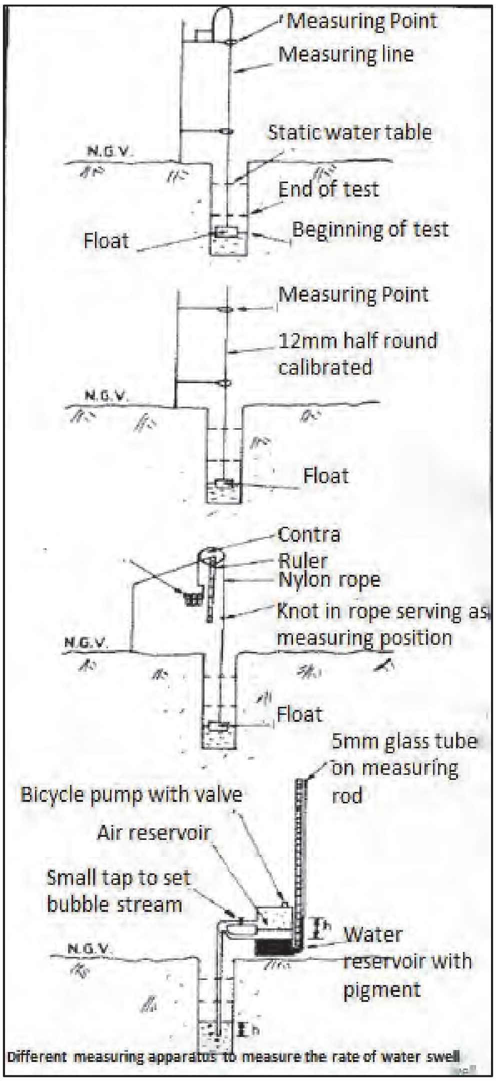


Figure 6-18: Measuring apparatus (Reinders, 1985)

6.6 Approaches to Sub-Surface Drainage Adopted in South Africa

In general the approach on a national basis with sub-surface drainage is according to the 1985 Sub-Surface Design Manual (Reinders, 1984). Some Provinces made regional adjustments but the basic approaches are still the same. The following norms and approaches are applied in the different provinces.

6.6.1 Western Cape Province

The Department of Agriculture Western Cape adopted in 1998 a set of norms for sub-surface drainage works which were in various manuals and letters on record. The documents referred to were: -

(i) The National "Sub-Surface Drainage Manual" reviewed manual of Reinders ((1984) (reviewed 1985))

(ii) The 1995 Simondium Drainage notes

(iii) The Villiersdorp meeting "Norms for Sub-Surface Drainage" 1993

(iv) Notes of the meeting "Determining Crop Needs for Drainage purposes" 1998

The norms (in Afrikaans) is complimentary to this research and can be used as such.

6.6.2 KwaZulu-Natal Province

In KwaZulu-Natal a similar set of steps to be followed to do a sub-surface drainage design were adopted and these are complimentary to this research and can be used as such.

7 TECHNICAL AND FINANCIAL FEASIBILITY OF DRAINAGE PROJECTS

7.1 Technical Criteria to Establish the Feasibility of Drainage

Agricultural land drainage is the removal of excess water from the land to enhance crop growth, including the removal of soluble salts from the soil (Bos and Boers, 1994). The main objective land drainage is to remove excess water in order to improve the profitability of farming the land. In reality, periods of excess water do occur on most farm land but these need not be harmful provided the amount of excess water is low, the periods of occurrence are of short duration and or the excess water occurs during a time that is not critical to the growth of the crop. Poor land drainage is manifested through high water tables on agricultural land. The main problems associated with poor land drainage can be categorized under impaired crop growth and impaired farm operations. The main aim, therefore, of drainage system design and management is to do with water table control. Water table control is effected through the installation of a drainage system (surface or subsurface or both) to remove the excess water.

The relationship between water table depth and crop performance is well documented for most crops, both under experimental and field conditions. While under experimental setups the water table is controlled throughout the season within a narrow range to give definitive yield responses, under field conditions the water table fluctuations are variable (in duration and timing) and so crop yield responses vary widely.

7.1.1 Objectives of drainage design criteria

A common drainage design criteria is the depth of the water table below the surface expressed as the ratio h/q which stands for the chosen combination of ground water level (h) and drain discharge (q) required to prevent the occurrence of excess water in the root zone. Although this is considered for steady state conditions, in actually fact it also caters for non-steady state conditions. A criterion with a low hydraulic head to drainage discharge ratio (h/q) drains the soil much faster, since it results in a high water table drawdown per day. The criteria in Table 7-1 represent both water table-discharge and water table-drawdown criteria, consequently taking care of both steady and unsteady state conditions. Smedema and Rycroft (1983) report that under conditions of North West Europe, drainage systems with h/q = 55 to 100 generally ensure safe groundwater levels for crop production, thus preventing severe adverse effects on soil structure, nutrient availability and delays in agricultural operations in late winter/early spring.

Table 7-1: Basic design criteria for groundwater drainage in humid climate zone of North West Europe (Smedema and Rycroft, 1983)

Condition	Drain discharge q (m/day)	Design water table depth z (m)	Hydraulic head h (m)	h/q (day)
Low value crops (most grasslands)	0.007	0.30-0.40	0.60-0.70	85-100
Sensitive and high value crops	0.007	0.50-0.60	0.40-0.50	55-70
Average conditions	0.007	0.5	0.5	70

It is inevitable that at times the water table would rise above the stated criteria but this should be for short duration depending on the crops being grown. Table 7-2 below gives the desirable water table levels for grasses and field crops during the growing season.

Table 7-2: Recommended depth of the water table applicable to the Netherlands

Soil texture	Water table depth which should not be exceeded for more than brief periods (m)	
	Grassland	Field crops
Course	0.4-0.6	0.6-0.9
Medium	0.6-0.9	0.9-1.2
Fine	0.6-0.9	1.2-1.5

Closely related to the above criteria is the so called SEW30 which is summation of daily occurrences of excess water within 30 cm of the soil surface. Closer drain spacing will reduce the average annual SEW30 values and this is desirable for most crops but generally is costly and may not be financially viable. Different countries in the world have different drainage design criteria of indices.

7.1.2 Drainage design factors

Subsurface drainage design is not an exact science because of the great variability that exists in the natural soils. Furthermore, rainfall is not constant and irrigations are not perfectly uniform. Certain soil properties are important in subsurface drainage design, these include (abstracted from Meyer, 2011):

- Hydraulic conductivity (K)

  Soil hydraulic conductivity (K) is the main factor in deciding whether a subsurface drainage scheme is feasible. K is defined by the volume of water that will pass through a unit cross-sectional area in unit time having a unit difference in water potential. Saturated hydraulic conductivity applies to drainage design; unsaturated hydraulic conductivity has much slower flow rates and applies more to the soil moisture status at and below field capacity. Initial K rates are high as the larger pores drain; when the water content is reduced to field capacity, K reduces to between 1/100 and 1/1000 of its initial rate at saturation. Low K values put the economics of subsurface drainage in question. Low K values are found in silty loam soils and heavier, although some sandy clay loams can have similarly low K values. Heavier soils such as clay loams, silty clay loams, silty clays and clays can benefit from subsoiling, and sometimes mole drains as opposed to subsurface drains. Where soils have K values greater than 2.0 m/day, they generally do not require subsurface drains.

- Drainable porosity (drainable pore space, storage coefficient, air capacity)

  Drainable porosity (DP) can be defined as the ratio between the change in the amount of soil water and the corresponding change in the level of the water table; i.e. the difference between saturation and field capacity. It thus approximates the volume of air that can replace water draining under gravity. If the drainable porosity of a soil is 10%, adding another 10 mm to a soil at field capacity will cause the water table to raise 100 mm. Drainable porosity is an indicator of the stability of the macropores – the number of which has a major influence on the total soil air space as well as the gaseous exchange and biochemical reactions.

- Texture

  Texture influences hydraulic conductivity and drainable porosity. In general, the lighter (sandier) the soil, the faster it will drain and the higher the drainable porosity. The heavier (clay) soils have slower hydraulic conductivities and smaller drainable porosities. Soils with strong structure, which are heavy, have high K values and may rely entirely on their structural pores for their conductivity. Vertic soils high in montmorillonite clays have high K values initially but swell when wet and the K value drops to very low values.

- Design drainage rate

  The amount of drainage water to be removed by the subsurface drainage system is described as a depth or volume per unit area per unit of time (mm/day) and is known as the design drainage rate or drainage coefficient (q). This has the same units as hydraulic conductivity. If salinity control is required, the leaching fraction must be added to the drainage coefficient. The drainage coefficient is used in drain spacing calculations. Examples of the computations used for drain spacing under steady state and transient state conditions are given in FAO, 2007 and King and Willardson, 2007.

- Drain depth

  The design water table level can be achieved by a range of depth and spacing combinations. In general, the deeper the drain, the wider the spacing can be. (See FAO (2007) for theoretical explanation, models and equations.) Initially the maximum allowable water table height is chosen for the design crop, which is equivalent to the required root zone depth mid-point between two laterals; the design sugarcane root zone is usually specified as 1.0 m, which commonly gives a drain depth of between 1.2-1.5 m. Drain depth is influenced by soil characteristics, the outfall elevation in relation to the secondary drainage system (where sufficient freeboard is needed), the drain gradient, machinery available, etc. Interceptor drains must be sunk into a less pervious layer, and a minimum depth of 1.0 m is recommended.

- Drain spacing

  Drain spacing is influenced greatly by economics as the closer the spacing, the more expensive the scheme. Where K values are relatively high, e.g. > 1 m/day, calculations will indicate comparatively wide lateral spacing. Deep and wide spacing increases the volume of soil to be drained and also the amount of salt removed. Excessive drainage water volumes may result, including increased downstream salinity levels. The closer together drains are spaced the higher will be the drainage coefficient and the faster the drain-out will be. However, where K values are below 0.1 m/day, very close drain spacings are required; should the K value be too 'slow' drain spacings will be too close to be economic and mole drains might be indicated.

- Drain Gradient

  Mostly the lateral will be laid parallel to the land surface. Ideal gradients range between 1:150 and 1:250. On flat land the gradient can be as little as 1:800, and on steep land, gradients of 1:50 are possible. Laterals can be laid at an angle to the general land slope in order to increase or decrease flow velocity. Gradient and pipe sizing are related in this respect; pipes must be sized to provide a minimum velocity so that self-scouring or self-cleaning takes place. With soils prone to silting, a minimum velocity in drainage pipes of 0.45 m/s is recommended. For more stable soils, a minimum velocity of 0.15 m/s is suggested. Gradients below 1:250 are prone to silting.

- Pipe sizing

  The maximum amount of water a drainage pipe can carry – its capacity – depends on its internal diameter, land slope and material. Plastic pipes of 70-90 mm in diameter are the most common laterals and 110-200 mm the most common collectors. Recommended sizes are computed at the design stage using standard flow diagrams provided by manufacturers.

- Available pipe materials

  There are a range of different pipe materials available, each with its advantages and disadvantages, e.g. clay tiles, semi-rigid slotted plastic pipes, flexible, perforated plastic pipes and pitch fibre pipes. Clay tiles are seldom used today, mainly due to the high labour requirement for installation. Plastic pipes are the most common, with flexible pipes used in conjunction with trenchless installation machinery and rigid pipes with excavated trenches.

7.2 Introduction to Financial Feasibility

The economic viability of drainage refers to the ability of the increase in benefits as a result of drainage to recover the cost required to drain. Financial feasibility refers to the ability of the farming unit to access sufficient additional finance to fund for the drainage required and maintain an overall increasing cash flow in the long term. Economic viability is a prerequisite for financial feasibility (Armour and Viljoen, 2008).

The Drain-Fin model assesses two sets of financial criteria namely:

- **Economic** Benefit Cost analysis
- **Financial** Whole-farm analysis

The economic analysis is an exercise to determine whether the benefits of sub-surface drainage exceeds installation direct and opportunity cost. The financial analysis, on the other hand, determines if the installation will be financially feasible, taking into account general accepted financing norms, etc.

The model also makes provision for the analysis of any external interventions, e.g. Government grants, subsidies, etc.

7.3 Economic Benefit Cost analysis

A decision-making tool used by Backeberg (1981), to evaluate capital investment on irrigation drainage is benefit cost analysis which includes:

- Internal Rate of Return (IRR),
- Net Present Value (NPV), and
- Benefit Cost Ratio (B/C ratio)

The Net Present Value (NPV) is the difference between the discounted present value of discounted present value of the capital and operating expenditure. The Benefit Cost Ratio (B/C Ratio) is obtained by dividing the present value of the income by the present value of capital and operating expenditure. The Internal Rate of Return (IRR) is the breakeven discount rate at which the B/C ratio equals one (1), or alternatively where the NPV equals zero (0).

7.4 Financial Whole-farm analysis

Financial Whole-farm analysis ratios and norms, includes:

- Projected Production Cost ratios,
- Projected Cash flow ratios,
- Projected Debt ratios, and
- Projected Bank balance

The above ratios are derived from the 20-year projected Whole-farm Cash flow-, Income Statement and Balance Sheet.

7.5 General accepted Financing Criteria and Norms

Traditionally, lenders apply the five C‟s of credit when determining the creditworthiness of agricultural borrowers (Wilson et al., 2006):

- The borrowers **Capacity** to repay the loan obligation and bear the associated financial risks, calculated by analysing both past and projected profitability and cash flow of the farm business. If a farmer has previously installed drainage, increased return as a result of drainage records will be useful; otherwise data from a close neighbour with similar conditions who has installed drainage, or verified simulation models can also be used.
- The borrowers **Capital** available for farm operations, assessed from balance sheets with liquidity and solvency calculations to gauge equity investment in the farm and how effectively it generates cash flows. Without sufficient capital (and managerial expertise) to optimise the returns from the investment in drainage (e.g. planting more capital intensive higher value long term crops), the investment may be underutilised.
- The borrowers‟ security **Collateral** as a final source of repayment if the borrower defaults on the terms of the loan agreement or dies. The higher the risk of the operation for which the loan is requested, the higher level of Collateral required. As drainage has no salvage value, the full costs of the drains often needs to be

covered by some form of collateral. The higher the percentage of a farmers' total land that needs to be drained, the less likely that the land itself can cover the collateral obligations.

- The **Conditions** for use of the funds, or the intended purpose of the funds required by the borrower are considered in terms of general economic conditions, interest rates, inflation and the demand for money in order to come up with a discount rate with which to calculate the net present value (NPV), benefit cost ratio (B/C) and internal rate of return (IRR), all useful in comparing funding alternatives.
- The **Character** of the borrower, i.e. the attitude of the borrower towards risk and financial track record available from credit bureaus, is also a very important factor for commercial lenders considering a loan application. In the case of subsidised state funding and grants the potential recipients character in terms of "money grabbing" and not applying the funds productively also needs to be evaluated to ensure efficient use of public funds.
- The model addresses "Capacity" and "Capital" using the following ratios:
- Production cost ratio (to ensure that production costs projections is in line with industry norms)
- Cash flow ratio (an indicator of repayment ability and the enterprise's ability to survive financial setbacks)
- Debt ratio (an indicator of solvency)

"Collateral", "Conditions" and "Character" cannot be calculated using quantitative inputs only and will differ for each analysis and also for different financiers. The model however makes provision for the user to choose "yes" or "no" to indicate whether the qualitative criteria namely collateral and character will pass criteria norms.

7.6 Condensed Description of the Model (DRAIN-FIN)

Figure 7-1 is a diagrammatical illustration of the model which was developed to conduct the research. The model is called the Drainage Financial Model (Drain-Fin Model).

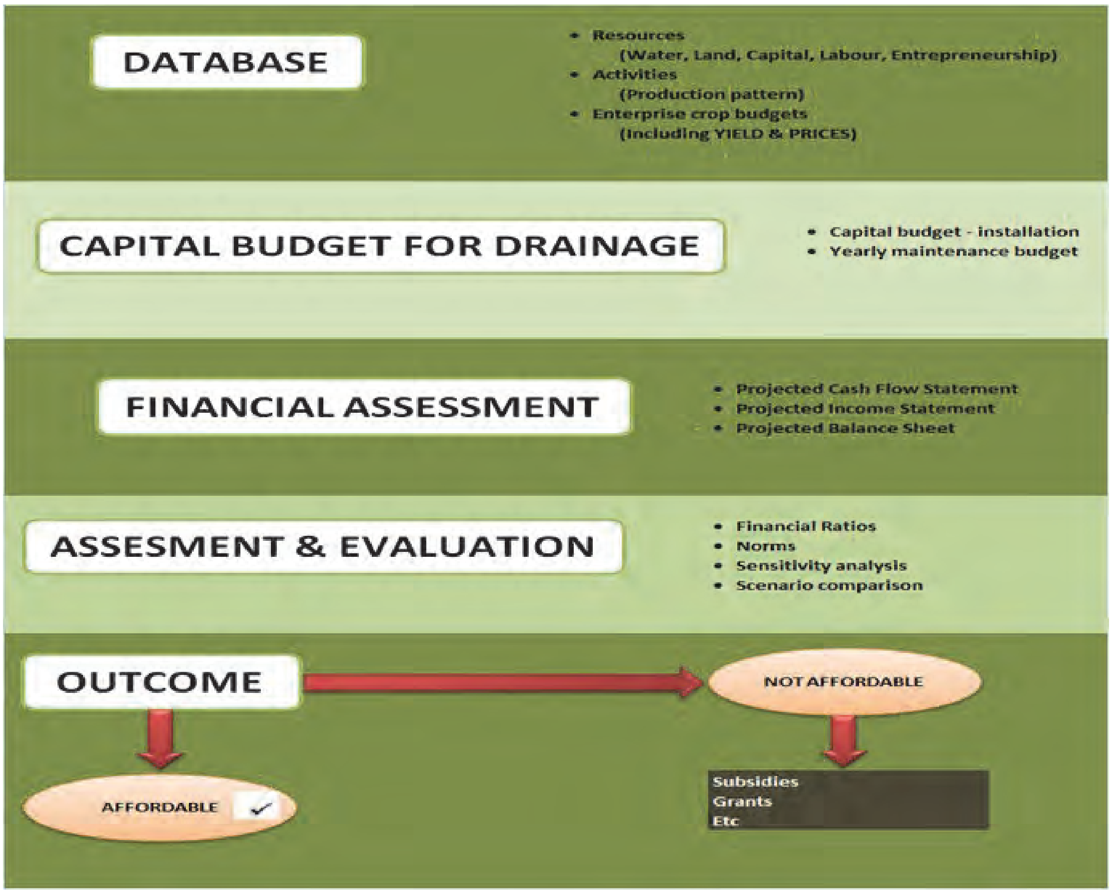


Figure 7-1: Diagrammatical illustration of the different components of the Drain-Fin Model

The different elements of the Drain-Fin model are briefly discussed in the next sections.

7.6.1 Model components

7.6.1.1 Database

The database consists of the following subsets:

- Farm composition and production plan/cropping pattern (including crop rotation)
- Tree/Orchard census for permanent crops
- Crop Enterprise budgets (production input costs and produce prices)
- Yield curves (with and without sub-surface drainage)
- Capital and other income and costs not captured in enterprise crop budgets
- Financial inputs pertaining to income statement and balance sheet

7.6.1.2 Capital budget and annual maintenance cost

The capital and maintenance costs for different sub-surface systems and different locations differ. To determine the optimal sub-surface drainage system from an economic and financial point of view, it is necessary to analyse different drainage systems (cost and effect on yields) with different scenarios.

7.6.1.3 Financial assessment and evaluation

The accurate composition of the projected Cash flow-, Income statement and Balance sheet is essential for financial assessment and evaluation. The Drain-Fin model makes provision for the comparison of up to ten different scenarios. These scenarios can be evaluated and compared in terms of Per-hectare analysis (Benefit cost ratio, NPV, IRR and Payback period) and/or Whole-farm analysis (Production cost ratio, Cash flow ratio, Debt ratio and projected bank balance).

The effect of subsidies, grants, etc. can easily be accommodated in the model to discount the monetary effect of government intervention on the economic and financial feasibility of sub-surface drainage.

7.6.2 Model Operation

The Drain-Fin model was developed in Microsoft Excel 2007 and comprises 22 worksheets which will be briefly discussed in the sections below.

7.6.2.1 DrainFin Model Menu

Figure 7-2 illustrates the user-friendly menu of the DrainFin Model. The menu buttons lead to the different sheets in the model. On each of the model sheets is there a “MENU” button (shortcut-key) to revert back the DrainFin Menu.

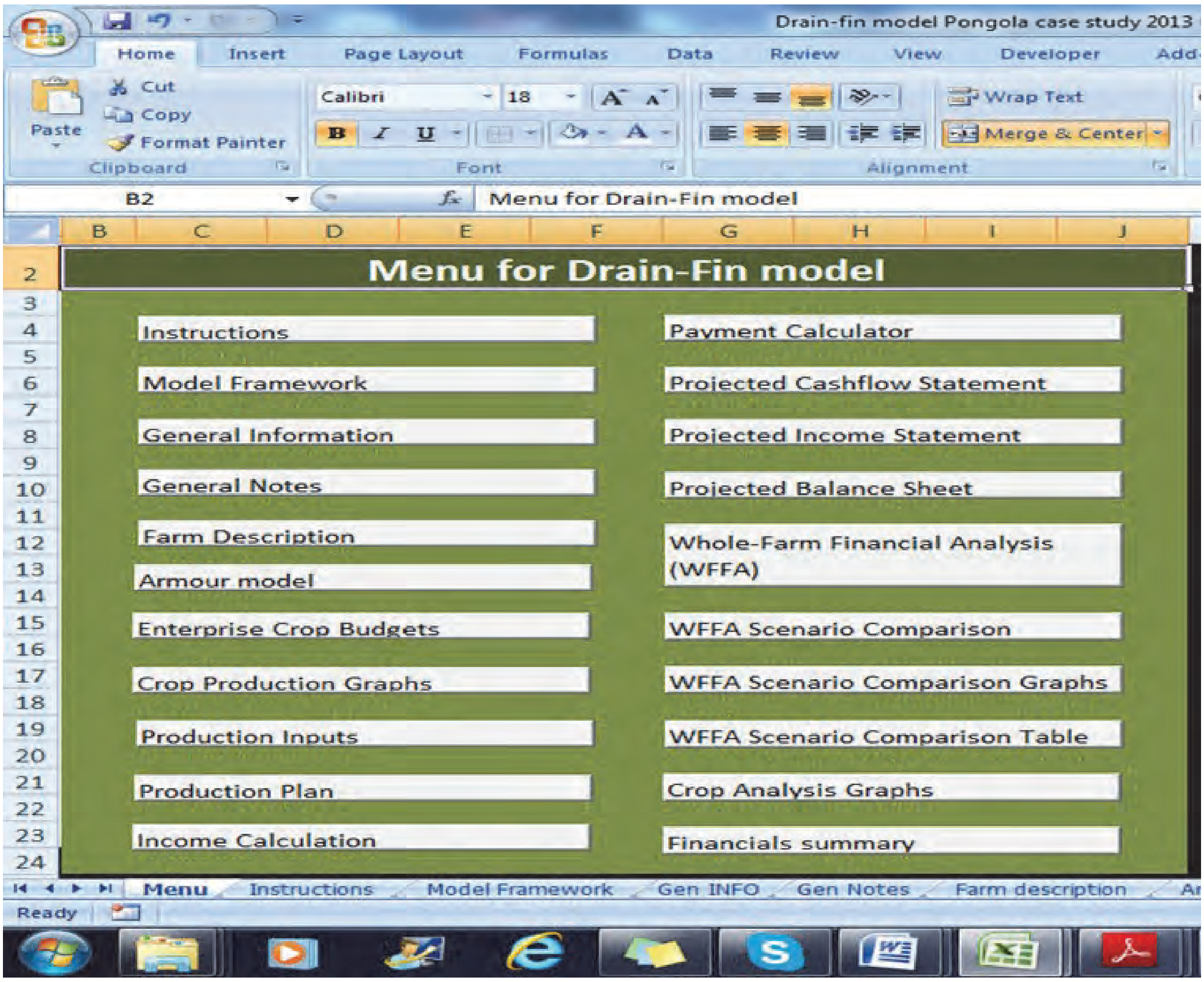


Figure 7-2: Drain-Fin model Menu

The development of the "DrainFin Menu" contributes to smooth operation of the model and ensure "ease-of-use".

7.6.2.2 Instructions

The "Instructions sheet" provides the user with step-by-step guidance through the model. Each sheet is discussed in order to provide the user with insight to the working of the model to ensure the correct programming of the model. Figure 7-3 is a snapshot of the "Instructions" sheet.

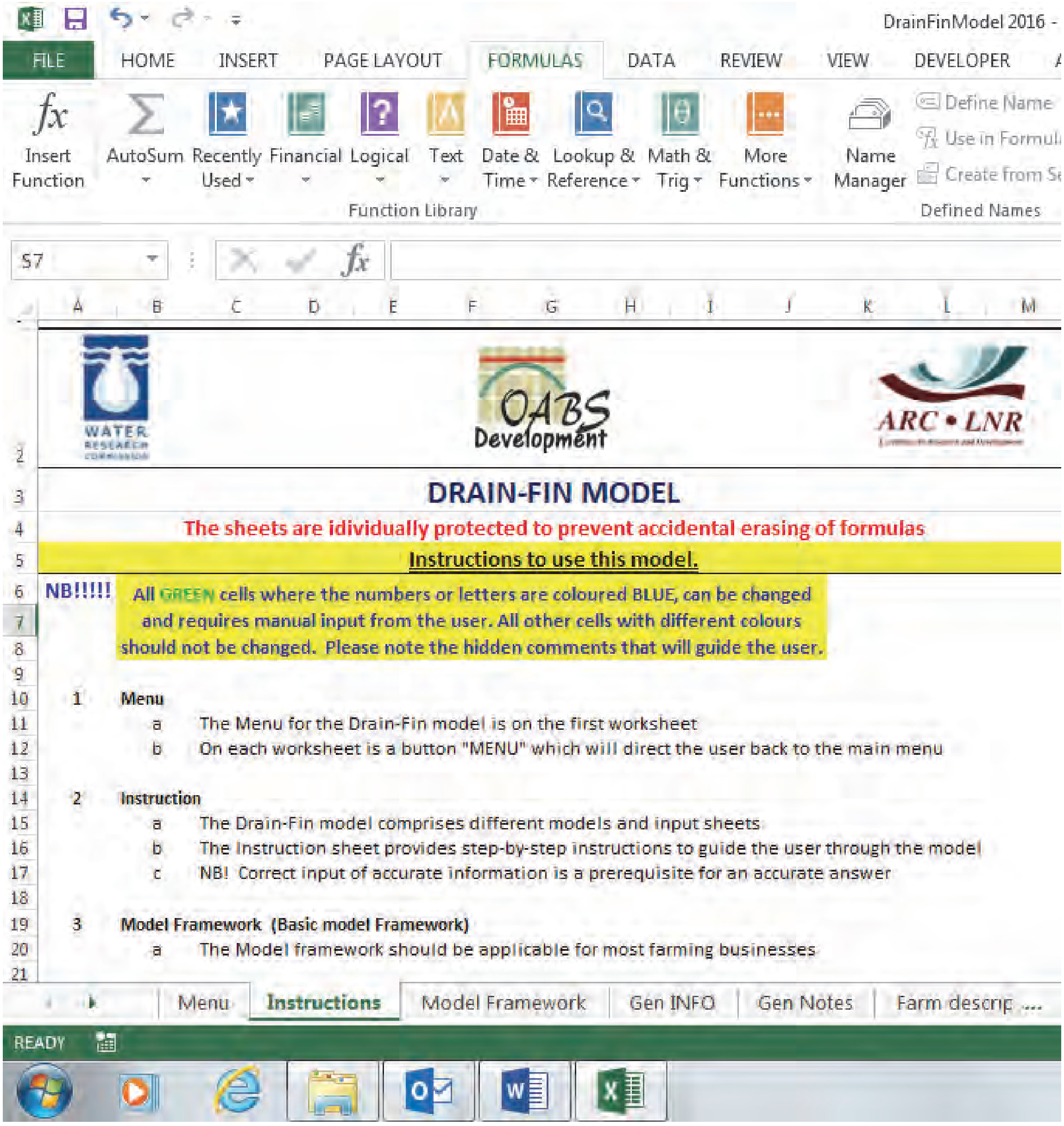


Figure 7-3: Drain-Fin model “Instructions” sheet

7.6.2.3 General information

The “General information” sheet requires general input, e.g. name, address, contact numbers, discount rates and interest rates (See Figure 7-4).

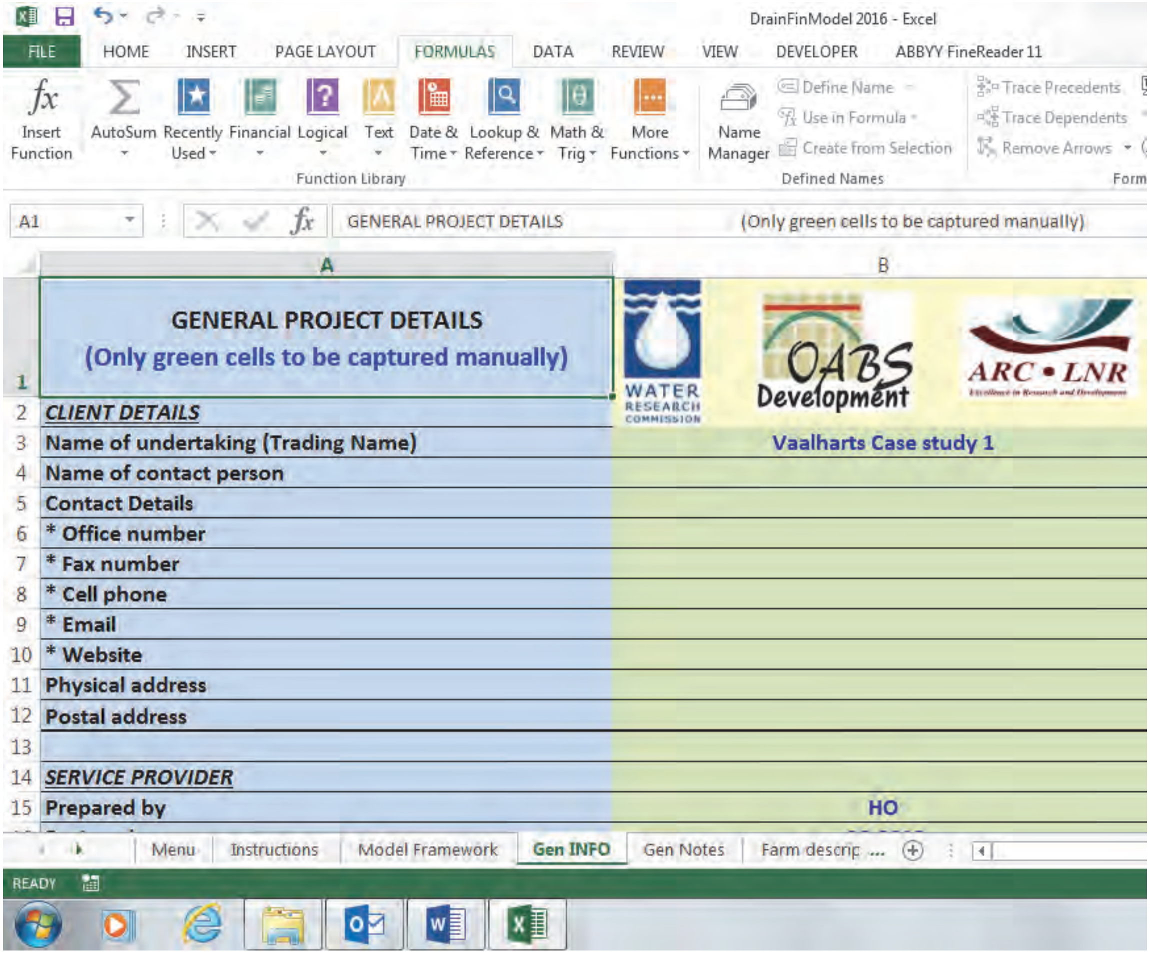


Figure 7-4: Drain-Fin model “General information” sheet

7.6.2.4 General notes

The “General notes” sheet provides a place for the user to make notes pertaining to the case study. Figure 7-5 shows the “General notes” sheet.

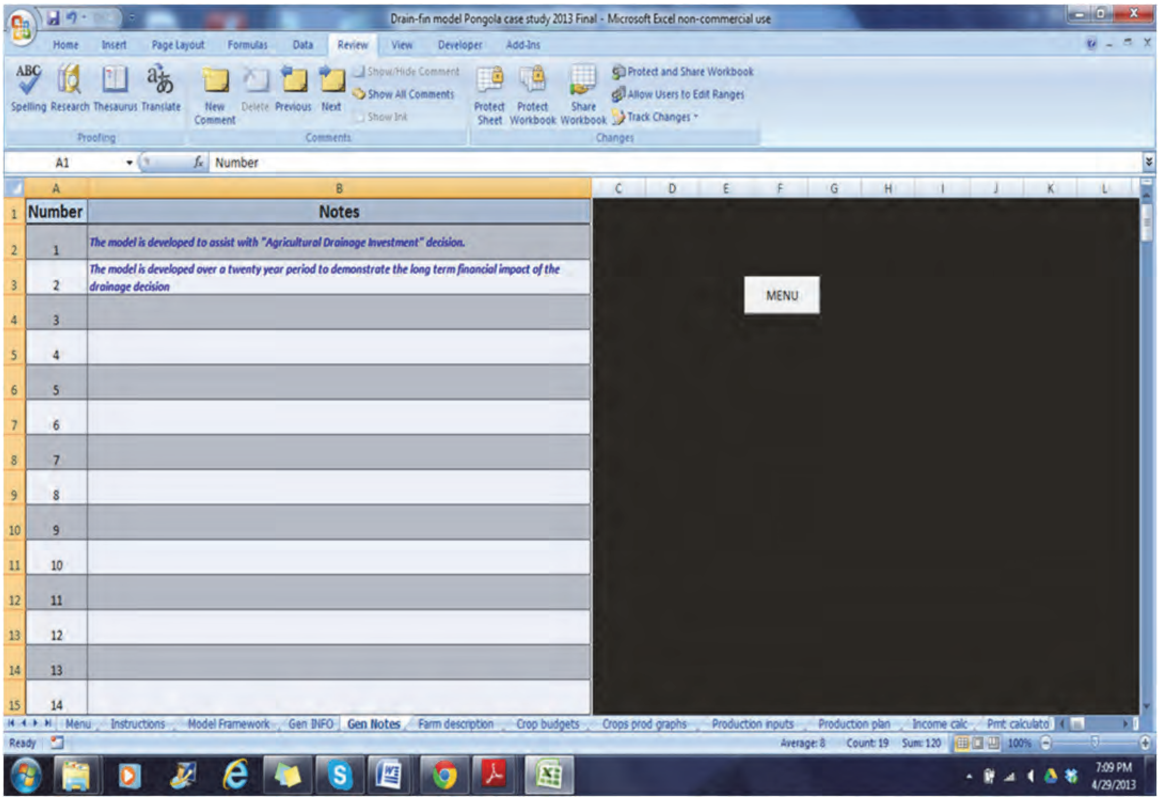


Figure 7-5: Drain-Fin model “General notes” sheet

7.6.2.5 Armour model

The Armour model sheet incorporates several modules of the original model that was developed by Armour and Viljoen (2008). These are:

- Bio-physical (land-water-salt) interaction
- Salinity build-up (zero drainage and runoff)
- Crop gross margin per hectare (with and without drainage)

These modules assist with the calculation of various aspects of drainage. The Maas and Hoffman equation (1977) is used to simulate water and salt logging to determine yield curves for 20 crops. These crops are: barley, beets, carrots, cotton, cucurbits, dry beans, fruit, lucerne, maize, olives, onions, pastures, peanuts, pecan nuts, potato, soybeans, sunflower, vegetable, vineyard and wheat.

Figure 7-6 illustrates a hypothetical example of salt build-up potential in the soil in the absence of drainage and wash-off and leaching. At a volumetric quota of 1 100 mm per hectare per year at a concentration of 100 mg per litre, relates to a mass of 11 tonnes of salt being added to the one hectare each year. In the first year a two (2) meter depth of soil will contain a mass of 20 tonnes of salt.

Irrigation water salt load	Quantity	UNIT		Factor		
Plot	1	ha		1	a	
Water Right	1,100	mm/ha/yr		1,100	b	
=	11,000	m^3 / yr	x	10	c	a*10
=	11,000,000	liters	x	1,000	d	c*1000
Irrigation water salinity	1,000	mg/l		1,000	e	
salts added	11,000,000,000	mg / year		<	f	d*e
=	11,000	kg / yr		1,000,000	g	f/1000000
=	**11.00**	**ton / year**		1,000	h	h/1000
Soil salt mass accumulation						
Soil water salinity TDS	**2,000**	**mg/l**	x	2	i	e*2
Soil water salinity EC	308	mS/m	/	6.5	j	i / 6.5
Soil water depth	2	m		2	k	
Soil water capacity	50	%		50	l	
Saturated soil water volu	10,000	m^3		<	m	ha^3 *k *l
=	10,000,000	liters		<	n	m*d
Soil salt mass	20,000,000,000	mg		<	o	n*i
=	20,000	kg in yr1		1,000,000	p	o/1000000
=	**20.00**	**ton in yr1**		1,000	q	q/1000

Figure 7-6: Bio-physical salt concentration to mass illustration

(Originated from Armour and Viljoen, 2008)

The first three columns of Table 7-3 are the data required for the 20 crops in the model.

Table 7-3: Crop specific data requirements for populating the model

	ECe Threshold	ECe Gradient	Max. Yield
	mS/m	*%/mS/m*	*ton/ha*
Barley	800	0.071	**6.00**
Beets	400	0.090	**35.00**
Carrots	100	0.140	**50.00**
Cotton	770	0.052	**5.00**
Cucurbits	250	0.130	**50.00**
Dry_Beans	160	0.096	**3.50**
Fruit	170	0.210	**21.00**
Lucerne	200	0.073	**20.40**
Maize	170	0.120	**14.00**
Olives	300	0.190	**6.40**
Onions	120	0.160	**55.00**
Pastures	600	0.071	**8.00**
Peanuts	320	0.290	**4.00**
Pecan_nuts	150	0.190	**1.60**
Potatoes	170	0.120	**45.00**
Soybeans	500	0.200	**6.00**
Sunflower	500	0.087	**4.00**
Vegetables	700	0.090	**40.00**
Vineyards	150	0.096	**30.00**
Wheat	600	0.071	**7.00**

(Source: Armour and Viljoen, 2008)

The first three columns of are input into the Maas and Hoffmann equation as shown in Figure 7-7 to determine the corresponding percentage loss in yield due of soil salinity.

Working of the Maas & Hoffman (1977) equation

Weighted ave. ECe (mS/m)	*330*	*= TDSiw*	*1056*		*mg/l*	*(x 6.4 /2)*
	Units	LUCERN	MAIZE	VINES	WHEAT	Onions
ECe Threshold	mS/m	200	170	150	600	120
ECe Gradient	%/mS/m	0.073	0.120	0.096	0.071	0.160
Max Physiological yield	ton/ha	20.40	14.00	30.00	7.00	55.00
% of max Physiological yield	%	91	81	83	100	66
Expected yield	ton/ha	18.46	11.31	24.82	7.00	36.52
Yield loss	ton/ha	1.94	2.69	5.18	0.00	18.48
Crop price	R/ton	R 600	R 1,500	R 1,000	R 2,000	R 23,532
Financial loss	R/ha	R -1,162	R -4,032	R -5,184	R 0	R -434,877

< Choose crop to view on graph

The Maas & Hoffman Equation

IF ECe < Threshold THEN

Y=100% of max yield

ELSE

Y=100-((Threshold-ECe)*Gradient))

% max Yield

ECe	LUCERN	MAIZE	VINES	WHEAT
0	100	100	100	100
50	100	100	100	100
100	100	100	100	100
150	100	100	100	100
200	100	96	95	100
250	96	90	90	100
300	93	84	86	100
350	89	78	81	100
400	85	72	76	100
450	82	66	71	100
500	78	60	66	100
550	74	54	62	100
600	71	48	57	100
650	67	42	52	96
700	64	36	47	93

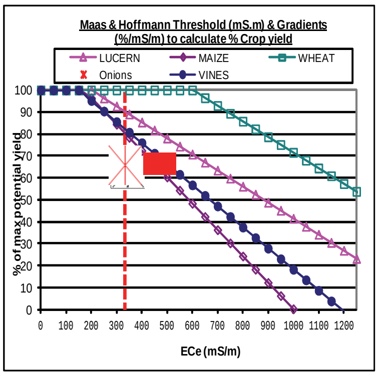


Figure 7-7: A demonstration of the Maas and Hoffman (1977) equation for converting Soil salinity (ECe) to yield loss (ton/ha) to financial loss (R/ha)

(Source: Armour and Viljoen, 2008)

Figure 7-7 goes a step further than calculating the expected yield; it puts a financial value to the lost production by multiplying the yield loss by the expected crop price. If this potential increase in value exceeds the annualised costs of drainage, then this is a first indication that drainage is feasible.

7.6.2.6 Crop budgets

The Enterprise Crop Budgets sheet makes provision for ten Permanent crops and ten Cash crops budgets.

7.6.2.6.1 Permanent Crop budget

The first step in setting up a Permanent Crop budget is to complete the Field/Orchard/Tree census for the specific crop (see Figure 7-8). This info is used to calculate the yearly net margin which is derived from yield, income and operational cost.

To be replaced after		11	years			budgets					
Orchard / tree census (ha)											
<1-yr old	18	8-yrs old	5	16-yrs old		24-yrs old		32-yrs old		Total ha	Sugarcane
1-yr old		9-yrs old	3	17-yrs old		25-yrs old		33-yrs old			88 ha
2-yrs old	3	10-yrs old	12	18-yrs old		26-yrs old		34-yrs old			
3-yrs old	18	11-yrs old		19-yrs old		27-yrs old		35-yrs old			
4-yrs old	5	12-yrs old		20-yrs old		28-yrs old		36-yrs old			
5-yrs old	16	13-yrs old		21-yrs old		29-yrs old		37-yrs old			
6-yrs old	5	14-yrs old		22-yrs old		30-yrs old		38-yrs old			
7-yrs old	3	15-yrs old		23-yrs old		31-yrs old		39-yrs old			

Figure 7-8: Case study farm – Field census

Figure 7-9 reflects the establishment cost for sugarcane. The model is developed in such a way that either detail or just total figures can be used in the crop budgets. In the example below, the total planting cost was used as input and not specified in the different components, e.g. seedbed preparation, irrigation, etc. This time-saving feature enhances the user-friendliness of the model.

1. Budget for	**Sugarcane**
Establishment cost	
Seedbed preparation	**0**
Irrigation, etc	**0**
Fertilizer	**0**
Seed / trees / ?	**0**
Weed control	**0**
Sundries & contingencies	**0**
Other	**0**
OR TOTAL PLANTING COST	**31,370**
TOTAL ESTABLISHMENT COST	**31,370**

Figure 7-9: Sugarcane – Establishment cost

Figure 7-10 show the calculation of yearly production cost. Although the model is designed for a twenty year projection, only five years are shown due to space constraints. Again, the user has the option to specify detail inputs or just total yearly production costs.

YEAR	0	1	2	3	4	5
Establishment cost	**31,370**					
Direct costs	***0***	***0***	***0***	***0***	***0***	***0***
Seed & plant material	0					
Fertilizer	0					
Organic material	0					
Pesticide control	0					
Herbicide control	0					
Repair & binding material	0					
Other	0					
Labour	***0***	***0***	***0***	***0***	***0***	***0***
Supervision	0					
Permanent labour	0					
Seasonal labour	0					
Other	0					
Mechanization	***0***	***0***	***0***	***0***	***0***	***0***
Fuel costs	0					
Repairs, parts & maintenance	0					
Licences & insurance	0					
Transport hired	0					
Other	0					
Fixed improvements	***0***	***0***	***0***	***0***	***0***	***0***
Repair & maintenance	0					
Insurance	0					
Other	0					
General expenditures	***0***	***0***	***0***	***0***	***0***	***0***
Electricity	0					
Water cost	0					
Land, property & municipal taxes	0					
Administration cost	0					
Other	0					
OR TOTAL YEARLY COST	0	18,845	18,845	18,845	18,845	18,845
TOTAL YEARLY COST	**31,370**	**18,845**	**18,845**	**18,845**	**18,845**	**18,845**

Figure 7-10: Sugarcane – Yearly production cost year 1 to year 5

The input field for sub-surface installation and yearly maintenance cost is reflected in Figure 7-11. Only the first five years is shown for illustration purposes.

YEAR	0	1	2	3	4	5
Additional drainage cost	32,390	969	1,601	1,283	1,493	2,230

Figure 7-11: Pongola – Sub-surface drainage installation and yearly maintenance cost

Figure 7-12 illustrates the “With” and “Without” drainage scenarios for harvest distribution, yearly produce price, yield, income, production cost and net margin.

Harvest distribution (Without drainage)	%	R/tonne
Sugar mill	100%	352
	0%	0
	0%	0
	0%	0
TOTAL HARVEST DISTRIBUTION	100%	

YEAR	0	1	2	3	4	5
Yield t/ha (Without drainage)	90	90	90	90	90	90
Income Export	31,680	31,680	31,680	31,680	31,680	31,680
Income Local	0	0	0	0	0	0
Income Juice	0	0	0	0	0	0
Income Other	0	0	0	0	0	0
Total income / ha	**31,680**	**31,680**	**31,680**	**31,680**	**31,680**	**31,680**
Less Total yearly cost / ha	31,370	18,845	18,845	18,845	18,845	18,845
Net margin / ha	310	12,835	12,835	12,835	12,835	12,835
Cumulative net margin / ha	310	13,145	25,980	38,815	51,650	64,485
Average R/ tonne	352	352	352	352	352	352

Harvest distribution (With drainage)	%	R/tonne
Sugar mill	100%	352
	0%	0
	0%	0
	0%	0
TOTAL HARVEST DISTRIBUTION	100%	

YEAR	0	1	2	3	4	5
Yield t/ha (With drainage)	90	115	120	125	130	135
Income Export	31,680	40,480	42,240	44,000	45,760	47,520
Income Local	0	0	0	0	0	0
Income Juice	0	0	0	0	0	0
Income Other	0	0	0	0	0	0
Total income / ha	**31,680**	**40,480**	**42,240**	**44,000**	**45,760**	**47,520**
Less Total yearly cost / ha	63,760	19,814	20,446	20,128	20,338	21,075
Net margin / ha	-32,080	20,666	21,794	23,872	25,422	26,445
Cumulative net margin / ha	-32,080	-11,414	10,380	34,252	59,674	86,119
Average R/ tonne	352	352	352	352	352	352

Figure 7-12: Sugarcane – Yields, harvest distribution and price per tonne

Figure 7-13 reflects the yearly yield and cumulative net margin for the "With" and "Without" drainage scenarios for year 1 to year 7. It clearly shows the improvement in sugarcane yield and subsequent net margin, as a result of sub-surface drainage.

Yield	1	2	3	4	5	6	7
Without drainage	90	90	90	90	90	90	90
With drainage	115	120	125	130	135	140	140
Cum net margin without	310	13,145	25,980	38,815	51,650	64,485	77,320
Cum net margin with drai	-32,080	-11,414	10,380	34,252	59,674	86,119	114,641

Figure 7-13: Sugarcane – Yearly yield and cumulative net margin for "With" and "Without drainage" scenarios year 1 to year 7

Figure 7-14 graphically illustrates the projected yield curve for sugarcane for "With" and "Without" sub-surface drainage. The projection shows that it takes up to 6 years to realise the full advantage of sub-surface drainage installation.

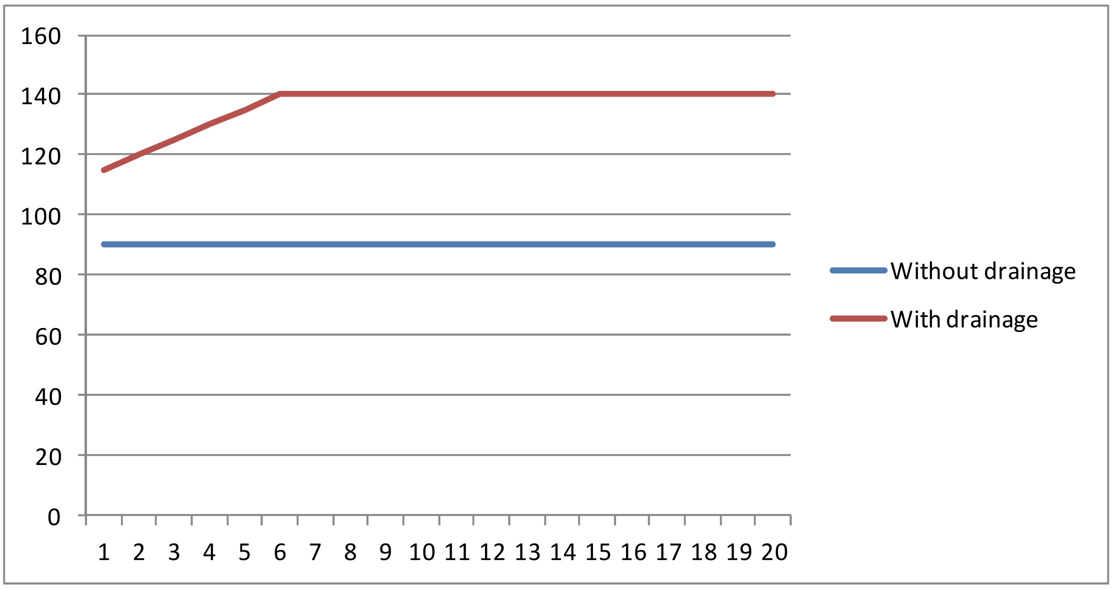


Figure 7-14: Sugarcane – Projected yield curve for "With" and "Without" sub-surface drainage

Figure 7-15 shows the Net cumulative margin per hectare for sugarcane for the "With" and "Without" sub-surface drainage scenarios.

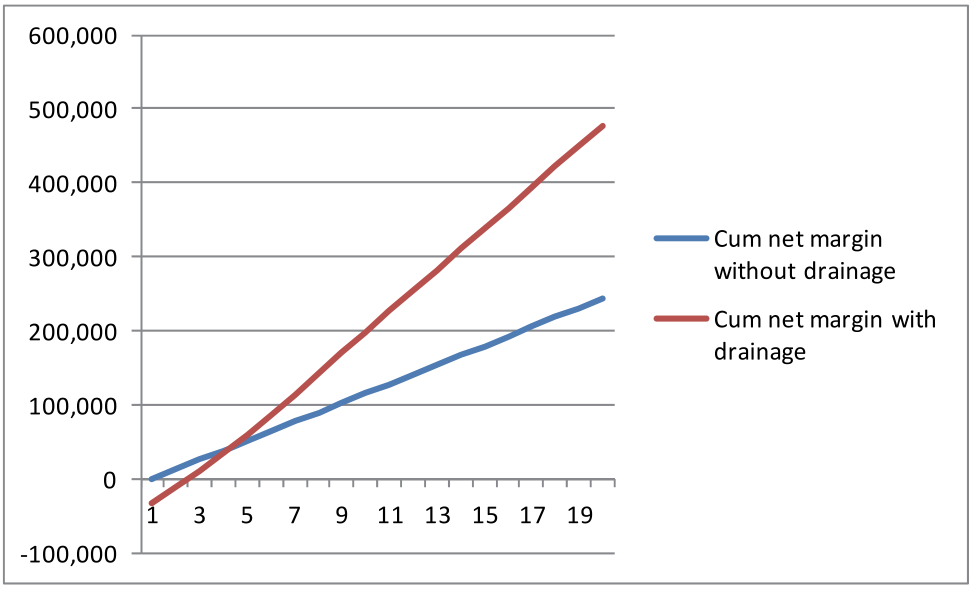


Figure 7-15: Sugarcane – Net Cumulative margin for "With" and "Without" sub-surface drainage

7.6.2.6.2 Cash crop budget

The model makes provision for ten cash crops enterprise budgets. These budgets are versatile and can be applied for different crops or different fields of the same crop.

7.6.2.7 Production plan

Figure 7-16 reflects the input field for the Production plan. The input field makes provision for the replacement schedule for permanent crops and the production plan for Cash crops. The replacement according to current management practices is automatically calculated and only needs confirmation by the user. The input field makes provision for a twenty year production plan.

Budget	YEAR		1	2	3	4	5
Budget	Permanent crops replacement (hectare)						
1	Sugarcane	Suggested planting	0	0	0	0	0
		Confirm hectares to plant		12	3	5	3
2	0	Suggested planting	0	0	0	0	0
		Confirm hectares to plant					
3	citrus	Suggested planting	0	0	0	0	0
		Confirm hectares to plant					
4	citrus	Suggested planting	0	0	0	0	0
		Confirm hectares to plant					
5	citrus	Suggested planting	0	0	0	0	0
		Confirm hectares to plant					
6	citrus	Suggested planting	0	0	0	0	0
		Confirm hectares to plant					
7	citrus	Suggested planting	0	0	0	0	0
		Confirm hectares to plant					
8	citrus	Suggested planting	0	0	0	0	0
		Confirm hectares to plant					
9	citrus	Suggested planting	0	0	0	0	0
		Confirm hectares to plant					
10	citrus	Suggested planting	0	0	0	0	0
		Confirm hectares to plant					
	Total Permanent crops replacement (ha)		**0**	**12**	**3**	**5**	**3**
Budget	Cash crops production (hectare)						
1	Maize						
2	?						
3	?						
4	?						
5	?						
6	?						
7	Maize						
8	?						
9	?						
10	Maize						
	Total cash crop prod (ha)		**0**	**0**	**0**	**0**	**0**

Figure 7-16: Production plan – Pongola case study

7.6.2.8 Drainage installation plan

Figure 7-17 shows the drainage installation plan for the Pongola case study. In this example sub-surface drainage is installed from Year 1 for sugarcane fields. The model can also be programmed to makes provision for different sets of the same crop, e.g. instead of Crop 1,2 and 3, it can simply be programmed as Field 1,2 and 3 for sugarcane. By making use of this programming technique, projection for installation of drainage on different fields in different years can be accommodated. The model is however limited to 10 different crops/drainage installation options.

Budget	YEAR Permanent crops	Notes	1	2	3	4	5
1	Sugarcane		y	y	y	y	y
2	0		n	n	n	n	n
3	citrus		n	n	n	n	n
4	citrus		n	n	n	n	n
5	citrus		n	n	n	n	n
6	citrus		n	n	n	n	n
7	citrus		n	n	n	n	n
8	citrus		n	n	n	n	n
9	citrus		n	n	n	n	n
10	citrus		n	n	n	n	n
Budget	Cash crops	Notes					
1	Maize		n	n	n	n	n
2	?		n	n	n	n	n
3	?		n	n	n	n	n
4	?		n	n	n	n	n
5	?		n	n	n	n	n
6	?		n	n	n	n	n
7	Maize		n	n	n	n	n
8	?		n	n	n	n	n
9	?		n	n	n	n	n
10	Maize		n	n	n	n	n

Figure 7-17: Drainage installation plan – Pongola case study

7.6.2.9 Projected financial statements

The financial statements for the farm business are compiled from farm records. A full set of financial statements for a farm business would consist of a balance sheet, an income statement and a cash flow statement. The balance sheet is often linked to a photo on a specific date. It is a picture of the farm's financial situation at a specific point in time, showing that the famers owes and owns. If the balance sheet is a photo, then the income statement may be compared to a video that shows us what has occurred from one balance sheet to the next. The cash flow statement shows all of the cash flowing into and out of the farm business for a specific period (Standard Bank, 2013). For future planning projected cash flow statement, income statement and balance sheet are of paramount importance.

7.6.2.9.1 Cash flow statement projection

Most of the information needed for financial analysis of the farm business is contained in the balance sheet and income statement. Most financial decisions can generally be based on information and analysis of this nature. An important shortcoming of balance sheets and income statements is that they do not take account of the cash flow or flow of funds in the farm business for the period under preview.

At first this might not seem important, but these days cash flow is probably the most important component of the financial management of the farm business. The large number of farm businesses currently experiencing cash flow and cash flow-related problems prove this point.

The income statement reflects the income and expenditure of the farm business. To realise the projected profit, large amounts of money need to be spent initially on items such as seed, fertiliser, herbicides, pesticides, fuel, stock-feed and licks. Because income is only realised after these expenses have been incurred, a farm business could show a profit during a financial year but have an overdrawn bank account for the best part of that year. Only once the income is realised will the overdraft be reduced or converted to a positive balance. This is currently the rule rather than the exception. Thus, as far as financing and financial management are concerned, cash flow analysis is of significant importance.

The most important feature of the cash flow statement is that only cash expenses and cash income are indicated at the time of payment or receipt. The cash flow statement is based on the cash analysis book. The cash flow statement reflects the sources from which funds were generated during the accounting period as well as the purposes for which these funds were used. The accounting period is divided into individual months so that the flow of funds can easily be traced during the period under review.

Because cash flow is an important consideration when it comes to financing the farm business, the bank and the monthly bank balance are important elements of the cash flow statement. The cash flow statement consists of three components, namely income, expenditure and the bank balance, in that order:

- Income consists of operating income (income from products, for example, wool, maize, milk), capital income (sales of livestock and machinery) and non-farming income. Only actual cash income is regarded as income, and only in the month of the actual receipt.
- Expenditure is classified as operating expenditure (seed, fertilizer and purchased stock-feed), capital expenditure (purchasing of livestock and machinery), debt repayments (interest and capital redemption) and non-farming expenditure. As in

the case of income, only actual payments are recorded in the cash flow statement, and then only in the month of payment.

Two aspects are especially important: Firstly, non-cash flow items, such as depreciation, are not recorded in the cash flow statement. Secondly, items such as seed and fertiliser are often bought on credit at cooperatives. These items are only recorded in the cash flow statement in the month that account is paid. If the account is partially paid, only the portion that has been paid should be recorded. Amounts in arrears are not reflected on the cash flow statement.

The surplus or shortfall for a specific month can be calculated by deducting the total expenditure from total income. The sum total of the surplus/shortfall and the opening bank balance give a new balance, which could be either negative or positive. If this balance is negative, the interest that has to be paid on the farm business' bank overdraft is added to calculate the closing balance. If the balance is positive, the amount is directly carried over to the closing balance because no interest is payable in this case. It should be borne in mind that interest on overdrawn balances is calculated on that month's balance only, that is, the interest charges will differ from month to month as the overdrawn balance fluctuates. The closing balance for one month is the opening balance for the next month.

A schematic presentation of how to calculate the net disposable income is given in Figure 7-18, illustrating the relationship between the income statement and the cash flow statement.

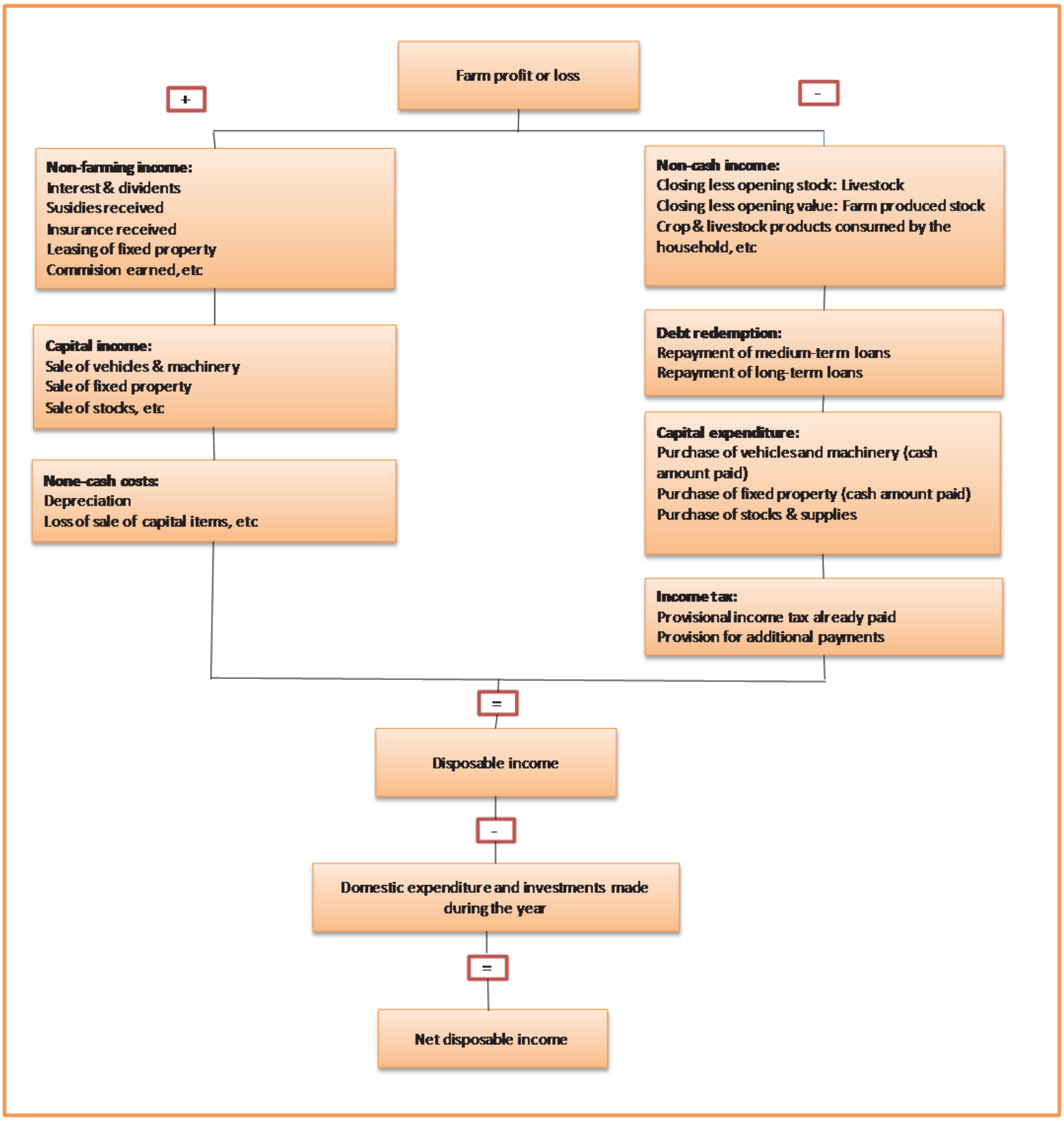


Figure 7-18: Schematic presentation of how to calculate the net disposable income

(Source: Standard Bank, 2013)

7.6.2.9.1.1 Mathematical specification of the Cash flow statement projection

In mathematical terms the Cash flow statement projection objective is as follows:

$$\text{Net cash flow} = \sum_{i=a}^{d} Ii - \sum_{o=l}^{q} Io$$

where:

I_a = Total crop production income

I_b = Total Livestock income

I_c = Total Capital income

I_d = Total Non-farm income

I_i = Interest rate on positive bank balance

O_l = Total Direct allocated production costs

O_m = Total Livestock production costs

O_n = Total Non-allocated production costs

O_o = Total Capital expenditure

O_p = Total Debt redemption

O_q = Total other expenditure

O_i = Interest rate on negative bank balance

7.6.2.9.1.2 Diagrammatical illustration of the Cash flow statement projection

The projected cash flow statement runs over a 20-year period to discount the effect of sub-surface drainage over its projected life-span. Included in the Cash flow projection are:

- Crop production income,
- Livestock income,
- Capital income,
- Other income (including non farm income),
- Direct allocated production costs,
- Non allocated costs,
- Capital expenditure,
- Debt redemption (including short-, medium- and long term payments), and
- Other expenditure (including private expenses, income tax, etc.).

The cash flow projection takes into account interest rates (debit and credit) and projects yearly end bank balance. It also calculates the Production cost ratio and Cash flow ratio which is both of paramount importance to evaluate the realism of the projection and the repayment ability of the business.

For the sake of brevity a condensed summary of the projected cash flow statement is reflected in Figure 7-19.

	YEAR		1	2	3	4	5	6	7	8	9	10
Total crop income			3,857,920	3,879,040	4,009,280	4,037,440	4,092,000	4,097,280	3,931,840	4,033,920	3,817,440	3,982,880
Total livestock income			0	0	0	0	0	0	0	0	0	0
Total capital & other income			2,850,320	0	0	0	0	0	0	0	0	0
Total projected income			**6,708,240**	**3,879,040**	**4,009,280**	**4,037,440**	**4,092,000**	**4,097,280**	**3,931,840**	**4,033,920**	**3,817,440**	**3,982,880**
Total crop expenses			1,807,850	2,322,796	1,951,908	2,039,242	1,946,765	2,054,362	2,515,489	2,030,162	2,604,586	1,939,150
Total livestock expenses			0	0	0	0	0	0	0	0	0	0
Total non allocatable costs			489,393	546,640	528,095	532,462	527,838	533,218	556,274	532,008	560,729	527,458
Total capital expenditure			2,850,320	0	0	0	0	0	0	0	0	0
Total debt redemption			745,962	745,962	745,962	745,962	651,320	651,320	651,320	651,320	463,876	463,876
Total Other expenditure			464,000	479,218	432,000	432,000	487,538	545,495	569,313	400,587	584,673	371,389
Total Expenditure			**6,357,524**	**4,094,616**	**3,657,965**	**3,749,666**	**3,613,462**	**3,784,395**	**4,292,397**	**3,614,077**	**4,213,865**	**3,301,873**
Excess / Defecit			350,716	-215,576	351,315	287,774	478,538	312,885	-360,557	419,843	-396,425	681,007
Bank balance : Initial (+ / -)			200,000	560,223	359,298	724,905	1,037,304	1,551,747	1,914,313	1,607,579	2,079,848	1,741,854
10.0%	Interest (Dt)		0	0	0	0	0	0	0	0	0	0
2.0%	Interest (Ct)		9,507	14,651	14,292	24,625	35,905	49,681	53,824	52,426	58,431	59,066
Bank balance : End			**560,223**	**359,298**	**724,905**	**1,037,304**	**1,551,747**	**1,914,313**	**1,607,579**	**2,079,848**	**1,741,854**	**2,481,927**
Production cost ratio (avg)		*67%*	*60%*	*74%*	*62%*	*64%*	*60%*	*63%*	*78%*	*64%*	*83%*	*62%*
Cash flow ratio (avg)		*106%*	*106%*	*95%*	*110%*	*108%*	*114%*	*110%*	*93%*	*113%*	*92%*	*122%*

	YEAR		11	12	13	14	15	16	17	18	19	20
Total crop income			4,092,000	3,857,920	3,879,040	4,009,280	4,037,440	4,092,000	4,097,280	3,931,840	4,033,920	3,817,440
Total livestock income			0	0	0	0	0	0	0	0	0	0
Total capital & other income			0	0	0	0	0	0	0	0	0	0
Total projected income			**4,092,000**	**3,857,920**	**3,879,040**	**4,009,280**	**4,037,440**	**4,092,000**	**4,097,280**	**3,931,840**	**4,033,920**	**3,817,440**
Total crop expenses			1,819,494	2,598,878	2,322,796	1,951,908	2,039,242	1,946,765	2,054,362	2,515,489	2,030,162	2,604,586
Total livestock expenses			0	0	0	0	0	0	0	0	0	0
Total non allocatable costs			521,475	560,444	546,640	528,095	532,462	527,838	533,218	556,274	532,008	560,729
Total capital expenditure			0	0	0	0	0	0	0	0	0	0
Total debt redemption			0	0	0	0	0	0	0	0	0	0
Total Other expenditure			624,262	730,267	442,527	531,948	684,423	675,612	726,566	705,609	530,540	707,522
Total Expenditure			**2,965,231**	**3,889,589**	**3,311,963**	**3,011,951**	**3,256,127**	**3,150,215**	**3,314,146**	**3,777,373**	**3,092,710**	**3,872,837**
Excess / Defecit			1,126,769	-31,669	567,077	997,329	781,313	941,785	783,134	154,467	941,210	-55,397
Bank balance : Initial (+ / -)			2,481,927	3,694,421	3,773,268	4,459,214	5,600,292	6,557,427	7,705,353	8,727,478	9,145,315	10,370,296
10.0%	Interest (Dt)		0	0	0	0	0	0	0	0	0	0
2.0%	Interest (Ct)		85,726	110,516	118,869	143,750	175,822	206,141	238,992	263,369	283,772	310,555
Bank balance : End			**3,694,421**	**3,773,268**	**4,459,214**	**5,600,292**	**6,557,427**	**7,705,353**	**8,727,478**	**9,145,315**	**10,370,296**	**10,625,454**
	0											
Production cost ratio (avg)		*69%*	*57%*	*82%*	*74%*	*62%*	*64%*	*60%*	*63%*	*78%*	*64%*	*83%*
Cash flow ratio (avg)		*126%*	*141%*	*102%*	*121%*	*138%*	*129%*	*136%*	*131%*	*111%*	*140%*	*107%*

Figure 7-19: Condensed summary of projected Cash flow statement – Pongola case study

Average production cost ratio equals 67% and 69% for the first and second 10-year period respectively, which falls within acceptable norms for the specific industry. Average cash flow ratio equals 106% and 126% for the same periods, which demonstrates repayment ability.

7.6.2.9.2 Income statement projection

Based on the financial information contained in the forgoing farming information system (that is, records of accounts receivable and accounts payable, records of income and expenditure) the farmer can summarise the financial results of the farm business on the income statement. Whereas the balance sheet reflects the financial status of a business at a specific date, the income statement indicates how this financial status was achieved. It therefore indicates how the assets were used during a certain period. The income statement is a summary of the income and expenditure of the farm business for a specific period, financial year, production year or tax year.

Because opening and closing balance sheets have been compiled for the opening and closing dates of the period covered by the income statement, a link can be drawn between the income statement and the balance sheet. This is known as the reconciliation of the net worth according to the opening and closing balance sheets.

The information contained in the income statement is schematically summarised in Figure 7-20. A discussion of the most important components of the income statement follows in the paragraphs below.

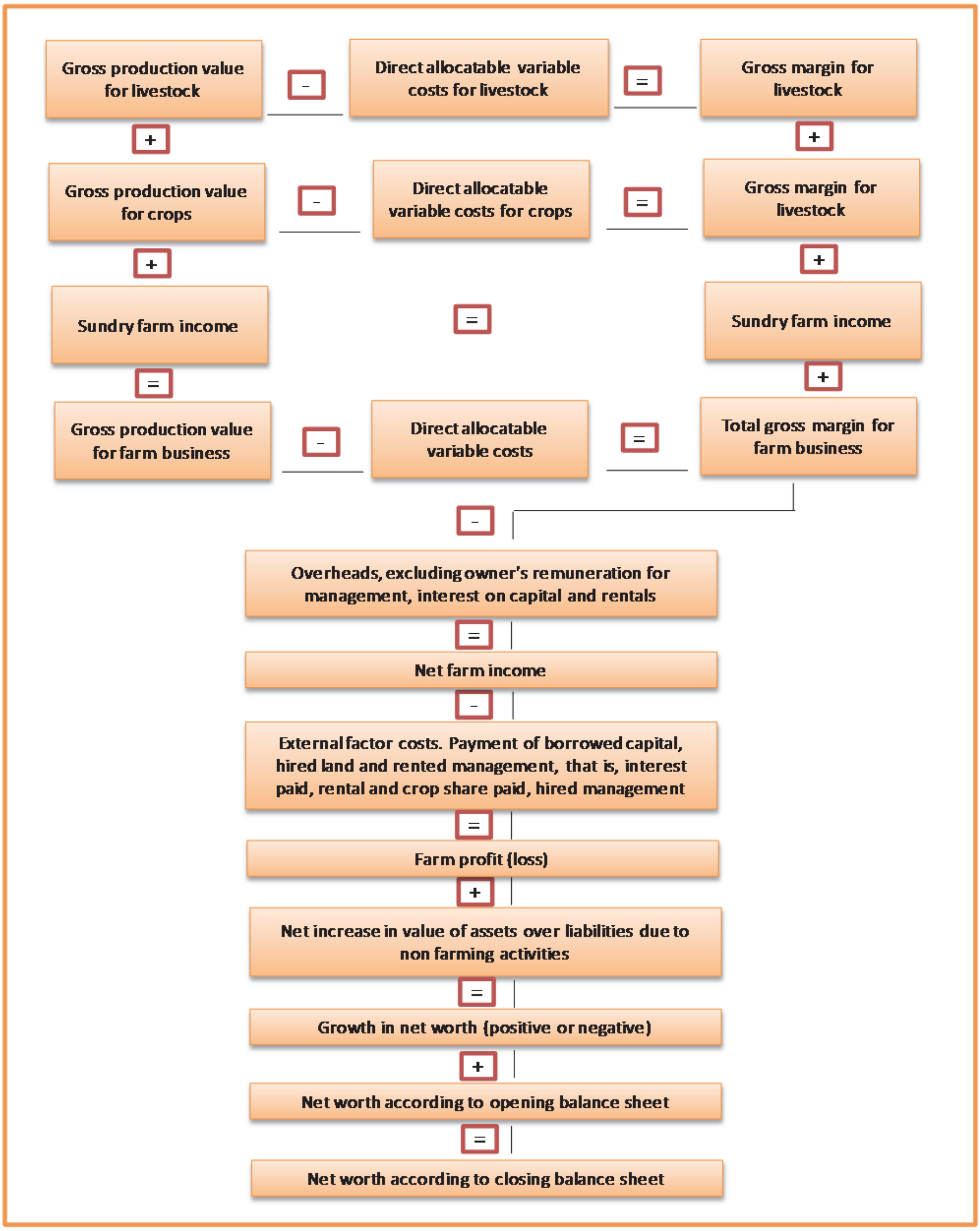


Figure 7-20: Schematic summary of information contained in the income statement

(Source: Standard bank, 2013)

Gross production value

The gross production value of the farm business consists of the gross production value for crop and livestock enterprises as well as sundry farm income:

- The gross production value for a livestock enterprise is the total value of livestock products plus any change in inventory. It is calculated as follows:
  - Trade income = Livestock sales + livestock slaughtered for household and labourers (including donations) + insurance received on livestock losses + other direct expenses – livestock purchases.
  - Plus change in inventory = Closing value of livestock + internal transfers (transfers to other livestock enterprise4s) – opening value of livestock – internal transfers (transfers in from other livestock enterprises).
- The gross production value of a cash crop enterprise is the total value of the products produced by the enterprise. It consists of the marketable yield, which represents the following:
  - Gross sales(including advances and interim and deferred payments) + insurance payments received due to crop losses + consumption by household and labourers (including donations) + crops used on the farm for stock-feed and seed (internal transfers) + stock adjustment (closing and stock less opening stock).
  - The gross production value of fodder and pasture crops is reflected by output figures for livestock enterprises that uses these crops.
- Sundry farm income is income generated by farming activities, but which cannot be directly allocated to a specific enterprise. Examples include income derived from contract work by using existing surplus capacity, bonus on turnover, casual income from renting out pasture, and selling hay and crops suitable for stock feed.

Gross production value is the sum total of the gross production value for all the enterprises plus sundry farm income, while gross farm income is equal to the gross production value less internal transfers for the accounting period.

Directly allocatable variable costs

Variable costs are that part of the total cost components that could vary within the framework of a specific production structure as the size of the enterprise varies and/or the intensity of production per unit changes. In other words, variable costs are those costs that can be controlled in the short-term.

Directly allocatable variable costs are those variable costs that can be readily allocated to an enterprise. For crop enterprises these include seed (bought and produced on the farm), fertiliser, herbicides, pesticides, specific contract work, casual labour, marketing costs, hired transport, crop insurance and packaging material. For livestock enterprises these would include items such as bought feed and licks, fodder produced on the farm, veterinary costs and remedies, contract work packaging material, marketing costs, hired transport and insurance.

Gross margin

The gross margin (GM) of an enterprise is the gross production value for that enterprise less directly allocatable variable costs. The total gross margin is calculated by adding together the gross margins of all enterprises in the farm business. Should further deductions be made from the gross margin, the margin over directly allocatable costs would be obtained. All comparisons between enterprises are based on the gross margin.

Net farm income

The net farm income (NFI) is the total gross margin less overhead costs (excluding remuneration and interest on capital and rentals). Overheads consists of all non-directly allocatable variable costs (fuel oil, lubricants, repairs and spare parts for vehicles, and implements and electricity) and fixed costs (depreciation, insurance on buildings and implements, licenses, regular labour, bookkeeping fees, bank charges and telephone and mailing costs). Net farm income does not imply profit as it is generally understood because management remuneration, interest on capital and rentals are excluded. The reason is that the NFI is solely used as a criterion for comparison between farm businesses. To prevent apples from being compared to pears, all external factor costs (management, interest and rental) are excluded. In this way a farmer can compare the NFI of the farm business – especially if it is expressed per capital investment or per area unit – to those of other businesses, regardless of whether the farm has been inherited, is being rented or has been bought on credit.

Farm profit

Farm profit (FP) is the NFI less remuneration of hired management, rentals and interest on capital, that is, the return to external factor costs. The farm profit is not the amount that is available for spending at the end of the year since compulsory redemption of capital and income tax must still be paid from this amount. During the course of the year amounts have been spent on items such as a voluntary redemption of capital, household expenses and machinery and equipment.

Non-farming activities

The net increase of the value of assets over liabilities as a result of non-farming activities is calculated as follows:

Non-farm income plus capital redemption plus capital profits plus own-capital inflow less capital losses less own-capital outflow les income tax less private and household imbursements less farm products consumed.

Net worth

The growth in net worth is calculated by adding the farm profit/loss to the net increase/decrease in the value of assets over liabilities as a result of non-farming activities. The growth in net worth is not an amount that is in the bank at the end of the year, but an amount that can be spend without reducing the initial own capital in the farm business. This could, for example, be tied up in products still to be sold or in payments still to be received.

7.6.2.9.2.1 Mathematical specification of the Income statement

In mathematical terms the Income statement projection objective is as follows:

$$[GNW] \quad = [GPV] \sum_{i=a}^{c} - \; [PMAD] \sum_{e=h}^{i} = [NFI] + \sum_{l=m}^{n} = \; [NFP] + \sum_{o=p}^{s} - \sum_{o=t}^{y}$$

where:

GNW	=	Growth in Net Worth
GPV	=	Gross Production Value
PMAD	=	Production, Marketing, Admin costs and Depreciation
NFI	=	Net Farm Income
NFP	=	Net Farm Profit
I_a	=	Total farm produce sales
I_b	=	Total consumption
I_c	=	Total stock adjustment
E_h	=	Total Production, Marketing and admin costs
E_i	=	Depreciation
L_m	=	Interest received
L_n	=	Interest paid
O_p	=	Non farm income
O_q	=	Capital appreciation
O_r	=	Capital profits
O_s	=	Own capital inflow
O_t	=	Capital loss
O_u	=	Own capital outflow
O_v	=	Dividends
O_w	=	Income tax provision
O_x	=	Private expenses
O_y	=	Farm produce consumed

7.6.2.9.2.2 Diagrammatical illustration of the income statement projection

Figure 7-21 shows a condensed summary of the 20-year projected income statement. The projected income statement makes provision for, amongst others, depreciation and income tax.

	YEAR	1	2	3	4	5	6	7	8	9	10
Total sales		3,857,920	3,879,040	4,009,280	4,037,440	4,092,000	4,097,280	3,931,840	4,033,920	3,817,440	3,982,880
Total consumption		0	0	0	0	0	0	0	0	0	0
Total stock adjustment		0	0	0	0	0	0	0	0	0	0
Total gross production value		**3,857,920**	**3,879,040**	**4,009,280**	**4,037,440**	**4,092,000**	**4,097,280**	**3,931,840**	**4,033,920**	**3,817,440**	**3,982,880**
Less: Total production, marketing and admin costs		2,297,243	2,869,436	2,480,003	2,571,704	2,474,603	2,587,580	3,071,763	2,562,170	3,165,315	2,466,608
Depreciation - Fixed improvements		197,000	197,000	197,000	197,000	197,000	197,000	197,000	197,000	197,000	197,000
Depreciation - Drainage system		142,516	142,516	142,516	142,516	142,516	142,516	142,516	142,516	142,516	142,516
Depreciation - Vehicles		140,000	140,000	140,000	140,000	140,000	0	0	0	0	0
Depreciation - Machinery & equipment		75,000	75,000	75,000	75,000	75,000	75,000	75,000	75,000	75,000	75,000
Net Farm income		**1,006,162**	**455,088**	**974,761**	**911,220**	**1,062,881**	**1,095,184**	**445,561**	**1,057,234**	**237,609**	**1,101,757**
Less: Interest paid (earned = -ve sign)		405,525	367,288	331,245	280,869	225,543	172,779	125,750	79,974	22,076	-16,895
Net Farm profit		**600,637**	**87,800**	**643,516**	**630,351**	**837,338**	**922,405**	**319,810**	**977,260**	**215,532**	**1,118,652**
Plus:	Non-farming income	0	0	0	0	0	0	0	0	0	0
	Capital appreciation	0	0	0	0	0	0	0	0	0	0
	Capital profits	0	0	0	0	0	0	0	0	0	0
	Own capital inflow	0	0	0	0	0	0	0	0	0	0
Less:	Capital loss	0	0	0	0	0	0	0	0	0	0
	Own-capital outflow	0	0	0	0	0	0	0	0	0	0
	Dividends / profits	0	0	0	0	0	0	0	0	0	0
	Income tax provision	47,218	0	0	55,538	113,495	137,313	-31,413	152,673	-60,611	192,262
	Private & househ expenses	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000
	Farm products consumed	0	0	0	0	0	0	0	0	0	0
Growth in net worth	**(GNW)**	**121,418**	**-344,200**	**211,516**	**142,812**	**291,843**	**353,092**	**-80,777**	**392,587**	**-155,857**	**494,389**

	YEAR	11	12	13	14	15	16	17	18	19	20
Total sales		4,092,000	3,857,920	3,879,040	4,009,280	4,037,440	4,092,000	4,097,280	3,931,840	4,033,920	3,817,440
Total consumption		0	0	0	0	0	0	0	0	0	0
Total stock adjustment		0	0	0	0	0	0	0	0	0	0
Total gross production value		**4,092,000**	**3,857,920**	**3,879,040**	**4,009,280**	**4,037,440**	**4,092,000**	**4,097,280**	**3,931,840**	**4,033,920**	**3,817,440**
Less: Total production, marketing and admin costs		2,340,969	3,159,322	2,869,436	2,480,003	2,571,704	2,474,603	2,587,580	3,071,763	2,562,170	3,165,315
Depreciation - Fixed improvements		197,000	197,000	197,000	197,000	197,000	197,000	197,000	197,000	197,000	197,000
Depreciation - Drainage system		142,516	142,516	142,516	142,516	142,516	142,516	142,516	142,516	142,516	142,516
Depreciation - Vehicles		0	0	0	0	0	0	0	0	0	0
Depreciation - Machinery & equipment		0	0	0	0	0	0	0	0	0	0
Net Farm income		**1,411,515**	**359,082**	**670,088**	**1,189,761**	**1,126,220**	**1,277,881**	**1,170,184**	**520,561**	**1,132,234**	**312,609**
Less: Interest paid (earned = -ve sign)		-85,726	-110,516	-118,869	-143,750	-175,822	-206,141	-238,992	-263,369	-283,772	-310,555
Net Farm profit		**1,497,241**	**469,598**	**788,957**	**1,333,510**	**1,302,042**	**1,484,021**	**1,409,176**	**783,930**	**1,416,005**	**623,164**
Plus:	Non-farming income	0	0	0	0	0	0	0	0	0	0
	Capital appreciation	0	0	0	0	0	0	0	0	0	0
	Capital profits	0	0	0	0	0	0	0	0	0	0
	Own capital inflow	0	0	0	0	0	0	0	0	0	0
Less:	Capital loss	0	0	0	0	0	0	0	0	0	0
	Own-capital outflow	0	0	0	0	0	0	0	0	0	0
	Dividends / profits	0	0	0	0	0	0	0	0	0	0
	Income tax provision	298,267	10,527	99,948	252,423	243,612	294,566	273,609	98,540	275,522	53,526
	Private & househ expenses	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000
	Farm products consumed	0	0	0	0	0	0	0	0	0	0
Growth in net worth	**(GNW)**	**766,973**	**27,071**	**257,009**	**649,087**	**626,430**	**757,455**	**703,567**	**253,389**	**708,484**	**137,638**

Figure 7-21: Condensed summary of projected Income statement – Pongola case study

7.6.2.9.3 Projected Balance sheet

The balance sheet is a financial statement that reflects the financial position of a farm business on a specific date. This date is usually the first and/or the last day of the financial year or at the end of a production season. The financial status of a farm business is determined by three aspects, namely assets, liabilities and net worth (ownership interest or own capital). The balance sheet is the systematic presentation of these three aspects for a specific date, with each item being identified and linked to a money value. The balance sheet is a representation of historical information that reflects the cumulative effect of finalised transactions without indicating how the current financial position was reached.

The assets recorded on the balance sheet represent everything the farm business owns, for example, land, fixed improvements, machinery and equipment, stocks and supplies, and cash. The asset side of the balance sheet is always based on the inventory. The liabilities recorded on the balance sheet represent all the liabilities of the farm business as at the date of the balance sheet. The difference between the assets and the liabilities recorded on the balance sheet indicates the net worth of the farm business on that date.

The net worth is also called ownership interest or own capital and represents the amount the farmer would retain if all assets were sold and all debts paid. If the net worth is negative, the farmer would be insolvent or bankrupt. The net worth is entered on the liability side of the balance sheet and represents the amount that the farm business owes the owner. The asset side of the balance sheet indicates all the assets of the business as at the date of the balance sheet, while the liability side indicates how these assets were financed.

There are a variety of balance sheet forms and formats. There is however a common link among them all. The balance sheet is organised by the basic accounting equation:

Total assets = Total liabilities + Net worth/equity

A = L + E

In other words, the value of assets must equal the value of the liabilities against those assets plus the value of the farm's equity. The equation balances because the assets must be funded by either debt or equity.

As the words 'balance sheet' imply, the two sides of the equation should always be equal. A transaction that affects one side of the equation must result in an identical change on the other side.

The ration between the various types of assets and liabilities is important when the financial position of a farm business is examined. For this reason assets and liabilities with similar features are grouped together and systematically recorded on the balance sheet.

Assets

(i) Assets are classified according to their liquidity or ability to be converted to cash. Accordingly, there are three categories of assets, namely current assets, medium-term assets and fixed assets.

(ii) Current assets (also known as short-term assets) are the most liquid assets and consist of items such as cash on hand, cash in the bank, stocks and supplies, debtors, finished and semi-finished products, short-term investments and prepaid accounts. These assets can easily be converted to cash in a 12-month cycle without disrupting the farm business.

(iii) Medium-term assets (also called movable assets) are used in the production process to produce saleable items over a period of time, but are usually depleted in the medium-term (normally 2-10 years). Moveable assets include items such as vehicles, machinery implements, tools, equipment, orchards, breeding stock, plantations and medium-term investments. Most of these assets are subject to depreciation.

(iv) Fixed assets are also used in the production process, but have a longer serviceable lifetime (usually longer than 10 years). Fixed improvements and land are examples of fixed assets.

Liabilities

Liabilities of the farm business are classified according to the period available for redeeming the debt or liability. Just like assets, liabilities can be classified into three categories, namely current liabilities, medium-term liabilities and long-term liabilities. The order in which liabilities are recorded on the balance sheet is once again based on the duration of the repayment period.

(i) Current liabilities (or short-term liabilities) are debt commitments payable within 12 months and include items such as bank overdrafts, unpaid cheques, accounts in arrears, accounts at the cooperative, trade creditors and provision for instalments on medium- and long-term loans.

(ii) Medium-term liabilities are debt commitments that have to be repaid within one to 10 years and include instalment sale credit, leasing and medium-term loans (private or at the Land Bank).

(iii) Long-term liabilities represent all debt commitments that have to be discharged over 10 years or longer. Mortgage bonds and other long-term loans are examples of long-term liabilities.

Net worth

Net worth, or owner's equity, represents the owner's claims against the business. Net worth is classified as contributed capital, which reflects the financial resources provided by the owner and retained earnings, which are claims generated by retaining the business' profits.

Contributed capital is that money that was invested in the business by the owner. It includes capital the owner in the farm business when it started as well as additional capital contributed at a later stage. Retained earnings are earnings that have been generated by the farm business in the course of its operations that have been reinvested in the business and not have been distributed to the owner.

A Balance sheet is drawn up on a specific date and can be completed for any chosen calendar day. If, however, the farmer wants to make a meaningful and informed financial analysis of the farm business, the period covered by the balance sheet should correlate with the period for which the income and expenditure (income statement) are summarised. An accounting period or financial year should therefore be chosen and all financial statements should be based on this period. The balance sheet should be completed at the end of this period, whether it is a calendar year, tax year or production year. Thus the closing balance sheet for one period would serve as the opening balance sheet for the following period.

It should once again be stressed that the inventory is the basis of the valuation and recording of assets on the balance sheet. The relevant items are carried over from the inventory to the balance sheet. The balance sheet reflects the financial position of the business on a specific date (in this case, the beginning and/or the end of the production year) and presents a static image of the business.

Two aspects of the balance sheet warrant further explanation:

- The value of hired items is not an asset and should therefore not be included in the balance sheet. For practical purposes the value of leased items is included under medium-term assets. Rented land and buildings are not included in the balance sheet, but for the sake of consistency and for comparative and analytical purposes these are included as a type of 'addendum' under the total assets of the business. The sum total of the total assets of the farm business and value of rented land represent the total capital employed in the farm business.

- Long- and medium-term loans are repaid in periodic instalments. If such an instalment is payable within the following 12 months, it is represents a short-term liability. The total instalment is brought into account under short-term liabilities. Instalments usually consist of two components, that is, an interest component and a capital component. Although the total instalment is included as short-term liability, the existing long- or medium-term loan is decreased by the capital component of the payment only. This aspect will be explained in more detail in the example at the end of this chapter.

7.6.2.9.3.1 Mathematical specification of the Projected balance sheet

In mathematical terms the Balance sheet statement projection objective is as follows:

$$[Equity] \quad = [Assets] \sum_{a=b}^{d} - \ [Liabilities] \sum_{l=e}^{g}$$

Where:

A_b = Current assets

A_c = Medium term assets

A_d = Fixed assets

L_e = Current liabilities

L_f = Medium term liabilities

L_g = Long term liabilities

7.6.2.9.3.2 Diagrammatical illustration of the projected Balance sheet statement

Table 7-4 reflects a condensed summary of the projected Balance sheet. The Debt ratio is an important tool to measure solvency of an enterprise.

Table 7-4: Condensed summary of projected Balance sheet – Pongola case study

YEAR	0	1	2	3	4	5	6	7	8	9	10
Total current assets	500,000	560,223	359,298	724,905	1,037,304	1,551,747	1,914,313	1,607,579	2,079,848	1,741,854	2,481,927
Total medium-term assets	1,450,000	1,235,000	1,020,000	805,000	590,000	375,000	300,000	225,000	150,000	75,000	0
Total Fixed assets	14,410,000	17,063,320	16,723,804	16,384,288	16,044,772	15,705,256	15,365,740	15,026,224	14,686,708	14,347,192	14,007,676
Total assets	**16,360,000**	**18,858,543**	**18,103,102**	**17,914,193**	**17,672,076**	**17,632,003**	**17,580,053**	**16,858,803**	**16,916,556**	**16,164,046**	**16,489,603**
Total current liabilities	745,962	745,962	745,962	745,962	651,320	651,320	651,320	651,320	463,876	463,876	0
Total medium-term liabilities	300,000	235,359	164,253	86,037	0	0	0	0	0	0	0
Total long-term liabilities	1,000,000	3,584,032	3,291,114	2,968,905	2,614,475	2,224,602	1,795,742	1,323,996	805,075	421,706	0
Total liabilities	**2,045,962**	**4,565,352**	**4,201,329**	**3,800,904**	**3,265,796**	**2,875,923**	**2,447,062**	**1,975,316**	**1,268,951**	**885,582**	**0**
Net worth (from balance sheet)	14,314,038	14,293,191	13,901,773	14,113,289	14,406,280	14,756,080	15,132,990	14,883,487	15,647,605	15,278,464	16,489,603
Net worth (from income statement)		121,418	-344,200	211,516	142,812	291,843	353,092	-80,777	392,587	-155,857	494,389
Total liabilities + Net worth	**16,360,000**	**18,858,543**	**18,103,102**	**17,914,193**	**17,672,076**	**17,632,003**	**17,580,053**	**16,858,803**	**16,916,556**	**16,164,046**	**16,489,603**
Debt Ratio	*13%*	*24%*	*23%*	*21%*	*18%*	*16%*	*14%*	*12%*	*8%*	*5%*	*0%*

YEAR	11	12	13	14	15	16	17	18	19	20
Total Assets	3,694,421	3,773,268	4,459,214	5,600,292	6,557,427	7,705,353	8,727,478	9,145,315	10,370,296	10,625,454
Cooperatives	0	0	0	0	0	0	0	0	0	0
Total current liabilities	13,668,160	13,328,644	12,989,128	12,649,612	12,310,096	11,970,580	11,631,064	11,291,548	10,952,032	10,612,516
Total assets	**17,362,581**	**17,101,912**	**17,448,342**	**18,249,904**	**18,867,523**	**19,675,933**	**20,358,542**	**20,436,863**	**21,322,328**	**21,237,970**
Total current liabilities	0	0	0	0	0	0	0	0	0	0
Total medium-term liabilities	0	0	0	0	0	0	0	0	0	0
Total long-term liabilities	0	0	0	0	0	0	0	0	0	0
Total liabilities	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Net worth (from balance sheet)	17,362,581	17,101,912	17,448,342	18,249,904	18,867,523	19,675,933	20,358,542	20,436,863	21,322,328	21,237,970
Net worth (from income statement)	766,973	27,071	257,009	649,087	626,430	757,455	703,567	253,389	708,484	137,638
Total liabilities + Net worth	**17,362,581**	**17,101,912**	**17,448,342**	**18,249,904**	**18,867,523**	**19,675,933**	**20,358,542**	**20,436,863**	**21,322,328**	**21,237,970**
Debt Ratio	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*

The projected balance sheet illustrates a declining debt ratio which is well within acceptable norms.

7.6.2.10 Economic and financial analysis

The economic viability of drainage refers to the per hectare ability of the direct increase in profitability as a result of drainage to repay the capital required to drain, whereas financial feasibility refers to the ability of the farming unit to access sufficient additional funds to pay for the drainage required and maintain an overall increasing cash flow in the long term or positive Net Present Value (NPV). Economic viability is a prerequisite for financial feasibility (Armour and Viljoen, 2008).

The Drain-Fin model assesses two sets of financial criteria namely:

- **Economic** Benefit Cost analysis
- **Financial** Whole-farm analysis

The economic analysis is an academic exercise to determine whether sub-surface drainage installation makes economic sense. The financial analysis, on the other hand, determines if the installation will be financially feasible, taking into account general accepted financing norms, etc.

7.6.2.10.1 Benefit Cost Analysis

A decision-making tool used by Backeberg (1981), to evaluate capital investment on irrigation drainage is benefit cost analysis which includes:

- Benefit Cost Ratio (B/C ratio),
- Payback period (average),
- Internal Rate of Return (IRR), and
- Net Present Value (NPV).

The Net Present Value (NPV) is the difference between the present value of income and present value of the capital and other expenditure. The Benefit Cost Ratio (B/C Ratio) is obtained by dividing the present value of the income by the present value of capital and other expenditure. The Internal Rate of Return (IRR) is the breakeven discount rate at which the B/C ratio equals 1, or alternatively where the NPV equals zero.

Table 7-5 demonstrates the Benefit Cost analysis per hectare.

Table 7-5: Benefit Cost analysis (per hectare)

Benefit-Cost Ratio	3.1 : 1
Payback period (average)	3.1 years
Internal Rate of Return (IRR)	39.7%
Net Present Value (NPV)	154,931

7.6.2.10.2 Financial Whole-farm analysis

Financial Whole-farm analysis ratios and norms, includes:

- Projected Production Cost ratios,
- Projected Cash flow ratios,
- Projected Debt ratios, and
- Projected Bank balance

The projected production cost ratio is the total direct production cost as a percentage of income. It is easy to compare with industry norms and serve as an indicator for the accuracy of the projection. The projected cash flow ratio illustrates total cash inflow as a percentage of total cash outflow. This is a very important indicator of liquidity and repayment ability. The projected debt ratio is an indicator for solvency, which, together with the cash flow ratio, reflects to a large extent the financial position the enterprise. The projected bank balance is merely an indicator of projected cash position.

The above ratios are derived from the 20-year projected Whole-farm Cash flow, Income Statement and Balance Sheet.

The yearly projected Production cost ratio is illustrated in Figure 7-22. The blue line illustrates the yearly production cost ratio and the red line the average ratio. The Production cost ratio is industry specific and should be measured against industry norms.

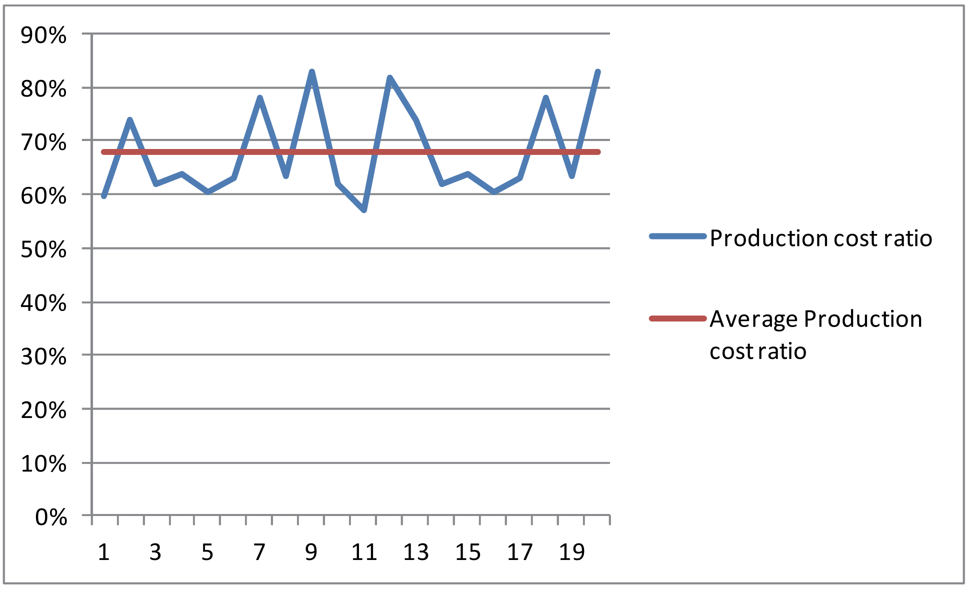


Figure 7-22: Yearly projected Production cost ratio

The yearly Cash flow ratio is an indicator of the entity's repayment ability and the ability to absorb financial losses. It measures expected cash income and expected cash pay-outs. A safe norm will differ from industry to industry but a good average will be above 115%.

Figure 7-23 illustrates the yearly and average projected Cash flow ratio of the entity.

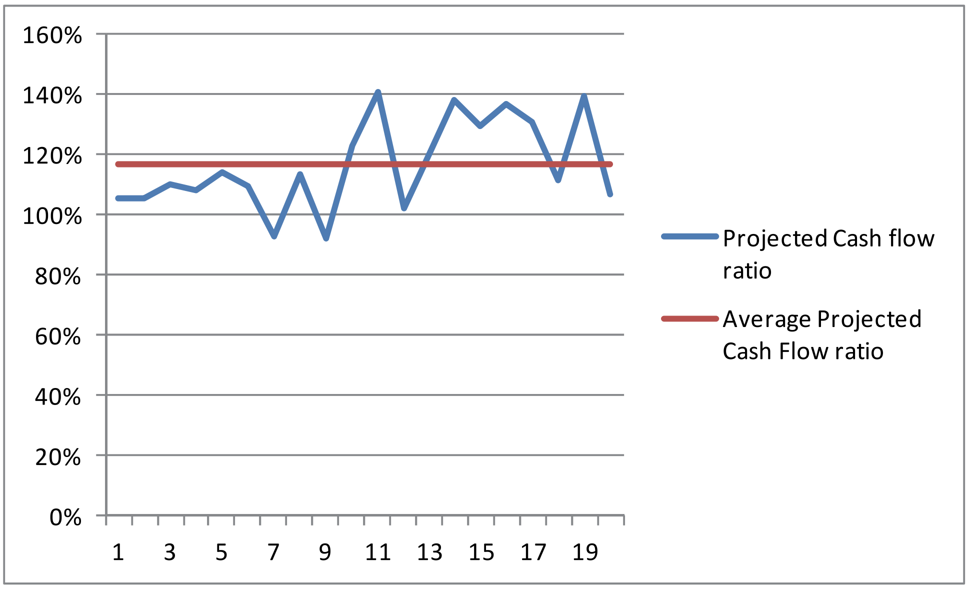


Figure 7-23: Yearly projected Cash flow ratio

The Debt ratio is a solvency indicator. As a general rule the projected Debt ratio should not exceed 50%. Figure 7-24 illustrates the yearly projected Debt ratio of the entity.

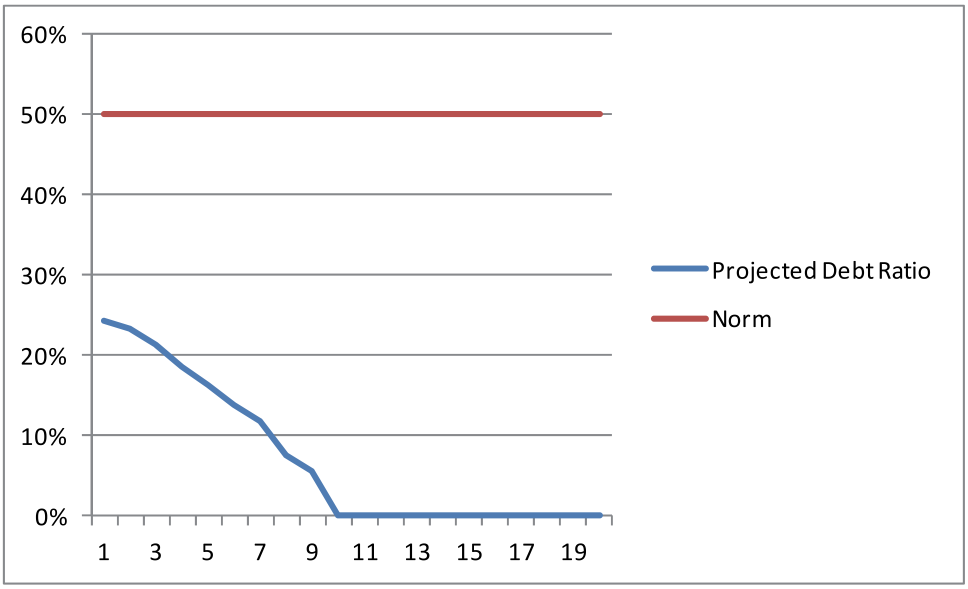


Figure 7-24: Yearly projected Debt ratio

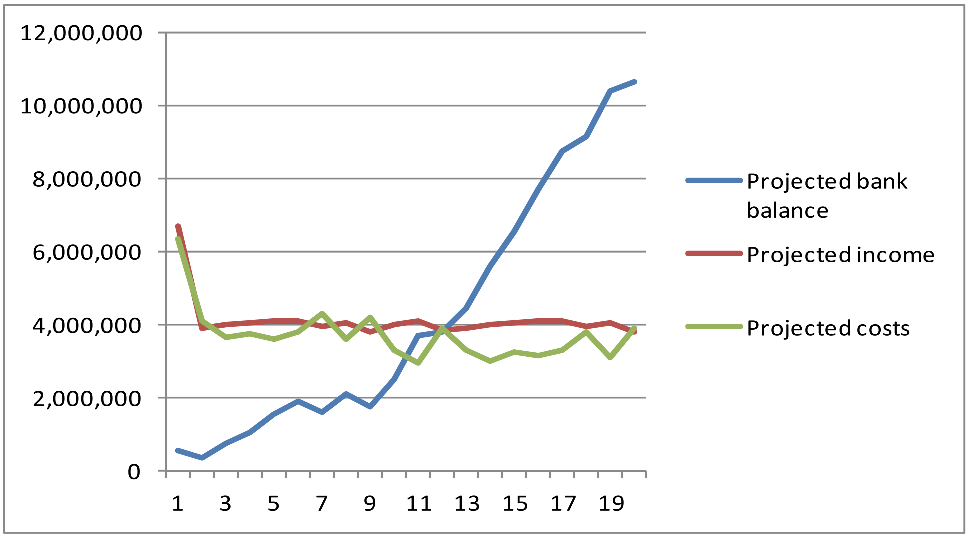


Figure 7-25 illustrates the yearly projected income, costs and bank balance.

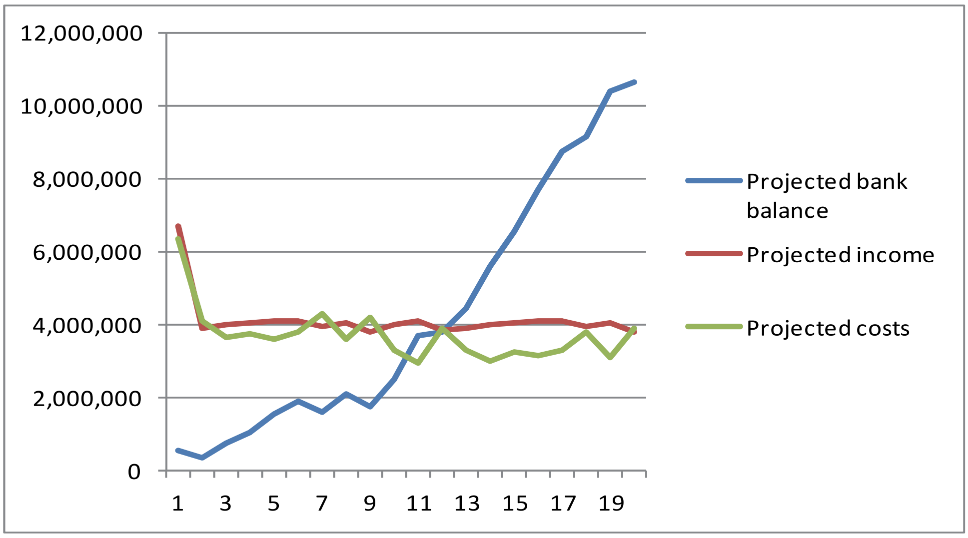


Figure 7-25: Yearly projected bank balance

The sheet also summarises the projected Cash flow statement, Income statement and Balance sheet as well as the most important financial ratios.

7.6.2.11 Scenario comparison

Table 7-6 illustrates the most important summarised financial data. This data can be "copied and pasted" to the Scenario comparison sheet, which makes provision for up to 10 different scenarios. Figure 7-26 shows a typical graphical comparison of two scenarios. The financial ratios and graphical illustration that is displayed on page simplifies the comparison of different scenarios.

Table 7-6: Scenario summary – Projected Cash flow-, Income statement and Balance sheet

Scenario						Nr		Description					
Graph data summary	Pongola Case study		Scenario			2		With drainage - 10% Starting debt ratio					
	1	2	3	4	5	6	7	8	9	10	11	12	13
Production cost ratio	60%	74%	62%	64%	60%	63%	78%	64%	83%	62%	57%	82%	74%
Average Production cost ratio	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%	68%
Projected Cash flow ratio	106%	106%	110%	108%	114%	110%	93%	113%	92%	122%	141%	102%	121%
Average Projected Cash Flow ratio	116%	116%	116%	116%	116%	116%	116%	116%	116%	116%	116%	116%	116%
Projected Debt Ratio	24%	23%	21%	18%	16%	14%	12%	8%	5%	0%	0%	0%	0%
Norm	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Projected bank balance	560,223	359,298	724,905	1,037,304	1,551,747	1,914,313	1,607,579	2,079,848	1,741,854	2,481,927	3,694,421	3,773,268	4,459,214
Projected income	6,708,240	3,879,040	4,009,280	4,037,440	4,092,000	4,097,280	3,931,840	4,033,920	3,817,440	3,982,880	4,092,000	3,857,920	3,879,040
Projected costs	6,357,524	4,094,616	3,657,965	3,749,666	3,613,462	3,784,395	4,292,397	3,614,077	4,213,865	3,301,873	2,965,231	3,889,589	3,311,963

Cash flow statement projection

	1	2	3	4	5	6	7	8	9	10	11	12	13
Total crop income	3,857,920	3,879,040	4,009,280	4,037,440	4,092,000	4,097,280	3,931,840	4,033,920	3,817,440	3,982,880	4,092,000	3,857,920	3,879,040
Total livestock income	0	0	0	0	0	0	0	0	0	0	0	0	0
Total production income	3,857,920	3,879,040	4,009,280	4,037,440	4,092,000	4,097,280	3,931,840	4,033,920	3,817,440	3,982,880	4,092,000	3,857,920	3,879,040
Total other	2,850,320	0	0	0	0	0	0	0	0	0	0	0	0
Total income	6,708,240	3,879,040	4,009,280	4,037,440	4,092,000	4,097,280	3,931,840	4,033,920	3,817,440	3,982,880	4,092,000	3,857,920	3,879,040
Direct Allocated costs as per crop budgets	1,807,850	2,322,796	1,951,908	2,039,242	1,946,765	2,054,362	2,515,489	2,030,162	2,604,586	1,939,150	1,819,494	2,598,878	2,322,796
Livestock prod costs	0	0	0	0	0	0	0	0	0	0	0	0	0
Non allocated costs	489,393	546,640	528,095	532,462	527,838	533,218	556,274	532,008	560,729	527,458	521,475	560,444	546,640
Capital expenditure													
Drainage installation	2,850,320	0	0	0	0	0	0	0	0	0	0	0	0
Other capital	0	0	0	0	0	0	0	0	0	0	0	0	0
Debt redemption													
Short term	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium-term	94,641	94,641	94,641	94,641	0	0	0	0	0	0	0	0	0
Long-term	651,320	651,320	651,320	651,320	651,320	651,320	651,320	651,320	463,876	463,876	0	0	0
Other priv exp	464,000	479,218	432,000	432,000	487,538	545,495	569,313	400,587	584,673	371,389	624,262	730,267	442,527
Total expenditure	6,357,524	4,094,616	3,657,965	3,749,666	3,613,462	3,784,395	4,292,397	3,614,077	4,213,865	3,301,873	2,965,231	3,889,589	3,311,963
Bank balance : End	560,223	359,298	724,905	1,037,304	1,551,747	1,914,313	1,607,579	2,079,848	1,741,854	2,481,927	3,694,421	3,773,268	4,459,214
Production cost ratio	60%	74%	62%	64%	60%	63%	78%	64%	83%	62%	57%	82%	74%
Cash flow ratio	106%	95%	110%	108%	114%	110%	93%	113%	92%	122%	141%	102%	121%
Control	0	0	0	0	0	0	0	0	0	0	0	0	0

......(continue...)

Income statement projection

	1	2	3	4	5	6	7	8	9	10	11	12	13
TOTAL Sales	3,857,920	3,879,040	4,009,280	4,037,440	4,092,000	4,097,280	3,931,840	4,033,920	3,817,440	3,982,880	4,092,000	3,857,920	3,879,040
TOTAL Consumption	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL stock adjustment	0	0	0	0	0	0	0	0	0	0	0	0	0
GROSS PROD VALUE	3,857,920	3,879,040	4,009,280	4,037,440	4,092,000	4,097,280	3,931,840	4,033,920	3,817,440	3,982,880	4,092,000	3,857,920	3,879,040
Less Costs	2,851,759	3,423,952	3,034,519	3,126,220	3,029,119	3,002,096	3,486,279	2,976,686	3,579,831	2,881,124	2,680,485	3,498,838	3,208,952
NFI	1,006,162	455,088	974,761	911,220	1,062,881	1,095,184	445,561	1,057,234	237,609	1,101,757	1,411,515	359,082	670,088
Interest	-405,525	-367,288	-331,245	-280,869	-225,543	-172,779	-125,750	-79,974	-22,076	16,895	85,726	110,516	118,869
Farm profit	600,637	87,800	643,516	630,351	837,338	922,405	319,810	977,260	215,532	1,118,652	1,497,241	469,598	788,957
Growth in Net Worth	121,418	-344,200	211,516	142,812	291,843	353,092	-80,777	392,587	-155,857	494,389	766,973	27,071	257,009
Control	0	0	0	0	0	0	0	0	0	0	0	0	0

Balance sheet projection

	1	2	3	4	5	6	7	8	9	10	11	12	13
Total current assets	560,223	359,298	724,905	1,037,304	1,551,747	1,914,313	1,607,579	2,079,848	1,741,854	2,481,927	3,694,421	3,773,268	4,459,214
Total medium-term assets	1,235,000	1,020,000	805,000	590,000	375,000	300,000	225,000	150,000	75,000	0	0	0	0
Total Fixed assets	17,063,320	16,723,804	16,384,288	16,044,772	15,705,256	15,365,740	15,026,224	14,686,708	14,347,192	14,007,676	13,668,160	13,328,644	12,989,128
Total Assets	18,858,543	18,103,102	17,914,193	17,672,076	17,632,003	17,580,053	16,858,803	16,916,556	16,164,046	16,489,603	17,362,581	17,101,912	17,448,342
Total current liabilities	745,962	745,962	745,962	651,320	651,320	651,320	651,320	463,876	463,876	0	0	0	0
Total medium-term liabilities	235,359	164,253	86,037	0	0	0	0	0	0	0	0	0	0
Total long-term liabilities	3,584,032	3,291,114	2,968,905	2,614,475	2,224,602	1,795,742	1,323,996	805,075	421,706	0	0	0	0
Total liabilities	4,565,352	4,201,329	3,800,904	3,265,796	2,875,923	2,447,062	1,975,316	1,268,951	885,582	0	0	0	0
Net worth	14,293,191	13,901,773	14,113,289	14,406,280	14,756,080	15,132,990	14,883,487	15,647,605	15,278,464	16,489,603	17,362,581	17,101,912	17,448,342
Debt Ratio	*24%*	*23%*	*21%*	*18%*	*16%*	*14%*	*12%*	*8%*	*5%*	*0%*	*0%*	*0%*	*0%*
Control	0	0	0	0	0	0	0	0	0	0	0	0	0

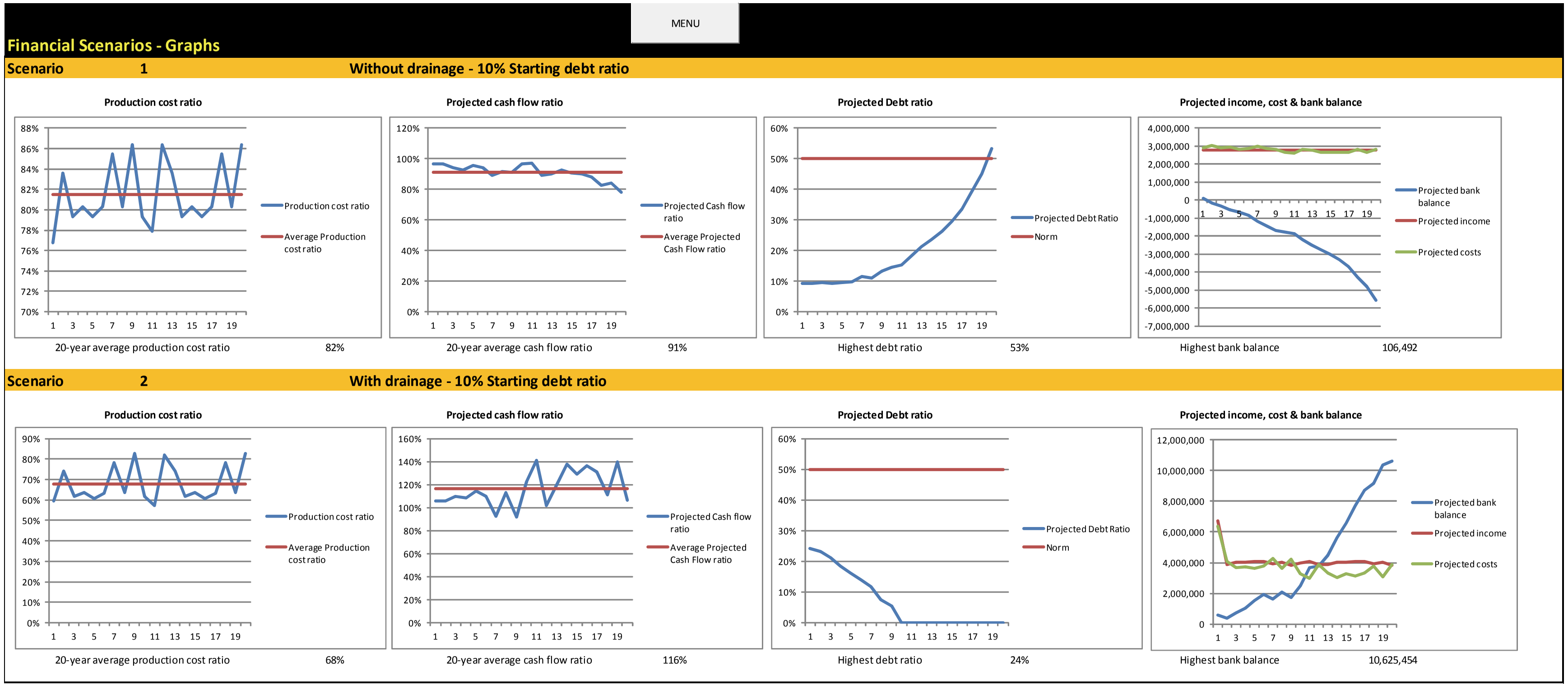


Figure 7-26: Scenario comparison

The financial ratios of different scenarios are displayed in Table 7-7, which offers an easy to compare summary of different scenarios.

Table 7-7: Scenario summary

Scenario nr & description		Production cost ratio *	Projected cash flow ratio *	Projected Debt ratio	Projected income, cost & bank balance
1	Without drainage - 10% Starting debt ratio	82%	91%	53%	106,492
2	With drainage - 10% Starting debt ratio	68%	116%	24%	10,625,454
3	Without drainage - 40% Starting debt ratio	82%	51%	621%	-837,800
	** 20-year average*				

** 20-year average*

7.7 Summary

This chapter has described the development of the DrainFin model and all its components, including database, enterprise crop budgets, drainage plan and capital budget, projected financial statements and scenario analysis to determine economic and financial viability.

The DrainFin model database consists of the following subsets:

- Farm composition and production plan/cropping pattern (including crop rotation)
- Tree/Orchard census for permanent crops
- Crop Enterprise budgets (production input costs and produce prices)
- Yield curves (with and without sub-surface drainage)
- Capital and other income and costs not captured in enterprise crop budgets
- Financial inputs pertaining to income statement and balance sheet
- Economic and financial analysis
- Finance decision support tool

The capital and maintenance costs for different sub-surface systems and different locations differ. To determine the optimal sub-surface drainage system from an economic and financial point of view, it is necessary to analyse different drainage systems (cost and effect on yields) with different scenarios.

The accurate composition of the projected Cash flow-, Income statement and Balance sheet is essential for financial assessment and evaluation. The Drain-Fin model makes provision for the comparison of up to ten different scenarios. These scenarios can be evaluated and compared in terms of Per-hectare analysis (Benefit cost ratio, NPV, IRR and Payback period) and/or Whole-farm analysis (Production cost ratio, Cash flow ratio, Debt ratio and projected bank balance).

The effect of subsidies, grants, etc. can easily be accommodated in the model to discount the monetary effect of government intervention on the economic and financial feasibility of sub-surface drainage.

Also included in this chapter is the graphical illustration and explanation of the inner workings of the DrainFin model.

8 SUMMARY AND CONCLUSION

The main objective of the Project was to develop technical and financial norms and standards for the drainage of irrigated lands in Southern Africa that resulted in a report and manual for the design, installation, operation and maintenance of drainage systems.

Literature reviews of local and international books, journal articles and internet publications were conducted, and from these sources, the terminology, definitions, practices and technology of the various drainage approaches were identified and documented. The descriptions included engineering, soil science, environmental and economic approaches on drainage. The review of literature also provided an overview of current drainage systems, practices and technologies worldwide, and those suited to South African conditions.

Water balance studies, international and local technical models applied in drainage design and management were reviewed. For the technical aspects, the following models were reviewed – Drainmod, WaSim and SaltMOD were reviewed. From this group the world renowned Drainmod model was selected for verification and validation for the Pongola (Impala) study site. For Breede River and Vaalharts study sites the Endrain model was applied.

Drainmod was applied to evaluate the technical feasibility of drainage in the Impala irrigation scheme case study. Endrain was applied in the cases of Breede River and Vaalharts irrigation schemes. Evaluations were carried out on existing installed drainage systems focusing on the type of drainage system, soil type, irrigation method, operation and management practices. The main output of the technical aspects of the research was the development of the appropriate drainage design criteria.

The Armour and Viljoen (2008) model was revised and the Drain Fin Model was developed for the financial feasibility assessments of drainage at the farm level. The financial evaluations focused on the capital management, financing methods, operation and maintenance expenditure, and financial parameters such as Net Present Value (NPV), Internal Rate of Return (IRR), Return on Capital Investment (RCI) and cost-benefit ratios (CBR) were used to select the best drainage alternatives.

From the research, technical and financial norms and standards were developed for the drainage of irrigated lands in Southern Africa that resulted in a manual for the design, installation, operation and maintenance of drainage systems.

9 REFERENCES

Armour, RJ. 2007. An economic case for drainage for sustainable irrigation: Case studies in the lower Vaal and Riet catchments. South African Journal of Economic and Management Sciences. Volume 10, no 4.

Armour, RJ, Viljoen MF. 2008. Analysis of the Financial and Economic Feasibility of Drainage in the Orange-Vaal-Riet and Lower-Orange Irrigation Areas. Water Research Commission Report No.TT448/08, ISBN 978-1-7705-951-1.

ASAE Standards. s99. Standards Engineering Practices Data. 46th ed. American Society of Agricultural Engineering. St. Joseph. Michigan. USA.

ASAE Standards. 2003. Standards Engineering Practices Data. 50th ed. American Society of Agricultural Engineering. St. Joseph. Michigan. USA.

Backeberg, G.R. 1981. Gedeeltelike Analise vir die Beplanning van die Ekonomiese Uitvoerbaarheid van Dreinering: Pongola-Staatswaterskema. Afdeling Landbouproduksie-Ekonomie, Departement van Landbou en Visserye, Pretoria. (Partial Analysis for the Determination of the Economic Feasibility of Drainage: Pongola Government Water Scheme.)

Backeberg, G.R. 2000. *Planning of Research in the field of agricultural water management.* Water Research Commission. Pretoria, South Africa.

Bahceci, I, Dinc, N, Tari, AF, Argar, AI and Sonmez, B. 2006. Water and salt balance studies, SaltMOD, to improve subsurface drainage design in the Konya-Cumra Plain, Turkey. *Agricultural Water Management.* 85 (2006), 261-271.

Bastiaanssen, WGM, Allen, RG, Droogers, P and Steduto, P. 2007. Twenty-five years modeling irrigated and drained soils: State of the art. *Agricultural Water Management.* 92(2007), 111-125.

Bobba, AG, Singh, VP and Bengtsson, L. 1995. Application of uncertainty analysis to groundwater modeling. *Environmental. Geology*. 26 (2), 89-96.

Borin, M, Morari, F, Bonaiti, G, Paasch, M and Skaggs, RW. 2000. Analysis of DRAINMOD performances with different detail of soil input data in Veneto regions of Italy. *Agricultural Water Management.* 42 (3), 259-272.

Breve, MA, Skaggs, RW, Parsons, JE, Mohammad, AT and Gilliam, JM. 1995. Simulation of Drainage water quality with DRAINMOD. *Irrigation and Drainage Systems.* 9, 259-277.

Breve, MA, Skaggs, RW and Parsons, JE. 1997. DRAINMOD-N, a nitrogen model for artificially drained soils. *Transactions of the ASAE.* 40, 1067-1075.

Bureau of Reclamation, 1978, Drainage Manual US Department of the Interior, Conrad, JE, Colvin, C, Sililo, O, Gorgens, A, Weaver, J and Reinhardt, C. 1999. *Assessment of the Impact of Agricultural Practices in South Africa.* Report No. 641/1/99. Water Research Commission, Pretoria, RSA.

Conservation of Agricultural Resources Act, 1983 (Act no. 43 of 1983), Department of Agriculture

Crop Glossary (Online) http://www.epa.gov/agriculture/ag101/cropglossary.html

Durnford, DS, and Hoffman, GJ. 1999. Drainage Design for Salinity Control. *Agricultural Drainage.* The American Society of Agronomy. Madison, Wisconsin, USA.

DWAF. 1993. *Water Quality Guidelines.* Department of Water Affairs and Forestry. Vol. 4. Agricultural Use. Pretoria. South Africa.

DWAF. 2004. *National Water Resources Strategy*. Department of Water Affairs and Forestry, Pretoria, South Africa.

Evans, RO and Fausey, B. 1999. Effects of Inadequate Drainage on Crop Growth and Yields. Chapter II In*: ASA Drainage Monograph.* P 13-54.

FAO. 1997. *Irrigation Potential in Africa: A Basin Approach.* FAO Land and Water Development Division, Rome.

FAO. 2002. Agricultural Drainage Water Management in Arid and Semi-arid Areas, by Tanji K.K., Kielen N.C., FAO Irrigation and Drainage Paper No. 61. Rome, Italy.

FAO. 2006. *Water in Agriculture; Opportunity untapped.* Food and Agricultural Organization of United Nations: Rome.

FAO. 2007. Guidelines and computer programs for the planning and design of land drainage. Food and Agricultural Organization of the United Nations. Irrigation and drainage paper No.62. Rome, Italy.

Feddes, RA, De Rooij, GH and Van Dam, JC. 2004. *Unsaturated Zone Modeling, Progress, Challenges and Applications.* Wageningen UR Frontis Series, Vol. 6. Kluwer Academic Publishers, www.wur.nl/frontis.

Freisem, C, Scheumann, W. 2001. Institutional Arrangement for Land Drainage in Developing Countries. International Water Management Institute. Working Paper No. 28. ISBN: 92-9090-457-7.

Glossary of Drainage Terminology (Online) http://www.watermaxim.co.uk/glossary-drainage.php

Gupa, GP, Prasher, SO, Chieng and ST, Mathur, IN. 1993. Application of DRAINMOD under semi-arid conditions. *Agricultural Water Management*. 24, 63-80.

Haan, PK and Skaggs, RW. 2003. Effect of parameter uncertainty on DRAINMOD Predictions. Hydrology and Yield. *Transactions of the ASAE.* 46 (4), 1061-1067.

Helwig, TG, Madramootoo, CA and Dodds, GT. 2002. Modeling nitrate losses in drainage water using DRAINMOD 5.0. *Agricultural Water Management.* 56 (2), 153-168.

Hess, TM, Leeds-Harrison, P and Cousell, C. 2000. *WaSim Manual.* Institute of Water Management. Cranfield University, Sisoe, UK.

Hirekhan, M, Gupta, SK and Mishra, KL. 2007. Application of WaSim to assess performance of a Subsurface drainage system under semi-arid monsoon climate. *Agricultural water Management.* 88 (2007), 224-234. India.

Horton, R and Kirkhan, D. 1999. Steady flow to drains and wells. In: Skaggs, RW and Van Schilfgaarde, J, (edition). Agricultural Drainage. Agronomy Monograph, No. 38, ASA/CSSA/SSSA, Madison, WI, USA.

Illinois Drainage Guide (Online) http://www.wq.illinois.edu/DG/terminology.htm

Luthin, J. 1964. *Drainage of Agricultural Lands.* The American Society of Agronomy. 677 South Segoe Road, Madison, WI 53711, USA.

Luo, W, Skaggs, RW, Madani, A, Cizikci, S and Mavi, A. 2001. Predicting field hydrology in cold conditions with DRAINMOD. *Transaction of the ASAE.* 44 (4), 825-834.

Martinez-Beltran, J, Gonzalez-Casillas, A, and Namuche-Vargas, R. 2007. *A component of the FAO Normative Programme on Land Drainage:* Mexico Case Study on the Evaluation of the Performance of Subsurface Drainage Systems. FAO and John Wiley and Sons, Ltd. www.interscience.wiley.com.

Murray, Biesenbach and Badenhorst. 1993. *Evaluation of the design and use of irrigation systems in the Breede River Valley with a view to control of potential drainage losses.* Report No. 256/1/93.Water Research Commission, Pretoria, RSA.

My Agriculture Bank (Online) http://www.agriinfo.in/default.aspx?page=maincatandsuperid=1

New Jersey Water Management Guide, 2007. Online: http://www.nj.nrcs.usda.gov/technical/engineering/

Noria, H, Liaghat, A and Kholghi, M. 2007. *Simulation of Systems In unsteady state condition, using system dynamics.* Department of Irrigation and Reclamation Engineering, University of Tehran, India.

Northcott, WJ, Cooke, RA, Walker, SE, Mitchell, JK and Hirschi, MC. 2001. Application of DRAINMOD-N. to fields with irregular drainage systems. *Transactions of the ASAE.* 44 (2), 241-241.

Oosterbaan, RJ. 1998. *SaltMOD, Description of Principles and Applications.* ILRI, Wageningen, the Netherlands. www.waterlog.info/saltmod.htm.

Oosterbaan, RJ. 2002. *Description of Principles, User Manual and Examples of Application.* International Institute for Reclamation and Improvement (ILRI). Wageningen, Netherlands. www.waterlog.info/saltmod.htm.

Oosterbaan, R.J. 1992. Agricultural Land Drainage: A wider Application through Caution and Restraint. In: ILRI Annual Report 1991, Wageningen, pp. 21-36.

Proceedings of the 10th International Drainage Workshop of ICID Working group on Drainage, 2008, ISBN 978-951-22-9469-5

Reinders, FB, 1985. Ondergrondse Dreineringshandleiding, Revised version, Directorate Agricultural Engineering, Department of Agriculture

Sarwar, A, Feddes, RA. 2000. Evaluating drainage design parameters for fourth Drainage Project Pakistan. Part II: modeling results. *Irrigation and Drainage*. 14, 281-299.

Sarangi, A, Singh, M, Bhattacharya, AK and Singh, AK. 2006. Subsurface drainage performance study using SALTMOD and ANN models. *Agricultural Water Management.* 84 (2006) 240-248.

Schultz, K, Beven, KJ and Huwe, W. 1999. Equifinality and the problem of robust calibration in nitrogen budget simulation. *Soil Science.* 63 (6) 1934-1941.

Scotney, DM, Van der Merwe, AJ. 1995. Irrigation: long-term viability of soil and water resources in South Africa. Proceedings of the South African Irrigation Symposium. Report No. TT71/95, Water Research Commission, Pretoria.

SCS. 1971. Drainage of Agricultural Land. In: *National Engineering Handbook.* United States Soil Conservation Service. Colorado, USA.

Sevenhuijsen R.J, 1994. Surface Drainage Systems. In: H.P. Ritzema (ed.), Drainage Principles and Applications, ILRI Publication 16, p.799-826. International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands

Singh, R, Helmers, MJ, Zhiming, Qi. 2006. Calibration and validation of DRAINMOD to design drainage systems for IOWA's tile landscapes. *Agricultural Water Management.* 85 (2006), 221-232.

Singh, J, Hudson, R, Cooke, R, Hirschi, M, Ellesworth, T, Gertner, G. 2002. Automatic Calibration of a Subsurface Drainage Model. ASAE Paper No. 022101. ASAE, St. Joseph, MI.

Skaggs, RW. 1976. Determination of hydraulic conductivity-drainable porosity ratio from water table measurements. *Transactions of the ASAE* 19, 73-80, 84.

Skaggs, RW. 1978. *A water management model for shallow water table soils.* Technical report No.134. Water Resources Research Institute, University of North Carolina, Raleigh, NC, USA.

Skaggs, RW. 1990. Simulation drainage system performance as affected by irrigation Management. In: *Symposium on Land Drainage for Salinity Control in Arid, Semi Arid Lands,* Vol. 1, February 25-March 2, Cairo, Egypt.

Skaggs, RW. 1980. *Methods for design and evaluation of drainage water management systems for soils with high water tables, DRAINMOD.* North Carolina State University, Raleigh, N.C.4)

Smedema, LK, Vlotman, WF, Rycroft, D. 2004. Modern Land Drainage – Planning, Design and Management of Agricultural Drainage Systems. Publ AA Balkema Publishers, Netherlands.

Skaggs, RW, Chestcheir, GM. 1999. Effect of subsurface drain depth on nitrogen losses from drained lands. ASAE Paper No. 99-2086, ASAE, St. Joseph, MI.

Workman, SR , Skaggs, RW. 1989. Comparison of two drainage simulation models using field data. *Transactions of the ASAE*. St. Joseph, MI.

Smedema, LK, Rycroft, DW. 1983. *Land Drainage Planning and Design Systems.* Cornell University Press, Ithaca, NY.

United States Department of Agriculture, Natural Resources Conservation Service, National Engineering Handbook, Part 624 (Section 16), Chapter 3, Surface Drainage.

University of Minnesota, Agricultural Drainage Publication Series: Issues and Answers.2012. (Online). http://www.extension.umn.edu/agriculture/water/agricultural-drainage-publication-series/).

Urama, CK. 2004. Land-use intensification and environmental degradation: empirical evidence from irrigated and rain-fed farms in south eastern Nigeria. *Environmental Management.* 75 (2005) 199-217.

Van der Stoep I. & Tylcote C. 2014. South African National Committee on Irrigation and Drainage Symposium. Presentation.

Wang, X, Mosley, CT, Frenkenberger, JR , Kladivko, EJ. 2006. Subsurface drain flow and crop yield predictions for different drain spacing using DRAINMOD. *Agricultural Water Management.* 79 (2006), 113-136.

Wang, X, Frenkenberger, JR, Kladivko, EJ. 2003. Estimating nitrate losses from subsurface drains using variable water sampling frequencies. *Transactions of the ASAE.* 46 (4), 1033-1040.

Water Management Guide – Part NJ650.14 (Online). ftp://ftpfc.sc.egov.usda.gov/NJ/technical_resources/engineering/NRCS_NJ_Water_Management_Guide/NJWMG_Glossary.pdf

Wilson CA, Featherstone AM, Kastens, TL, Jones, JD. 2006. Determining What's Really Important to Lenders: Factors Affecting the Agricultural Loan Decision-Making Process. Staff Paper 06-07 Purdue University, Department of Agricultural Economics. http://agecon.lib.umn.edu/cgi-bin/pdf view.pl?paperid=24032

Water Research Commission, Workshop regarding research on the engineering aspects of irrigation application and drainage systems, October 1983, Co-ordinating Committee of Irrigation research, Pretoria.

Young, EG. 1999. *Non-steady flow to Drains.* American Society of Agronomy. Madison, Wisconsin, USA.

Zaoh, SL, Gupa, SC, Huggins, DR, Moncrief, JF. 2000. Predicting subsurface drainage, corn yield, and nitrate nitrogen losses with DRAINMOD-N. *Environmental Quality.* 29 (3), 817-827.