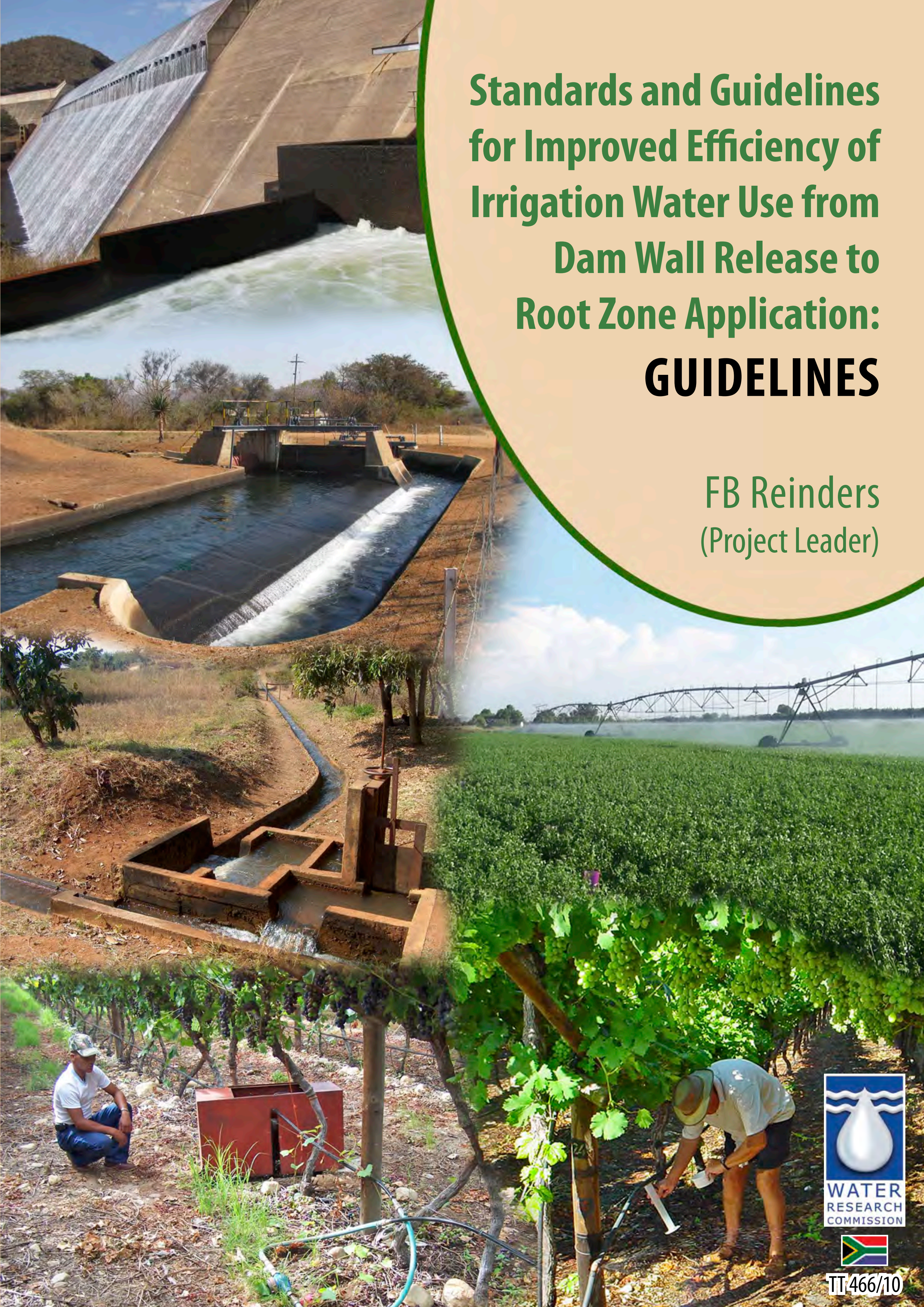

Standards and Guidelines for Improved Efficiency of Irrigation Water Use from Dam Wall Release to Root Zone Application:

GUIDELINES

FB Reinders
(Project Leader)

WATER RESEARCH COMMISSION

TT 466/10

Standards and Guidelines for Improved Efficiency of Irrigation Water Use from Dam Wall Release to Root Zone Application

VOLUME 2 OF 3

GUIDELINES

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Water Research Commission

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ARC-Institute for Agricultural Engineering

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BC	Beneficial consumption
CI	Confidence Interval
CMA	Catchment Management Agency
DWA	Department of Water Affairs
GWCA	Ground Water Control Area
IB	Irrigation Board
ICID	International Commission on Irrigation and Drainage
IWMI	International Water Management Institute
NBC	Non-beneficial consumption
NRF	Non-recoverable fraction
NWA	National Water Act, Act 36 of 1998
RF	Recoverable fraction
SC	Storage change
WC/WDM	Water conservation and water demand management
WRC	Water Research Commission
WUA	Water Users Association

1 Introduction

According to the International Water Management Institute (IWMI) (Comprehensive Assessment of water management in Agriculture, 2007), the world's growing population is a major factor behind's today's water scarcity but the main reasons for water problems are:

- lack of targeted investment ,
- insufficient human capacity ,
- lack of commitment ,
- ineffective institutions, and
- poor governance.

The material presented here is the result of a five year long solicited research project funded by the WRC, and is aimed at providing a sound basis from which especially the first two problems listed above can be addressed.

As the biggest water use sector (in terms of annual volumetric use) in South Africa, irrigation water users are often called upon to "improve efficiency", however, when the question is asked what this request practically implies, answers are not as forthcoming. Major constraints include the lack of a common understanding of the term "efficiency", the perception that any efficiency initiative will cost the water user money but the benefit goes to the authorities, and also the fear of reduced water use allocations if greater efficiency is achieved.

In practice it has been found that commercial farmers are quite willing to invest in practices and technologies that make business sense, and often these also make sense from a water management perspective.

These guidelines are therefore aimed assisting both water users and authorities to obtain better understanding of how irrigation water management can be improved, thereby building human capacity, so that targeted investments can be made with fewer social and environmental costs. Using lessons learnt during the WRC project, best practices and technologies are introduced and illustrated.

The guidelines consist of 4 modules addressing the following:

- Module 1: Fundamental concepts
- Module 2: In-field irrigation systems
- Module 3: On-farm conveyance systems
- Module 4: Irrigation schemes

2 Optimising the beneficial water use component in the irrigation sector

When using water to produce crops, it should not only be considered as a scarce and valuable resource but also an agricultural input to be used optimally. Not all the water that is abstracted from a source for the purpose of irrigation, reaches the intended destination where the plant can make best use of it – the root zone. The fraction of the water abstracted from the source that can be utilised by the plant, can be called the beneficial water use component. Optimised irrigation water supply is therefore aimed at maximising this component and implies that water must be delivered from the source to the field both efficiently (with the least amount along the supply system) and effectively (at the right time, in the right quantity and at the right quality).

2.1 The need for improved performance

An awareness regarding the need for improved water management in agriculture was already recognised in the late 1990s, when various organisations and researchers started to develop procedures to assess irrigation system performance. Rapid appraisal processes, benchmarks, performance indicators and best management practices were touted as possible solutions to improve water management. These approaches all recognised that improved performance goes beyond the physical aspects of water use, and made provision for the assessment of indicators that can be divided into four broad categories, namely, agricultural output, water supply, economic aspects and environmental aspects.

This was due to the fact that irrigation and drainage are essentially services to irrigated agriculture – providing and removing water to suit the crops' needs (Malano & Burton, 2001). Thus, in the irrigation and drainage sector, we are interested in improving the level of service provision to water users, thereby enabling them to maintain or increase levels of agricultural production. There are many reasons why organisations may be interested in improving performance. The private sector is primarily driven by a desire to improve return on investment or return to shareholders; in the public sector the aim is to improve the level of service provision.

It was further recognized that:

- irrigation and drainage service providers operate in a natural monopoly environment
- irrigation and drainage entails complex and interacting physical, social, economic, political, technical and environmental processes
- performance of irrigation and drainage schemes is site specific.

2.2 Benchmarking and performance indicators

The type of approaches being attempted in irrigation originated in the corporate business sector as means by which companies could gauge (and subsequently improve) their performance, relative to key competitors. By studying key competitors' outputs, and the processes used to achieve those outputs, many organisations have been able to adopt best management practices and enhance their own performance. In some cases, organisations have done so well that they have, in turn, become the organisation that others use as a benchmark.

Within the focus area of this material alone, various performance indicators were suggested for quantification in order to assess the performance of irrigation water supply and application systems, with the term "irrigation efficiency" regularly occurring. Unfortunately the concept of irrigation efficiency is frequently misunderstood, leading to the widespread belief that water just disappears with low irrigation efficiencies and re-appears with improvements. Such beliefs are an over-simplification. Often the actual amount of water consumed in irrigation, i.e. the evaporated component, hardly changes at various levels of "efficiency". It could even increase with systems which are perceived to be more efficient.

There is also a widespread illusion that efficiency relates more to the type of irrigation systems rather than to the way a particular system has been designed and managed. A closer analysis and refinement of existing systems and water management strategies would often yield far greater benefits than switching from one system to another. This "water accounting" or "water balance" approach has been recognised internationally as the way forward when assessing irrigation efficiency (Perry, 2007).

2.3 Fundamental concepts for improved performance

Taking the current situation regarding water management into account, the following fundamental principles apply when improving irrigation system performance at all management levels:

- Lawful water use
- Water conservation and water demand management
- Systems approach
- Water balance
- Appropriate technologies
- Incentives.

These concepts are discussed in more detail in the next chapters.

3 Lawful Water Use

Both surface and ground water sources are used extensively for irrigation in South Africa. Water can be taken for irrigation directly from a river, or via a canal or shared pipeline, or from a groundwater aquifer.

The allocation of water and the use thereof by individual users from the different sectors is regulated by legislation. The act currently in force, is the National Water Act (NWA) (Act 36 of 1998), which determines that the government is the official protector or supervisor of the country's water.

This act, which was promulgated on 1 October 1998, meant the beginning of a new era in water allocation and management, because of the drastic changes made to the previous act. One of the most important changes is that ownership of water lapses, as water is now seen as a communal resource, of which the government is the protector, and that access to the use thereof is based on obtaining permission in the form of a permit.

This approach is meant to contribute to the implementing of an integrated catchment area management system, wherein the available water as resource is divided between the users of different sectors in the catchment areas of the country.

For the irrigation sector, the relevant sections in the NWA are in Chapter 4, namely sections 21 to 55. Key aspects for the irrigation sector are specifically described in the following sections (Van der Merwe, 2009):

- Water uses ("Taking water from a water resource" and "storing water") (section 21).
- Permissible water use (section 22)
- Registration (section 26)
- Verification of existing lawful use (section 35)
- Transfer of water use entitlements (section 25)
- Procedure for licence applications (section 41).

3.1 Water uses

There are nine recognised uses of water in the NWA, of which the first two is applicable to irrigation water users as listed in section 21:

For the purposes of this Act, water use includes -

(a) taking water from a water resource;

(b) storing water;

Taking water from a water resource is the most common water use under which irrigation falls – a water resource includes a river, stream, dam, weir, lake, pan, spring, borehole, aquifer, wetland or any surface run-off. Abstracting water from an off-channel dam having no catchment (for example a balancing dam), a canal, or a pipeline is not taking of water from a resource. The Minister may however require a person to have a licence to take water from a government waterwork through a canal or pipeline.

3.2 Permissible water use

As described in Section 22 (1), a person may only use water -

(a) without a licence -

(i) if that water use is permissible under Schedule 1;

(ii) if that water use is permissible as a continuation of an existing lawful use; or

(iii) if that water use is permissible in terms of a general authorisation issued under section 39;

(b) if the water use is authorised by a licence under this Act;

The different authorisations are as follows:

- **Schedule 1**

Schedule 1 entitles a person to take water for reasonable domestic use in the person's household, for small gardening not for commercial purposes and for watering of animals grazing on the land. *(No need to register)*

- **Existing lawful use**

A water use that was lawfully exercised in the two years before the commencement of the NWA on 1 October 1998, subject to the conditions under which it was lawfully exercised. Under certain circumstances, water uses that do not qualify may be 'declared' as existing lawful use as described in section 33 of the NWA. *(Must be registered by the user)*

- **General authorization**

In certain areas, specific relatively small uses are generally authorized, meaning that while staying within the limitations provided in Government Gazette Notice 398 of 26 March 2004, a licence is not necessary. *(Must in specified cases be registered by the user)*

- **License**

In the absence of any of the previous three types of authorization, water may not be used without a licence issued under Chapter 4 of the NWA. *(Is automatically registered)*

3.3 Water use registration

Registration is the process of officially notifying the Department of Water Affairs of a lawful water use, but a registration certificate is not an entitlement or an authorisation to use water. Before it gets the status of an entitlement, the use should be verified according to section 35 of the NWA. In verification two questions are asked:

- Did the water use take place during the qualifying period? (1 Oct 1996 to 30 Sept 1998)

- Was it lawful at that time, according to the relevant legislation?

Water users who want to confirm that a specific water use complies with the requirements of existing lawful use, can at any stage apply for verification (section 35). The application should be submitted at the relevant Department of Water Affairs regional office. The Department of Water Affairs may require the applicant, at the applicant's expense, to obtain and provide all necessary information, in order to take a decision.

3.4 Transfer of water use

Temporary transfers can be done at WUA level and is described in section 25 (1) of NWA. Permanent transfers are described in section 25 (2), and are subject to requirements being met:

- An entitlement to use water may be surrendered in order to facilitate a particular license application.
- That particular license application should be submitted at the relevant Department of Water Affairs regional office.
- The surrender only becomes effective if and when such application is granted.

A person who wishes to obtain a licence to use water, must apply to the relevant regional office for a licence. The contact information of the regional offices as well as all documentation are provided on the Departmental web site: www.dwa.gov.za

For integrated water resources management to work, all water users should ensure that they comply with the lawful use allocated to them.

4 Water Conservation and Water Demand Management

Fifty years ago the world had fewer than half as many people as today. They were not as wealthy, they consumed fewer calories, ate less meat, and thus required less water to produce their food. The pressure they inflicted on the environment was lower, and they took from our rivers a third of the water that we are taking now (Comprehensive Assessment of Water Management in Agriculture, 2007).

Today the competition for scarce water resources in many places is intense, with many river basins not having enough water to meet their demands, or even enough for their rivers to reach the sea. In many basins, the lack of water has become a constraint to producing food for hundreds of millions of people. Agriculture is central in meeting this challenge because the production of food and other agricultural products takes 70% of the freshwater withdrawals from rivers and groundwater.

The trend lines shout out that we are not doing the right things. Inequity in the benefits of water use will grow between haves and have-nots to the detriment of food production. The pollution and depletion of rivers and groundwater will continue. Enough food grown at the aggregate global level does not mean enough food for everyone.

The hope lies in closing the gap in agricultural productivity in many parts of the world and in realizing the unexplored potential that lies in better water management along with non-miraculous changes in policy and production techniques. The world has enough freshwater to produce food for all its people over the next half century – in which the world population is expected to increase by nearly 50% – but all role-players should take action now before the opportunities to do so is lost.

The projection is that 75% of the additional food we need over the next decades could be met by bringing the production levels of the world's low-yield farmers up to 80% of that of what high-yield farmers get from comparable land but better water management plays a key role in bridging that gap.

Although the greatest potential increases in yields are in rainfed areas, where many of the world's poorest rural people live and where managing water is key to such increases, there will probably be some need to expand the amount of land we irrigate to feed the increased world population. This will require dealing with the associated adverse environmental consequences but with improved water management at all levels, there is real scope to improve production on many existing irrigated lands and also free up water for expansion of irrigated land.

To produce enough food to satisfy a person's daily dietary requirements takes about 3000 litres of water converted from liquid to vapour – or about 1 litre per calorie – while only about 2 to 5 litres of water are required for drinking.

In future, more people will require water, but the amount of water required per person can be reduced by changing what people consume and how they use water to produce food. Globally, about 80% of agricultural evapotranspiration (when crops turn water into vapour) comes directly from rain and about 20% from irrigation.

In South Africa, our reliance on irrigation is greater than this global average due to the arid and semi-arid climate in large parts of the country. Although the NWA (1998) does not make provision for water conservation and water demand management (WC/WDM), as part of the implementation of the National Water Resources Strategy (NWRS) various interventions are considered to reconcile demand with supply (Backeberg, 2007). These include the following:

- Demand management – implementing cost recovery through consumer tariffs and user charges to influence the behaviour of water users and to install technologies which reduce waste and losses of water such as undetected leakages.
- Resource management – regulation of streamflow through storage; control of abstractions and releases; and assessment of the groundwater resource at specific localities.
- Re-use of water – recycling of return flows and treatment of water.
- Control of alien invasive vegetation – clearing of invading alien vegetation and controlling the spread of such vegetation to increase surface runoff.
- Re-allocation of water – enable gradual transfers between use sectors with differential benefits through compulsory licencing, supported by water demand management and trading of water use authorizations.

The WC/WDM strategy for agriculture provides a framework for “regulatory support and incentives designed to improve irrigation efficiency …. in order to increase productivity and contribute to reducing income inequalities among people supported by farming activities”. A plan of action is envisaged which must present the following strategic outputs:

- appropriate measures that reduce wastage of water
- progressive modernization of water conveyance, distribution and application infrastructure, equipment and methods
- preventative maintenance programmes
- water allocation processes that promote equitable and optimal utilization of water
- generation of sufficient irrigation information which is accessible to all stakeholders
- implementation of water audits from the water source to the end user.

In the case of five of these action points, conditions and regulations for WC/WDM for water use sector authorization have been published and are currently being reviewed (Backeberg, 2007). For irrigation and agricultural water use the emphasis is on five categories: (1) measuring devices and information systems; (2) water audits, accounting and reporting to the responsible authority; (3) water management planning and WC/WDM measures; (4) management of return flows; and (5) education and awareness raising.

The Minister of Water and Environmental Affairs is therefore responsible to ensure that the nation's water resources are protected, used, developed, conserved, managed and controlled in ways which take into account amongst other things, the promotion of efficient, sustainable and beneficial use of water in the public interests. A means of achieving this is that when making regulations in terms of the National Water Act, the Minister must take into account the conservation of water resources. To address this requirement, the Department of Water Affairs is in the process of developing "PROPOSED REGULATIONS RELATING TO LIMITING THE PURPOSE, MANNER OR EXTENT OF WATER USE BY WATER CONSERVATION MEASURES AND THE MONITORING, MEASUREMENT AND RECORDING OF RAW WATER CONSUMPTION AND THE DISPOSAL OF WATER CONTAINING WASTE" which will define the actions that water users will have to take in future to implement WC/WDM.

Finally, in addition to water scarcity, energy demand and cost affects water management and will do increasingly so in future. Energy prices are rising, pushing up the costs of pumping water, manufacturing fertilisers and transporting products. This will have implications for access to water and irrigation.

In order to make best use of available water and energy, it is imperative that we develop and manage irrigation water supply and application systems with demand in mind, so that we can minimise our water footprint – to see how little we can demand from the sources rather than how much we can supply.

5 Irrigation water supply and application systems

As explained, the purpose of an irrigation system is to supply water to a crop for food or fibre production. The infrastructure required to make this possible usually includes the following components, applicable to the different levels of water management as shown in Figure 1:

- An in-field irrigation system to apply the water to the crop
- An on-farm water conveyance system to convey the water to the field edge
- An on-scheme water distribution system such as a canal or river, shared by a number of water users to convey the water to the farm edge

When assessing the performance of the whole supply and application system (from the river to the field), it is important to recognise the *purpose* of the different components, so that optimisation can be done effectively.

The purpose of the in-field irrigation system is to apply the right amount of water at the correct application rate to all the plants in the field with as little non-beneficial consumption (losses) as possible – timing of applications, application rate (accuracy) and distribution uniformity is therefore characteristics of an in-field irrigation system that should be considered.

The purpose of the on-farm conveyance system is to convey the water from the source to the field at the lowest possible energy requirement – operational economy and conveyance efficiency of the system components are therefore of importance.

The purpose of the on-scheme system is to be a reliable and sustainable source as well as conveyance system of water – quantity and quality of the water delivered by this system will therefore be important aspects of the system, as well as operational economy and conveyance efficiency.

Optimisation of the performance of the any component of these systems furthermore requires careful consideration of the implications of decisions made during both development (planning and design) and management (operation and maintenance) of the component. Optimisation through management alone will be severely limited in its potential if the infrastructure was not developed with technical, economical and environmental efficiency in mind.

Every decision that we make when developing and managing water supply and application systems has an effect on the water and energy demand of the system. Every level of the management system should be optimised to serve its specific purposes in an integrated manner so that synergy is achieved.

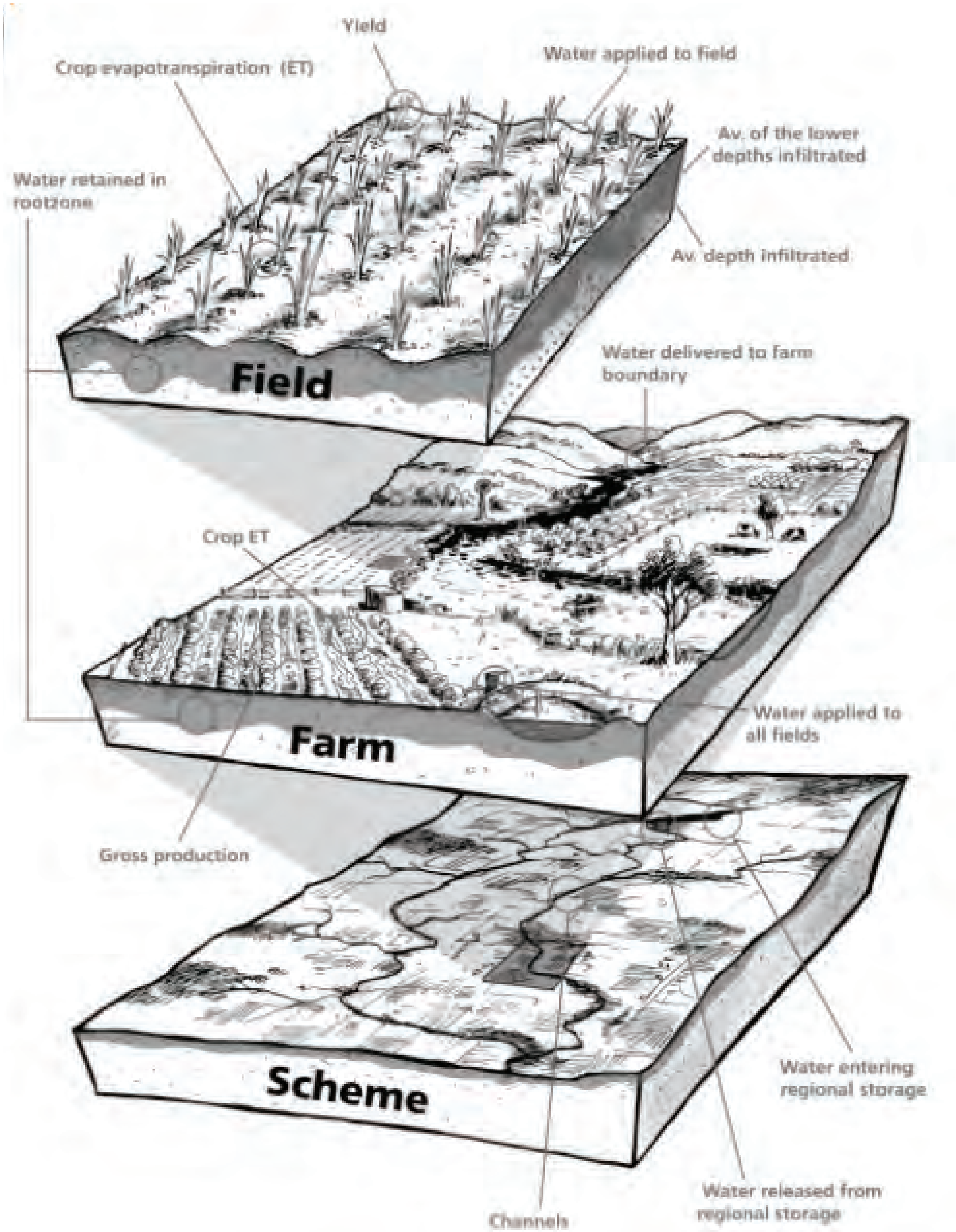

Figure 1 Levels of agricultural water management systems (Fairweather, Austin & Hope, 2003)

6 The water balance

Rather than thinking about irrigation efficiency as a percentage, irrigation system performance should be considered in terms of a water balance. A water balance is an accounting of all water volumes that enter and leave a 3-dimensional space over a specified period of time (Burt, 1999). Changes in internal water storage must also be considered. Both the spatial and temporal boundaries of a water balance must be clearly defined in order to compute and to discuss a water balance. A complete water balance is not limited to only irrigation water or rainwater or groundwater, etc., but includes all water that enters and leaves the spatial boundaries.

A recent paper by Perry (2007) presents the newly developed analytical framework for irrigation efficiency as approved by the International Commission on Irrigation and Drainage (ICID). In the paper, the author describes in detail the history and subsequent confusion regarding the calculation and interpretation of so-called irrigation or water use "efficiency" indicators. The framework and proposed terminology is scientifically sound, being based on the principle of continuity of mass. It promotes the analysis of irrigation water use situations or scenarios in order to expose underlying issues that can be addressed to improve water management, rather than simply the calculation of input-output ratios as done in the past.

It was reviewed and accepted by the ICID as the analytical framework and associated terms that will better serve the needs of technical specialists from all water-using sectors, policymakers and planners in achieving more productive use of water and tracing the implications of interventions on other uses and users. ICID recommends that this terminology be used in the analysis of water resources management at all scales, and form the basis for its research papers and other published outputs.

A schematic representation of the ICID framework as described by Perry (2007) is shown in Figure 2 and discussed further in this document.

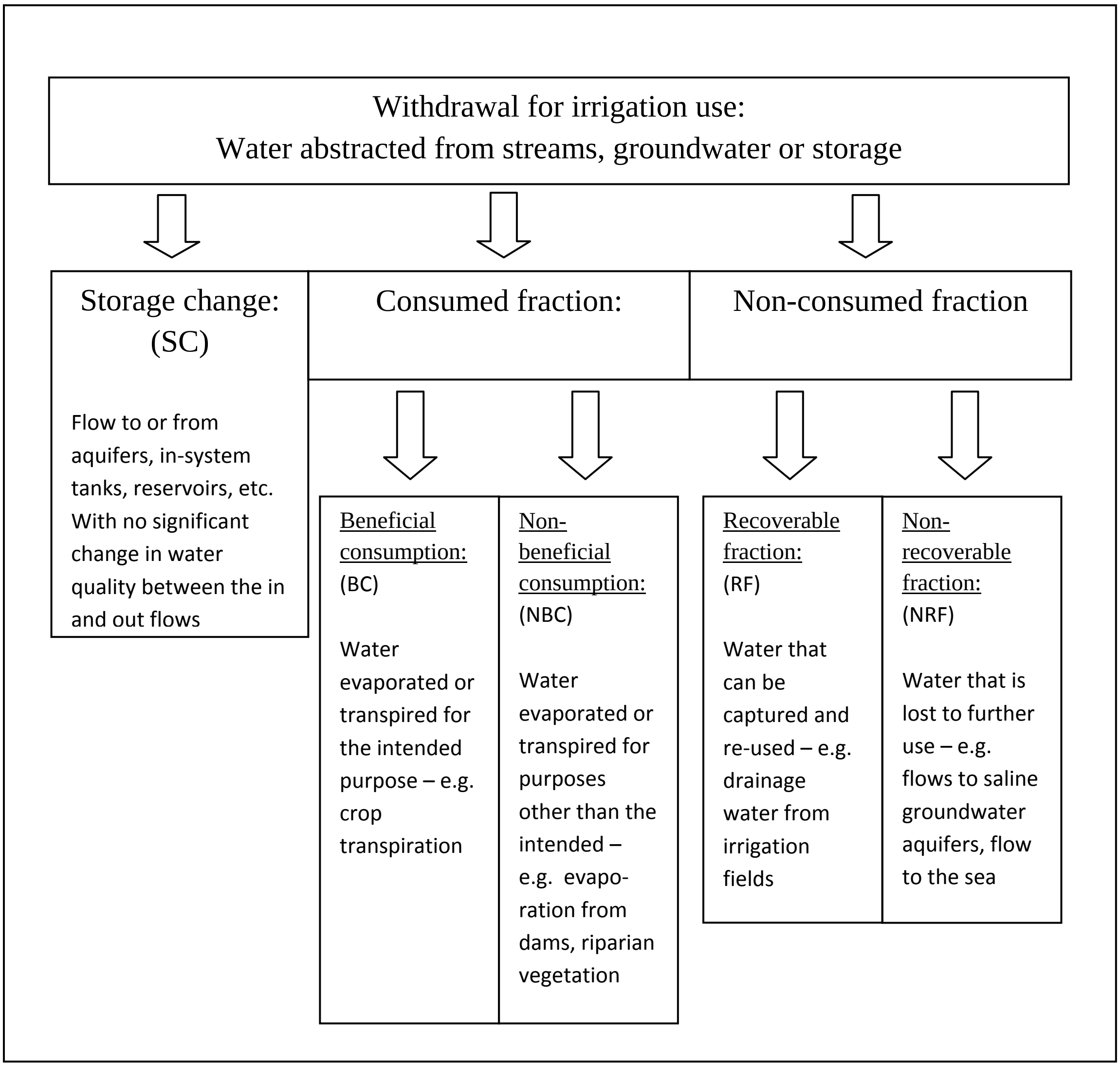

Figure 2: ICID Analytical framework for irrigation water management (After Perry, 2007)

Definition of terms:

1. Water use: any deliberate application of water to a specified purpose. The term does not distinguish between uses that remove the water from further use (evaporation, transpiration, flows to sinks) and uses that have little quantitative impact on water availability (navigation, hydropower, most domestic uses).

2. Withdrawal: water abstracted from streams, groundwater or storage for any use – irrigation, domestic water supply, etc.

   a. Changes in storage (positive or negative) – changes in storage include any flows to or from aquifers, in-system tanks, reservoirs, etc. The key characteristic of storage is that the water entering and leaving is essentially of the same quality.

   b. Consumed fraction (evaporation and transpiration) comprising:

i. Beneficial consumption: Water evaporated or transpired for the intended purpose – for example evaporation from a cooling tower, transpiration from an irrigated crop.

ii. Non-beneficial consumption: Water evaporated or transpired for purposes other than the intended use –for example evaporation from water surfaces, riparian vegetation, waterlogged land.

c. Non-consumed fraction, comprising:

i. Recoverable fraction: water that can be captured and re-used – for example, flows to drains that return to the river system and percolation from irrigated fields to aquifers; return flows from sewage systems.

ii. Non-recoverable fraction: water that is lost to further use – for example, flows to saline groundwater sinks, deep aquifers that are not economically exploitable, or flows to the sea.

The basis of the framework is that any water withdrawn from a catchment for irrigation use will contribute either to storage change, to the consumed fraction or to the non-consumed fraction at a point downstream of the point of abstraction. The water that is consumed, will either be to the benefit of the intended purpose (beneficial consumption) or not (non-beneficial consumption). Water that is not consumed, but remains in the system will either be recoverable (for re-use) or non-recoverable (lost to further use). To improve water availability in the catchment, the relevant authority will have to focus its attention on reducing non-beneficial consumption and the non-recoverable fraction.

The advantages of using a water balance approach are the following:

- It can be applied at all levels of water management and potentially to all water use sectors within a catchment
- It necessitates the management authority to develop an understanding of water movement within its area of jurisdiction through proper hydrological analysis
- It avoids the use of confusing performance indicator terminology

6.1 Boundaries

When defining boundaries for water balance areas, it is necessary to define both spatial (related to area) and temporal (related to time) boundaries. It is also necessary to define boundaries of authority, or in other words, management levels.

Within the irrigation water supply and application infrastructure described above, there are two distinct levels of management: firstly the farmer or water user, and secondly, the water management authority or authorities. These include Water Users Associations (WUA) or Irrigation Boards (IB). In cases where farmers abstract water directly from a river in a

Ground Water Control Area (GWCA), the water management authority will be a Department of Water Affairs (DWA) regional office, or a Catchment Management Agency (CMA).

6.1.1 Spatial boundaries

Water balances can be conducted for different geographical areas: a field, a farm, the area controlled by a water user association, a catchment, etc. The same concepts apply to *all* areas but one must be absolutely clear about which boundaries apply to the areas under consideration.

Spatial boundaries should be set horizontally and vertically, to define at which points water enters or leaves the water balance area. Table 1 defines the suggested spatial boundaries for the different levels of water management in irrigation.

Table 1: Spatial boundaries of water balance areas

Area	Upper boundary	Lower boundary	Horizontal boundary
In-field application systems (from field edge to root zone)	Crop canopy	Bottom of root zone	Field edges
On-farm distribution system (from farm edge to field edge)	Water surface	Bottom of canal / pipe walls / drainage system	Farm edges
On- scheme conveyance system	Water surface	Bottom of canals / pipe walls	Scheme edges
River system (from on-river dam to scheme / farm edge)	Water surface	Bottom of river	All river inflows and outflows

The efficiency of water delivery and consumption at different levels, is linked and interdependent. Improved management can often be achieved at one management level (e.g. on-farm) by improving infrastructure at another level (e.g. on-scheme); for example, by building on-scheme balancing dams, greater flexibility of supply to the farm edge can be ensured, leading to better timed on-farm irrigation applications, with an increased beneficial water use fraction in-field, due to reduced deep percolation.

6.1.2 Temporal boundaries

The temporal boundaries of the water balance will be determined by the purpose for which the balance is done.

As water is allocated for irrigation use on an annual basis, a one year period is generally recommended as a temporal boundary. However, all of the values of water balances change from one year to another, and it is advisable that water balances should be examined annually to obtain a better understanding of the effect of climatic changes from one year to another.

In some cases, such as at field level, the time scale may be reduced to the length of a season for a specific crop. A daily soil water balance can also be done for specific reasons such as irrigation scheduling, as an annual balance at this level will be useless.

6.2 Partitioning the water balance

Partitioning the water balance involves a process of classifying the destinations of water which crosses the water balance area boundaries within the defined time period. When the ICID framework (Perry, 2007) is applied, this means identifying all the possible components of the water balance area and classifying them according to the framework component (storage change, consumed fraction, non-consumed fraction, etc.).

The South African framework presented here, covers four levels of water management infrastructure (Table 2) – the water source, bulk conveyance system, the irrigation scheme and the irrigation farm.

Table 2: Four levels of water management infrastructure

Water management level	Infrastructure system component		
Water Source	Dam/Reservoir		Aquifer
Bulk conveyance system	River	Canal	
Irrigation scheme	On-scheme dam		
	On-scheme canal		
	On-scheme pipe		
Irrigation farm	On-farm dam		
	On-farm pipe / canal		
	Irrigation system		

In South Africa, most of the irrigation areas consist of a dam or weir in a river from which water is released for the users to abstract, either directly from the river or in some cases via a canal. Water users can also abstract water directly from a shared source, such as a river or dam/reservoir, or the scheme-level water source could be a groundwater aquifer. Once the water enters the farm, it can either again contribute to storage change (in farm dams), enter an on-farm water distribution system or be directly applied to the crop with a specific type of irrigation system.

Table 3 shows the proposed partitioning of water balances at the different water management levels for the possible scenarios that may occur at all the management levels. Although care has been taken to include all possible system components and water destinations, practitioners are encouraged to customise the framework for their specific circumstances. With respect to the typical infrastructure encountered in the field, the management responsibilities for the different water use components can therefore be described as follows:

> The **water management authorities** are responsible for managing water supply infrastructure used for conveying water from the dam wall in a canal, river or pipe to the user. Alternatively an authority may also be responsible for managing a groundwater aquifer from which different users abstract water individually. In open channel systems, surface storage such as balancing dams may also be found. **The on-scheme infrastructure should be developed and managed in such a way that the users receive the right amount of water at the right time, with as little unaccounted-for (non-beneficial and non-consumed) water as possible.**
>
> The **water user** is responsible for managing the water from the point where he/she receives it from the management authority up to the point where it infiltrates the root zone (and possibly beyond). The water user may first store the water on-farm before distributing it to different irrigation blocks, with or without adding additional energy through pumping the water, and finally applying the water with a specific type of irrigation system. **The on-farm infrastructure should be developed and managed in such a way that the right amount of water is applied to the crop at the right time so that energy is used as efficiently as possible, production is optimized, and as little water as possible is lost to non-beneficial consumption and the non-recoverable fraction, while the recoverable fraction is utilized or minimalised.**

The water balance approach can be applied at any level, within defined boundaries, or across all levels to assess performance within a complete WMA. When drawing up the water balance, all water entering the water management level as “Inflow” (second column in Table 3), should be allocated to a specific destination within or exiting the water management level boundaries (third column in Table 3).

In order to improve water use efficiency in the irrigation sector, actions should then be taken to reduce the non-beneficial consumptive (NBC) and non-recoverable fractions (NRF) at all levels. In Table 3, desired ranges for the NBC and NRF components have been included to help the practitioner evaluate the results obtained when first constructing a water balance. The values shown here are based on actual results obtained in the course of the project, as documented in the main report, and can be adjusted if more accurate, locally relevant data is available in an area. However, as circumstances differ greatly from one irrigation area to the next, it is recommended that water managers at all levels assess a specific system component’s performance against the same component’s previous years’ data in order to achieve continuous improvement, rather than against other (seemingly similar) system components from different areas.

When trying to quantify the different components, one is faced with the dilemma of the lack of data available. It is possible to construct a water balance with limited data by presenting the results for combined water destinations. For example, at the irrigation system level, it is often easier to measure or calculate the combined beneficial consumptive and recoverable fractions (transpiration, leaching requirement, drainage water, etc.) than the non-beneficial or non-recoverable fractions – by constructing the water balance, the NBC and/or NRF can be calculated and then assessed.

Finally, it is recommended that the water user’s lawful allocation is assessed at the farm edge, in order to encourage on-farm efficiency. At scheme level, conveyance, distribution and surface storage losses need to be monitored by the WUA or responsible organisation, acceptable ranges set, and agreement obtained with the DWA where in the system provision should be made to cover the losses.

Table 3: Framework allocation of typical irrigation system components

Water balance framework system component (based on infrastructure)	Inflow of water into system component	Possible water destinations within the system component	Framework classification	Desired Range, % of inflow
Dam / reservoir	Total amount of water released from storage	Increase flow in bulk conveyance system (river or canal) Operational losses at the point of release	SC NRF	 <5
River bulk conveyance system (from on-river dam to scheme / farm edge) (if applicable)	Total amount of water entering the river	On-scheme surface storage On-scheme distribution system Farm edge (on-farm surface storage, distribution system or irrigation system) Evaporation from water surface Seepage in river bed Transpiration by riparian vegetation Unlawful abstractions Operational losses (unavoidable)	BC BC BC NBC NRF NBC NBC NRF	 <5 <10 <5 0 <10
Canal bulk conveyance system (from on-river dam to scheme / farm edge) (if applicable)	Total amount of water entering the main canal	On-scheme surface storage On-scheme distribution system Farm edge (on-farm surface storage, distribution system or irrigation system) Evaporation from canal Seepage in canal Unlawful abstractions Operational losses (unavoidable, egg filling canal, tailends) Operational losses (inaccurate releases, spills, breaks, etc.)	BC BC BC NBC NRF NRF RF NRF	 <1 <5 0 <10 0
On-scheme surface storage	Total amount of water entering a scheme dam	Increase volume of water stored On-scheme distribution system (release from dam) Farm edge (on-farm surface storage, distribution system or irrigation system) Evaporation from dam Seepage from dam Operational losses (spills)	SC BC BC NBC NRF NRF	 <1 <1 <1
Shared (scheme-level) groundwater aquifer compartment	Total aquifer recharge	Increase groundwater storage Farm edge (on-farm surface storage, distribution system or irrigation system)	SC BC	
On-scheme canal distribution system (if applicable)	Total amount of water entering the on-scheme	Farm edge (on-farm surface storage, distribution system or irrigation system)	BC	

	canal distribution system	Evaporation from canal Seepage in canal Unlawful abstractions Operational losses (unavoidable, e.g. filling canal, tailends) Operational losses (inaccurate releases, spills, breaks, etc.)	NBC NRF NRF RF NRF	<1 <5 0 <10 0
On-scheme pipe distribution system (if applicable)	Total amount of water entering the on-scheme pipe distribution system	Farm edge (on-farm surface storage, distribution system or irrigation system) Operational losses (unavoidable) Leaks	BC RF NRF	 <5 0
On-farm surface storage	Total amount of water entering a farm dam	Increase volume of water stored On-farm distribution system (release from dam) Irrigation system (abstraction from dam) Evaporation from dam Seepage from dam Operational losses (spills, leaks)	SC BC BC NBC NRF NRF	 <1 <1 <1
On-farm distribution system	Total amount of water entering the on-farm pipelines or canals	Irrigation system On-farm distribution system leaks Operational losses (unavoidable)	BC NRF RF	 0 <5
Irrigation system (from field edge to root zone) *Intended destination of the water released.*	Total amount of water entering the irrigation system (Gross Irrigation Requirement, GIR)	Increase soil water content Transpiration by crop In-field evaporation (beneficial) Frost protection irrigation water Leaching (intended, beneficial but non-recoverable) Interception (unavoidable) In-field evaporation (non-beneficial, excessive) In-field deep percolation (non-intended, non-recoverable) In-field run-off (uncontrolled) Drainage water (surface & subsurface, recoverable) Operational losses (unavoidable)	SC BC BC BC BC NBC NBC NRF NRF RF NRF	 <1 0 0 0 <5

BC: Beneficial consumption NBC: Non-beneficial consumption
RF: Recoverable fraction NRF: Non-recoverable fraction
SC: Storage change

6.2.1 Measurement errors

The use of the water balance implies that a large number of measurements need to be made to quantify the different components. Once the water balance components have been identified and quantified, an estimate of the confidence interval (CI) for each value should be made (Burt, 1999). A CI of “6” indicates that one is 95% certain that the correct value lies between plus or minus 6% of the value stated in the water balance. The purpose of using CIs on figures and tables is to reinforce the fact that we rarely know many values with precision, even though discussions of those values often seem to assume that we do know them as absolute values. It is better to include all water components in the water balance, even if they have a large confidence interval rather than ignore them because they are perceived to be inaccurate.

7 Appropriate technologies

The use of modern technology can assist the irrigator and authorities to optimise irrigation water management at all levels. By planning and budgeting for the implementation of such technologies, affordable solutions can be found in most cases.

The use of suitable, quality equipment result in more durable systems with longer life cycles, less leakages and lower energy requirements. Applying maintenance practices recommended by the manufacturers will further prolong the working life of any piece of equipment.

Computer based-decision support systems are available for both on-farm and on-scheme applications, to improve the delivery of water and to assist with early detection of possible system problems.

Many suitable and proven technologies are also available to collect the information necessary as input for the decision support programmes, such as soil water content, flow rates, pressure, flow depth, as well as soil and water quality parameters, and most of the measurements can be managed remotely using modern communication technology such as modems and the internet, enabling real-time water management and more effective decision-making.

Appropriate modern technologies should be used as far as possible to improve water management.

8 Incentives

In the context of this document, an incentive is motivational factor, such as the expectation of a benefit or reward (e.g. improved profit) that encourages action, or motivates effort towards the optimisation of the beneficial water use component. The threat of a negative effect (e.g. penalties for excess water use) may also be seen as an incentive.

According to Backeberg (2007), water users must understand the economic value of water as a scarce resource; and respond to incentives to use less water which could then reduce the demand from a source. Sustained reduced consumption of water, in turn, can lead to postponement of new capital infrastructure and delay increases in the cost of water supply. At scheme level, demand management can improve the financial independence of organizations such as water user associations (WUA) by balancing the budget through increased revenue collection and reduced unaccounted water and non-payment by users or consumers.

Informed decisions regarding irrigation system selection and design as well as improved irrigation management at farm and field level can result in reduced costs of other production inputs such as electricity, labour, fertilisers and even pesticides. Reduced costs and increased yields lead to greater profitability.

The annual operating cost of the different irrigation systems should be considered and compared during system selection. The capital cost of the system cannot be considered in isolation and life cycle costing principles should be applied – the lower operating cost of a system with a higher capital cost but better performance can be an incentive for the water user to invest into the system.

Decisions made during the selection and design of irrigation systems will influence the flow rate and operating pressure of the system, which directly influences the power requirements and therefore the energy cost. Furthermore, a properly designed system consisting of high quality irrigation equipment will ensure uniformly applied water, and fertiliser, if applicable, affecting crop yield.

The IRRICOST program (Meiring, Oosthuizen, Botha & Crous, 2002) was developed to estimate both the annual fixed and variable costs. The IRRICOST program uses the paradox database system as well as binary files. The user manual and a demonstration programme can be downloaded from the University of the Free State website (Meiring, Oosthuizen, Botha & Crous, 2002).

Appropriate irrigation system operation and maintenance practices will furthermore prevent increased water and energy requirements, ensuring irrigation is scheduled and applied as intended, creating the best possible conditions for crop production in terms of productive use of water and plant health.

Higher yields, greater water productivity and reduced input costs are incentives that water users should be made aware of, together with the added benefits of good irrigation management practices.

9 Summary

This module introduced the guidelines, which are based on the following fundamental concepts:

- Lawful water use

  For integrated water resources management to work, all water users should ensure that they comply with the lawful use allocated to them.

- Water and energy demand management

  In order to make best use of available water and energy, it is imperative that we develop and manage irrigation water supply and application systems with demand in mind, so that we can minimise our water footprint – to see how little we can demand from the sources rather than how much we can supply.

- Systems approach

  Every decision that we make when developing and managing water supply and application systems has an effect on the water and energy demand of the system. Every level of the management system should be optimised to serve its specific purposes in an integrated manner so that synergy is achieved.

- Water balance

  On-farm infrastructure should be developed and managed in such a way that the right amount of water is applied to the crop at the right time so that energy is used as efficiently as possible, production is optimized, and as little water as possible is lost to non-beneficial consumption and the non-recoverable fraction, while the recoverable fraction is re-utilized or minimalised.

  On-scheme infrastructure should be developed and managed in such a way that the users receive the right amount of water at the right time, with as little unaccounted-for (non-beneficial and non-consumed) water as possible.

- Appropriate technologies

  Appropriate modern technologies should be used as far as possible to improve water management.

- Incentives

  Higher yields, greater water productivity and reduced input costs are incentives that water users should be made aware of, together with the added benefits of good irrigation management practices.

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Standards and Guidelines for Improved Efficiency of Irrigation Water Use from Dam Wall Release to Root Zone Application

EFFICIENT WATER USE GUIDELINES

Module 2

DEVELOPING AND MANAGING

EFFICIENT IN-FIELD IRRIGATION SYSTEMS

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List of Acronyms and Abbreviations

AE	Application Efficiency
ARC	Agricultural Research Council
ARC-IAE	Agricultural Research Council's Institute for Agricultural Engineering
BC	Beneficial consumption
BEWAB	*Besproeiingswater Bestuursprogram*/Irrigation water management program
CI	Confidence Interval
CLIMWAT	An FAO weather data set
CMA	Catchment Management Agency
CV	Coefficient of variation
DUL	Drained upper limit
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry (now DWA)
EC	Electrical conductivity
ESP	Exchangeable sodium percentage
ET	Evapotranspiration
FGWR	Farm Gross Water Requirement
FIE	Farm Irrigation Efficiency
FldNTGR	Field Net to Gross Conversion Ratio
GAR	Gross application rate
GIR	Gross irrigation requirement
GWCA	Ground Water Control Area
IAEA	International Atomic Energy Agency
IB	Irrigation Board

ICID	International Commission on Irrigation and Drainage
IPARM	A computer program to calculate infiltration parameters
ISCDSP	Irrigation Scheduling Calendar Decision Support Program
IWMI	International Water Management Institute
mg/l	milligrams per litre
mS/m	milliSiemens/metre
NAR	Net application rate
NBC	Non-beneficial consumption
NIR	Net irrigation requirement
NRF	Non-recoverable fraction
OFCE	On-Farm Conveyance Efficiency
PVC	Polyvinyl Chloride
RF	Recoverable fraction
RSC	Residual sodium carbonates
SABI	South African Irrigation Institute
SAPWAT	A computer model for planning crop irrigation requirements
SAsched	A computer programme to assist with irrigation for sugarcane
SAR	sodium adsorption ratio
SC	Storage change
SIRMOD	A computer program to calculate infiltration parameters
SWB	Soil Water Balance
TAW	Total Available Water
TDR	Time Domain Reflectometer
TDS	Total Dissolved Solids

UN-FAO	United Nations Food and Agricultural Organisation
VINET	A vineyard irrigation system design and scheduling program
WMA	Water Management Area
WRC	Water Research Commission
WUA	Water Users Association
ZIMsched 2.0	An irrigation systems and crop yield simulation model

1 Introduction

The purpose of the in-field irrigation system is to apply the right amount of water, at the correct application rate, to all the plants in the field, with as little non-beneficial consumption (loss) as possible: Consideration should therefore be given to characteristics of an in-field irrigation system such as application efficiency, application rate (accuracy) and distribution.

In-field irrigation system components include:

- nozzles,
- emitters,
- lateral and manifold pipes, and
- earth furrows or beds.

Optimising the performance of any component of the system requires careful consideration of the implications of decisions made during both the development (planning and design), and the management (operation and maintenance) of the component. The potential for optimisation through management alone will be severely limited if the infrastructure was not initially developed with technical, economical and environmental efficiency in mind.

The most efficient in-field irrigation system will therefore be one that:

- Is planned to take the natural resources available in the field, and the management requirements of the irrigator into account,
- Is designed according to sound design principles, based on limiting discharge variation and energy requirements in the field,
- Consists of quality components manufactured to a high standard with low coefficients of variation and low energy requirements,
- Is operated according to the design specifications and site-specific irrigation water requirements of the crop,
- Is maintained according to the equipment manufacturers' and/or irrigation designer's recommendations, and
- Is regularly evaluated to assess the level of performance and to detect problems as early as possible.

Each irrigation system is characterised by a specific flow rate and operating pressure, which is the outcome of the planning and design functions respectively. Together, the flow rate and the operating pressure determine the energy requirements of the system, as well as the size of all the water supply and conditioning infrastructure required for the system. The correct planning and design of the in-field irrigation system components is therefore of great importance as it determines the amount of water, energy and finance required to develop and manage an irrigation system.

This module provides guidelines on how these aspects of in-field irrigation system development and management can be addressed through different methodologies.

2 Planning

The most efficient system will be one that is planned to take the natural resources available in the field, and the management requirements of the irrigator, into account.

The natural resources include the soil, water and climate at the specific location, while the management requirements are the agronomic practices applicable to the specific crop, the time and labour aspects applicable to the specific farm/irrigator, and the water application characteristics of the specific irrigation system.

The most significant outcome of the planning process of an irrigation system (in terms of efficiency) is the determination of the system flow rate that will be required from the water source to ensure that the application of irrigation water maximises the beneficial use component of the water balance. Every decision made during the planning process should therefore be considered carefully, as it has a direct effect on the water availability and the energy requirements on the farm, and on abstraction rates from the source and the water balance.

2.1 Principles of irrigation

Irrigation systems are used to manage the amount of water stored in the soil. Evapotranspiration (ET) or consumptive use is the combination of water evaporated from the soil surface and the water transpired by plants. ET causes soil moisture to decrease over time: If rainfall or irrigation does not replace this water, soil moisture falls to the extent that plants reduce growth and ultimately wilt and die.

In the absence of rainfall, irrigation is used to maintain soil moisture at a level where plant growth generally is not limited. When irrigation is applied, the rate at which water moves through the soil depends on the soil type. In clay soils, this rate is quite slow, while in sandy soils, the rate is usually quite rapid. After irrigation or significant rainfall, the upper layers of the soil may become saturated, depending on the amount applied. Water applied in excess of what the soil can retain will drain into the deeper layers, (usually the groundwater system) or contribute to surface runoff. The excess soil water drains out under the force of gravity, and after a few hours in light, free-draining soils, (or perhaps several days in tighter soils), the soil is said to be at field capacity or at the full point (drained upper limit). Plant growth generally does not take place in saturated soils, so excess watering may have a detrimental effect on plant growth.

As the soil dries out, the rate of evaporation from the surface falls fairly quickly until the soil surface is dry. The remaining soil moisture, which is usually the majority of the available water, is used by plants for transpiration and growth.

The rate at which plants absorb water reduces as the soil dries out, because it becomes progressively harder for the plants to remove the water from the soil. Initially plants are easily able to draw water from the soil, and growth is not affected. After some time the soil becomes dry enough to slow plant growth. The soil moisture level at this stage is known as the critical deficit, or the stress point. If the rate at which the atmosphere demands water from the plants exceeds the rate at which plants can absorb moisture, temporary wilting may occur. This soil moisture level is often considered to occur at a soil suction (soil tension) of about 1 bar, although this varies with different crop types. For maximum growth rates, irrigation should be applied before the soil has dried to this point.

If the crop is not irrigated or water is not received from other sources, the soil will eventually dry out to the point where permanent wilting occurs, and the plants will die. The amount of water in the soil between the stress point and field capacity is called the readily available soil water. In most cases, effective irrigation is achieved when soil water is maintained between the stress point and a level just below field capacity. There are, however, circumstances where deficit irrigation, (where some stress is tolerated and soils dry to below the stress point), is the most effective and efficient practice. This is often the case, for example, where water is limited relative to available land.

In summary, irrigation is most often about keeping soil water between the stress point and drained upper limit, so that growth is not limited.

2.2 Soils

Not all soils are equally suitable for irrigation farming, and some are not suitable at all. In South Africa, the potential of the soil for irrigation is usually classified according to the following system of five irrigation soil potential classes:

- Class 1 – Highly suitable for irrigation with few or no limitations or preconditions. Topography is flat, soils are well drained, of moderate permeability and are deep, medium textured with good available water holding capacity.
- Class 2 – Suitable for irrigation with slight limitations such as undulating topography, moderately well drained soils, moderately slow or moderately rapid permeability or moderate depth of soil.
- Class 3 – Low suitability with moderately severe limitations such as significantly rolling topography, imperfect or somewhat excessively drained soils, slow or rapid permeability, or shallow soils.
- Class 4 – Not suitable for irrigation under most conditions with severe limitations.
- Class 5 – Soils with severe limitations, not recommended at all, such as soils in natural waterways, soils in the river floodplain, soils presently eroded or soils showing the presence of any permanent or potential water table.

Irrigation soil potential Classes 1 and 2 can be recommended for irrigation. Class 3 is normally not recommended for large-scale irrigation development under average conditions, but small areas may be considered if they adjoin or are enclosed by areas of irrigation Classes 1 and 2.

When assessing the suitability of soils for irrigation, the following information is taken into account:

- Effective soil depth
- Texture of the soil
- Soil structure
- Soil chemistry
- Colour of the soil
- Soil potential maps

2.2.1 Effective soil depth

Soil depth is one of the most important aspects which should be investigated. It not only influences the root development and soil water reservoir, but also the degree of drainage past the root zone. To maintain a salt balance, some deep percolation is required due to excess rain or irrigation and this water must be able to drain away without any problems. A profile hole should be dug, or a soil auger used to determine the depth of the soil down to the limiting layer.

Basically, a limiting layer may be described as a layer with poor water conductivity, which is harder or denser than the soils above. If the soil depth is more than 900 mm, it may be classified as irrigable. Soil as shallow as 450 mm may be irrigated: however, the choice and management of an appropriate irrigation system will be constrained. Whilst soil may also be ridged, for example for the planting of fruit trees, this requires excellent irrigation management.

The five derived irrigation potential classes used in terms of soil depth are:

- Class 1 – 900 to 1500 mm
- Class 2 – 600 to 900 mm
- Class 3 – 300 to 600 mm
- Class 4 – 150 to 300 mm
- Class 5 – 0 to 150 mm

2.2.2 Texture of the soil

Soil texture influences, amongst other things, infiltration rate, permeability, water holding capacity, internal drainage and the erodability of soils. The ideal texture is neither too fine and nor too coarse, and must have a good distribution of particle sizes.

2.2.2.1 Sand

Too high a sand content promotes wind erosion, causes low water holding capacities and high infiltration rates. Too low a sand content results in soils which are difficult to cultivate, have low infiltration rates and poor drainage properties.

2.2.2.2 Clay

Soils with between 10% and 35% clay, and without significant different textural layers are considered irrigable (Irrigation soil potential Class 1). Soils with distinct different textural layers, less than 10% clay or more than 35% clay are classified as Irrigation soil potential Class 3 or worse.

It must be remembered that the finer the soil particles, the greater the contact surface, the higher the volume of water held, the larger the volume of water that may be absorbed, the smaller the air pores and the greater the volume of water that is available to the crop. However, this water may not be easily available, because it is 'tightly' held.

2.2.3 Soil wetness

Soil wetness is a reflection of the rate at which water is removed from the soil by both runoff and percolation. Position, slope, infiltration rate, surface runoff, permeability, and redoximorphic features (soil mottling or colour patterns formed in the soil by the oxidation and reduction of iron and/or manganese caused by saturated conditions within the soil) are significant factors influencing the soil wetness class. Profile morphology is used to determine the depth of water saturation whilst the maximum height of signs of hydromorphy is used as the depth limit.

- Class 1: Not wet above 1 500 mm
- Class 2: Wet in some part between 1 000 and 1500 mm
- Class 3: Wet in some part between 500 and 1 000 mm
- Class 4: Wet in some part between 250 and 500 mm
- Class 5: Wet in some part above a depth of 250 mm

Soils of Wetness Class 2 and above should not be irrigated without careful attention to drainage requirements.

2.2.4 Soil structure

A moderately developed granular structure is preferable. The structure must be stable in water and therefore not dispersive, otherwise soil crusting can develop. Soil crusting leads to aeration problems, low infiltration rates and increases the erodability of the soil. A too strongly developed structure is indicative of a high clay content, with its accompanying problems.

2.2.5 Soil chemistry

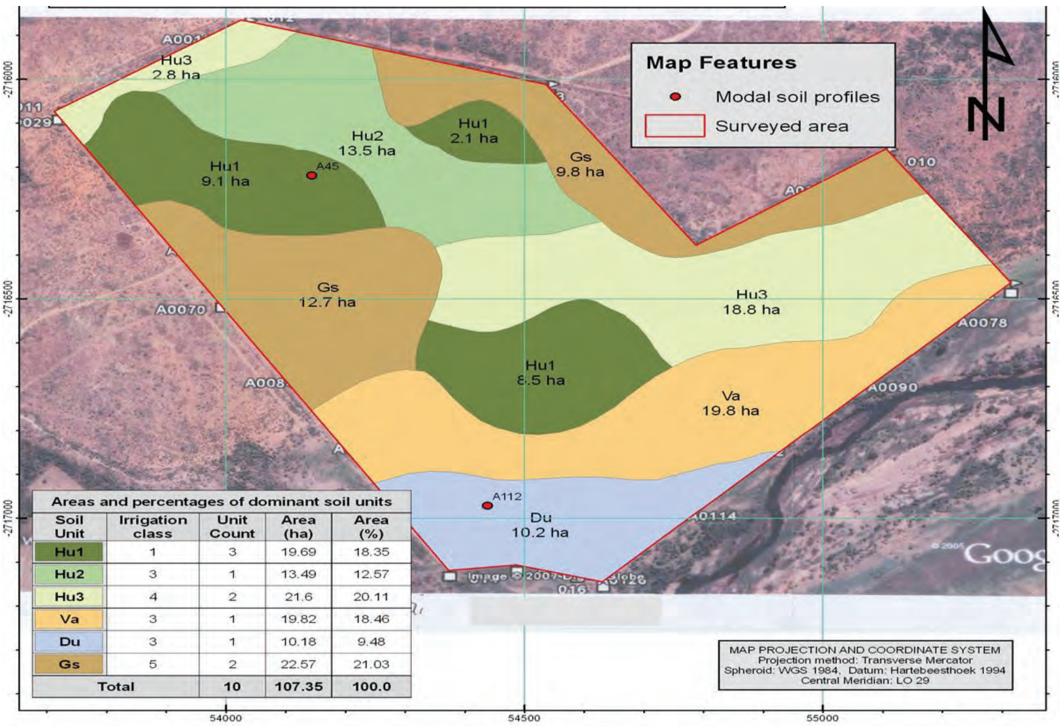
Provided that the pH of the soil lies between 7,5 and 5,5, and the soil's electrical conductivity (EC) is less than 300 mS/m, the soil is suitable for irrigation. If these values are exceeded, the sodium (Na) adsorption ratio (SAR) and the exchangeable sodium percentage (ESP) must be determined. Under these circumstances, it is advisable to contact your local soil expert for advice. The SAR is determined by the ratio of Na to Calcium (Ca) and Magnesium (Mg) (Na:(Ca + Mg)) in soils. A high SAR-value may indicate sodium problems in the soil. The SAR of a soil is approximately equal to (1 to 2 times) the ESP of the soil. The ESP gives a very good indication of the structural stability of a soil and the physical reaction that can be expected when the soil is irrigated. If the soil pH is lower than 5,5, the possibility of aluminium (Al) poisoning exists.

2.2.6 Colour of the soil

Although the colour of soil can give an indication as to the irrigability of the soil, the soil profile should be inspected and sampled for chemical analysis for the best recommendations. The colour of the soil alone should not be relied upon.

2.2.7 Soil potential maps

When planning irrigation systems, the information about different soil characteristics such as type, depth and texture can be presented on individual maps and then combined to determine those parts of the proposed development area in which there are fewer or no limiting characteristics, as shown in Figures 1 to 4. (Nell, 2009).



Areas and percentages of dominant soil units				
Soil Unit	Irrigation class	Unit Count	Area (ha)	Area (%)
Hu1	1	3	19.69	18.35
Hu2	3	1	13.49	12.57
Hu3	4	2	21.6	20.11
Va	3	1	19.82	18.46
Du	3	1	10.18	9.48
Gs	5	2	22.57	21.03
Total		10	107.35	100.0

Figure 1: Soil type map (Nell, 2009)

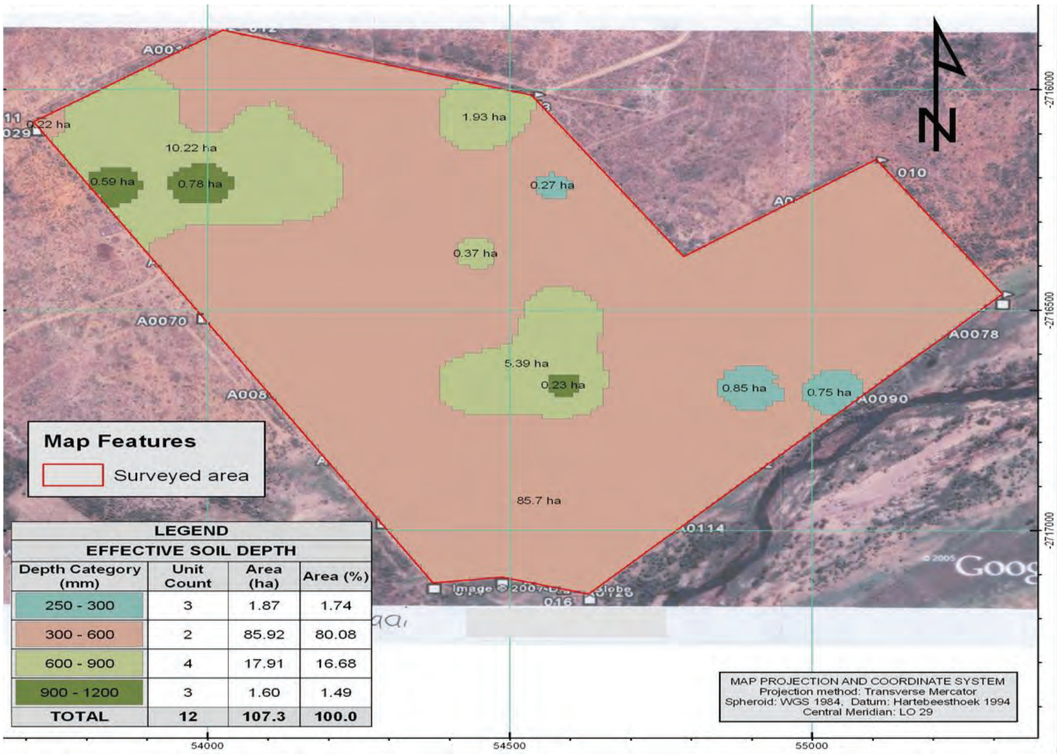


Figure 2: Soil depth map (Nell, 2009)

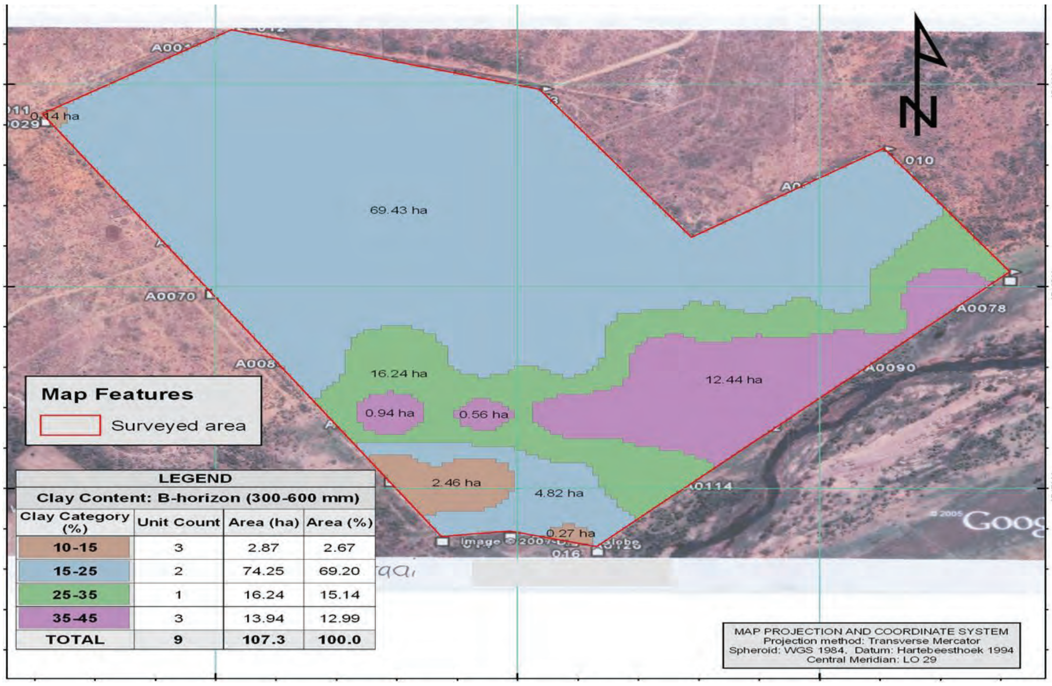


Figure 3: Soil texture map (clay content) (Nell, 2009)

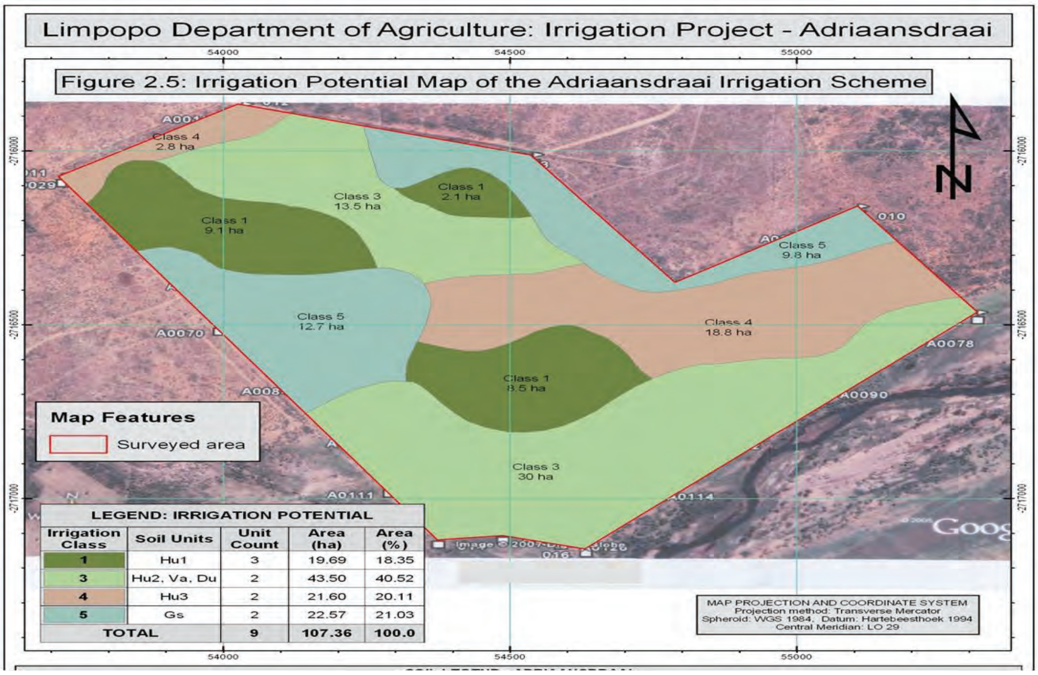


Figure 4: Soil potential map (Nell, 2009)

2.3 Water quality

Impurities carried in solution or in suspension determine water quality. When planning irrigation systems, both water quantity and water quality have to be taken into account. Water quality is discussed here, while the amount of water available and required (quantity) are discussed in Module 3.

Water quality problems are escalating in South Africa as pressure on water resources increases, especially in rivers where effluent from industrial or municipal users is present, whilst rainfall and other forms of precipitation pick up impurities and silt as the water flows over the ground surface to streams. Water in streams and rivers pick up additional impurities. Runoff and excess irrigation may pick up nitrates, pesticides and other soluble compounds that may cause water to be unsuitable for irrigation. The water quality can negatively influence the crop yield (quantity and quality), the suitability of the soil for irrigation, and the operation of the irrigation system.

Whether or not water of a certain quality is acceptable for irrigation depends on climate, soils, crops grown, and depth of water applied. In general, water quality problems are worse in shallow groundwater areas, in streams during low flows, and in the downstream reaches of streams. Stream pollution from industrial wastes, as well as tide and wind conditions, affect the quality of irrigation water. Brackish water is contaminated by acids, salts and organic matter.

A water analysis will show whether the water is acceptable for irrigation, according to the guidelines provided in Table 1.

Table 1: Water quality guidelines for irrigation

Water Quality Constituent	CLASS 1	CLASS 2	CLASS 3	CLASS 4
Salinity (Electrical Conductivity – EC) (mS/m)	0-40	40-90	90-270	270-540
Sodicity (SAR)	0-1.5	1.5-3.0	3.0-5.0	5.0- 10.0
Boron (mg/l)	0-0.2	0.2-0.9	0.9-1.5	1.5-3.0
Chloride (Cl) (mg/l)	0-105	105-140	140-350	>350
Sodium (Na) (mg/l)	0-70	70-115	115-160	160-200
Nitrogen (mg/l as N)	0-5	5-30	>30	
Iron (Fe) (mg/l)	< 0,05	0,05-5	5-10	10-20
Manganese (Mn) (mg/l)	<0,05	0,05-0,2	0,2-5	5-10
pH (Acceptable range)	6.5-8.4			

Water with an EC in excess of 40 mS/m may lead to soil salinisation, unless some of the salts are leached and soil is well drained and permeable. In sodic soils (where more than 15% of the element ions attached to the clay particles are sodium – i.e. soils with a high SAR), irrigation water with a low EC will affect the structure of the soil, possibly leading to infiltration problems due to dispersion and crusting.

If water quality doesn't meet the recommended criteria, a soil expert should be consulted. International marketing agreements (such as Globalgap) may also stipulate their own water quality standards that have to be met, which may determine the marketability of the crop.

2.3.1 The effect of water quality on irrigation equipment

Corrosive/aggressive irrigation water may reduce the life expectancy of irrigation pipelines and equipment, whilst water which is susceptible to sedimentation can reduce the flow rate due to full or partial blockage of drippers and sprinkler nozzles. This in turn can lead to unequal water distribution, resulting in yield losses.

A water analysis against the appropriate water quality guidelines can be useful for early detection of problems such as blockage, corrosion and sedimentation. Different indices can be used to identify whether the irrigation water is corrosive or if sedimentation will take place. However, a single index can be interpreted incorrectly, and it is therefore recommended that as many indices as possible are used to evaluate the water quality. The most conservative approach should be followed for planning purposes and where necessary, an expert must be approached for the necessary inputs.

Table 1 shows the most important indices for irrigation water and the levels at which corrosion or sedimentation may take place (DWAF, 1996), whilst Table 2 describes the physical, chemical and biological factors that may cause blockages in drip systems.

Table 2: Indexes that indicate directives for corrosion or sedimentation in irrigation pipelines (DWAF, 1996)

Indexes	Corrosion	Sedimentation
Langelier index	<-0,2	>0,2
Ryznar index	>6,5	<6,5
Corrosivity index	≥0,1	-
Aggressiveness index	≤10	-

Table 3: Physical, chemical and biological factors that can cause dripper blockage (Bucks et al., 1979)

Physical	Chemical	Biological
- Inorganic materials	- Alkaline heavy metals	- Algae
Sand (50-250µm)	Cations	
Silt (2-50 µm)	calcium	
Clay (<2 µm)	magnesium	
	iron	
	manganese	
	Anions	- Bacteria
	carbonates	filament
	hydroxides	slime
	silicates	
	sulphides	
- Organic materials	- Fertilisers	- Microbiological activities
Water plants	ammonia	iron
phytoplankton	iron	manganese
algae	copper	sulphates
Water animals	zinc	
zooplankton	manganese	
snails	phosphate	
Bacteria (0,4-2µm)		
Plastic pipe cuttings		
Oil		

Blockage of drippers is mainly caused by the following factors:

- Physical: Blockage is a result of suspended solids. Very fine particles tend to remain in suspension but may flocculate out in places where the water velocity is low or the water turbulence drops. The most obvious place where sedimentation is likely to occur is at the ends of laterals, causing these emitters to become blocked first. Although a single particle will not necessarily cause blockage, a quantity of particles can collect and thus block emitters.
- Chemical: Blockages can occur as a result of a chemical reaction in the water, resulting in a deposit, usually due to the presence of either Calcium and magnesium carbonates, iron and magnesium sulphides, or iron and manganese oxides.
- Biological: Algae growth and microbiological activities may cause blockages, often originating in storage dams that are rich in nitrates. Algal residues may come through the filters with clay particles, serving as a food source for bacterial slime. Fertiliser application through the irrigation system, especially where the laterals are exposed to the sun will lead to an increase in the formation of bacterial slime. These slimes can block emitters, or can serve as binding agents that combine fine silt and clay particles, leading to blockage. Before any fertiliser is applied in this way, it must be mixed with the available irrigation water in a transparent container (a so-called flask test). If the mixture becomes milky within 24 hours, or forms a deposit, then it is a good indication that dripper blockage will occur. This type of fertiliser must therefore be avoided.

Blockage material is identified by the colour of the deposit in the blocked dripper. Salt deposits are white, iron oxides are a rusty colour, and blockage material resulting from microbiological activities is black. Each type of blockage has a unique solution. A water analysis that indicates the exact nature of blockage is therefore essential.

The water quality guidelines against which to quantify the blockage hazard of the irrigation water, especially those of dripper systems, are shown in Table 4.

Table 4: Water quality guidelines to quantify the blockage hazard of the irrigation water (Reinders et al., 2002)

Cause	Blockage hazard	
	Low	High
Physical:		
Suspended solids, e.g. silt, cay and organic material (mg/ℓ)	<50	>100
Chemical:		
pH	<7,0	>8,0
Bicarbonate (mg/ℓ)	<100	>200
Calcium (mg/ℓ)	<0,1	>50
Manganese (mg/ℓ)	<0,2	>1,5
Iron (mg/ℓ)	<500	>1,5
Total diluted solids (mg/ℓ)	≤0,5	>2 000
Nitrates (mg/ℓ)		>10
Biological:		
Bacteria (per mℓ)	<10 000	>50 000
Some suppliers of drip irrigation systems consider water with an iron content of 0,8 mg/ℓ in storage dams and borehole water with an iron content of 0,3 mg/ℓ as a high blockage hazard for emitters. Water with a manganese content of 0,3 mg/ℓ is also considered a blockage hazard. These causes are interactive with each other, e.g. the removal of organic material will reduce biological activities.		

2.3.2 The effect of water quality on crops

2.3.2.1 pH of the irrigation water

The pH of the irrigation water indicates on a scale of 0-14 whether the water is acid (<7), neutral (7) or alkaline (>7) Readings between 6.5 and 8.4 are usually acceptable for crop cultivation (Jensen, 1983). Because of the buffering capacity of the soil and the wide series of pH-values that crops can handle, the pH of the irrigation water is not normally considered as critical. However, where very high or low pH-values are recorded, possible causes other than that of the irrigation water must be investigated.

2.3.2.2 Total dissolved solids

Total dissolved solids (TDS) refer to the quantity of different inorganic salts that are present in the water. A close relationship exists between the TDS of the water and its electrical conductivity (EC). Since it is much easier to measure the EC than the TDS, EC measurements are used to provide an estimation of the TDS, using the following conversion: 6,5 x EC (mS/m) = TDS (mg/ℓ) [DWAF, 1996].

The EC reading gives an indication of the potential problems that can be experienced with the salt quality of the irrigation water. Further, irrigation water can dissolve the salts that are already present in the soil profile. The total quantity of salts in the soil water is therefore the dissolved salts present in the root zone and in the irrigation water.

The dissolved salts in the root zone can impact on:

- The intake of the quantity of available water through the root system of the crop: The saltier the water is, the more difficult it is for the plant's root system to extract water.
- The soil structure, and
- The intake by the root system of toxic ions (chloride, boron and sodium).

Whilst the EC reading gives an indication of how "salty" the water is, it does not show what ions are present at what concentration. The relationship of EC to the salinity of the irrigation water, the tolerance of crops to that salinity level, and the possible symptoms of excess salinity that occur in crops being irrigated with such water is shown in Table 5.

Table 5: The relationship of EC to salinity, and the tolerances and symptoms of irrigated crops

EC (mS/m)	Salinity of irrigation water	Tolerant crops	Symptoms of excess salinity in crops under irrigation
0-50	Low to very low	For all crops	Not applicable
50-75	Medium	Sensitive crops will be influenced. Irrigation of soils cause few problems	Leaf scorch on the edges of the leaves and leaf losses especially where leaves of crops are wetted
75-300	High	Increasing number of crops show a reduction in growth	Leaf scorch and eventually wilting of crops as EC rises
>300	Very high	Not suitable for irrigation, except tolerant crops that are cultivated in sandy soils with excellent drainage	Crop cultivation in most cases is not possible

All units of ions must be in mg/litre and me/litre to apply existing water quality directives and to determine whether the sum of cations and anions is in balance.

The conversion factors between the different units are as follows;

me/ℓ = mg/ℓ/equivalent weight

1 dS/m = 100 mS/m = 100 mmhos/m = 1 mmhos/cm = 1 000 µmhos/cm = 1 000 µS/cm

Equivalent weight = atom mass/number of charges of specific ion

mmol/ℓ = mol/m³ = me/ℓ/number of charges of specific ion

mg/ℓ = mol/m³ x atom mass

The quality of the irrigation water must not only be evaluated according to the total concentration of ions in the water, but also by the specific ions that occur. The ions that occur mainly in irrigation water are shown in Table 6.

Table 6: Characteristics of the ions occurring in irrigation water

Ions	Symbol	Atom mass	Number of charges	Equivalent weight
Chloride	Cl	35.5	1	35.5
Sulphates	SO_4	96	2	48
Carbonates	CO_3	60	2	30
Bicarbonates	HCO_3	61	1	61
Nitrates	NO_3	62	1	62
Sodium	Na	23	1	23
Potassium	K	39.1	1	39.1
Calcium	Ca	40	2	20
Magnesium	Mg	24.4	2	12.2
Boron	B	10.8	1	10.8

The application of irrigation water can lead to the concentration of salts in the root zone: The roots of the crops take up the soil water but remove very little salts from the soil-water solution. Water may also evaporate from the soil surface, leaving many of the salts behind. The combination of these processes can lead to the build-up of salts in the root zone, even with low salinity irrigation water. The quantity of salts that build up will depend on the concentration and combination of the ions that are present in the water.

2.3.2.3 Toxicity

Toxicity is mostly caused by an excess of chloride, sodium and boron occurring in the soil water which is taken up by the roots and transported to the leaves where it concentrates, often causing leaf scorch. Other symptoms of toxicity are premature leaf loss, and wilting. The toxicity of the ions differs, and must be determined before planting to prevent possible problems.

Chloride

A high chloride concentration in the irrigation water may be toxic in most cases, and can lead to leaf scorch and harvest losses if an overhead irrigation system is used. Water quality directives for chloride in irrigation water for drip and sprinkler systems are shown in

Table 7.

Table 7: Water quality directives for chloride (mg/ℓ) for different irrigation systems (Waterwise on the farm, 2002)

Ions	Degree of leaf scorch problems with chlorine		
	None	Moderate	Serious
Drip irrigation	< 140	140-350	> 350
Overhead irrigation	< 70	70-150	> 150

If the chloride content of the irrigation water exceeds 350 mg/ℓ (10 me/ℓ), serious problems with leaf scorch will be encountered when overhead irrigation is used. The chloride tolerance of leaf wetting for different crops is classified in Table 8.

Table 8: Chloride tolerance classes for different crops (DWAF, 1996)

Tolerance class	Sensitive	Mildly sensitive	Mildly tolerant	Tolerant
Chloride concentration (mg/ℓ)	$\leq$ 175	175-350	350-700	> 700
Crops	Almonds, Apricots, Citrus, Plums, Grapes	Peppers, Potatoes Tomatoes	Barley, maize, Cucumber, Lucerne, Sorghum	Cauliflower, Cotton. Sugar beet, Sunflower

Boron

Although boron is an essential ion for crops, it can be toxic from a concentration as low as 0,6 mg/ℓ. Excess boron usually collects in the leaves, and can cause the crop to wilt. Water quality directives for boron are shown in Table 9.

Table 9: Water quality directives for boron (Jensen, 1983)

Ion	Degree of problems with boron		
	None	Mild	Serious
Boron (mn/ℓ)	< 0.75	0.75-2.0	> 2.0

The boron tolerances for different crops are classified in Table 10.

Table 10: Boron tolerance classes for different crops

Tolerance class	Sensitive	Semi-tolerant	Tolerant
Boron concentration (mg/ℓ)	0.3-1.0	1.0-2.0	> 2.0
Crops	Lemons, grapefruit, avocados, oranges, apricots, peaches, cherries, grapes, apples, pears, plums, walnuts and pecan nuts	Pumpkin, maize, wheat, barley, olives, peas, radishes, tomatoes, cotton, potatoes, and sunflowers	Carrots, lettuce, cabbage, turnips, onions, lucerne, beetroot, dates, and asparagus

Sodium

Many crops need only a small amount of sodium. Sodium occurs in higher concentrations in water than any other chemical, since sodium salts are much more soluble. A high concentration of sodium ions in the water causes yellowing of the leaves and eventual leaf loss. Too much absorbed sodium is responsible for crust formation and low infiltration and dispersion in soils. Sodium binds to chloride, a combination that is toxic in nature and results in leaf scorch. Water quality directives for sodium are shown in Table 11.

Table 11: Water quality directives for sodium (Smal et al., 2003)

Ion	Degree of problems with sodium		
	None	Mild	Serious
Sodium (mg/ℓ)	< 70	70-160	> 160

The sodium tolerances of different crops to leaf wetting are classified in Table 12.

Table 12: Sodium tolerance classes for different crops (DWAF, 1996)

Tolerance class	Sensitive	Mildly sensitive	Mildly tolerant	Tolerant
Sodium concentration (mg/ℓ)	$\leq$ 115	115-230	230-460	> 460
Crops	Almonds, apricots, citrus, and plums	Grapes, peppers, potatoes, and tomatoes	Barley, maize, cucumber, lucerne, and sorghum	Cauliflower, cotton, sugar beet, and sunflower

2.3.3 The influence of water quality on soils

Irrigation with brackish water leads to the concentration of salts in the ground water, and also influences the cation collection of the soil particles. While the irrigation water remains slightly salty, the soil structure will remain intact, but once better quality water is used, structure problems can then occur.

2.3.3.1 Sodium adsorption relation

Sodium adsorption relation (SAR) pertains to the ability of sodium in the groundwater to influence crop cultivation and soil structure negatively. When soil water solution SAR values are high, sodium ions in the solution displace the absorbed calcium and magnesium ions on the soil particles, a process known as cation exchange. The higher the SAR value, the greater is the effect on crop cultivation and soil structure. High SAR values can be lowered by reducing the sodium concentration, or by increasing the calcium and/or the magnesium concentration, by adding gypsum (Smal et al., 2003). SAR can be determined by means of $SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$

Equation 1:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \qquad \text{Equation 1}$$

Where

Na = Sodium concentration (me/ℓ)

Ca = Calcium concentration (me/ℓ)

MG = Magnesium concentration (me/ℓ)

Table 13 shows directives for the effect of SAR on crop cultivation and the soil structure:

Table 13: The influence of SAR on crop cultivation and soil structure (Waterwise on the farm 2002)

Effect of SAR	Degree of problems with SAR		
	None	**Mild**	**serious**
Crop cultivation	< 3	3-9	> 9
Soil structure	< 6	6-9	> 9

2.3.3.2 Residual sodium carbonates

The residual sodium carbonates (RSC) value of irrigation water is defined as the difference between the bicarbonates and the calcium, as well as the magnesium ions. Calcium and magnesium ions may react with the bicarbonates and form a carbonate deposit, increasing the relative quantity of sodium as a result. A high RSC value of the available irrigation water can influence crop cultivation and soil structure negatively, e.g. dispersal of soils. Equation 2 can be used to determine the RSC value of irrigation water:

$$\mathbf{RNK = HCO_3 - (Ca + Mg)} \qquad \text{Equation 2}$$

Where

HCO_3 = Bicarbonate concentration (me/ℓ)

Ca = Calcium concentration (me/ℓ)

Mg = Magnesium concentration (me/ℓ)

Table 14 provides water quality directives for RSC.

Table 14: Water quality directives for RSC (T-Tape)

RSC	Degree of RSC problems		
	None	Mild	Serious
(mg/ℓ)	<70	70-150	> 150
(me/ℓ)	<1.5	1.5-3	> 3

Water with a carbonate content greater than 90 mg/ℓ can cause a white deposit on the leaves of the plants (whitewashing), especially when overhead irrigation systems are used.

2.4 Crops, climate and crop water requirements

The next step in the irrigation planning process is to determine the irrigation water requirement of the specific crop. The water uptake of crops depends on the following factors:

- the size of the leaf canopy
- the evaporative power of the atmosphere or the 'atmospheric evaporative demand', and
- resistance in the soil-plant system to water uptake.

The atmospheric evaporative demand is the driving force for crop water use, and depends on the prevailing weather conditions at any given time. Evaporative demand is higher on hot, sunny, dry and windy days, than on days when conditions are overcast and still. Crop water requirements can therefore differ substantially from day to day and from one locality to another, depending on the weather.

There are four important factors that determine the evaporative demand of the atmosphere. These are:

- Temperature,
- Wind speed,
- Solar radiation and
- Relative humidity.

The radiation from the sun provides most of the energy to evaporate water. Relative humidity is used to calculate what is called the vapour pressure deficit – or the 'drying power' of the air: The drier the atmosphere, the more easily evaporation occurs. Air temperature is important, as more evaporation can be expected on a warm day than on a cool day. It also influences the vapour pressure gradient from the leaf surface to the atmosphere. Finally, wind carries humid air away from the surfaces of leaves, reducing the resistance to water loss.

Automatic weather stations are used to measure the weather variables for different localities. When these variables are measured, the evaporative demand (in mm of water per day) can be calculated using the Penman Monteith reference evaporation equation.

2.4.1 Evapotranspiration

The calculation of crop water use through evapotranspiration is the first, essential element of any estimation of crop irrigation requirements. It is recommended that reference evaporation is calculated according to procedures contained in the internationally accepted guideline for estimating irrigation requirements – the United Nations Food and Agricultural Organisation Irrigation and Drainage Report No. 56 (FAO 56); which uses the Penman-Monteith equation as shown in Equation 3:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Equation 3

where:

ET0	= Reference evapotranspiration [mm/day]
Rn	= net radiation at crop surface [(MJ/m³)/day-1]
G	= soil heat flux density [(MJ/m²)/day]
T	= mean daily air temperature at 2 m height [°C]
u2	= wind speed at 2 m height [m/s]
es	= saturation vapour pressure [kPa]
ea	= actual vapour pressure [kPa]
es-ea	= saturation vapour pressure deficit [kPa]
Δ	= slope vapour pressure curve [kPa/°C]
γ	= psychrometric constant [kPa/°C]

The ET_o value that is calculated with the Penman-Monteith equation represents so-called “short grass” reference evapotranspiration, which can be defined as the rate of evapotranspiration from a hypothetical crop which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water. A typical value for grass reference evaporation on a warm summer day will be around 8 mm per day. This is a very useful number for irrigators, as it gives an indication of the upper limit to expected water use on a particular day. If for example, the reference evaporation for a particular day is only 2 mm, it will be impossible for a crop to evaporate 8 mm – there is just not enough energy available to do so.

Previously, pan evaporation figures were used as reference. These are still valid, but they have limited application in modern irrigation management and research. The equation is calculated using weather data values for a local weather station where the irrigation is to take place.

The water used by a specific crop, or crop evapotranspiration (ET_c) is determined by multiplying the short grass reference evapotranspiration (ET_o) with a growth stage-specific crop coefficient (K_c), which serves as an aggregation of the physical and physiological differences between crops and the reference condition.

The relationship can be expressed by Equation 4Equation 4:

$$ET_c = K_c \times ET_o \qquad \textbf{Equation 4}$$

Where:

ET_c	=	crop evapotranspiration
K_c	=	growth stage-specific crop coefficient
ET_o	=	short grass reference evapotranspiration

2.4.2 Crop coefficients

All annual and deciduous crops have a similar growth and development pattern: New growth starts at the beginning of the season with new foliage developing, and very little ground cover. As the crop develops, foliage size increases until the soil surface is mostly or fully covered. Plants then usually go into a reproductive phase where seed and fruit are developed. These ripen towards the end of the season, the foliage dies off, and at the end of the season the soil surface is bare again. A similarity to this pattern is also found in perennial crops, and even in evergreen crops grown in non-tropical areas, where although the foliage stays active, a slow-down in growth activities usually occurs during the cooler season.

The complex physiology and phenology that can be observed in the plant's behaviour as described above affects the crop water requirement and is best introduced into the irrigation planning process through the four-stage crop growth cycle as described by Allen et al (1998) in FAO 56 and shown in Table 15:

Table 15: Definition of the four stages of the crop growth cycle (Allen et al., 1998)

Stage name	Description
Initial stage	Germination and early growth, when the ground surface is barely covered by foliage (ground cover less than 10%)
Crop development stage	From the end of the initial stage to effective full ground cover (when ground cover reaches 70-80%)
Mid-season stage	From reaching full effective ground cover until the reaching of maturity, as indicated by colour change of leaves and leaf drop
Late season stage	From the end of the mid-season stage to full maturity or harvest

K_c is therefore the ratio between ET_c and ET_o for the specific crop calculated on a daily basis, and can be determined for the different growth stages of a specific crop.

Modern ET_c calculation methods as described in FAO 56 recognise that wetting events (such as rainfall or irrigation) have an effect on K_c, a fact that was often ignored in the earlier days of irrigation science. The number of wetting events as well as the percentage of soil surface wetted influence the ET_c: This needs to be taken into account when determining Kc. This is done by splitting Kc into two separate coefficients, one for crop transpiration, known as the basal crop coefficient (K_{cb}), and one for evaporation from the soil surface (K_e). The calculation of ET_c (Equation 5) therefore now becomes:

$$\mathbf{ETc = (K_{cb} + K_e) \times ET_o} \qquad \textbf{Equation 5}$$

or

$$\mathbf{ET_c = (K_{cb} \times ET_o) + (K_e \times ET_o)} \qquad \textbf{Equation 6}$$

Where:

ET_c crop evapotranspiration

K_{cb} basal crop coefficient

K_e evaporation from the soil surface

ET_o short grass reference evapotranspiration

The first component of Equation 5, (K_{cb} x ET_o) primarily represents the transpiration component (T) of ET_c: A crop will transpire at the potential rate as long as water in the root zone is not a limiting factor (and therefore even when the soil surface is dry).

The second component of the equation (K_e x ET_o) represents the evaporation component (E) of ET_c. Where the topsoil is wet following rain or irrigation, this component will be at a maximum. As the soil surface dries, the component will decrease until no practically measurable evaporation is taking place. The evaporation depends on the fraction of the surface area wetted by either rain or irrigation as well as the fraction of soil exposed to sunlight and ventilation, and will therefore vary for different crops (e.g. orchards vs. field crops), different irrigation systems (e.g. sprinkler irrigation vs. drip irrigation) and the crop's canopy cover in that growth stage.

2.4.3 Irrigation requirements

The amount of crop evapotranspiration (ET_c) is defined as the maximum amount of water that the crop would require under ideal circumstances (i.e., when there are no other limiting factors). In nature, this water is supplied by rainfall. In crop production, if the rainfall is not enough to sustain the expected yields for the planting densities and fertiliser applications that have been made, additional water is applied with an irrigation system. Due to the range of climatic zones in South Africa, there are some parts of the country where no irrigation is necessary, and other parts where crops are totally dependent on irrigation water. Therefore, if significant amounts of rainfall occur during the growing season of the crop for which the system is planned, the rainfall should be subtracted from the ET_c to determine the net irrigation requirement (NIR) measured in mm.

Not all rain that falls is available to plant roots, because of non-beneficial interception losses (Although, as explained in Module 1, not all plant interception is non-beneficial), as well as evaporation, run-off and deep percolation. Rainfall intensity also plays a role: high application rate rain storms, for example, can result in much water being lost as run-off. The timing of the rain relative to other wetting events also influences effectiveness: a saturated profile, recently irrigated, will not be able to store more water if it is applied.

A relatively large quantity of water could therefore potentially be subtracted (as losses) from the measured rainfall. The remaining amount is known as effective rainfall. The amount of rainfall deemed to be effective is highly dependent on the irrigation management strategy.

There are various models and equations used to determine effective rainfall (R_e). Use of a daily water budgeting model, like, for example, SAPWAT3 to estimate effective rainfall is probably the best option.

The net irrigation requirement to be supplied by an irrigation system can therefore be calculated as shown in Equation 7 and Equation 8:

a). If no or little rainfall occurs during the growing season:

$$\mathbf{NIR = ET_c} \qquad \textbf{Equation 7}$$

Where:

NIR net irrigation requirement

ET_c crop evapotranspiration

b). If rainfall is taken into account:

$$\mathbf{NIR = ET_c - R_e} \qquad \textbf{Equation 8}$$

Where:

NIR net irrigation requirement

ET_c crop evapotranspiration

R_e effective rainfall

2.5 The Water Balance

When considering the performance of irrigation systems, it is helpful to think in terms of the components of the water balance, or the fates of applied water. Ideally, the bulk of the applied water should contribute to the objective of irrigating: i.e. to preventing undesirable crop water stress. This relates to keeping stomata open, so that photosynthesis is not unduly inhibited.

Figure 5 illustrates the various fractions of water applied which are involved in defining irrigation performance at the field level. The various components of the water balance (fates of applied water) are:

- Deep percolation
- Surface runoff/stormflow
- Evaporation from the exposed soil surface
- Spray evaporation, wind drift and plant interception
- Transpiration

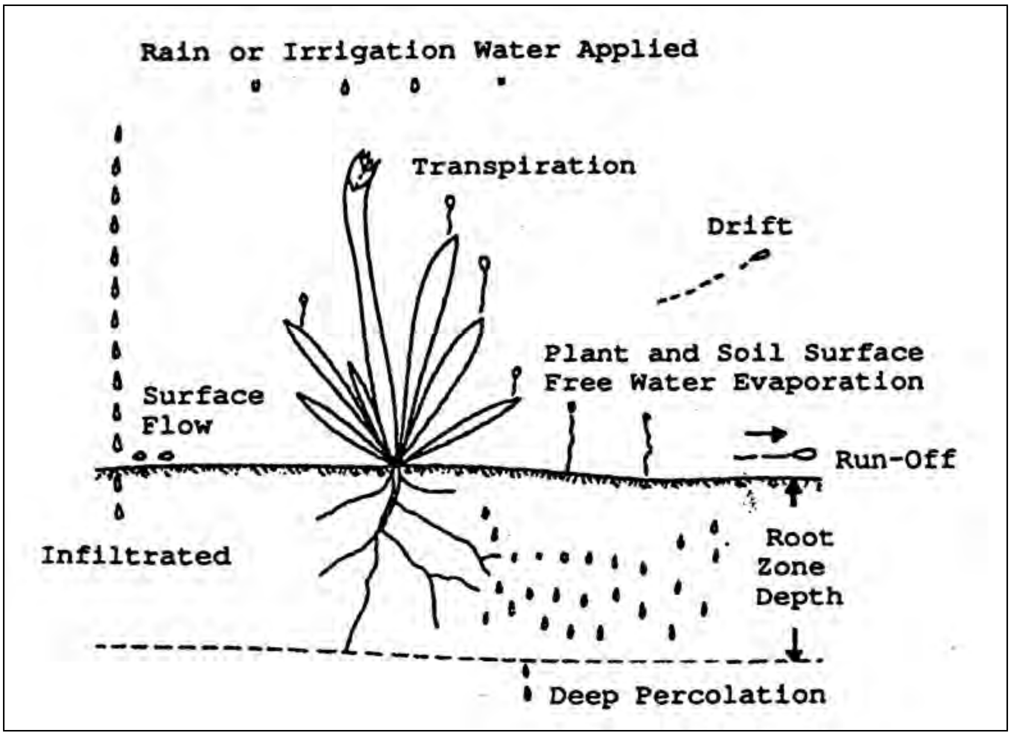


Figure 5: Various fates of water in the soil-plant-atmosphere system (ASCE, 1978)

2.5.1 Deep percolation

Deep percolation: non-consumed; non-beneficial or beneficial; non-recoverable or recoverable

Deep percolation is water which percolates below the active root zone. It can result from excess irrigation or rain, relative to available soil water storage capacity and the non-uniformity of irrigation water over a field area. It is generally non-beneficial, except when leaching of excess salts from the soil profile is an objective, in which case the desired 'leaching fraction' could be considered a beneficial water use.

Most deep percolation eventually re-enters the hydrological system in the form of return flows downstream of the field. Thus, the boundaries of the water balance area and the quality of the return flow water determine whether deep percolation is considered a 'recoverable' or 'non-recoverable' water use. If the boundaries of the water balance are the field edges, it is considered non-recoverable; however, if the boundaries are extended to include downstream users or the water supply source is downstream of the return flows, it should be considered to be 'recoverable' (provided it is of a usable quality). In a catchment-scale context, most deep percolation is recoverable.

From an in-field perspective, deep percolation (in excess of that required to maintain a salt balance) is undesirable, and can take with it expensive nutrients, especially nitrogen. Deep percolation mainly results from applying excessive water relative to what the soil can take. Deep percolation is often exacerbated because of misperceptions regarding 'irrigation efficiency', particularly with furrow irrigation. In order to replenish a soil water deficit of, say, 50 mm, an excessive amount of water is often applied because the 'efficiency' of furrow irrigation is assumed to be low. For example, a deficit of 50 mm would be replenished by applying 83 mm of water if the efficiency was assumed to be 60%, (i.e. 50/0.6 = 83 mm), with most of the excess water applied percolating below the root zone, with no benefit accruing.

Thus if furrow, or any other type of irrigation is assumed to be inefficient when making day-to-day water management decisions, it is likely to become inefficient due to excessive amounts of water being applied.

2.5.2 Surface runoff/stormflow

Surface runoff/stormflow: non-beneficial; non-consumed; recoverable or not recoverable

Surface runoff/stormflow may be defined as the surface water that leaves an area's boundary. For a given field, runoff is not consumed but neither is it a beneficial water use. Like deep percolation, runoff can be recovered and re-used elsewhere, or even on the same field; thus whether or not it is recoverable depends on the water balance boundaries and the location of the water supply source. Runoff may, however, erode top soils, picking up sediments and agricultural chemicals, especially phosphorous, leading to degraded water quality that often precludes 'recovery'. The poor quality of surface runoff may also result in excessive silt build up and loss of capacity in downstream storage works.

Surface runoff is undesirable, and mainly results from water being applied at excessive rates in terms of what can infiltrate immediately or be stored on the soil surface to infiltrate later. With centre pivots, surface runoff can be a major problem because the outer towers of a pivot cover relatively large areas compared to the towers near the centre of a pivot. As a result, relatively large quantities of water need to be applied at the outer towers, often at rates in excess of what the soil can take. Furthermore, the action of sprinkler droplets often causes a fine crust to form at the soil surface, especially in soils with high silt content and no cover, and this can further exacerbate surface runoff. Crusting is a particular problem of 'big gun' irrigation systems where large droplets land on the soil surface with relatively high energy.

2.5.3 Evaporation from the exposed soil surface

Evaporation from the exposed soil surface: mainly non-beneficial; consumed; non-recoverable

Although evaporation from the soil surface does result in some small compensating reduction in transpiration from a growing crop, it is the most significant non-beneficial, consumed and non-recoverable component of the water balance: It is essentially "wasted" water. Evaporation of water from the soil surface is dependent on the following factors:

- Agronomic practices
- The type of irrigation system and its management

2.5.3.1 Agronomic practices

These can either inhibit or encourage evaporation from the soil surface. For example, practices such as surface mulching/trashing, and narrower row spacing can significantly reduce the component of water evaporated from the soil surface.

2.5.3.2 Irrigation system type and management

Systems that apply water to a large proportion of the field's surface area will lose large amounts of that applied water. This is due to evaporation from the soil surface, especially if the water is applied to the soil surface frequently, in relatively small amounts, prior to the development of a full crop canopy – as is often the case with centre pivots! Research has shown that when water is applied at intervals of four days, evaporation from the soil surface is nearly four times greater than if the interval between irrigations is extended to 20 days (Allen *et al.*, 1998). With furrow irrigation the surface wetted fraction is much less compared to pivots. Typically only 40-60% of the surface is wetted and the intervals between irrigation water applications are relatively long so this component of the water balance is typically less with furrow compared to pivots.

2.5.4 Spray evaporation, wind drift and plant interception

Spray evaporation, wind drift and plant interception: partly non-beneficial; consumed; non-recoverable

Spray evaporation, wind drift and plant interception depend to a large degree on the irrigation system, the type of emitter and also the prevailing weather conditions. Researchers have found it very difficult to accurately assess the contributions made by spray evaporation and wind drift to overall water loss from the system. This is because spray evaporation is accompanied by a largely compensating reduction in evaporation of water from the soil and plants, because less energy is available to evaporate water from the soil and plant surfaces after the evaporation of the irrigation spray.

The contribution of spray evaporation to the micro-climate during very hot conditions (namely a reduced vapour pressure deficit and lower temperature), may also result in enhanced photosynthesis, relative to a non-sprinkler irrigated crop. For these reasons, if the goal of irrigation is to reduce undesirable crop stress, as opposed to storing water in the root zone, some daytime spray evaporation “loss” should actually be considered a beneficial water use which contributes to photosynthesis by keeping stomata open.

In similar vein, researchers have noted that evaporation of water intercepted by crop canopies is not a major loss: It can contribute beneficially to keeping stomata open for photosynthesis. Reported measurements of net water losses (i.e. those not compensated for by other reductions) from spray evaporation and canopy intercepted water are typically less than 10% (McNaughton, 1981).

Wind-drift, especially to non-cropped areas, is not beneficial and consumed. Spray evaporation, wind-drift and plant interception are not an issue with furrow irrigation but wind-drift in particular can be a major issue with sprinkler irrigation systems, particularly big-guns.

2.5.5 Transpiration

Transpiration: beneficial; consumed; not recoverable

Transpiration is the process of evaporation of liquid water within a plant through the stomata and plant surfaces into the air. Crops lose water through their leaves, via stomata which facilitate exchange of gases (needed for photosynthesis) and water vapour. The vapour exchange with the atmosphere is controlled by stomatal aperture. Nearly all water taken up by a plant’s root system is lost by transpiration and only a small fraction is used by the plant.

Transpiration is normally considered to be a beneficial and necessary water loss. The rate of transpiration, like that of direct evaporation, depends on available energy supply, the vapour pressure gradient and wind, so there is opportunity for some optimisation of growth areas/regions in order to minimise transpiration losses relative to attainable yields. For example, crops grown in a high wind area would require more water than a similar yielding crop in a low wind area.

Transpiration is also dependent on soil water content, both excess and deficient, soil water salinity, crop management, plant physiology and growth stage, so there could also be opportunities in plant breeding to minimise transpiration relative to yield.

2.6 Irrigation systems

2.6.1 System selection

There are a variety of irrigation systems available in South Africa from which to select, as shown in Figure 6. The various factors that play a part in the selection are:

- Water
- Soil
- Topography
- Climate
- Energy costs
- Crop
- Labour
- Capital costs
- Personal considerations

The following diagram illustrates the classification of irrigation systems.

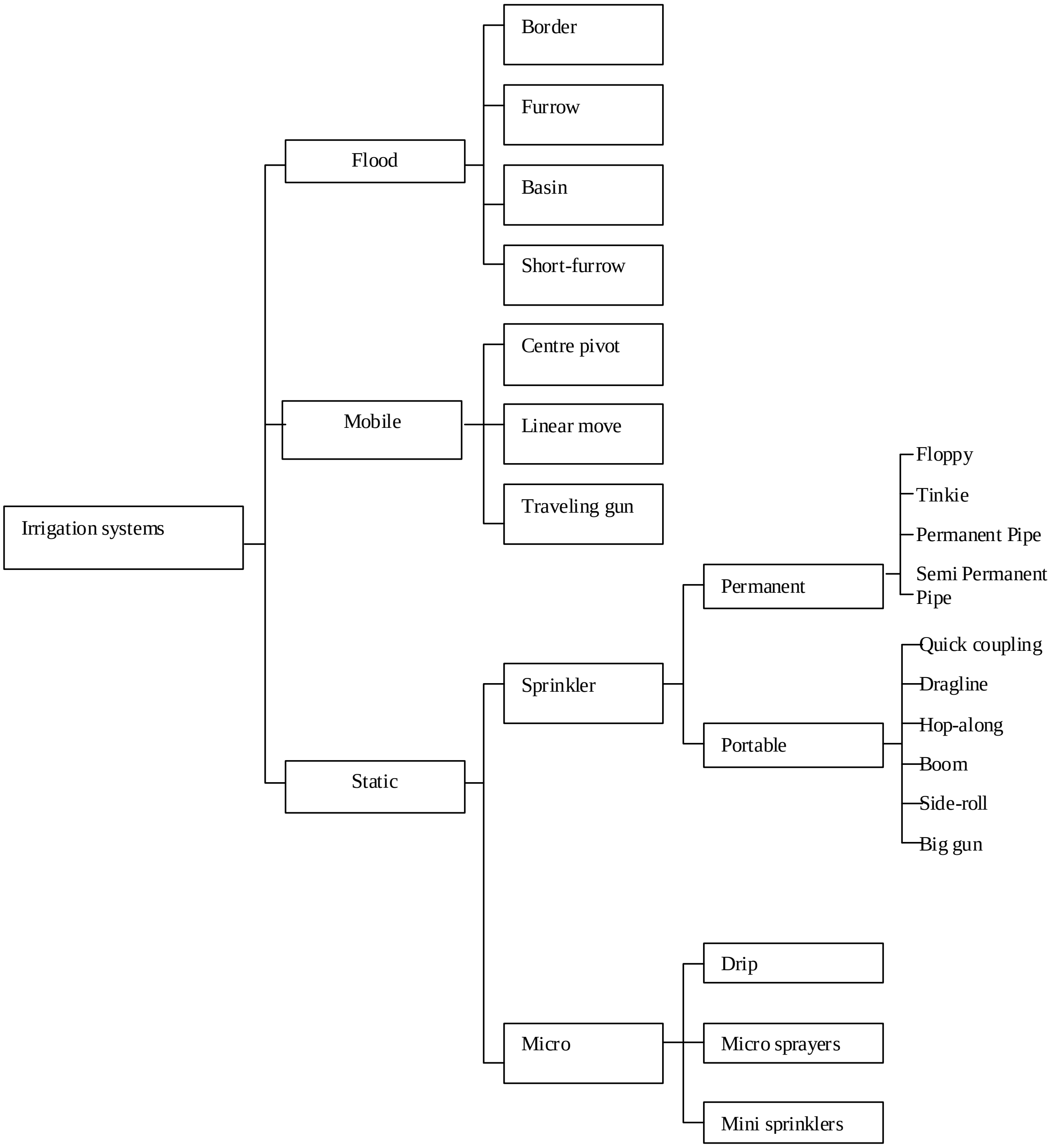


Figure 6: Types of irrigation systems (Koegelenberg, Irrigation Design manual, 2003)

2.6.1.1 Water

The amount, quality and cost of available water may influence the choice of an irrigation system. If the amount of available water is a limiting factor on the area to be irrigated, it might be more profitable to select a sub-surface drip irrigation system, which is very flexible and has lower evaporation losses. Where irrigation water contains harmful chemical substances that could burn the leaves of the plant or influence the quality of the product, overhead irrigation systems that wet the foliage should be avoided.

2.6.1.2 Soil

For irrigation of soils with a very high sand fraction, micro sprayers would be preferable to drippers. However, if the soil has a very high clay fraction and a low infiltration rate, a dragline system might be more suitable than a large centre pivot.

2.6.1.3 Topography

Topography plays an important role where systems such as linear and flood irrigation systems are concerned and may dictate the choice of a system.

2.6.1.4 Climate

In very hot climatic conditions, water applied by sprinkler or floppy irrigation may result in a more favourable micro-climate which cools the plant and enhances growth.

2.6.1.5 Energy costs

Energy requirements and therefore operating costs of some systems (e.g. big gun, travelling gun and the high-pressure travelling boom) are considerably higher than for low-pressure systems (e.g. drip irrigation), and should therefore be taken into consideration with system selection.

2.6.1.6 Crop

The crop to be irrigated will have a big influence on the choice of an irrigation system. For example, it would be ineffective to irrigate wheat with a drip system which is only suitable for row crops. It would also be difficult to move the portable pipes of a quick coupling system in an orchard.

2.6.1.7 Labour

A shortage of labour may dictate the use of self propelled or permanent systems, rather than movable systems.

2.6.1.8 Capital cost

Micro irrigation systems are generally more expensive than for instance portable systems. The farmer may for economic reasons rather select the cheaper portable system, even though it might not be the ideal system for the application.

2.6.1.9 Personal considerations

Although each system has its own range of application, the final choice rests with the user: the farmer. Each farmer has personal preferences that are influenced by various factors, for instance whether the system is adaptable to current farming practice, the level of training of labourers, whether or not the system can be adapted for other uses and the reliability of the supplier.

2.6.2 Irrigation uniformity

Irrigation uniformity is a characteristic of the type of irrigation system used, together with the standard to which a given system has been designed, is operated and is maintained. It can also be affected by soil infiltration characteristics and by land preparation.

Because the sprinkler packages are well researched and designed, centre pivots characteristically apply water with very good uniformities. With furrow irrigation, by contrast, controlling water flow into individual furrows and ensuring even infiltration along the length of a furrow is relatively difficult to achieve. Thus, the range of uniformities encountered with furrow irrigation is relatively wide and watering can be relatively uneven. Furrow irrigation is therefore often considered to be inefficient, because in order for areas of a field currently receiving relatively low amounts of water to receive sufficient water, other sufficiently watered areas of the field must now receive excess water, leading to excessive deep percolation. Nevertheless, though relatively complex, it is possible for furrow systems to be designed and operated with very high uniformities, similar to that which can be expected from centre pivots, especially on deep soils with medium to high clay contents.

2.6.2.1 Water destination diagrams

Water destination diagrams provide a good means of illustrating the relationships between irrigation uniformity and the water balance. They also serve to illustrate why systems such as furrow irrigation are sometimes considered inefficient, when the real problem is low uniformity.

Figures 8 and 9 show water destination diagrams for an assumed soil water depletion level of 3 units (for example, centimetres). In Figure 8 the average amount of water applied is 4 units, whilst in Figure 9 the average water applied is 3 units. The low quarter distribution uniformity, (DU_{lq}) and field application efficiency, (AE), are defined as shown in Equation 9 and Equation 10 (Burt and Styles, 2007):

$$\mathbf{DU_{lq}} = \frac{\textbf{Average low quarter depth of water}}{\textbf{Average depth of water accumulated in all elements}} \qquad \text{Equation 9}$$

$$\mathbf{AE(\%)} = \frac{\textbf{Average depth of water that contributes to target}}{\textbf{Average depth of water applied x 100}} \qquad \text{Equation 10}$$

The DU_{lq} in Figure 7 is 0.75 and the AE is 75%. In Figure 8 the DU_{lq} is still 0.75 but the AE is 92%, however, half the field (as opposed to 1/8th of the field in Figure 8) is under-irrigated.

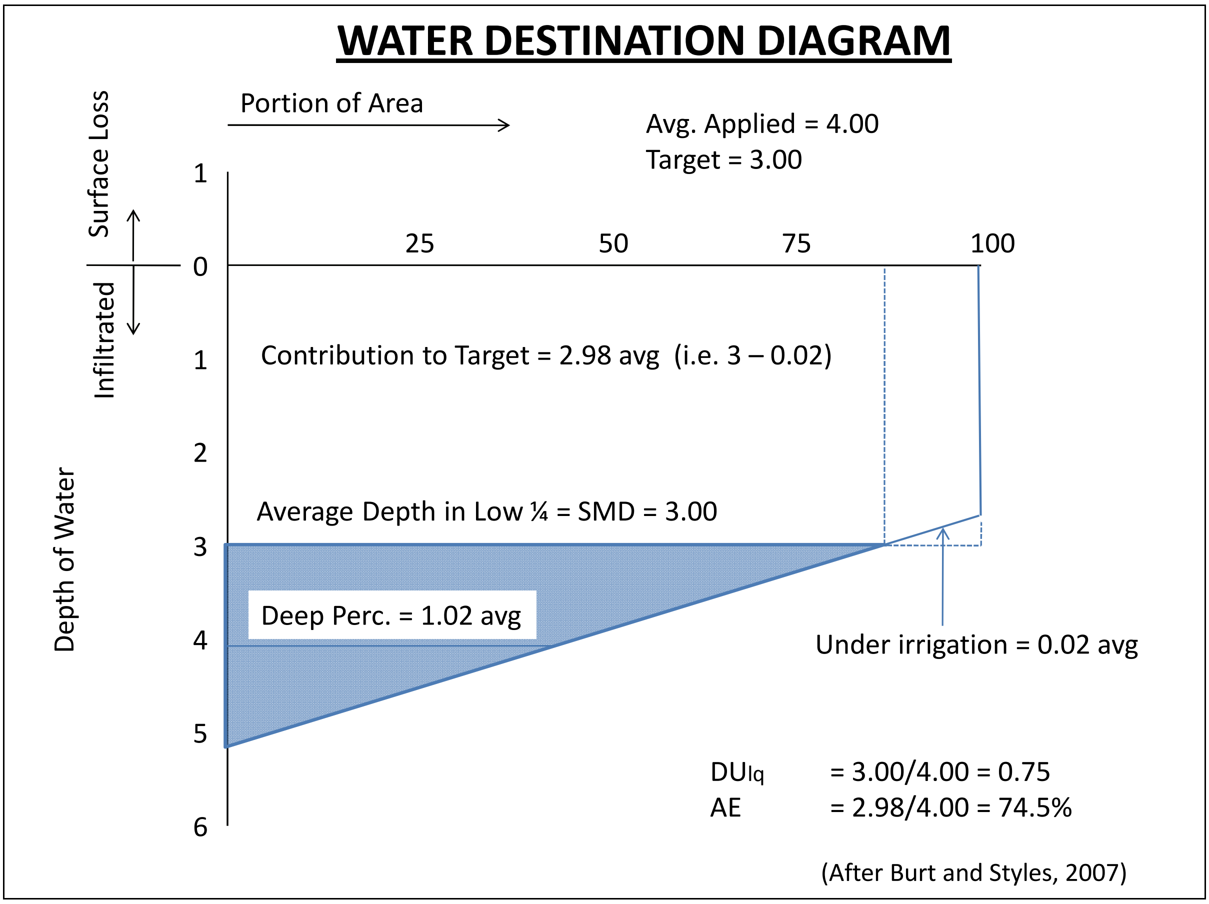


Figure 7: Water destination diagram illustrating relationship between the low quarter distribution uniformity, DU_{lq} and application efficiency, AE, for what is traditionally consider to be ideal irrigation scheduling where only 1/8th of the field is under-irrigated (after Burt and Styles, 2007)

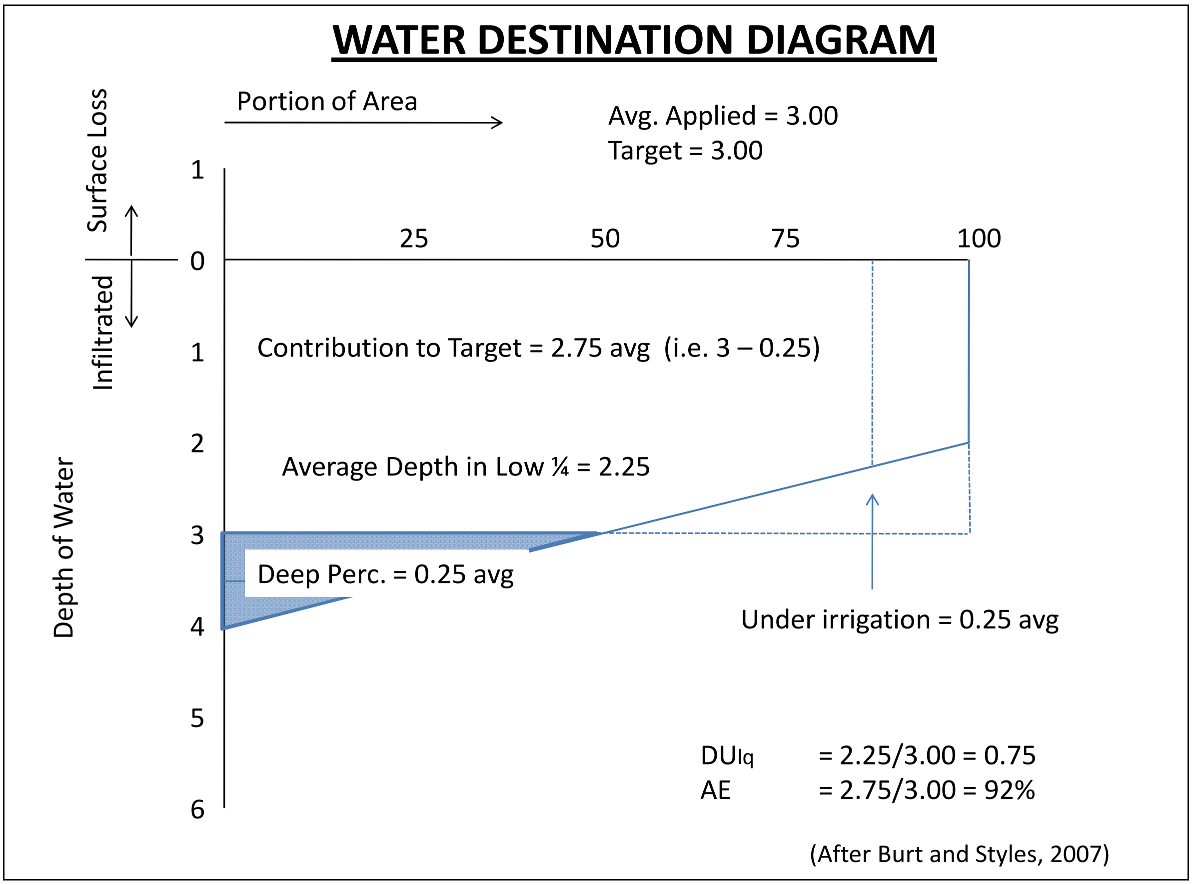


Figure 8: Water destination diagram illustrating relationship between the low quarter distribution uniformity, DU_{lq} and application efficiency, AE, when the average infiltrated depth equals the depth needed and thus half of the field is under-irrigated (after Burt and Styles, 2007)

The water destination diagram in Figure 8 represents the traditional approach to accounting for non-uniformity in irrigation scheduling and was based on the following assumptions:

- Under irrigation on half the field was considered unacceptable because of potential yield decline
- Over-irrigation was not considered to cause yield decline
- It was considered a reasonable compromise to have a relatively small proportion (1/8th) of the field under-irrigated, as to irrigate such that 100% of the field received the required water was considered to be too wasteful (Burt and Styles, 2007).

Therefore, it was recommended that the DU_{lq} be used to determine the optimum amount of irrigation water to apply. Assuming no surface losses or spray evaporation and wind-drift losses, Equation 11 was proposed to compute the gross amount of irrigation water to apply:

Gross to apply = Soil water deficit or “target”/DU_{lq} Equation 11

This traditional approach to accounting for DU_{lq} has likely resulted in the default irrigation efficiencies that many people refer to, e.g. furrow assumed to be, say, 65% efficient and pivot assumed to be, say 85% efficient. Unfortunately the rationale for these assumed efficiencies, i.e. the typical or assumed non-uniformity, is seldom considered, and water is often thought to just 'disappear' with the assumed low efficiencies. As illustrated in Figure 7 and Figure 8, most of the water does not 'disappear' but contributes to increased deep percolation which will eventually return to the downstream system as return flow.

The traditional approach to calculating gross irrigation applications (and the associated assumptions regarding efficiencies) will result in 7/8th of the field being over-irrigated. The approach is based on the premise that over-irrigation will not be damaging. However, there are many crops and situations where over-irrigation will in fact be highly detrimental, causing root asphyxiation (lack of oxygen), a rising water table, de-nitrification and nutrient leaching; all of which could have a very negative impact on crop yields. Over-irrigation on 7/8th of a field would be especially detrimental with crops such as wine grapes, or where there is poor drainage and/or a high water table (Burt and Styles, 2007).

2.6.2.2 Using Simulation models to Assess the Benefits of Adjusting for Non-Uniformity

ZIMsched 2.0 is an irrigation systems and crop yield simulation model, which accounts for the impacts of non-uniform water applications and both too little and too much water on crop yields (Lecler, 2004). Simulations with ZIMsched 2.0 showed that the traditional approach to determining gross irrigation water applications for a DUlq value of 0.75, resulted in only a 2% gain in crop yield relative to simulations where no adjustment is made to irrigation water applications. Furthermore, the amount of irrigation water applied and the deep percolation 'losses' were substantially increased when irrigation applications were adjusted for the DUlq using Equation 8.

The bottom line is that assuring high irrigation uniformity is of primary importance, and should be the goal of good design and maintenance procedures. It is very unlikely that low crop yields caused by non-uniform irrigation water applications will be improved by assuming low irrigation efficiencies and increasing the water applications accordingly. Such an approach could mask the real problem, namely poor uniformities, and lead to long term drainage and salinity problems due to a raised water table.

2.6.3 Irrigation system efficiency

The irrigation system efficiency value used during the planning of irrigation systems, makes provision for losses that may occur between the inflow to the irrigation system (the same irrigation block or system as mentioned), and the point where the water is available to contribute to crop requirements (typically in the root zone of the crop, but also including positive impacts on the micro-climate). The losses may include filter backflush water, non-beneficial spray evaporation losses and wind drift, in-field conveyance losses, and other possible minor losses. No adjustment is recommended to account for the non-uniformity of application, as this can lead to excessive non-beneficial runoff and/or deep percolation losses and little benefit, as discussed in Section 2.6.2. Rather, the designer should aim to design a highly uniform irrigation system.

The system efficiency defines the ratio between nett and gross irrigation requirements (NIR and GIR). NIR is therefore the amount of water that should be available to the crop as a result of the planned irrigation system and GIR is the amount of water supplied to the irrigation system that will be subject to the envisaged in-field losses.

In view of the increased pressure on our water resources, the system efficiency is one of the important selection criteria for an irrigation system. During evaluation of existing systems, the system performance should be described in terms of a water balance, defining where the water is going, rather than just as a percentage value for planning or benchmarking purposes.

The ICID framework was applied by the project team to re-assess the system efficiency indicators that are typically used by irrigation designers to make provision for losses in a system and convert net to gross irrigation requirement. A new set of system efficiency values for design purposes is proposed. These values are illustrated in Table 16 and are considerably higher than the present system design norms.

The previously used application efficiency values are shown in the “Norms” column, while the different water use components at the point of application with a specific irrigation system has each been allocated a column under “Losses”. The approach makes provision for non-beneficial spray evaporation and wind drift, in-field conveyance, filter and other minor losses to occur. The sum of all these losses makes up the value in the column ‘Total losses”. The new proposed default system efficiency values (η_s) in the last column were obtained by subtracting the total losses from 100%.

If an irrigation system is evaluated, the system efficiency value can now also be compared with these default values and possible significant water loss components identified for improvement. The approach therefore is more flexible and easy to apply than the original efficiency framework where definitions were limiting the applications.

The default values were determined by considering typical values for the different loss components. It is, however, up to the irrigation designer to adjust the loss component values and thereby customise the system efficiency for a specific design or situation.

Table 16: Comparison between the present design norms and the proposed default system efficiency values

Irrigation system	Norms	Losses				Proposed default system efficiency (net to gross ratio) (%)
	Present application efficiency value (%)	Non-beneficial spray evap and wind drift (%)	In-field conveyance losses (%)	Filter and minor losses (%)	Total Losses (%)	
Drip (surface and subsurface)	90	0	0	5	5	95
Microspray	80	10	0	5	15	85
Centre Pivot, Linear move	80	8	0	2	10	90
Centre Pivot LEPA		0	0	2	2	98
Flood: Piped supply	80	0	0	2	2	98
Flood: Lined canal supplied	60	0	5	2	7	93
Flood: Earth canal supplied		0	12	2	14	86
Sprinkler permanent	75	8	0	2	10	90
Sprinkler movable	70	10	5	2	17	83
Travelling gun	75	15	5	2	22	78

The values given in this table are guideline values determined by the project team and referenced to the available literature, (for example, McNaughton, 1981; Tolk et al., 1995 and Thompson et al., 1997).

The implication of the new proposed system efficiency values are shown schematically for drip, centre pivot and sprinkler (moveable) systems in Figure 9. In the example, the net irrigation requirement is 100 mm. In the case of drip irrigation with the previous application efficiency values, the GIR would have been 111.1 mm, while using the new proposed system efficiency value to calculate the net to gross ratio, the GIR will be 105.3 mm. In effect, the gross amounts of water planned for, using the new proposed values, will be less than before even though the net requirements stay the same.

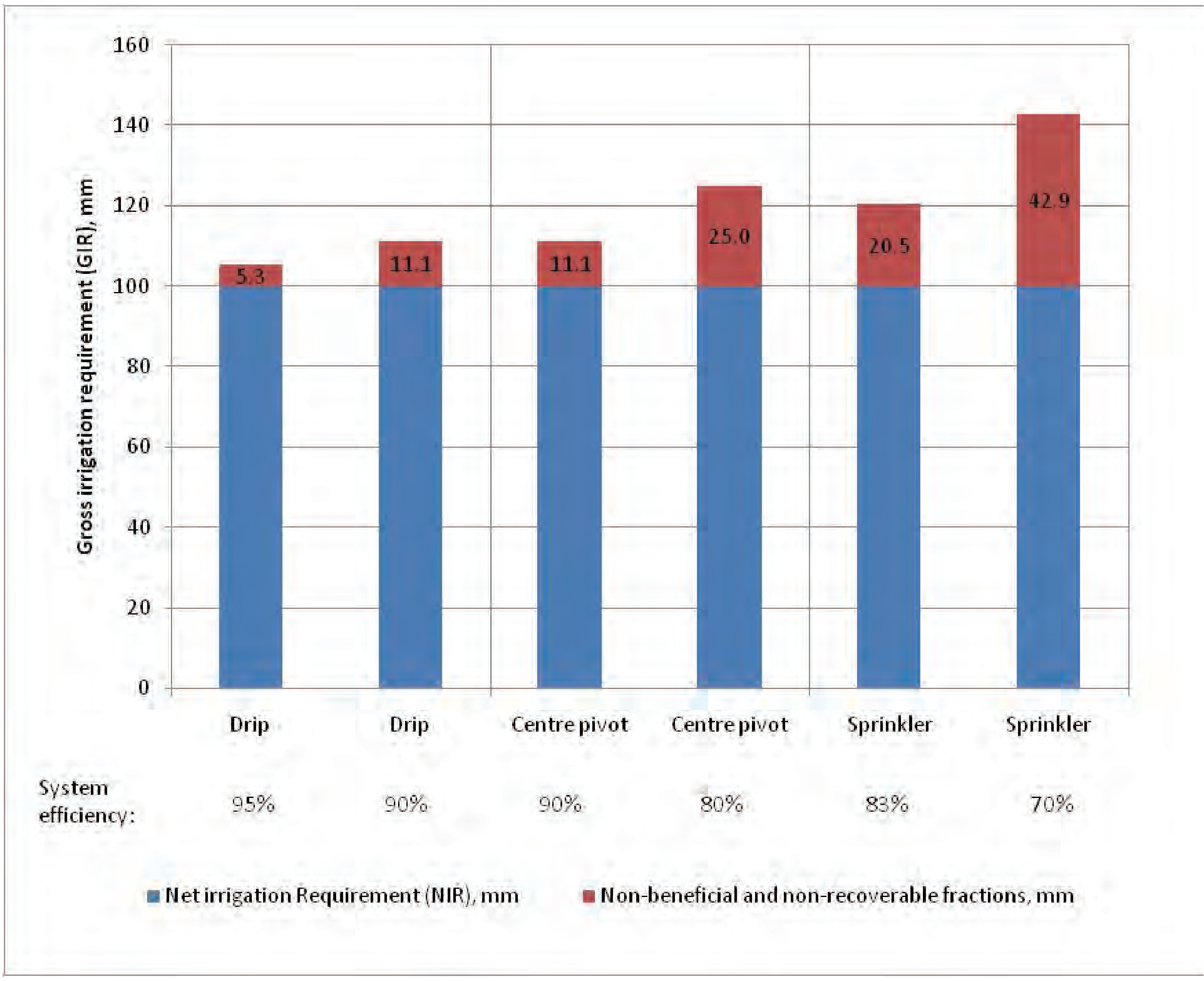


Figure 9: Example of net to gross irrigation requirement calculations using new values

The main difference between the previous values and the present recommendations is that the new values do not include an adjustment for non-uniform water applications. The reasons for not increasing gross irrigation amounts for non-uniform water applications are discussed more fully in Section 2.6.2, but in essence, increasing gross irrigation amounts to try and compensate for poor uniformity is likely to yield little benefit and could lead to long term drainage and salinity problems due to excessive deep percolation and a raised water table. The recommendation is to rather deal with the problem of poor uniformity specifically. For planning purposes, the GIR at the field edge should therefore be calculated as NIR x ηs, and when using the SAPWAT programme for planning purposes, the DU value should be set to 100% (see section 2.8 below).

If poor uniformity results in low crop yields, the uniformity needs to be corrected for improved performance. Simply applying more water is unlikely to result in improved crop yields as large parts of the field will suffer from over-irrigation, and the risk of long term problems developing due to a raised water table will increase.

2.6.4 Exposed and wetted soil area

This characteristic of irrigation systems can have a substantial impact on evaporation from the soil surface and the associated early season crop coefficients, and is therefore of great importance when planning, designing or operating irrigation systems with efficient water use in mind. Evaporation from the soil surface often does not occur uniformly over the entire surface in crops with incomplete ground cover, but is greater between plants where exposure to sunlight occurs and where air ventilation is able to transport vapour from the soil surface to above the canopy. This is especially true when only part of the soil surface is wetted by irrigation (Allen et al., 1998). This aspect of irrigation systems can be accounted for in the SAPWAT3 planning programme which is described in Section 2.8.

Where the complete soil surface is wetted, as by precipitation or sprinkler, then the fraction of the soil surface from which most evaporation occurs (See Equation 9), f_{ew}, is defined as $(1 – f_c)$ where f_c is the average fraction of soil surface covered by vegetation and $(1 – f_c)$ is the approximate fraction of soil surface that is exposed.

However, for irrigation systems where only a fraction of the ground surface is wetted, f_{ew} must be limited to f_w, the fraction of soil surface wetted by irrigation. Therefore, f_{ew} is calculated in **Equation 12** as:

$$\mathbf{f_{ew} = min(1 – f_{c2}f_w)} \qquad \text{Equation 12}$$

Where:

- $1 – f_c$ = Average exposed soil fraction not covered (or shadowed) by vegetation [0.01-1]
- f_w = Average fraction of soil surface wetted by irrigation or precipitation [0.01-1]
- f_{ew} = Exposed and wetted soil fraction, i.e. fraction of soil from which most evaporation occurs

The limitation imposed by **Equation 12** assumes that the fraction of soil wetted by irrigation occurs within the fraction of soil exposed to sunlight and ventilation. Drip irrigation might be the exception because in most cases the wetted area is under the crop canopy. In this case, it may be necessary to reduce the values to about one-half or one-third of the shown value (Allen et al., 1998). See Figure 10.

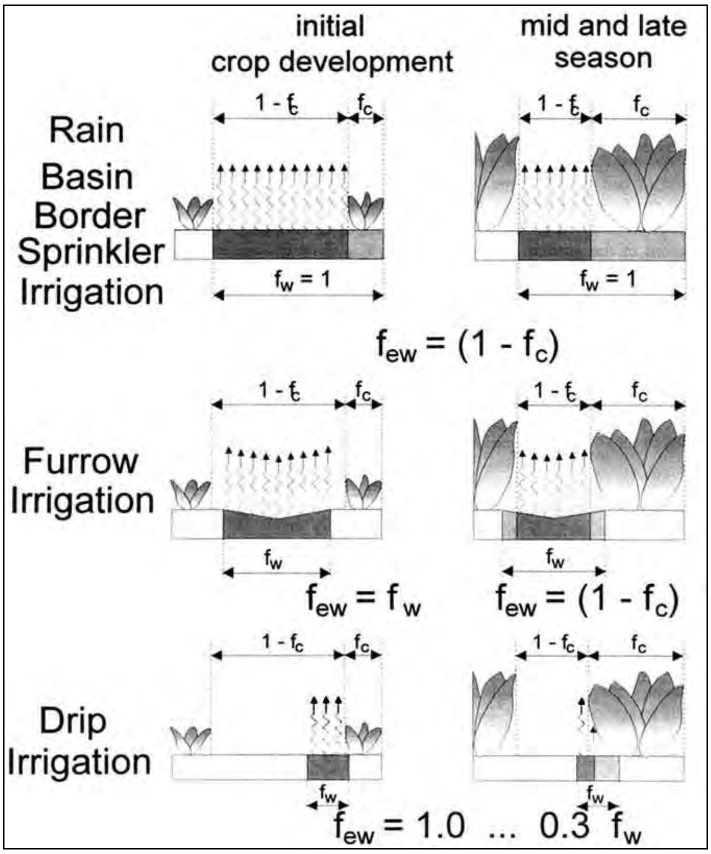


Figure 10: Determination of variable f_{ew} (cross-hatched areas) as a function of ground surface coverage (f_c) and the fraction of the surface wetted (f_w) (Allen et al., 1998).

2.6.4.1 Fraction of soil surface wetted by irrigation or precipitation

Table 17 presents typical values for f_w. Where a mixture of irrigation and precipitation occur within the same drying period or the same day, the value of f_w should be based on a weighted average of the f_w for precipitation (f_w = 1) and the f_w of the irrigation system. The weighting should be approximately proportional to the infiltration from each water source (Allen et al., 1998).

Table 17: Common values of fraction of soil surface wetted by irrigation (Allen et al., 1998)

Wetting event	**f_w**
Precipitation (rain/snow)	1.0
Sprinkler irrigation	1.0
Basin irrigation	1.0
Border irrigation	1.0
Furrow irrigation (every furrow), narrow bed	0.6-1.0
Furrow irrigation (every furrow), wide bed	0.4-0.6
Furrow irrigation (alternated rows)	0.3-0.5
Trickle irrigation	0.3-0.4

2.6.4.2 Exposed soil surface ($1 - f_c$)

The fraction of soil surface that is covered by vegetation is termed f_c. Therefore, ($1 - f_c$) represents the fraction of the soil that is exposed to sunlight and air ventilation and which is the site for the majority of evaporation from the wet soil. The value for f_c is limited to <0.99. The user should assume appropriate values for the various growth stages. Typical values for f_c and ($1 - f_c$) are given in Table 18.

Table 18: Common values of fractions covered by vegetation (f_c) and exposed sunlight ($1 - f_c$) (Allen et al., 1998)

Crop growth stage	f_c	$1 - f_c$
Initial stage	0.0-0.1	1.0-0.9
Crop development stage	0.1-0.8	0.9-0.2
Mid-season stage	0.8-1.0	0.2-0.0
Late season stage	0.8-0.2	0.2-0.8

Application of **Equation 12** predicts that f_c decreases during the late season period in proportion to K_{cb}, even though the ground cover may remain covered with senescing vegetation. This prediction helps to account for the local transport of sensible heat from senescing leaves to the soil surface below (Allen et al., 1998).

Where fc is not measured, fc can be estimated using the relationship described in Equation 13.

$$f_c = \left(\frac{K_{cb} - K_{c\,min}}{K_{c\,max} - K_{c\,min}} \right)^{(1+0.5h)}$$

Equation 13

where

f_c = the effective fraction of soil surface covered by vegetation [0-0.99],

c_b = the value for the basal crop coefficient for the particular day or period,

K_c min = the minimum K_c for dry bare soil with no ground cover [0.15-0.20],

K_c max = the maximum K_c immediately following wetting

h = mean plant height [m].

2.6.5 Minimum and maximum application rates

When planning irrigation systems, it is important to ensure that the system supplies water at a suitable application rate. If the application rate is too high, especially in the case of overhead systems, infiltration problems can occur due to the fact that the water is applied faster than it can be absorbed by the soil. However, if the application rate is too low, especially in the case of micro-spray systems, excess non-beneficial evaporation and wind drift losses can occur.

2.6.5.1 Gross application rate

The gross application rate (GAR) of the system (which is equal to the emitter discharge divided by the effective wetted area of the emitter) has to comply with design norms for the minimum allowable application rates as set by the South African Irrigation Institute (SABI), as outlined below:

- Micro irrigation:

  Micro sprinkler systems: GAR > 3 mm/h

- Sprinkler irrigation:

  Portable systems GAR > 5 mm/h (also applicable to moving sprinkler systems like centre pivots)

  Permanent systems GAR > 4 mm/h

2.6.5.2 Net application rates

The net application rate (NAR) of the system (which is equal to the GAR divided by the FldNTGR) should not exceed the infiltration rate of the soil, as provided by a soil scientist.

This is especially important in the case of centre pivot systems. The danger of the NAR exceeding the soil's infiltration rate is much greater at the tower furthest from the centre, where the highest application rate occurs, than for towers nearer to the centre.

It is generally accepted that the soil's infiltration rate is influenced by various factors such as soil texture, soil moisture content, density and droplet size. Field observations, however, have shown that crust formation is a determining factor. The crust is mainly formed by external energy of rain and irrigation droplets, which break down and rearrange soil particles during wetting.

The application-rate of a specific centre pivot is fixed, and is determined by the selected sprinkler package. It is a function of the flow rate, machine length and the width of the sprinkler-wetting strip. With a centre pivot, the system moves around the centre anchor. In a single time interval, sprinklers on the last tower have to travel further and also cover a larger area than those closer to the centre. Therefore, the application-rate progressively increases towards the outer sprinklers to obtain the required total even application along the centre pivot length.

Potential run-off occurs where the application rate is higher than the infiltration rate of the soil. Potential run-off may be limited by improved surface conditions like a covering layer and plant growth, which break the water's kinetic energy. Practical experience has shown that smaller droplets from low-pressure sprinklers provide a better infiltration than larger droplets from low-pressure sprinklers. Land slopes and tilling practices (hollows in the land) also promote surface storage. Having some sort of surface cover or mulch should be encouraged to mitigate infiltration problems.

2.7 Management

The management requirements of the irrigator, especially in terms of available operating hours per 24 hour period, have a direct effect on the flow rate at which water has to be supplied to the irrigation system (and which is therefore required from the source). The flow rate is equal to the volume of water required by a specific field divided by the time available to apply the water, and can therefore be reduced by increasing the number of hours within which the field is irrigated. The resulting flow rate should of course still conform to the minimum and maximum application rate norms as discussed above.

Reducing the flow rate also has financial implications, as smaller flow rates require smaller pipe sizes and also less energy inputs, which means less capital and operating costs for the owner of the system. If fertigation is practised, however, the system flow rate should be checked against the requirements of the fertigation system to ensure it is not too low.

2.8 Computer models for planning

SAPWAT is the generally recognised computer model for planning the irrigation requirements of a wide range of crops in South Africa. Version 3 of the model (SAPWAT3) has at its core the procedures contained in the internationally accepted guideline for estimating irrigation requirements: the United Nations Food and Agricultural Organisation Irrigation and Drainage Report No. 56 (FAO 56); which uses the Penman-Monteith equation.

2.8.1 Weather data

The Penman-Monteith equation is calculated using weather data records of solar radiation (sunshine), air temperature, humidity and wind, which together provide the energy input for calculating reference evapotranspiration. Precipitation information is also required as part of the water balance equation.

A comprehensive weather data base is included in SAPWAT3, comprising:

- The complete FAO CLIMWAT weather data set of 3262 weather stations from 144 countries.
- A derived weather station for each quaternary drainage region of South Africa which provides comprehensive coverage of the country with 50 years of historical (1950-1999) daily weather data. This capability has major implications when it comes to water use planning and strategy development. This data set was developed from the South African Atlas of Climatology and Agrohydrology by a team from the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal.

Crop development is linked to climate parameters, and for this purpose the internationally recognised Köppen-Geiger climatic system, which is based on temperature-rainfall combinations, is included in SAPWAT3. The climate of a weather station is automatically reflected on selection.

2.8.2 Crop coefficients

SAPWAT3 utilises the FAO four-stage crop development curve procedure (see Figure 11) for relating crop evapotranspiration (ET_c) to short grass reference evapotranspiration (ET_o) by applying a stage-specific crop coefficient (k_c) (See Section 2.4.), which serves as an aggregation of the physical and physiological differences between crops and the reference condition.

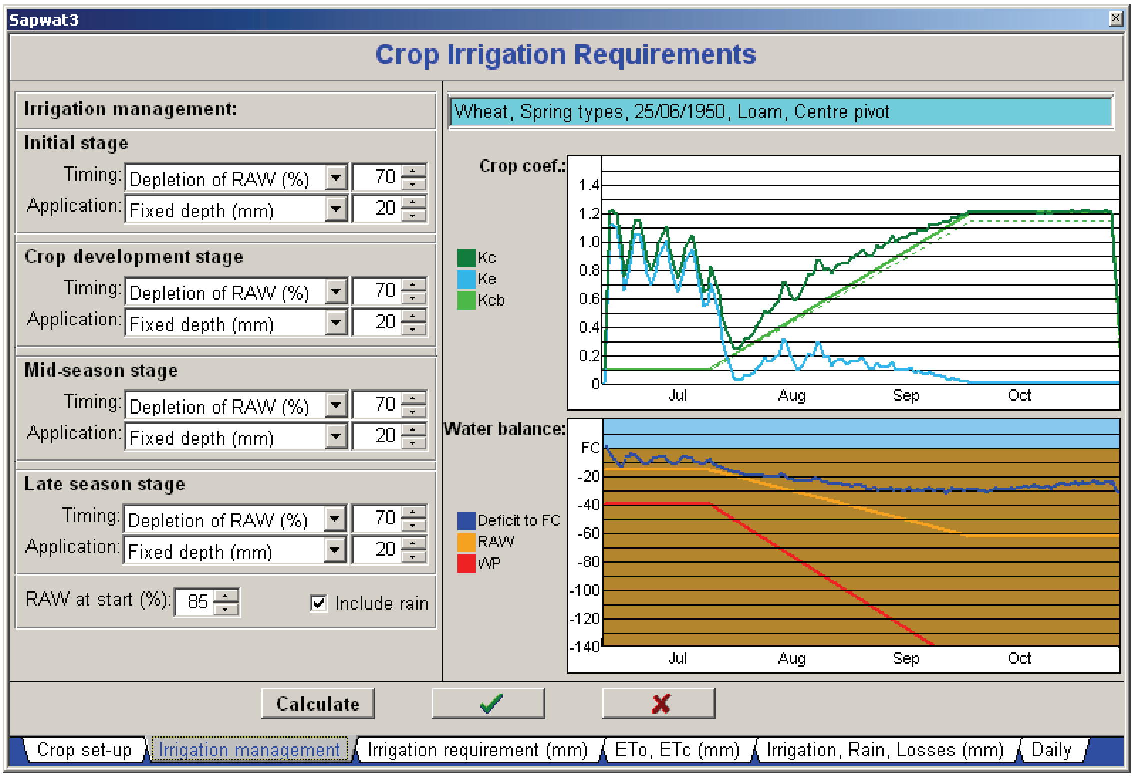


Figure 11: Crop development stages and crop coefficients in SAPWAT3

Typical values of expected average crop coefficients under a mild standard climatic condition, as well as correction factors for deviating climates and conditions, are published in FAO 56 and are applied in SAPWAT3. Default stage length values for each of the crops and their options listed for each of the five climatic zones covering Southern Africa are included in SAPWAT3. Crop characteristics have been reviewed with the help of experienced local crop scientists.

2.8.3 Crop evapotranspiration

SAPWAT3 makes use of the FAO 56 procedure that separates soil evaporation (represented by k_e in Figure 11), from plant transpiration (k_{cb}) and therefore, conforms to the FAO 56 defaults that determine soil water characteristics and evaporation parameters. It also accounts for the different wetting characteristics of various types of irrigation systems, as described in Section 2.6. Furthermore, a statistical analysis is done on the results to show irrigation requirements for different levels of non-exceedence, giving the user the choice of designing for different levels of risk which would influence the capital cost and running cost of an irrigation system. The different water requirements are impacted by the effective rain in the different seasons. Typical screen output can be seen in Figure 12, with the median irrigation requirement in mm per month and summed for the season highlighted in yellow.

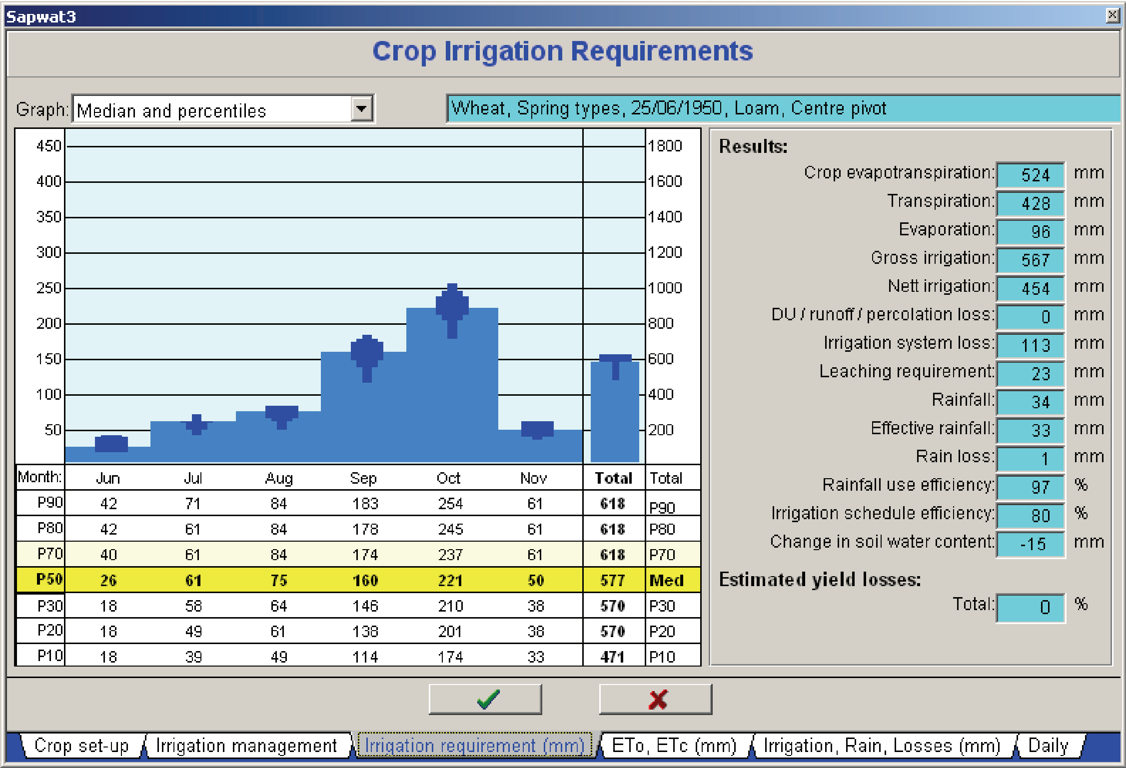


Figure 12: Screen output showing irrigation requirements in SAPWAT3

2.8.4 Additional program functions

SAPWAT3 also includes methodologies for estimating crop irrigation requirements for non-standard situations, such as for saline soils and water, and water stress situations due to inadequate water supply.

Furthermore, the program can estimate the irrigation requirements for a single crop, for a field of multiple crops, for a single farm, for a group of farms or Water User Association (WUA), for a group of WUAs, for a Water Management area (WMA) or for a catchment. Provision is made for printing comprehensive output tables, saving to file or exporting for further processing by spreadsheet applications.

Planning irrigation water use without considering the economic impact gives an incomplete picture on which to base future planning for crop production. A newly included enterprise budget module solves this problem.

Finally, SAPWAT3 also includes a rainwater harvesting module aimed at small areas, typically small farms or household gardens. The 50 year daily weather records provided by the quaternary weather stations are particularly useful because a thorough understanding of the rainfall pattern is essential when assessing the viability and developing of suitable systems for rainwater harvesting for both irrigation and household requirements. This module calculates the required harvest area and storage required for a specific situation.

In all program functions, the user has full editing rights on all supporting data sets so that data can be added or edited to reflect local defaults, making it a useful tool for developing different "what if" scenarios.

2.8.5 Program availability

SAPWAT3 is available from the WRC, who funded its development. See http://www.wrc.org.za.

2.9 Irrigation strategy

The irrigation strategy adopted by management can also have a major effect on an irrigation system's design and performance. Non-beneficial portions of the water balance (relative to field boundaries), including those due to wind drift, evaporation from the soil surface, surface runoff and deep percolation (especially if uniformities are poor), all increase with increasing irrigation water application.

In addition, with increasing water application, the effective use of rainfall is likely to diminish as the high probability of rain falling on an already wet soil results in the rain contributing to non-beneficial runoff and deep percolation, instead of transpiration. The net result is that if crop yield versus actual transpiration and applied irrigation water is plotted, the yield versus applied irrigation water line curves away from the yield versus transpiration line, as shown in Figure 13.

This is one of the reasons why the application of the large amounts of irrigation water needed to maximise crop yields may not result in optimum system performance, and may not realise maximum economic return. Adjusting the irrigation strategy is often the best way of ensuring gains in irrigation systems performance and overall profitability.

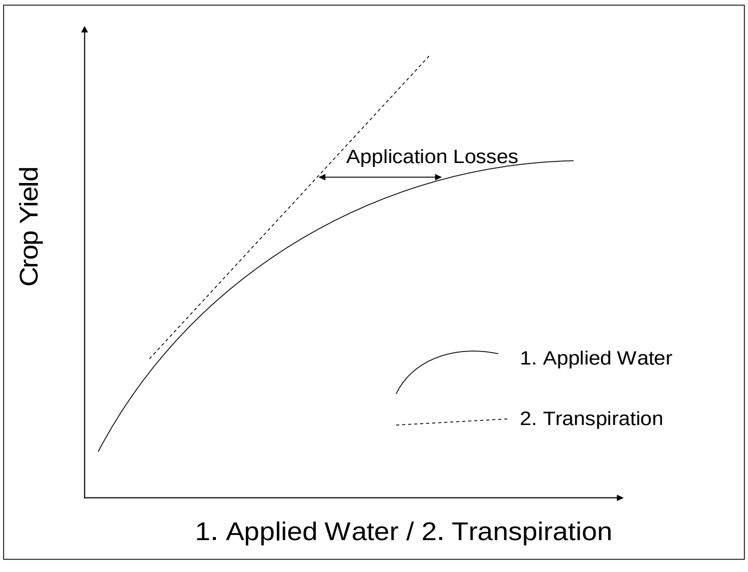


Figure 13: General form of a crop production function (after English, 1990)

Deficit irrigation is an optimising strategy whereby net returns, as opposed to crop yields, are maximised. This is often achieved by reducing the amount of irrigation water applied to a crop to levels that result in some yield reduction caused by water stress, i.e. deliberate under-irrigation. The fundamental goals of deficit irrigation are to:

- reduce non-beneficial components of the water balance, and
- maximise profits through a reduction in capital and operating costs.

Recognition of the following points is fundamental to an understanding of deficit irrigation:

- Water losses increase as the number and the magnitude of irrigation water applications increase.
- The application of irrigation water is costly, in terms of both direct costs but more importantly in terms of lost opportunities.
- The determination of an optimal irrigation strategy is very dependent on water supply and demand interactions, particularly when a shortage of water or a shortage of land is the factor limiting production.

Irrigation water application costs are related to actual costs of water, interest on capital equipment, energy, labour and also opportunity costs, especially if water is limited. When water, (rather than land) is limited, the water saved by reducing irrigation applications per hectare may be used to irrigate additional land either immediately or in subsequent seasons during droughts after having been saved or “banked” in storage works. Whilst per hectare yields may be lower, the potential to irrigate additional land can result in a significant increase in total income over a given production period. The potential income from irrigating the additional land is an opportunity cost of water, which can be substantial. If land is limited, the question is ‘simplified’ to what irrigation application amount results in the maximum difference between irrigation application costs and yield related returns.

In Figure 14, two cost functions and a revenue function are shown.

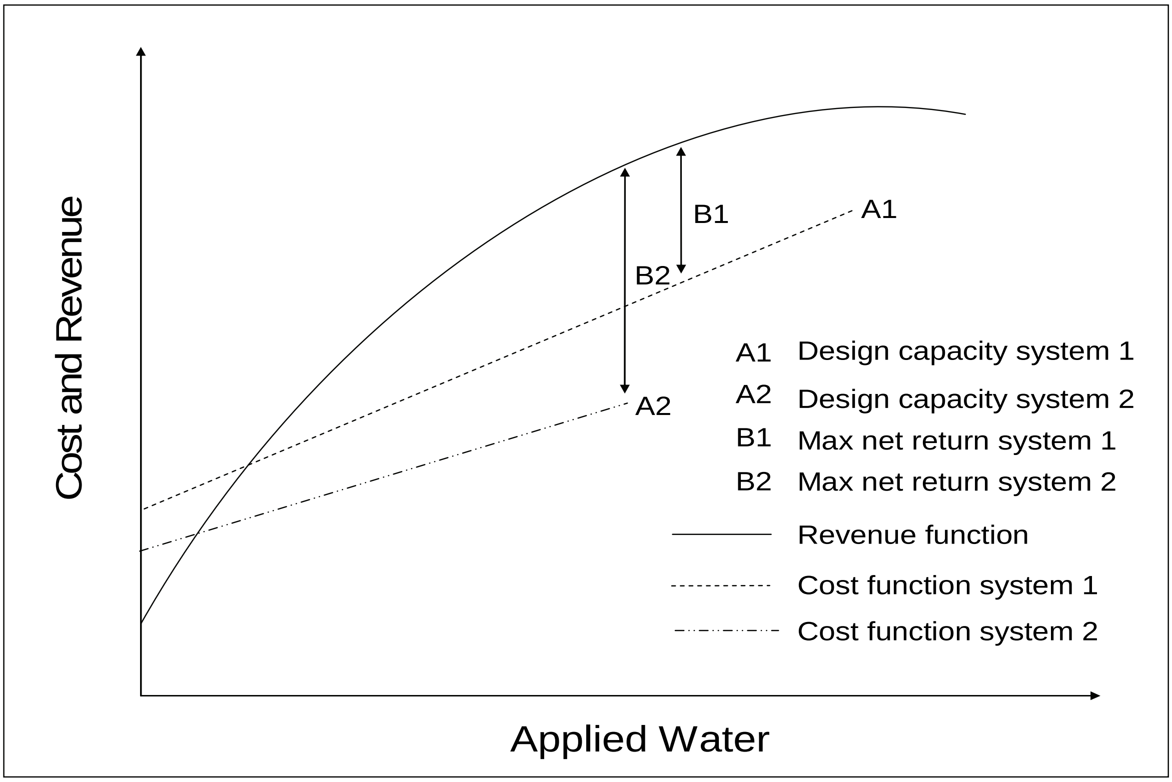


Figure 14: Cost and revenue functions (after English, 1990)

From the figure it can be seen that:

- The revenue function has the same shape as the yield versus applied water curve, because revenue is simply the product of yield and crop price.
- The lower limit of the cost functions represents fixed field costs, for example, capital costs, crop insurance, fixed costs of irrigation, planting, tillage, chemical use and harvesting.
- The slope of the cost functions represents the marginal variable field costs of production, for example, pumping costs, water costs and yield related costs such as harvesting and haulage.
- The upper limit of the cost functions represents the maximum water delivery capacity of the two different irrigation systems.

The maximum water delivery capacity of an irrigation system is a hardware limitation that can have very significant cost and system flexibility implications. In order to provide a high water delivery capacity, larger pumps, motors, pump-houses, mainlines, sub-mains, laterals and/or canals are required. Therefore, designing or specifying irrigation systems with excess capacity can result in substantial cost implications.

On the other hand, if the peak irrigation system capacity is too small, excessive crop yield losses may occur. For example, for the two systems shown in Figure 14, the system with the smaller capacity, i.e. System 2, does not have sufficient capacity to irrigate for maximum crop yields. However, the implications of lower capital and operating costs are such that the net returns are nearly double those attainable with the larger system, i.e. System 1, even though the attained crop yields are lower.

Knowledge of the crop response to different watering strategies and system limitations is needed to determine an optimum deficit irrigation strategy. The WRC has supported the development of the Soil Water Balance (SWB) model which can be used to investigate crop responses to different watering strategies. Other models which are more suited to a specific crop such as sugarcane include: SAsched, ZIMsched 2.0, My Canesim and Aquacrop.

3 Design

The most efficient system will be one that is designed according to sound design principles based on limiting discharge variation and energy requirements in the field.

The selection of a specific emitter determines the minimum pressure required by the irrigation system, while the application of design norms leads to correct sizing of lateral and manifold pipes. The combined effect of the emitter flow rates and operating pressure influences the energy requirement of the system.

The most efficient system will consist of quality components manufactured to a high standard with low coefficients of variation and energy requirements.

The installed system can only apply water as uniformly and energy efficiently as the components of the system allow. Emitters with a low coefficient of variation (CV), or pipes with high friction coefficients, have a detrimental effect on a good design. Similarly, poor installation and maintenance practices can result in leaks and reduced life cycle length.

The most significant outcome of the design process of an irrigation system (in terms of efficiency) is the system operating pressure that will be required from the water supply system, in order to apply irrigation water as uniformly and at the lowest possible pressure. Every decision made during the design process should therefore be considered carefully as it has a direct effect on water distribution in the field and energy requirements on the farm.

3.1 Norms and Standards

Irrigation engineering is a highly specialised design discipline, with every type of irrigation system having its own specific design norms that have to be adhered to, to ensure an efficient system is designed. Some of the principles of irrigation design are discussed here, but for details of design norms and irrigation designers, contact SABI: http://www.sabi.co.za

3.1.1 Pressurised irrigation systems

Pressurised irrigation systems include all systems where water under pressure is supplied in pipelines to emitters, through which the water is applied to the soil surface or below the soil surface in the root zone, such as centre pivot, sprinkler, micro and drip irrigation systems.

Emitters are mounted on connecting pipes, usually called laterals, while the laterals are connected to each other with pipes called manifolds, in the case of micro and drip irrigation, or directly to the mainline in the case of sprinkler systems.

The purpose of the emitter is to apply water at a specific flow rate (as determined during the planning process and called the design emitter discharge, q_e) over a specific area of soil in the field. The characteristics of emitters are such that the emitter discharge is determined by the pressure of the water at the emitter – the design discharge will be delivered at a specific pressure called the design operating pressure. At pressures higher than the design operating pressure, the emitter will discharge more than the design discharge, and at pressures lower than the design operating pressure, the emitter will discharge less than the design discharge. The discharge-pressure relationship is characterised by Equation 14:

$$\mathbf{q_e = K.p^x} \qquad \text{Equation 14}$$

q_e = emitter discharge in litre/hour

where

K = discharge coefficient, include q_e and units

p = operating pressure in meter

x = discharge exponent

This relationship is presented graphically in Figure 15:

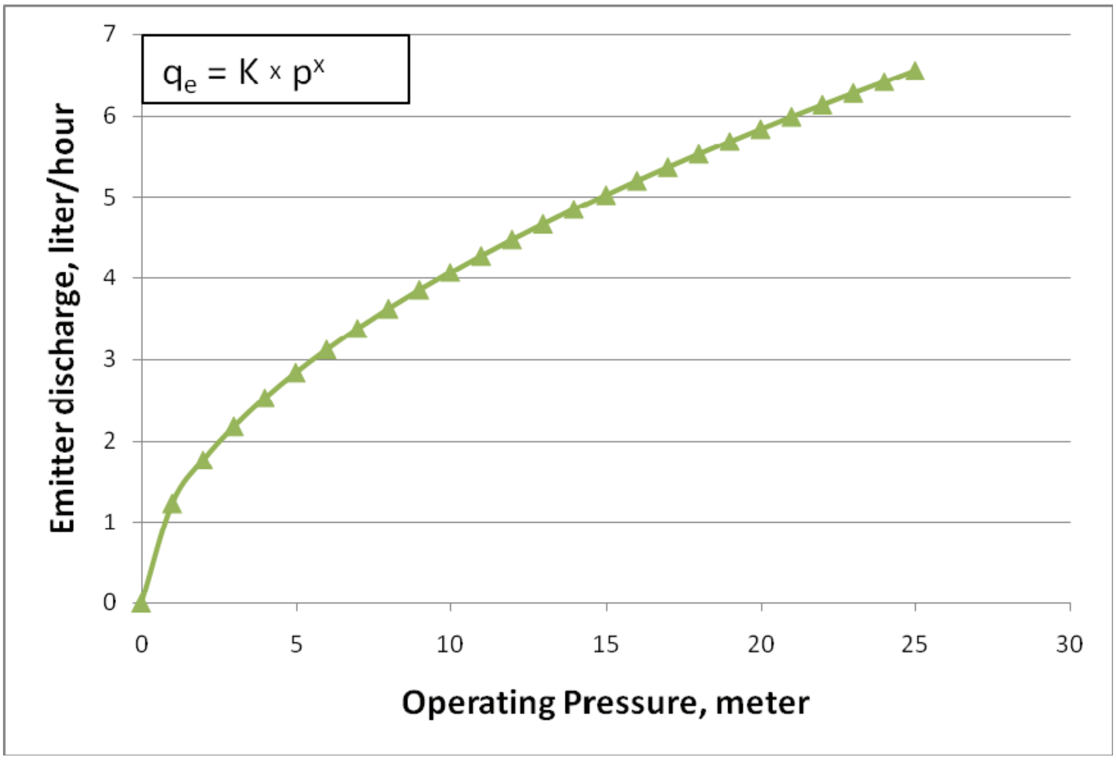


Figure 15: Example of emitter discharge – operating pressure relationship of emitters

An efficient irrigation system is one that applies the water as uniformly as possible across the whole field.

In order to design an irrigation system that applies water at an acceptable uniformity, the irrigation designer should ensure that all the emitters are operating at approximately the same pressure. This can be achieved either by accurate sizing of the lateral and manifold pipe sizes according to hydraulic principles, by using appropriate pressure regulating valves, or by using pressure compensated emitters, which contain a regulating mechanism, (often a diaphragm), that will ensure the emitter will discharge water at a specific rate as long as the pressure in the lateral is within a specified range.

In the case of the hydraulic design approach, the allowable emitter discharge variation is calculated, and the allowable operating pressure determined accordingly. The lateral and manifold pipe sizes are then selected to ensure that the pressure will always be within the upper and lower limits (Figure 16). Correct lay-out (orientation) of laterals and manifolds/mainlines contributes greatly to the uniformity that can be achieved within the in-field irrigation system, and also on the pipe sizes (and classes) that have to be used to achieve this uniformity.

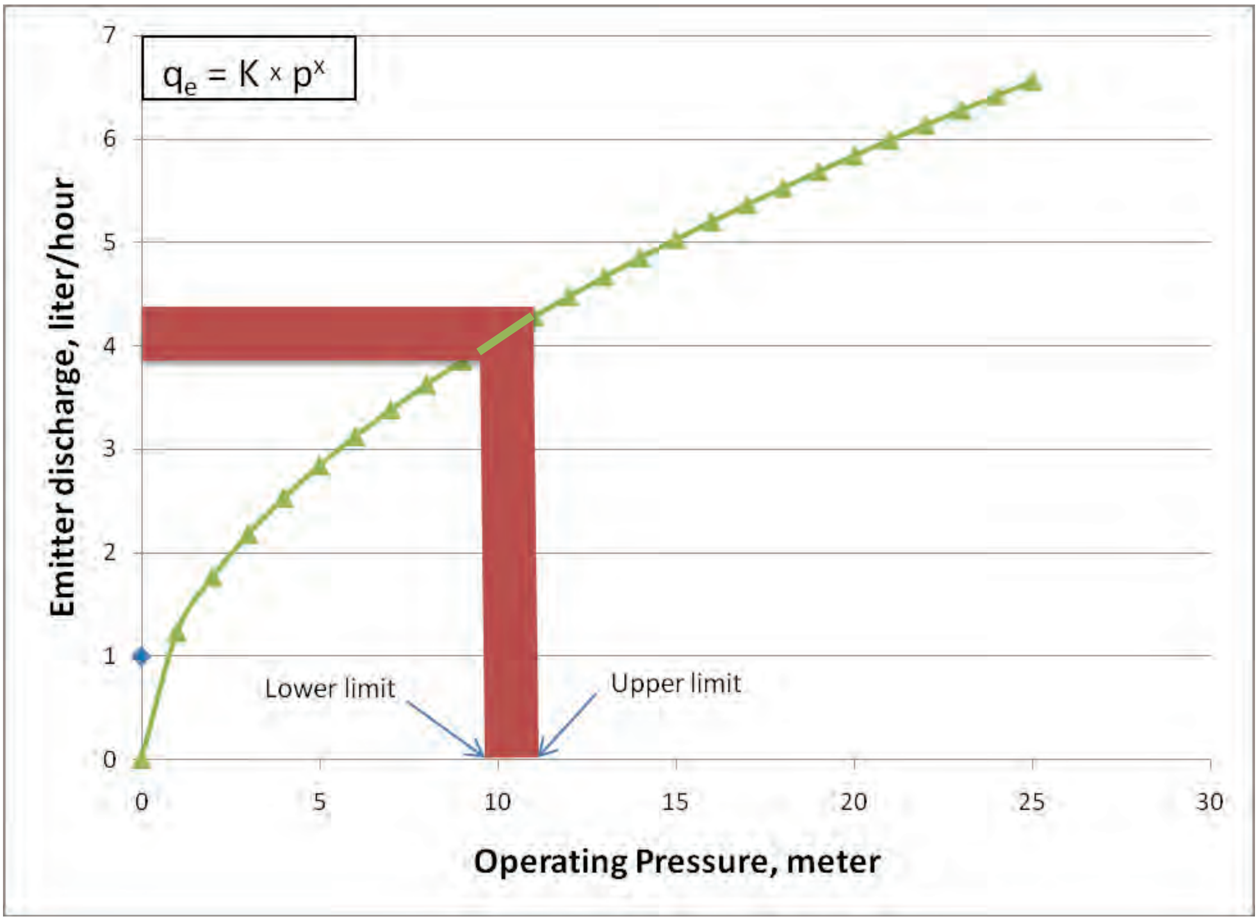


Figure 16: Hydraulic design approach to uniform irrigation systems

In the case of pressure compensated emitters, the regulating mechanism has an effect on the discharge – pressure relationship of the emitter, so that the discharge will remain constant over a specified pressure range, as shown in Figure 17. Pressure-compensated emitters are available for all types of pressurised systems, but are more expensive than non-compensating emitters.

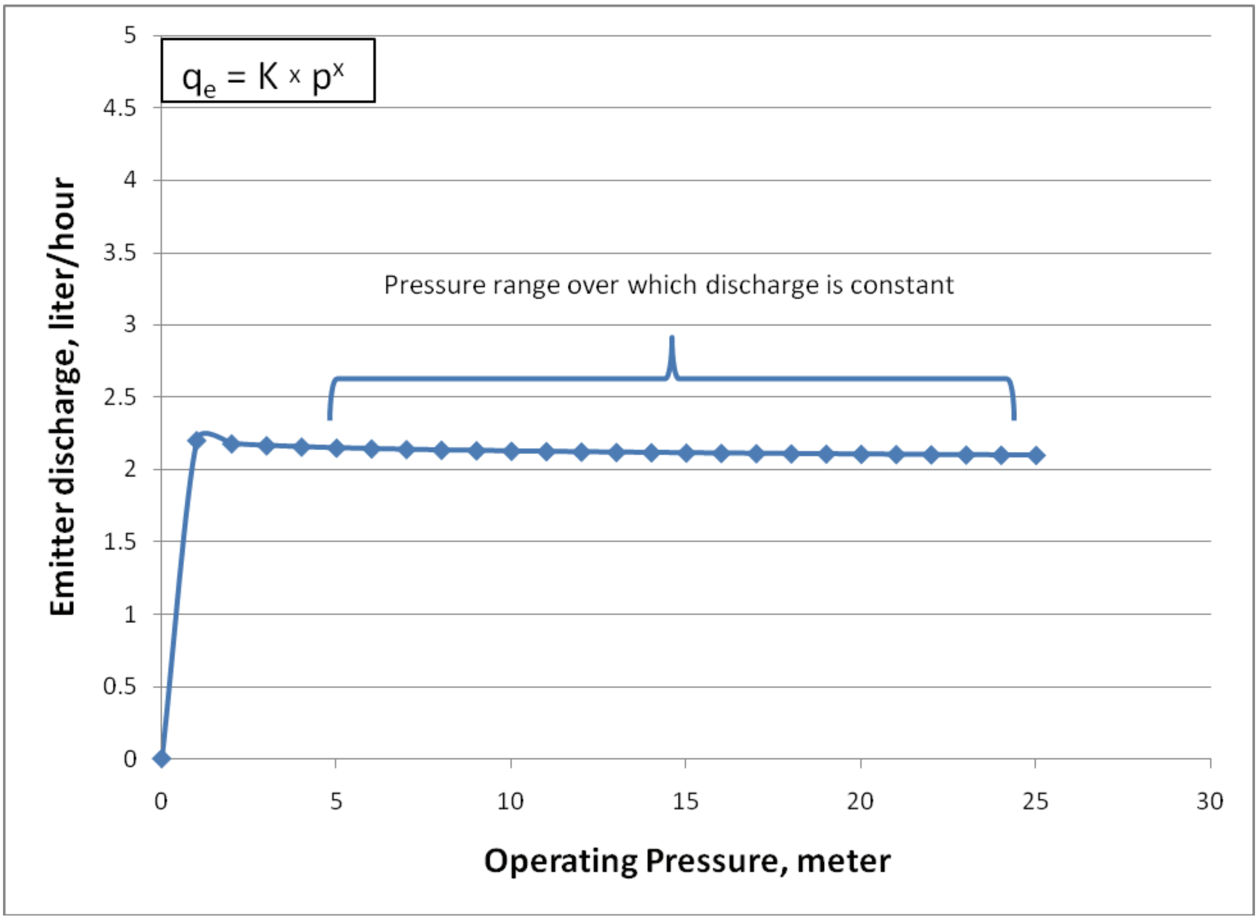


Figure 17: Example of emitter discharge – pressure relationship of pressure compensated emitters

Different types of irrigation systems have different uniformity indicators that are applied to design and evaluate the uniformity of the in-field system. The different indicators for design purposes are shown in Table 19 to Table 25. When evaluating existing systems, the distribution uniformity of the lower quarter (DU_{lq}) is the indicator used.

Table 19: Uniformity indicator for design of centre pivots

Parameters	Equation	Criteria
Heermann and Hein uniformity coefficient (CU_H)	$CU_H = 100 \times \left(1 - \frac{\sum \lvert y_i - \bar{y} \rvert}{\sum y_i} \right)$	> 85% (M)

Table 20: Uniformity indicator for design of travelling guns

Parameters	Equation	Criteria
Christiansen uniformity coefficient (CU)	$CU = 100 \times \left(1 - \frac{\sum \lvert y_i - \bar{y} \rvert}{\sum y_i} \right)$	> 80%

Table 21: Uniformity indicators for design of permanent sprinkler systems

Parameters	Equation	Criteria
Christiansen uniformity coefficient (CU)	$CU = 100 \times \left(1 - \frac{\sum \lvert y_i - \bar{y} \rvert}{\sum y_i} \right)$	> 80% (M)

Table 22: Uniformity indicators for design of moveable sprinkler systems

Parameters	Equation	Criteria
Christiansen uniformity coefficient (CU)	$CU = 100 \times \left(1 - \frac{\sum \lvert y_i - \bar{y} \rvert}{\sum y_i}\right)$	> 80% (M)

Table 23: Uniformity indicators for design of drip systems

Parameters	Equation	Criteria
Statistical uniformity value for emitter discharge (U_s)	$U_s = 100 \times \left(1 - \frac{CV}{100}\right)$	> 80% (M)
Emission uniformity (EU)	$\mathrm{EU} = \left(1 - \frac{1.27 \times \mathrm{CV}}{\sqrt{\mathrm{n}}}\right) \times \left(\frac{q_{e\min}}{q_{eave}}\right) \times 100$	See Table 11

Table 24: EU criteria for drip irrigation

Type of emitter	Number of emitters per plant	Topography/Slope	EU(%)	
			Min	Max
Point - source	≥ 3	≤ 2%	90	95
Point - source	< 3	≤ 2%	85	90
Point - source	≥ 3	Undulating terrain or slope > 2%	85	90
Point - source	< 3	Undulating terrain or slope > 2%	80	90
Line - source	All	≤ 2%	80	90
Line - source	All	Undulating terrain or slope > 2%	70	85

Table 25: Uniformity indicators for design of Micro sprayer systems

Parameters	Equation	Criteria
Statistical uniformity value for emitter discharge (U_s)	$U_s = 100 \times \left(1 - \frac{CV}{100}\right)$	> 80% (M)
Emission uniformity (EU)	$EU = \left(1 - \frac{1.27 \times CV}{\sqrt{n}}\right) \times \left(\frac{q_{e\,min}}{q_{eave}}\right) \times 100$	• Level terrain (slope < 2%): EU > 95% • Undulating terrain/slopes > 2%: EU > 90%

3.1.2 Surface irrigation systems

Surface irrigation refers to irrigation systems where water flows over the soil surface under controlled conditions with the purpose of delivering the desired amount of water to infiltrate the soil. Surface irrigation can be divided into three main categories:

- Basin irrigation,
- Border strip irrigation, and
- Furrow irrigation.

Although surface irrigation appears to be relatively simple, it is probably the most difficult irrigation system to design and evaluate. As with sprinkler irrigation, the aim of the designer and operator is to ensure that relatively even amounts of water are applied to all parts of the field in amounts well matched to soil water holding characteristics and crop water requirements.

The performance of surface irrigation systems is influenced by infield factors such as inflow rates, field lengths, furrow shape (for furrow irrigation), field slope, surface roughness and soil infiltration properties. For furrow irrigation, the furrow spacing should comply with machinery wheel spacing so that infield mechanical procedures can continue without compaction damage to crops.

For effective surface irrigation the designer and operator should ensure that the water applied or flowing into individual basins, border strips or furrows does not vary by more than 10%. For furrow irrigation, flows into individual furrows are limited according to the following guidelines, due to the potential for erosion:

Q	≤	0.95/S	-	erosion resistant soils
Q	≤	0.8/S	-	average soils
Q	≤	0.63/S	-	moderately erodible soils
Q	≤	0.32/S	-	highly erodible soils

Where:

Q	=	flow into the furrow (l/s)
S	=	furrow slope (%)

The depth of water applied per irrigation application should be less than 50% of the soil's total available water (AW) value. The low quarter distribution uniformity (DU_{lq}) for water infiltrated down the length of the field should be > 70 %. DU_{lq} is the average irrigation depth of the least-irrigated 25% of the field divided by the infiltration depth over the whole field. DU_{lq} needs to be assessed based on field measurements of advance and recession fronts and soil infiltration characteristics. DU_{lq} is derived in Equation 15:

$$DUlq = \frac{Z_{lq}}{\frac{V_{rz} + V_{dp}}{L}}$$ Equation 15

Where:

Z_{lq} is the depth of infiltrated water in the least-irrigated 25% of the field.

V_{rz} is the volume of water per furrow spacing or basin or border strip that is actually stored in the root zone.

V_{dp} is the volume of water per furrow spacing or basin or border strip that percolates below the root zone.

L is the field length (Walker, 2003).

Conveyance systems for surface irrigation are often very problematic, causing water logging in the surrounding area and insufficient flows to the field. Seepage losses in the in-field supply system should be < 12%. This can be achieved through use of appropriate materials, for example, layflat piping or lining canals with relatively impermeable material.

If furrows are not blocked a tail water management system should be in place.

3.2 Equipment

In the design process, emitters, pipes and fittings have to be selected, and the specific components' characteristics used in the design calculations. When selecting irrigation equipment, some of the criteria that should be considered include:

- Quality and performance
- Availability of spares and after sales service
- Theft risk

3.2.1 Quality and performance

It is best to use emitters and plastic pipes from reputable, established dealers and manufacturers who will be able to provide the designer and irrigator with the necessary information for correct design and operation. Emitters should have a low manufacturer's CV, which is an indicator of the quality of the manufacturing process, while plastic pipes and fittings should be made from good quality raw material, especially in the case of pipes, where a pipe with a smooth inner surface results in lower pipe friction and therefore lower energy requirements. The cheapest equipment is usually cheap for a reason and care should be taken when sourcing equipment.

3.2.2 Availability of spares and after sales service

Selected equipment should be readily available so that repairs and replacements can be done easily. Local suppliers are better equipped to provide after sales service and assist the irrigator.

3.2.3 Theft risk

Many water users have lately come to avoid using metal (especially brass and copper) components, due to theft of in-field equipment. Some suppliers also specify the use of aluminium cables, as copper cables are also often stolen.

3.3 Installation

The installation of the in-field irrigation system includes laying the mainlines or manifolds, laying the laterals, and joining the emitters to laterals, and laterals to the manifold or mainline. In the case of moving systems such as centre pivots, the structure also has to be built, and gearboxes and wheels fitted. The in-field equipment also has to be connected to the water supply system, usually by means of a valve, as discussed in Module 3.

All actions taken during the installation process should again be done with efficient water use in mind. Pipes, especially PVC, should be handled and installed correctly to prevent damage that can later develop into leaks. Connections between different pipes or between pipes and emitters should be waterproof as far as possible to limit leaks.

For complete guidelines on the supply, transportation, handling, storage, installation and testing of different pipe materials, please consult the *Irrigation User's Manual of the Agricultural Research Council's Institute for Agricultural Engineering* (ARC-IAE). Alternatively, most reputable pipe and irrigation equipment suppliers also provide guidelines on installing their products.

Following the installation of the irrigation system, all pipes should be flushed to remove soil and other impurities that could have entered the system during installation. Thereafter the system is commissioned, which is described in more detail in Module 3.

3.4 Design report

A professional irrigation designer should provide the irrigator with a design report that contains at least the following information:

- Layout plan
- List of quantities
- Detailed drawings
- Pump curve
- Maintenance and management manuals
- SABI peak design form

- Cost estimation

3.4.1 Layout plan

This should comprise of the layout of the blocks and detailed plans of each block. Two copies are required, one for installation purposes and one for the producer's records.

3.4.2 List of quantities

A list of the items required for each block or system is needed so that quotations can be obtained from irrigation equipment suppliers. The list of quantities can also be used as a checklist for the equipment that is delivered by the irrigation equipment supplier.

3.4.3 Detailed drawings

Detailed drawings of equipment are required to make installation easier, and should include:

- Valve connections: Drawings of the valves with the desired accessories.
- Filter banks: Drawings of the complete filter installation with manifolds and valves.
- Pumps: Drawings of the pump with necessary equipment.

3.4.4 Pump curve

The producer uses a pump curve, on which the duty point is indicated, to easily read off the efficiency and power requirement of the pump. The pump curve is also needed in case the existing irrigation scheme is expanded in the future.

3.4.5 Maintenance and management manuals

A comprehensive manual is required to ensure that the performance of the installed irrigation system is not adversely affected by incorrect maintenance and management practices.

3.4.6 SABI peak design form

The SABI peak design form contains technical specifications that should be evident in the design. The required operating flow rate and pressure for the irrigation system at critical points, as well as many other parameters are included to help the irrigator manage the system.

3.4.7 Cost estimation

A cost estimate must be made for the whole project and, if applicable, for each phase.

4 Operation

The most efficient system will be one that is operated according to the design specifications and site-specific irrigation water requirements of the crop.

The irrigation designer will provide the irrigator with the required operating pressures of the irrigation system, which should result in the system applying irrigation water a rate that is suitable to the soil.

The operation of the system requires that the irrigator should apply a scheduling method to make decisions regarding water applications. Operation should be monitored with appropriate technologies to assess whether the system is performing as the designer intended (by measuring flow and pressure), and if it is having the desired effect on the soil water content, as indicated/predicted by the scheduling system (by measuring soil water content).

4.1 Scheduling

An irrigation scheme is typically designed around the peak demand period. For the rest of the year, it will be necessary to reduce the amount of water applied, according to the crop's reduced requirements. If this is not done, the short term effect will simply be the expense of pumping unnecessary water onto the land. In the long term, however, the effect could be serious, with the development of water-logging and perhaps salinity/sodicity accompanied by a dramatic drop in yields and consequent negative return on investment. Thus, irrigation systems managers, by their actions and/or instructions, often have the greatest (positive or negative) impact on irrigation systems performance, and on whether the bulk of the water balance is beneficial or non-beneficial.

The amount of water applied at each irrigation application is a very important performance characteristic of an irrigation system. This is largely determined by management and to a lesser extent by design. Further, a manager needs to determine *when* to apply a given amount of water. Irrigating according to an appropriate schedule will result in an appropriate amount of water being applied at an appropriate time such that most of the water applied contributes to beneficial water use and crop yields are maximised for a given amount of water.

4.1.1 Amount of water applied

The amount of water applied is often constrained by the type of irrigation system. In centre pivot irrigation systems, for example, whilst the amount of water applied at each irrigation application is easily controlled by varying the rotational speed, the upper limits of application may be limited by excessive run-off. For most furrow irrigation systems, by contrast, application amounts are relatively inflexible, being largely dictated by layouts and soil infiltration characteristics. With many furrow irrigation systems it can be very difficult to control the magnitude and the evenness of water applications, especially when trying to apply relatively small amounts of water per application, e.g. < 50 mm.

When the amount of water applied per irrigation application is not well matched to readily available soil water, performance will be poor because of:

- excessive crop stressing, if the soil is consistently depleted below the stress point to a level coinciding with larger irrigation applications;
- excessive runoff and deep percolation losses and associated drainage problems if large irrigation applications are applied at relatively low soil water depletion levels in order to avoid excessive drying of the soil and crop water stress;
- excessive evaporation losses, which can also be problematic if small amounts of water are applied relatively frequently with, for example, centre pivots.

Part of developing an appropriate irrigation schedule is to predict or measure the soil water deficit so that an appropriate amount of water is applied, avoiding the aforementioned problems.

4.1.2 Timing water applications

Soil water deficits can be predicted by direct measurements or by water budgeting. Monitoring soil water content is discussed in Section 4.2.3. Various systems of recording the theoretical balance of soil moisture, with crop water consumption being debited to the account, and rainfall and irrigation being credited, are available in tabulated and computerised forms.

4.1.2.1 Soil water budgeting principles

The basic principles of a simple water budget are described as follows:

1. Use an appropriate crop coefficient and reference evaporation value to determine the daily evapotranspiration.
2. On a daily basis, subtract the appropriate evapotranspiration from the available moisture brought forward. Rainfall and irrigation must be added to the available moisture. To initialise a water budget, the soil moisture value is typically assumed to be equivalent to the soil's field capacity or drained upper limit following reasonable rain or irrigation.
3. Rainfall is typically assumed to be effective provided the Total Available Water (TAW) of the soil is not exceeded. Once the TAW is exceeded further rainfall is often ignored when doing simple hand calculations. In many more accurate computer simulation models the actual time for the excess rain or irrigation to drain, such that the soil returns to field capacity or the drained upper limit, as well as the proportion of the rain lost to run-off or deep percolation, is represented more accurately. For simple hand calculations the following procedure can be used:

	Available moisture, day one
minus	Daily evapotranspiration
plus	Rainfall
plus	Irrigation
=	Available moisture, day two

Example:

Assume that at 08:00 on 29 January the available moisture in the soil profile is 84 mm. The average daily evapotranspiration for January is 6 mm per day. During the afternoon of 29 January it rained, with an effective rainfall of 18 mm recorded. No irrigation was carried out on the field that day. Thus we can determine that, at 08:00 on 30 January, the available moisture will be 96 mm, calculated as follows:

	Available moisture (29 January – day one)	=	84 mm
minus	Estimated evapotranspiration (29 January)	=	6 mm
	Result a	=	78 mm
plus	Effective rainfall (29 January)	=	18 mm
	Result b	=	96 mm
plus	Nett irrigation (29 January)	=	0 mm
	Available moisture (30 January – day two)	=	96 mm

4. When two or more fields approach the soil moisture deficit level requiring irrigation, a decision must be made as to which field should be irrigated first. Try out the various possible courses and rotate the equipment between the fields so that the least stress is caused to the crops.

In practise, it is not sufficient to depend entirely on a single method of irrigation scheduling. Soils are seldom uniform over large areas, and the TAW and amount of irrigation water applied could vary considerably within a field. The farmer must become familiar with his fields to enable him to check field conditions. The use of a soil auger to 'feel' the moisture content of the soil between irrigations can be of great value in this respect, even though the exercise is really only useful to see whether the soil is excessively wet or very dry. Ideally some type of soil water monitoring device should be installed at strategic locations to affirm the water budget calculations (See Section 4.1.2.2).

4.1.2.2 Soil water budgeting decision support tools

Increasingly, spreadsheet programs and customised software are being used to compute soil moisture profit and loss for the fields of farms or estates. Climatic data can be punched in to the computer by hand or downloaded from a weather station or the internet, and appropriate field information is keyed in.

The computer undertakes detailed and representative calculations describing crop growth and the water balance, and provides tabular and graphical information to manage the timing and amount of irrigation water to be applied. Often, because the crop growth and water balance calculations are more detailed and representative of real field conditions, use of computer-based water budgeting decision support tools can result in significant water and energy savings and improved crop yields. Water budgeting simulation models available in South Africa include:

The Soil Water Balance model

The SWB model is a user-friendly, generic crop irrigation scheduling model. It is used to simulate crop growth, the soil water balance and crop water use. Daily weather input data is required in order to run the model for real-time scheduling. Soil layer characteristics such as layer thickness, soil water contents at field capacity, wilting point and soil bulk density need to be supplied once off for each field.

The SWB model can estimate real-time crop water requirements (day-to-day water use during the growing season) and recommend the irrigation amount and date, based on the current crop water usage and set user preferences. If farmers do not have access to daily weather data or computers, the SWB model can be used to develop site-specific irrigation calendars. In such instances the long-term temperature, as well as soil and management inputs for a specific locality are used to generate site-specific irrigation calendars for a season ahead.

The calendar, which recommends irrigation dates and amounts, can be printed out and used as a guide to manage irrigations. Calendar recommendations must be corrected by deducting rainfall if needed. The SWB model is freely available to irrigators, and can be downloaded from www.up.ac.za/UPWI/SWB

BEWAB (Besproeiingswater Bestuursprogram/Irrigation water management program)

BEWAB is a water balance model that uses research data to make irrigation recommendations. The water consumption of the crop is estimated according to day-to-day irrigation requirement curves, which were fixed by historical readings. BEWAB was developed by Prof. A.T.P Bennie, and is described in the WRC's report. *"'n Waterbalansmodel vir besproeiing gebaseer op profielwatervoorsieningstempo en gewasbehoeftes"* (Bennie *et al.*, 1988)

VINET 1.1 – (Estimated Vineyard Evapo-transpiration for Irrigation System Design and Scheduling)

VINET 1.1 was designed to aid the producer in the decision-making process on when, how much and for how long irrigation must be applied. In the past, decision-making was made difficult because of the variation between vineyards due to differences in foliage, soil and climatic factors. Dr PA Myburgh and Mr C Beukes, both from the ARC-Infruitec-Nietvoorbij, developed VINET 1.1. The research was partly funded by Dried Fruit Technical Services, Deciduous Fruit Producers Trust and Winetech.

SAsched, My Canesim, Irrigation Scheduling Calendar Decision Support Program)

These are all available from the South African Sugarcane Research Institute. They aim to provide scheduling guidelines for the irrigation of sugarcane.

SAsched is spreadsheet-based and requires daily rainfall data; information on soil water holding characteristics (at least texture and depth); either mean monthly or near-real-time daily estimates of reference evaporation (either A-pan, FAO 56 short grass or reference cane); and daily values for maximum and minimum temperature.

My Canesim is an internet based simulation model and can be configured to provide irrigation scheduling advice via SMS's.

The Irrigation Scheduling Calendar Decision Support Program **(**ISCDSP) can be used to provide print-outs showing optimum irrigation cycle times for cane cut at different times in the year dependent on various agronomic conditions and the amount of water applied per cycle. The ISCDSP includes a "Rain delay calculator" which shows recommendations for delaying irrigation following different amounts of rain at different times during the year.

4.2 Monitoring

The purpose of irrigation system monitoring is to ensure that the system functions as described in the design report. Monitoring is a continuous process, consisting of activities undertaken on a daily basis by the system operator, and should therefore be simple and easy to do so as to not interfere with the operator's other tasks. The in-field irrigation system can be monitored at the following locations:

- At the inlet to the irrigation system (moving systems), block (drip/micro/permanent sprinkler), lateral (portable sprinkler) or furrow
- On the soil surface
- In the soil profile
- At the outflow of the drainage system, if applicable

The data from the monitoring activities should be stored in a suitable data management system for easy access and analysis. Finally, no amount of measurements can replace the value of first-hand observations made in the field or orchard, and the irrigator should verify the results of their operational activities by observing the condition of the soil and the plants.

Monitoring activities, data management and verification are discussed in more detail below. Monitoring data, in particular of the amount of irrigation water applied, is fundamental to irrigation scheduling and is needed to assess the effectiveness of an irrigation strategy and to make improvements if necessary.

4.2.1 At the inlet to the irrigation system, block, lateral or furrow

At this location, in the case of pressurised irrigation systems, the pressure in the system should be monitored and compared against the design inlet pressure provided in the design report. A system operating at the correct pressure will supply the correct amount of water, and it is easier to measure pressure than flow at an inlet.

Deviation from the design inlet pressure will provide the operator with an early warning of leakages or pipe bursts (low pressure), worn nozzles (low pressure), blocked emitters (high pressure) and other in-field problems. Pressure in pipes can be measured with a pressure gauge, either permanently installed (Figure 18) or portable, which is read manually at the point of measurement. Piezo-electric pressure gauges can also be used and the electronic readings conveyed to a central point, for instance the pump station, via telemetry. This does however require electricity to be available at the point of measurement.

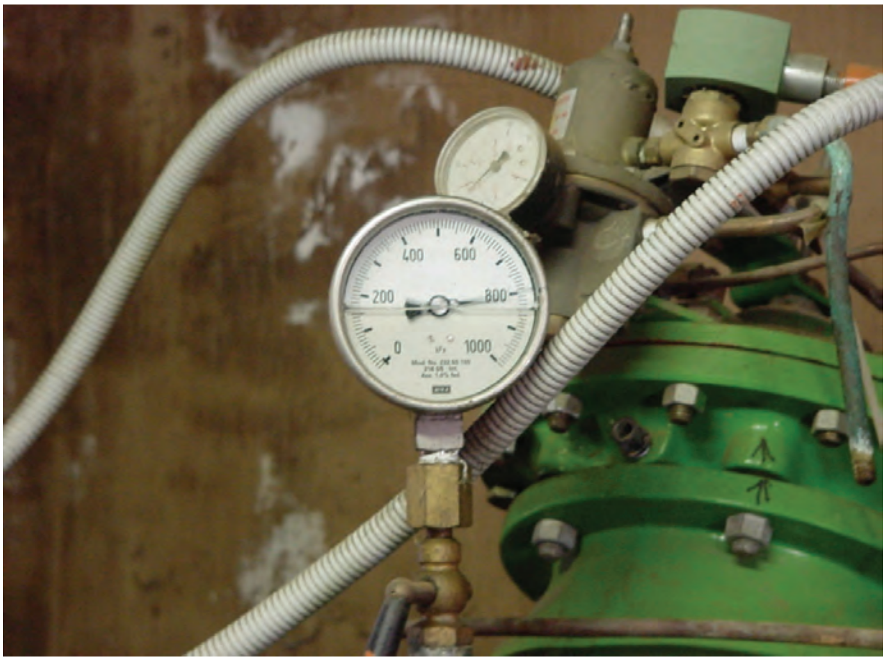


Figure 18: Picture of pressure gauges

Flow can also be measured at system, block or lateral inlets, but this is more expensive than pressure measurement.

In the case of surface irrigation systems there is no pressure in the system, and flow is more often measured. Measuring flows to surface irrigated fields is very important for monitoring overall application depths. Various types of open-channel flow measuring systems can be used. Of the options available, long-throated flumes provide many advantages. Details of options for open channel flow measurement are given in WRC Report TT248/05.

Measuring the rate of inflow to individual furrows provides very useful information on both the depth and distribution of irrigation applications. Simple procedures to measure flows into furrows are described in the following section.

4.2.2 On the soil surface

In order to assess performance, it is also useful for the irrigator to know the amount of water that has been applied by the irrigation system to the soil surface.

4.2.2.1 Overhead Sprinkler Systems

In the case of overhead systems, a rain gauge can be used to monitor the amount of water applied. The rain gauge should be emptied after every rainfall or irrigation event. Tipping bucket rain gauges can automate this function by recording the amount of water applied, together with a time and date stamp for downloading to a computer, either manually or via telemetry.

4.2.2.2 Drip and Micro Systems

In the case of drip and micro irrigation, individual emitters can be monitored regularly by collecting the delivery from the emitter in a measuring cylinder, but due to the number of emitters in a field, it is easier to monitor the total pressure and/or flow at the block inlet.

4.2.2.3 Surface Systems

In the case of surface irrigation, the Greller head measuring device (see Section 6.2.4.) can be used together with calibrated siphons to determine the flow-rate into individual furrows. Once the flow-rate into furrows has been determined, the average depth of water applied is easily determined by converting the flow-rate to a volume and dividing this volume by the representative furrow area. An example calculation is shown in Figure 19. Alternatively, the flow-rate in a supply canal can be measured, and similar principles used to determine the average depth of water applied to the total area supplied by the canal. Thus, using flow rate and duration, the total volume of water applied is calculated, then divided by the area serviced to determine the average application depth.

Furrow Length (m)	100	
Furrow Spacing (m)	1.5	
Area per furrow (m^2)	150	(length (m) x spacing(m))
Flowrate into Furrow (l/s)	2	
Duration of flow (min)	40	
Volume applied (m^3)	4.8	(flowrate (l/s)/1000 x duration(min) x 60)
Depth Applied (mm)	32	(Volume (m^3)/Area(m^2) x 1000)

Figure 19 Example calculation of the average depth of water applied to an individual furrow

4.2.3 Water in the soil

Tools to monitor soil water can provide pertinent data on how a particular irrigation scheduling strategy/system is performing. It is recommended that at least two soil water content measurements be made in the soil profile – one in, and one below, the root zone. By monitoring the root zone, the irrigator ensures that there is adequate water available to the roots; by monitoring below the root zone, the irrigator can control excess irrigation and manage soil health.

With advances in communications technology, it has now become easier to obtain continuous soil water content or soil water potential readings than when measuring devices had to be read manually. Continuous measurement provides many advantages over the manual methods and should be used if possible.

4.2.3.1 Criteria to consider when selecting a soil water monitoring system

In the irrigation sector, soil water status may be measured in terms of soil water content or soil water potential.

Soil water content can be divided into gravimetric or volumetric soil water content. Gravimetric soil water content is a description of the weight of water for a given weight of soil. Gravimetric methods of measuring soil water content involve removing and oven drying a soil sample, which can be impractical for irrigation management applications. Volumetric soil water content is a description of how much water is present in a given volume or depth of soil, typically expressed in mm water per mm soil. Volumetric soil water content is generally determined indirectly, by measuring soil attributes that vary with changing water content.

Soil water potential is a measure of the suction energy required by the crop to extract water. Soil water potential (in soil physics terms) describes the forces that drive water movement. The phrase *soil water tension* is also often used. Tension refers to the strength with which the soil particles cling on to water.

There are ongoing debates about whether volumetric soil water content or soil water potential is the best method of measurement. A universal challenge when measuring soil water content is to determine whether the water content measured is too wet, i.e. above the drained upper limit (DUL), or too dry, i.e. below the water content at which the plant experiences stress (Charlesworth, 2000).

In addition, two adjacent patches of soil at equilibrium, i.e. at the same soil water potential, can have significantly different water contents, and a change in water content at one location may not equate to a similar change in water content at an adjacent location. Since soil water potential describes the energy required by the crop to extract the water from the soil, soil water potential is a more direct indicator of potential crop stress and whether or not the soil is above the DUL.

Before expanding on what tools are available, the criteria to be considered when selecting an appropriate tool are listed and discussed below in order of priority:

Ease of use

It is strongly advised that ease of use be the first consideration when selecting monitoring tools. Ease of use is largely related to the effort, skill and support required to operate and interpret data from a soil monitoring system.

Cost

Historically, cost has probably been the most important factor when considering what tool to use. In the current economy, with rapidly increasing costs in water and electricity tariffs, the cost of *not* using such tools is more likely to play a role. In other words, irrigators are advised to consider not just the cost of the tool, but more importantly, the cost benefits of more precise irrigation and increased yields when monitoring tools are used to better manage irrigation.

Accuracy

Marketing and branding of products can make it difficult for a potential user to decide on whether a product is suitable for their needs or not.

There are two things that a potential user should be particularly aware of. The first is related to calibration of the sensor. One should identify if site or logger specific calibration of the sensor is required, and determine if the means to perform this calibration is readily available. The need for accurate calibration may also depend on how the data is to be used (e.g. for establishing trends or determining absolute values). For example, a soil water content sensor such as a capacitance probe may be used to capture and evaluate trends of the soil water status. These trends can often be interpreted without the need for specific calibrations. However, if absolute values of soil water content are required, (for example, to determine a water balance), then more accurate calibration or tools may be required.

The second issue is related to the sensitivity of sensor performance to incorrect/correct installation procedures. Capacitance type sensors, for example, are very sensitive to the way they are installed. Achieving good surface contact between the soil and sensor is imperative during installation but can be very difficult to achieve with certain sensors. Air gaps, for example, can negatively affect the quality of data obtained.

Robustness

Robustness in this case refers to the suitability of the monitoring system to the harsh agricultural environment. Aspects such as protection against pests (e.g. rodents and ants) must be considered. This is especially troublesome for systems that have long cables running from many sensors in different parts of the field to a central transmitter. Waterproof housing of data loggers and connection points is also an important consideration. In addition, in South Africa, theft has become an increasingly worrying problem. Small, inconspicuous, hidden or well camouflaged battery packs and housing for loggers are preferred. Solar panels may be inappropriate, as they are likely to be stolen.

4.2.3.2 Available tools and current trends

A detailed review of soil water sensors is given by Charlesworth (2000) and IAEA (2008). In this section pertinent aspects of the review are summarised, including soil water content and soil water potential sensors. In addition, some of the current trends and popular tools are also presented.

Soil Water Content

Neutron probe, time domain reflectometers (TDRs) and capacitance type sensors can be used to measure soil water content. The neutron probe and TDRs are very accurate methods of monitoring soil water status. The neutron probe, shown in Figure 20, emits fasting moving neutrons via a pre-installed access tube into the ground.

Figure 20: Neutron probe (IAEA, 2008)

Simply put, the fast moving neutrons collide with the hydrogen atoms in the soil water and become slower moving. The neutron probe then detects the slow moving neutrons and relates it back to soil water content (Charlesworth 2000 and IAEA, 2008). TDR instruments on the other hand send an electromagnetic signal down steel probes buried in the soil. The signal reaches the end of the probes and is reflected back to the TDR control unit. The time taken for the signal to return varies with the soil dielectric. The soil dielectric is a measure of the soil's ability to conduct an electromagnetic impulse, which is related to the water content of the soil surrounding the probe. (Charlesworth, 2000).

The neutron probe and TDR can be calibrated to provide very accurate methods of monitoring soil water status. They are, however, relatively expensive and require specialised knowledge, both to record measurements and to interpret the data. Furthermore, in the case of the neutron probe, field data gathering is time consuming and labour intensive. The neutron probe also makes use of radioactive materials: a strict safety programme is necessary regarding the operation, transport and storage of the equipment.

Capacitance probes, otherwise known as frequency domain reflectometers, are relatively inexpensive compared to neutron probes and TDR instruments, and are becoming increasingly popular. As shown schematically in Figure 21, the capacitance probe typically consists of a plastic tube which houses concentric parallel electrodes.

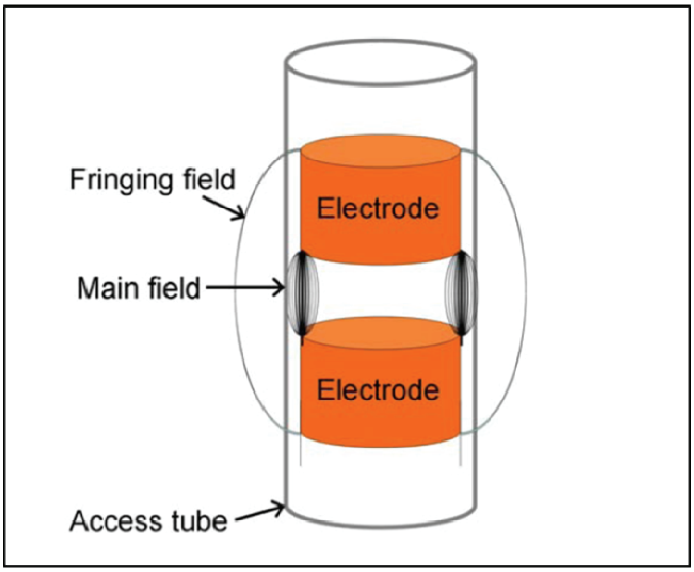


Figure 21: Schematic describing the operation of a capacitance probe (IAEA, 2008)

Using a voltage charge, an oscillating electric field is generated between the two electrodes and extends into the soil medium through the wall of the plastic tube. This is represented in Figure 21 as the main and fringe field. The fringe field then allows for the measurement of a frequency which is correlated to the soil dielectric and thus the soil water content. Electrodes, are usually placed at strategic intervals along the length of the access tube, as shown in Figure 21, in order to the monitor soil water content at various depths in the soil profile. An example of a capacitance probe is shown in Figure 22.

Figure 22: Example of a capacitance probe (DFM, 2008)

The concern, however, is that dielectric sensing instruments such as capacitance probes generally have a relatively small measurement sphere (Charlesworth, 2000). Typically, the measurement sphere ranges up to about a 10 cm radius, with 95% of the sphere of influence within 5 cm (Charlesworth, 2000). This is concerning, since the sampled area is generally representative of the soil which is disturbed during sensor installation and correct installation is therefore critical.

As with all soil water content sensors, it is risky to use absolute values of readings or changes in readings without a detailed and site/soil specific calibration of the particular sensor. However, for most practical management purposes, careful analysis of trends in the sensor readings is normally adequate to determine when the soil water is below the stress point or above the drained upper limit.

Soil water potential sensors

Tensiometers and porous type instruments such as gypsum blocks and Watermark sensors can be used to monitor soil water potential. Tensiometers are one of the oldest and most widely used instruments for irrigation scheduling. As shown in Figure 23, tensiometers consist of a water filled polyvinyl chloride (PVC) tube attached to a porous ceramic cup on one end and a vacuum pressure gauge on the other. Tensiometers are typically permanently buried so that water can move freely through the porous cup either to or from the soil. Since the tensiometer is an airtight device, a suction pressure (vacuum) equivalent to the soil water potential is created as water flows out of the tensiometer. The pressure gauge then reflects the movement of water into or out of the instrument, thereby measuring the soil water potential. Recently the introduction of data loggers has eliminated the tedious exercise of manually recording soil water potentials.

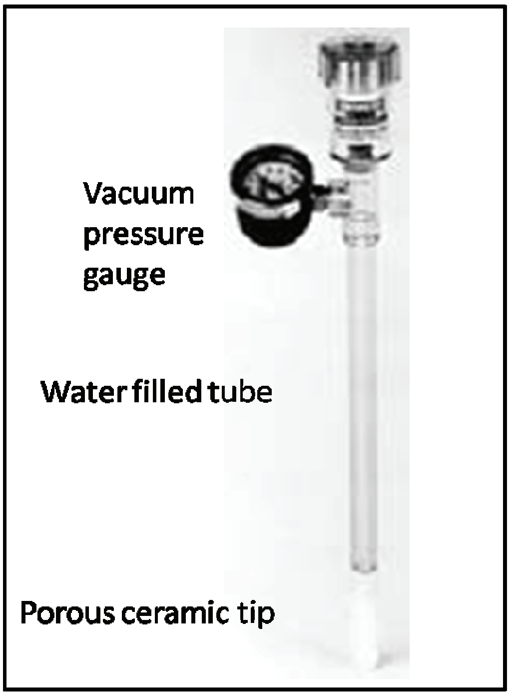


Figure 23: Example of tensiometer (IAEA, 2008)

Tensiometers, however, are limited to soil water potentials above -85 kPa (White, 2003). If the soil dries out to water potentials below -85 kPa, air enters the device, breaking the vacuum with which the tensiometer operates. For this reason, tensiometers can be a high maintenance apparatus. The installation of tensiometers also requires considerable knowledge and attention.

The effective and rational use of tensiometers in irrigation agriculture requires that they should be placed correctly. At least two tensiometers at varying depths are required for deep-rooted crops. The shallower tensiometer will indicate when irrigated should be started, while the deeper tensiometer indicates whether irrigation is done correctly (i.e. that the matrix potential at that depth will not rise substantially higher than approximately -5 kPa, field capacity). For shallow-rooted crops, only one tensiometer is necessary.

Correct irrigation application amounts can be inferred by interpreting tensiometer responses to different amounts of irrigation, as illustrated in Figure 24.

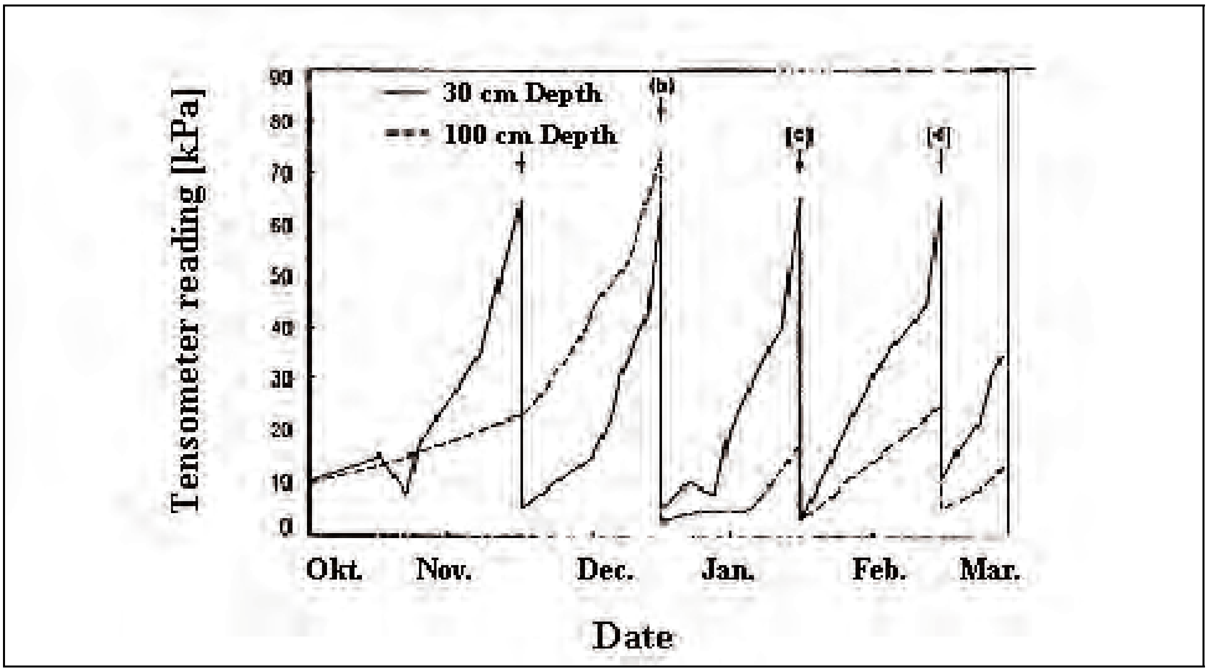


Figure 24: An example of the changes in the tensiometer reading at two depths as a function of water consumption and irrigation (Koegelenberg, 2004)

- Irrigation (a) did not wet the soil deeply enough and the deeper tensiometer's readings kept rising.
- Irrigation (b) was slightly too heavy and the tensiometer indicated a water saturated condition for too long (readings smaller than 19 kPa).
- Irrigations (c) and (d) were given at the right time, and the correct amount of water was applied.

With drip irrigation, a single tensiometer can be placed within the zone of root activity. In this case the soil water potential trends, rather than absolute values are used to inform irrigation practices. If the tensiometer is becoming wetter, this indicates that the rate of water applied exceeds crop water use, and that irrigation applications should be reduced. Conversely, if the tensiometer is becoming dryer (indicated by soil water potentials becoming lower) irrigation applications should be increased. Utilising absolute soil water potential or water content values to guide irrigation with drip irrigation is not advised, because of the high variability in these values over very short distances.

Other soil water potential sensors include the gypsum block and Watermark as illustrated in Figure 25, and the newly released MPS-1 sensor from Decagon (2008), shown in Figure 26. Gypsum blocks are inexpensive, but a major problem is that the gypsum block breaks down and dissolves over a period of time. The calibration relationship between gypsum block readings and soil water potential is therefore not fixed. The Watermark and MPS-1 sensors are therefore potentially better options.

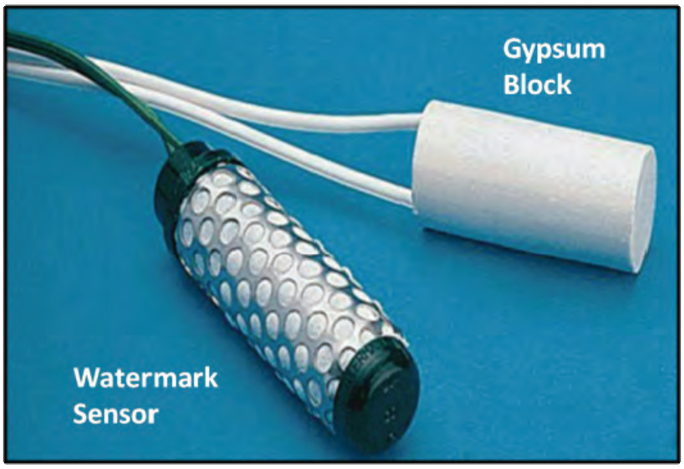


Figure 25: Illustration of Watermark and Gypsum Block sensors (IAEA, 2008)

The Watermark is a granular matrix sensor, similar to a gypsum block. It consists of two concentric electrodes embedded in a porous reference matrix material, which is surrounded by a synthetic membrane for protection against deterioration. A stainless steel mesh and rubber outer jacket make the sensor more durable than a gypsum block. The porous sensor exhibits a water retention characteristic in the same way as a soil: as the surrounding soil wets and dries, the sensor also wets and dries. Movement of water between the soil and the sensor results in changes in electrical resistance between the electrodes in the sensor. The electrical resistance can then be converted to soil water potential through a calibration equation (Chard, 2008).

It should be noted that the Watermark sensor is sensitive to soil temperature, which may therefore need to be monitored and accounted for in the calibration equation for very accurate work (Shock *et al.,* 1998). The Watermark sensor can be used to determine soil water potential down to approximately -200 kPa (IAEA, 2008).

Caution must, however, be used when selecting a data logger. The Watermark sensors are more suited to high frequency AC excitation. Such data loggers, however, are more costly and have higher power requirements (Allen, 2000). A DC excitation logger can be used but will require calibration (Allen, 1999).

Similar to the Watermark, the MPS-1 sensor (Figure 26) makes use of porous ceramic disks, with a water retention characteristic that wets and dries out as the soil wets and dries out (Decagon, 2008). In the case of the MPS-1, however, the dielectric permittivity of the porous ceramic plates is measured. This is different from the Watermark sensor which measures the electrical conductance of the porous material.

Figure 26: MPS-1 soil water potential sensor (Decagon, 2008)

Water content and water potential are related by a relationship unique to a given material. The ceramic used with the MPS-1 has a wide pore size distribution and is consistent between disks. So, if the water content of the ceramic is measured accurately, then a calibration curve is generated that will give a standard calibration for the MPS-1 in terms of water potential. This calibration is not dependent on the type of soil into which the MPS-1 was installed. (Decagon, 2008).

This is attractive, bearing in mind the reduced complexity of data processing for farmers. One standard calibration can be used, irrespective of soil characteristics. In addition, the MPS-1 reportedly measures soil water potential from -10 kPa at saturation down to -500 kPa (Decagon, 2008), which is significantly more than the -200 kPa achieved by the Watermark.

Wetting front sensors

The Wetting Front Detector (WFD) was originally developed as a simple irrigation scheduling tool to fill a perceived gap in the market (Backeberg, 2010). This 'gap' was anticipated to be for a tool that made 'intuitive' sense to farmers and linked water management with salt and nutrient management The FullStop WFD is a funnel shaped device that is buried in the soil and provides a visual signal when the soil water suction falls to 2 kPa during an irrigation event. The FullStop collects a water sample from the wetting front, which can be analyzed for water quality parameters, such as electrical conductivity (EC) and nitrate levels.

Much progress was made between 2000 and 2003 through the Water Research Commission (WRC) Project No. 1135 "Building Capacity in Irrigation Management with Wetting Front

Detectors" (WRC Report No TT 230/04). This involved the testing of the device under controlled conditions, on-farm evaluation, and obtaining feedback from irrigators. The initial research and on-farm experience showed enormous promise and the device was commercialised in a relatively short space of time. In 2003, the FullStop was nominated by the South African National Committee on Irrigation and Drainage (SANCID) and won the international prize for innovative technology and "outstanding contribution to water saving and water conservation in agriculture", awarded by the International Commission on Irrigation and Drainage (ICID) in Montpellier, France. The FullStop WFD is manufactured in South Africa by Agriplas under licence of the CSIRO in Australia, was released onto the market in 2004 and over 13 000 units have been sold world-wide.

Figure 27: Fullstop Wetting Front Detector (Steyn, 2008)

The WFD helps the irrigators to understand their current irrigation strategy, and to organise their experiential knowledge. Irrigators build their own rules of thumb around the response of the WFD. They combine their existing knowledge, which is gathered within the constraints of their own farming systems, to come up with WFD responses that help them to balance accuracy with risk. They use the WFD to evaluate different fertigation or leaching strategies in a learning-by-doing approach. WFDs can therefore play an invaluable role as a learning tool, complimenting years of farmer experience. Since the WFD is a learning tool combining water, salt and nutrients, a comprehensive training package for farmers and advisors was developed. It will help to organise irrigator's existing knowledge, help them to make sense of new information, and help them to develop management strategies that will improve water, salt and nutrient management.

4.2.4 Drainage system

The amount and quality of water flowing in the drainage system downstream of an irrigation system is a good indicator of the quality of the water management applied.

The amount of drainage water flowing in surface drain can be measured with a variety of devices, including flumes and weirs as described in the ARC – IAE's Irrigation Design Manual. Alternatively, there are ultrasonic and other electronic devices available to measure flow velocity and/or flow depth as described in the WRC publication, *Guidelines for irrigation water measurement in practice* (WRC Report nr TT 248/05).

Measuring the quality of the drainage water will provide the irrigator with information on whether fertilisers are being leached out of the soil profile, and also what quality of water is being discharged back into the environment. A variety of probes are available for the standard measurement of EC and acidity (pH).

4.2.4.1 Monitor soil and water

Annual soil and water samples should be sent to laboratories for analysis of salt and sodium levels, in all irrigated fields and for all associated water sources. Water sampling may need to be done more frequently as the quality of water often changes during a season. If there are any concerns regarding the results of soil and water analyses, appropriate soil science and/or agricultural engineering professionals should be consulted.

4.2.4.2 Monitor water table

If there is insufficient natural drainage, and/or deep percolation is excessive, the water table will rise. Generally the water table should be maintained at least 0.8 m from the surface. If the water table rises to within 0.8 m of the soil surface due to irrigation, soil health will deteriorate in the root zone and crop yields will decline. Salts will be deposited in the root zone as a result of the high water table and large areas of land can become unproductive.

Thus, in addition to monitoring soil and water quality, holes should be augered on all irrigated fields on a regular basis, particularly during the main growing and rainfall season, to establish if there is a water table problem. If such a problem is suspected, a more thorough investigation is needed in order to develop an optimum mitigation strategy. Part of a more thorough investigation is to establish a network of observation wells, and monitor water table levels on a regular basis throughout a season. Furthermore, the irrigation system hardware and the watering strategy will need to be carefully evaluated in order to determine if these are contributing to the problem.

4.2.4.3 Monitor and evaluate irrigation system

If the irrigation system is performing poorly, parts of the field may receive excessive water relative to other parts of the field, even if overall water applications are not excessive. The resultant deep percolation from these areas could contribute to a rise in the overall water table levels. Furthermore if (due to poor scheduling) the irrigation water applications are excessive compared to crop water usage and leaching requirements, the resultant deep percolation would exacerbate any water table problems. Drainage systems are expensive; therefore, both the irrigation system and its management need to be optimised to ensure that costs of drainage infrastructure are minimised for new installations or to ensure that any existing drainage installations are not overloaded and rendered ineffective (see Section 6 for information on evaluating irrigation systems).

4.2.5 Data management

In order for the irrigator to fully benefit from time-consuming and often expensive monitoring practices, it is important that data be collected regularly and stored in a way that makes it easily accessible, in a user-friendly format.

Many scheduling and measuring devices are supplied with their own software, especially in the case of electronic equipment. This makes it possible for the irrigator to analyse the data and present it in graphical format. Irrigation consultants can also provide this service at a fee, supplying the irrigator with a recommendation regarding irrigation requirements in the field where the scheduling devices are installed. Consultants often offer additional, related services that add value to the scheduling advice, such as weather predictions, and pesticide or herbicide recommendations. This supports crop health, which in turn results in the optimal use of irrigation water and yields.

4.2.6 First-hand observations/inspections

As stated earlier, no amount of measurement can replace the value of first-hand observations made in the field or orchard. Computer models can be used to predict water requirements, and sophisticated equipment used to monitor soil and other parameters, but the effect of the actions taken by the irrigator should also be verified by observing the condition of the soil and the plants. Profile holes should be dug periodically to investigate water distribution and root development under the irrigation system.

5 Maintenance

The most efficient system will be one that is maintained according to the equipment manufacturers' and/or irrigation designer's recommendations.

An irrigation system is an asset to the producer, and this chapter aims to present the principles of managing these assets as effectively as possible, while keeping in mind the operational safety, health and environmental issues that a producer is faced with at farm level.

Lack of maintenance results in decreased system performance, for example by:

- increased blockages in micro irrigation emitters (resulting in lower uniformity);
- increased losses through leaks or worn sprinkler nozzles (resulting in higher flow rates, lower pressures, low uniformity, and higher energy requirements), and
- reduced flow rates/higher friction loss in unflushed pipes.

The acquisition and operation of irrigation systems requires significant financial inputs from the producer. An irrigation system that is well-maintained performs well in terms of efficiency and consistency, requires few emergency repairs and helps the producer to optimise their crop production system, thereby maximising profits.

An effective maintenance program for irrigation systems includes:

- Servicing schedules (including an inventory and spares in stock to be kept), and
- Replacement schedules for the different components.

Some general guidelines on maintenance of in-field irrigation systems are provided below as published in the ARC-IAE's Irrigation User Manual, but complete information on the maintenance of different irrigation system components can be accessed in the same publication. Most manufacturers also provide specific maintenance schedules for their products.

5.1 Micro irrigation systems

Table 26 indicates intervals for maintenance actions appropriate to micro-irrigation systems.

Table 26: Maintenance schedule for micro-irrigation systems (manual control)*

Action	With each cycle	Monthly	Annually
Inspect system for leakages	X		
Check system pressure and flow rate	X		
Flush laterals (depending on the water quality		X (or weekly)	
Service air valves and pressure control valves			X
Check hydraulic and electrical connections			X
Check functioning of hydraulic valves on filter bank and inspect moving parts			X
Chlorine treatment (depending on the water quality and method of application)			X
Take water sample at end of system and evaluate water quality changes			X

*The recommended maintenance schedule can be adapted for automatic systems, e.g. system pressure can be monitored monthly.

5.2 Sprinkler irrigation systems

Table 27 indicates intervals for maintenance actions appropriate to sprinkler irrigation systems.

Table 27: Maintenance schedule for sprinkler irrigation systems (manual control)*:

Action	With each cycle	Annually
Inspect the system for leakages	X	
Check system pressure and system flow	X	
Service air valves and hydrants		X
Check sprinklers for wear and replace springs, washers and nozzles where necessary		X
Flush mainlines		X
Replace rubbers at quick coupling pipes where necessary		X

*The suggested maintenance schedule can be adapted for automatic permanent systems, e.g. system pressure can be monitored monthly.

After the irrigation season, and before the pipes are stored, the following must be done:

- Mark all the holes in quick coupling pipes with paint so that they can be repaired.
- Remove all gaskets from pipes if they are stored in the sun.
- Replace all damaged and hardened gaskets.
- Replace all worn male and female pipe fittings.
- Replace all dragline pipes that have more than three joints.
- Check standing pipes for corrosion and replace if necessary.
- Ensure that all standing pipes are the same length and straight.

5.3 Moving irrigation systems

Table 28 indicates intervals for maintenance actions appropriate to moving irrigation systems.

Table 28: Maintenance schedule of centre pivots

Action	**After each revolution**	**After each 4th revolution**	**Seasonal**
Electrical			
Switch on pivot and listen to each motor and starter. If any abnormal sound is heard, remove and service.			X
Replace end tower's electric bulb (if out) and remove dust, insects and water where necessary.			X
Check tower panel and main control cabinet. Clean panels, remove dust, insects e.g. wasps, etc.			X
Inspect condition of wiring of pivot			X
Inspect electrical motor cable condition, earth conductor and connections			X
Structure			
Tighten all bolts and nuts where necessary. Ensure that earth conductors are clean.			X
Grease pivot		X	X

Grease pin that holds swing mechanism of towable pivots to prevent rusting		X	X
Check system for leakages. Repair if necessary			X
Replace gearbox oil			X
Drain and replace lubricants in motors			X
Grease moving parts and roller bearings	X		X
Check U-couplings, grease if necessary			X
Check wheel bolts and adjust as prescribed	X	X	X
Check wheel pressure and adjust as prescribed	X		X
Check flange fittings for leakages, secure and replace if necessary	X		X
Inspect framework for sturdiness – tighten bolts if necessary	X		X
Check that all the safety switches work			X
Check that all the drainage valves work	X		X
Clean sand trap if necessary	X		X
Sprinklers			
Check nozzles for wear, replace if necessary			X
Check that the pressure meter works correctly			X
Check the condition of the sprinklers			X
Check pivot pressure and pressure at beginning of towers			X
Check for blockages in nozzles	X	X	X
Flush the system			X
Equipment			
Check functioning of end nozzles and check nozzle for wear			X

Inspect cut-off action of end nozzle – repair or replace if necessary			X
Check stop in slot micro switch, adjust if necessary	X		X
Test the automatic reverse-action movement of pivots by switching the hand lever forward and back			X
Fill wheel tracks deeper than 150 mm with timber or stones		X	

With linear systems, the following additional measures must be kept in mind when maintenance is undertaken:

Drive			
All electrical cables must be checked regularly and replaced if necessary. Check bearings and belts and adjust if necessary.			X
Alignment			
Check alignment according to manufacturer's prescriptions. Where a system uses a supply line that must be towed, the road must be as even and dry as possible to make the towing of pipe easier.			X

6 Evaluation

The most efficient system will be one that is regularly evaluated to assess the level of performance and detect problems as early as possible.

Evaluation differs from monitoring, in the sense that it is performed periodically rather than continuously. Irrigation system evaluation is an important tool that should be applied to assess whether the system is performing as intended by the designer and whether the irrigator's maintenance practices are effective.

The objectives of evaluating the performance of an irrigation system are to:

- determine if the system is working according to a farmer's assumptions and design specifications in terms of the amount of water applied, and to thereby provide a basis for improved irrigation scheduling,
- determine how much variation there is in the amounts of water applied and whether or not the measured variation has a significant impact on crop yields, deep percolation (drainage) and runoff losses, fertiliser use efficiencies and production costs,
- determine the causes of the variation in applied water and to investigate and recommend cost effective remedial action,
- assess whether or not the conveyance system is sized within design norms that were based on a fair balance between capital and operating costs,
- check the efficiency with which power is being used, and
- produce recommendations to improve on any aspects that would result in the effective use of water and energy.

The information from an evaluation should help a farmer reduce input costs, increase returns and, if necessary, provide motivation for a designer to implement remedial measures if a design was not up to standard (Griffiths and Lecler, 2001).

There are a number of published evaluation methodologies for the various types of irrigation systems. A particularly useful resource is the *Manual for the Evaluation of Irrigation Systems* published by ARC-IAE (Koegelenberg and Breedt, 2003). It is not the intention of these guidelines to reproduce the details contained in these Manuals, but rather to provide a commentary on how the methodologies can be adopted and applied to different irrigation systems.

6.1 Benchmarks/Performance Indicators

A multitude of uniformity indices have been reported, including:

- Christiansen's coefficient of uniformity,
- Statistical uniformity,

- Distribution uniformity, and
- Emission uniformity.

All of the indices rely on assessing the amount of water applied during a given irrigation event and the spatial variability in application amounts. Thus, rather than specifying a particular index to be used, we recommend that an adequacy chart be provided, together with a table of the data used to derive the chart. Provision of this data will allow a range of uniformity indexes to be calculated and compared if necessary, and provide a visual perspective of the in-field variability of water applications.

The data used to derive an adequacy chart can also be used for water balance assessments, i.e. to provide information on relative depths of applied water for different sections/portions of a field. An example of an adequacy chart and associated data-table is shown in Figure 28 and Table 29.

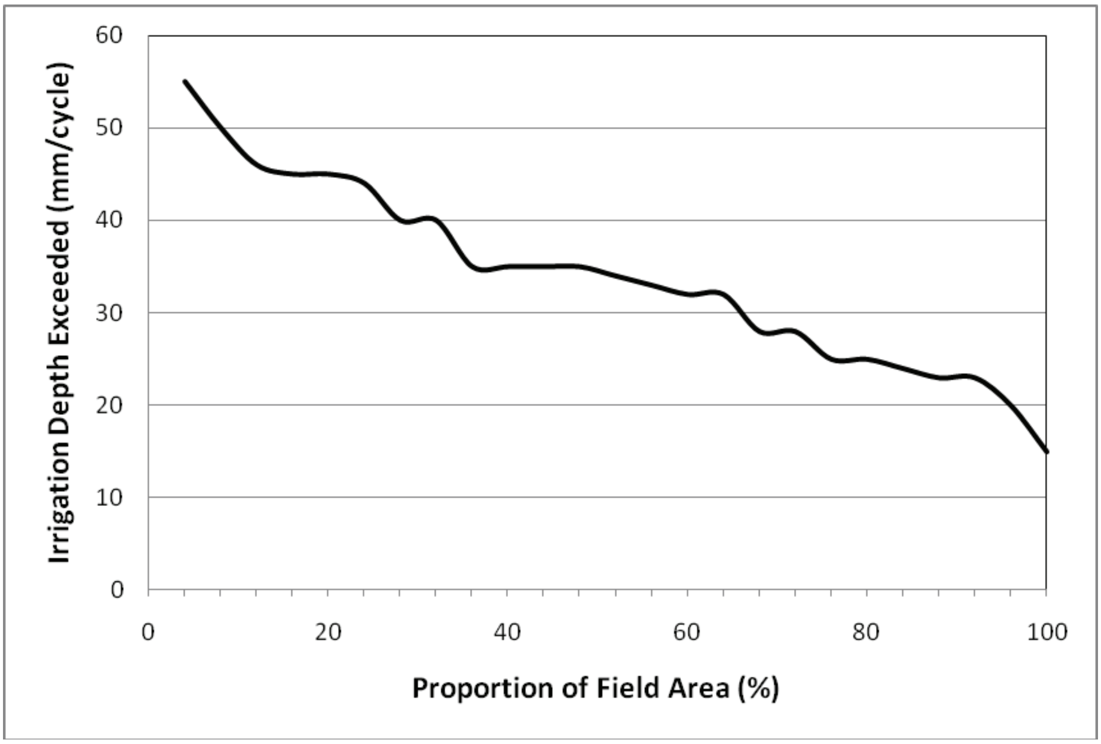


Figure 28: Example of an irrigation adequacy chart plotted using data shown in Table 29.

Table 29: Field measurements, ranked, used to plot the adequacy chart shown in Figure 28, and used to calculate a given performance index, i.e. the low quarter distribution uniformity, DU_{lq}

Position No.	Depth Applied (mm/cycle)		Proportion of field area (%)	Depth Exceeded (mm/cycle)
1	32		100	15
2	40		96	20
3	20		92	23
4	23		88	23
5	35		84	24
6	32		80	25
7	15		76	25
8	45		72	28
9	40	➡	68	28
10	35		64	32
11	24		60	32
12	25		56	33
13	28		52	34
14	35		48	35
15	45		44	35
16	46		40	35
17	50		36	35
18	34		32	40
19	35		28	40
20	25		24	44
21	28		20	45
22	33		16	45
23	23		12	46
24	44		8	50
25	55		4	55
			Average in low 1/4	21.7
			Average applied	33.9
			DUlq	64.0

Note: DU_{lq} = Average in low ¼/Average applied x 100 = 21.7/33.9 x 100 = 64.0

A universal challenge to assessing uniformity is obtaining a field-wide perspective of application amounts and variability rather than the detail of only a relatively small (and possibly unrepresentative) portion of a field. When applying the standards and statistics used in drip evaluations it is recommended that at least 25 readings of water application per field are taken, such that each reading in the adequacy table is representative of 4% of the field area. This represents challenges and modifications to standard evaluation methods which are discussed in the sections that follow.

6.2 Methods for evaluating irrigation hardware

The recognised evaluation methods for different irrigation systems are described in detail in the *Manual for the Evaluation of Irrigation Systems* published by the ARC-IAE (Koegelenberg and Breedt, 2003). Evaluation of in-field systems focuses on measuring flow and pressure, and assessing the distribution uniformity of the system. Flow and pressure measurements are compared with the design values as stated in the design report. The adequacy chart and table can be used to assess representative irrigation application amounts and whether or not there are problems with uniformity. The DU_{lq} calculated from data shown in the adequacy table should exceed 70% for all irrigation systems.

6.2.1 Overhead sprinkler

In the sprinkler method of irrigation, water is applied above the ground surface as a spray resembling rainfall. The spray is developed by the flow of water under pressure through orifices or nozzles. The pressure is usually obtained by pumping, and the irrigation water is distributed to the field through pipelines (Koegelenberg F H, 2003). There are a variety of systems within the overhead sprinkler group, including:

- Big guns
- Centre pivots
- Linear moves
- Hand-moved sprinklers, and
- Permanent and semi-permanent sprinklers (e.g. 'floppy' irrigation systems)

In order to develop irrigation adequacy charts and diagrams, the water applied to representative portions of a field needs to be determined. The amount of water applied to representative portions of a field can be measured by:

- Measuring flow-rates at individual sprinklers
- Measuring the amount of water caught in catch-cans
- A combination of the above

Detailed evaluation procedures for sprinkler irrigation are described in the *Manual for the Evaluation of Irrigation Systems* by ARC-IAE (Koegelenberg and Breedt, 2003). However, it is often necessary to modify these procedures to obtain data to represent a whole field area, rather than focusing in detail on just small portions of a field at a given point in time. Furthermore the definitions of "Application Efficiency" and "System Efficiency" given by Koegelenberg and Breedt (2003) have been updated in these guidelines.

The following refinements to the procedures to evaluate hand-moved sprinkler, permanent and semi-permanent sprinkler are advised.

Refined procedures to assess uniformity of hand-moved, permanent and/or semi-permanent sprinkler irrigation systems

The challenge with evaluating sprinkler irrigation is to obtain a field-wide perspective of irrigation application amounts and variability, rather than a detailed view of only a relatively small and possibly unrepresentative portion of a field at a particular point in time.

The wetting pattern and discharge of sprinklers is primarily a function of pressure (assuming there are no mechanical problems with sprinkler movement). In a good design, the spacing and operating pressure of the sprinklers is selected such that the overlapping spray patterns result in a uniform application of a desired amount of water over the field area. Problems arise if the sprinkler spacings are inappropriate, if the nozzles are worn or if the operating pressures are too high or too low.

Another major issue, particularly with hand-moved sprinklers, is that sprinkler stand times are not the same and/or the movement of the sprinklers is irregular, resulting in different portions of a field being watered very differently. Thus, even if the system is operating perfectly in terms of pressures, flow rates and spacings, the watering pattern will be uneven with associated poor performance.

The process of evaluating the depth and variability of water applied to a whole field by using traditional sprinkler evaluation methods involving catch-can grids is impractical, because in typical evaluation procedures, catch-cans are laid out in only small and likely unrepresentative portions of a field. Further, even these limited catch-can tests are very time consuming, and often require that system hydraulics are compromised in order to have sprinklers operating at all corners of an array of catch-cans at the same time. Compounding this situation even further is the fact that the climatic conditions on a given day can have a significant impact on catch-can readings: ‘test-day’ conditions may not be representative of typical operating conditions. Also, the movement and (maybe more importantly), the potentially irregular movement of sprinklers is not assessed.

To overcome these challenges and to gain an overall perspective of sprinkler irrigation performance, a multi-stage approach is recommended, similar to furrow irrigation.

In the first stage, the flow-rates, pressure, nozzle size and stand times of 25 representative sprinklers is measured and used to determine an adequacy chart and table, each sprinkler representing 4 % of the total field area. These adequacy charts and tables show the average amount of water applied per representative sprinkler area and the variation between sprinklers (for example, see Figure 29 and Table 30).

In a further stage, the pressure, nozzle size and sprinkler spacing are compared to manufacturer recommendations for the given sprinkler type. Depending on these results, a process to optimise performance is initiated. This would require input of an experienced irrigation engineer whose recommendations may include:

- adjusting field valve pressure settings, if possible
- replacing worn nozzles
- repairing pumps
- selecting more appropriate sprinklers
- changing pipe sizes or pumps or sprinkler types/sizes.

Software to simulate performance includes Catch3D (Allen, 2001) which can be used to calculate the uniformities due to different sprinkler layouts/spacings, wind and operating pressures.

6.2.2 Moving sprinkler systems

Moving sprinkler systems consist of centre pivot, big gun and linear move systems. The evaluation procedures for these systems are well described by Koegelenberg and Breedt (2003). The only modification would be to use the data to produce adequacy charts and tables in order to be consistent with other systems. Here the area represented by each catch can reading will depend on its position relative to the centre of the pivot. This needs to be accounted for in the calculations used to produce the adequacy chart and table as shown for example in Figure 29 and Table 30.

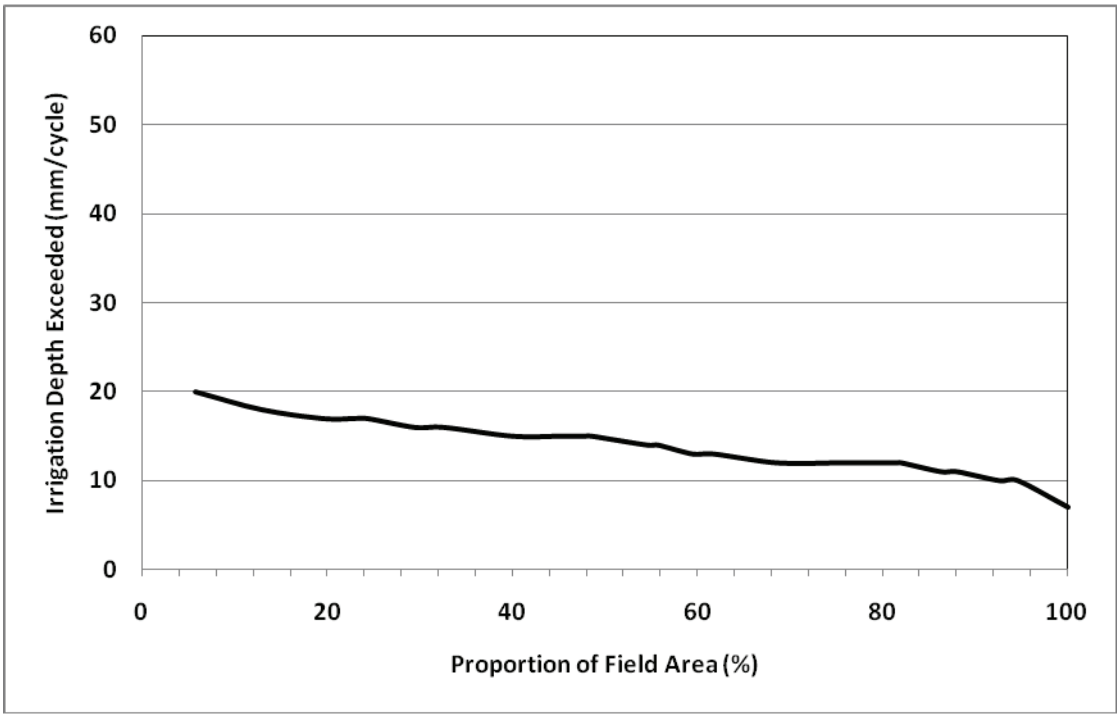


Figure 29 Example of an irrigation adequacy chart, plotted using data shown in Table 30 and with the Y-axis range the same as used for Figure 28 in order to illustrate the difference in uniformity

Table 30 Field measurements used to plot the adequacy chart shown in Figure 29, and used to calculate a given performance index, in this case the low quarter distribution uniformity, DUlq

Catch Can No.	Distance from Centre (m)	Represent-ative Area (m^2)	Catch Can Reading (mm/cycle)	Data transferred to	Represent-ative Area (m^2)	Catch Can Reading (mm/cycle)	Percent of Field Area	Cumulative Percent of Field Area
1	10	78.5	12		746.1	7	5.4	100
2	15	117.8	15		274.9	10	2.0	95
3	20	157.1	14		628.3	10	4.6	93
4	25	196.3	17		235.6	11	1.7	88
5	30	235.6	11		589.0	11	4.3	86
6	35	274.9	10		78.5	12	0.6	82
7	40	314.2	13		353.4	12	2.6	81
8	45	353.4	12		549.8	12	4.0	79
9	50	392.7	15		863.9	12	6.3	75
10	55	432.0	16		942.5	12	6.9	69
11	60	471.2	17		314.2	13	2.3	62
12	65	510.5	13		510.5	13	3.7	59
13	70	549.8	12		157.1	14	1.1	56
14	75	589.0	11		824.7	14	6.0	55
15	80	628.3	10		117.8	15	0.9	49
16	85	667.6	15		392.7	15	2.9	48
17	90	706.9	16		667.6	15	4.9	45
18	95	746.1	7		1021.0	15	7.4	40
19	100	785.4	20		432.0	16	3.1	33
20	105	824.7	14		706.9	16	5.1	29
21	110	863.9	12		196.3	17	1.4	24
22	115	903.2	17		471.2	17	3.4	23
23	120	942.5	12		903.2	17	6.6	19
24	125	981.7	18		981.7	18	7.1	13
25	130	1021.0	15		785.4	20	5.7	6
						Weighted Average in low 1/4		13.2
						Weighted Average applied		14.0
					DUlq			93.9

Note: The weighted average is determined by multiplying the catch can reading by the percentage of the field area represented by the reading, summing these for a particular percentage of the field area, (e.g. the ¼ of the field receiving the lowest amounts of water) and dividing the result by the percentage of the field area in question, i.e. 25 for the weighted average in the low ¼, thus:

Weighted Average in low ¼ = (7 x 5.4 + 10 x 2.0 +........+ 12 x 4.0)/25 = 13.2

Weighted Average = (7 x 5.4 + 10 x 2.0 +........+ 12 x 4.0 +......+ 20 x 5.7)/100 = 14.0

DU_{lq} = Weighted Average in low ¼/Weighted Average x 100 = 13.2/14.0 x 100 = 93.9

6.2.3 Micro irrigation systems

Micro systems consist of either micro-sprayers or drippers (surface or sub-surface). With drip systems water is applied more frequently (often daily). Typical components for micro- systems include a pump, filters, chemical injectors, main and submain lines, laterals and emitters or micro-sprayers. The emitters of both systems, especially drip systems, have relatively small flow paths: blockages can cause major problems.

Evaluation procedures for micro-systems are well described by Koegelenberg and Breedt (2003). The only modification would be to use the data to produce adequacy charts and tables in order to be consistent with other systems. It should also be noted that each micro-emitter is designed to water a particular zone of a field, and blanket coverage is often not desired. Thus, the adequacy charts and tables should reflect water applied per zone with at least 25 zones per field included in the measurements.

6.2.4 Surface irrigation

Surface irrigation refers to irrigation systems where water flows over the soil surface under controlled conditions with the purpose of delivering the desired amount of water to infiltrate the soil. Although surface irrigation appears to be relatively simple, it is probably the most difficult irrigation system to design and evaluate. Since furrow irrigation is the most widely practiced form of surface irrigation, the focus of these guidelines is on furrow irrigation. The principles can, however, be extended to other forms of surface irrigation.

The hydraulic performance and water balance of furrow irrigation depends on the furrow length, the inflow rate, the cut-off time, the land slope, the spacing and shape of the furrows, the resistance to flow in the furrows, the infiltration characteristics of the soil, and the in-field variability of all of these factors.

One of the main issues in traditional furrow evaluation methods is that the process of evaluating the depth and variability of water applied to a single furrow can be complex and time-consuming. There can be hundreds of furrows in a single field, so a detailed evaluation of just one or two furrows is hardly representative. Compounding this situation even further is the fact that a given furrow can perform very differently depending on operator input and antecedent soil water conditions. Therefore, a large number of evaluations are needed, often repeated on the same furrow during a season, in order to gain confidence in the results.

To overcome this potential variability and gain an overall perspective of furrow irrigation performance, a multi-stage approach is recommended:

- In the first stage, the amount of water applied to 25 representative furrows per field is measured and can also be used to determine an adequacy chart as with the previous examples. It will show the average amount of water applied per furrow and the variation between furrows.

- In a further stage, detailed evaluations on selected furrows can be performed to determine the variation in applied water down the length of a furrow, for different depths of application, and to investigate ways to optimise performance, (i.e. reduce the variation in water applications and adjust the magnitude to suit soil and crop conditions).
- In a further stage, a selection of furrows can be evaluated at different times during the season in order to assess how performance may change with crop growth.

Commentary on methods to undertake these measurements follows.

Measuring average depth of water applied to furrows and determining field-wide adequacy charts.

The rate of inflow to a furrow can be measured using, for example, a calibrated syphon and head measuring device or a calibrated flume/weir. The outflow, if any, can be measured with a calibrated flume.

In Australia, the "Irrimate TM" tools have been developed for evaluating surface irrigation systems. These include a digital siphon flowmeter to determine inflow volume, water advance sensors, and a digital in-furrow downstream flume to measure outflow volume (Raine et al., 2005).

In Zimbabwe, Griffiths and Lecler (Griffiths 2007) developed a simple and efficient method to measure the difference in height in the water level between the supply canal and the furrow, which facilitates the use of calibrated syphons to measure furrow in-flows. The simple head measuring device is shown in Figure 30, and was named a "Greller". The use of the Greller allowed measuring in-flows to furrows to be integrated with standard irrigation-operator responsibilities, thus allowing the collection of a vast and representative amount of furrow in-flow data in an effective and efficient manner.

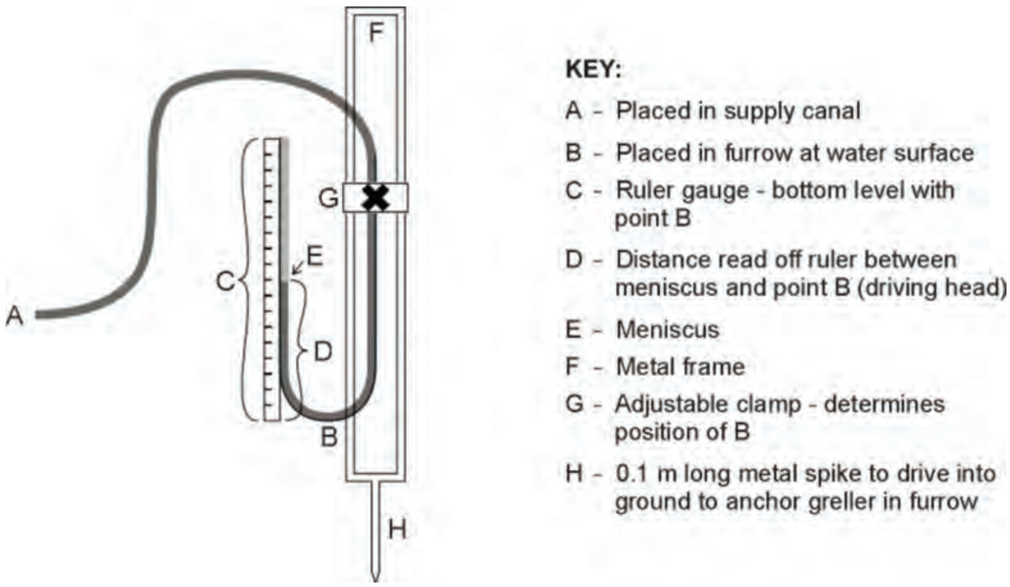


Figure 30: The Greller device used to measure the head driving flow in a siphon (Griffiths 2007)

The Greller measures the driving head for flow in a syphon to an acceptable level of accuracy. As shown in Figure 30, the tube at point A is placed in the supply canal (the feeder), point B is placed in the furrow and positioned so that it just touches the water in the furrow after the inflow has stabilised. The difference in water level between the feeder and the furrow water levels is represented by a meniscus (E) in the tube and the bottom of the ruler (B), shown as D.

Once the flow-rate into furrows has been determined, the average depth of water applied is easily calculated by converting the flow-rate to a volume, i.e. by multiplying the flow-rate by the time during which water flows into the furrow, and dividing the volume by the representative furrow area, i.e. furrow length multiplied by furrow spacing. An example calculation is given in Figure 19, Section 4.2.3. The application depths can then be used to produce an adequacy chart and table.

Assessing and optimising in-furrow performance

Furrow performance can be optimised by taking a number of detailed measurements in-field and then using the field data to calibrate computer simulation models. The simulation models can then be used to undertake "what-if" analyses whereby various parameters are varied in an effort to improve performance.

The approach is complex and time-consuming, and requires input of appropriately qualified irrigation engineering experts. A brief description of the procedure follows, whilst detailed descriptions of the methods are available in the FAO 45 publication (Walker, 1989), Burt (1995) and Koegelenberg and Breedt (2003).

In addition to measuring furrow in-flow and outflow rates, the important measurement parameters to optimise furrow performance are:

- furrow slopes

- depth and area of water flowing in the furrow
- advance front
- recession front

After the measurements are taken, the data can be used to calculate the infiltration parameters using the 'two-point' method (Elliot and Walker, 1982), the 'advance' technique using Infiltv5 (Durack, 2001) and more recently IPARM (Gillies and Smith, 2005), which uses the outflow data as well as advance data to calculate infiltration parameters.

The furrow topographic characteristics and infiltration parameters can then be used in simulation software, e.g. SIRMOD (Walker, 1989) and/or SRFRv3.31 (Strelkoff et al., 1998). This software can be used to predict irrigation performance, for example, system uniformity and the water balance assuming given soil water deficits for different gradients, soils, field dimensions, and planting arrangements. This prediction capability may facilitate the modification of operational furrow irrigation guidelines and, if necessary, be incorporated in the design and layout so that performance is optimised.

Both Tilley and Chapman (1999) and Raine et al. (2005) state that the software which is currently used in Australia (SIRMOD) is used mostly for showing farmers the benefits of management practices and has been very effective in this regard. An area of concern, however, is the accuracy of the calculated infiltration parameters and whether they are representative of the field as a whole.

6.3 Evaluation in terms of the water balance/Interpretation of results

The rational quantification of the water balance, in relation to the uniformity of applied water, the environment and the water management approach, forms the basis of assessing the performance of irrigation and water management systems at the field scale. This can be done by:

- Applying the evaluation procedures and tools described in Section 6.2 to record in-field operating characteristics of irrigation system hardware, i.e. to determine adequacy charts and tables.
- Obtaining a description of the irrigation scheduling strategy/rationale or obtaining historical records of irrigation water applications, i.e. the timing and amount of water applied.
- Using an appropriate water balance and crop yield simulation model to predict how an irrigation system (with the recorded watering characteristics and operated according to the given scheduling strategy) would impact predicted crop yields and water budgets.

This approach is illustrated diagrammatically in Figure 31. Models which can be used in this process include:

- SAPWAT3 – if only the water balance components are to be evaluated. SAPWAT3 is not really designed to reflect crop yield impacts, or to reflect the impact of non-uniform water applications on the water balance. The impacts of non-uniform water applications can however be assessed by doing multiple simulations with each simulation representing a representative portion of the adequacy chart.

- SWB model – if both the water balance and crop yield impacts are assessed. As with SAPWAT3, the SWB model is not designed to reflect the impact of non-uniform water applications on the water balance. However, these impacts could be assessed by doing multiple simulations, with each simulation reflecting a representative portion of the adequacy chart.
- *ZIMsched 2.0* – if sugarcane is the crop being irrigated. *ZIMsched 2.0* is unique in that it does account for the impact of non-uniform irrigation on the water balance and predicted crop yields: however, it is designed for sugarcane only.

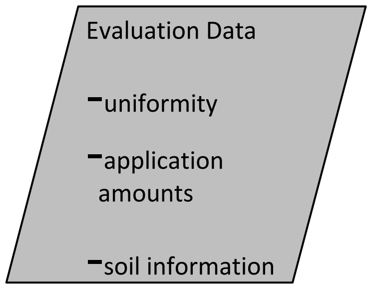


Figure 31: Diagrammatic depiction of the methodology to evaluate irrigation hardware and water management systems (after Lecler, 2004)

6.4 Application

The application of system evaluation methods is well supported by both the ARC-IAE and SABI. The ARC-IAE has a mobile irrigation laboratory that contains all the necessary equipment to evaluate any type of irrigation system, and evaluations can be done on request by the ARC staff. SABI presents annual system evaluation courses that are based on the ARC-IAE's manual, and include a mini kit of equipment with which course delegates can perform most of the basic evaluation activities.

6.5 Trouble shooting

After a system has been evaluated, the results should be interpreted and followed up with the necessary maintenance or trouble shooting activities. In some cases, corrective interventions may be easy and inexpensive to implement, but in some cases there may be a need for significant changes to the irrigation system.

The ARC-IAE's Irrigation User Manual contains guidelines on trouble shooting of different irrigation systems.

7 Summary

The following guidelines should be adhered to when planning, designing and managing in-field irrigation systems:

- Assess the suitability of soils for irrigation, according to the irrigation potential classification system, and determine the soil water holding capacity and infiltration rate
- Assess the water requirements of the crop to be irrigated
- Assess the suitability of water quality for irrigation, according to the South African Water Quality Guidelines for agricultural use
- Use the SAPWAT3 computer programme to determine irrigation water requirements, incorporating the Penman-Monteith equation, quaternary weather station data and irrigation system specific application efficiency parameters
- Use the SABI irrigation design norms to design the irrigation system components
- Apply a sound scheduling strategy supported by reliable soil water content measurements and verified with in-field check when operating the irrigation system
- Regularly monitor the irrigation system's performance against the design parameters
- Periodically evaluate the performance of the irrigation system and perform the necessary maintenance and trouble-shooting to ensure optimal performance.

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Standards and Guidelines for Improved Efficiency of Irrigation Water Use from Dam Wall Release to Root Zone Application

EFFICIENT WATER USE GUIDELINES

Module 3

DEVELOPING AND MANAGING

EFFICIENT ON-FARM CONVEYANCE SCHEMES

i

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List of acronyms and abbreviations

ARC-IAE	Agricultural Research Council – Institute for Agricultural Engineering
BC	Beneficial consumption
CI	Confidence Interval
CMA	Catchment Management Agency
CV	Coefficient of variation
DWA	Department of Water Affairs
GWCA	Ground Water Control Area
H	Pressure head, m
HP	Horse Power
IB	Irrigation Board
ICID	International Commission on Irrigation and Drainage
IWMI	International Water Management Institute
η	Efficiency
NBC	Non-beneficial consumption
NRF	Non-recoverable fraction
P	Power, kilowatt
Q	Flow rate
RF	Recoverable fraction
SC	Storage change
VSD	Variable Speed Drive
WUA	Water Users Association

1 Introduction

The purpose of the on-farm conveyance system is to convey the water from the farm edge to the field at the lowest possible energy requirement – operational economy and conveyance efficiency of the system components are therefore of importance.

The on-farm conveyance system include the control valves, mainlines, filters, pumps, motors, switchgear, transformers, cables, automation and drainage. Optimisation of the performance of any component of the system requires careful consideration of the implications of decisions made during both development (planning and design) and management (operation and maintenance) of the component. Optimisation through management alone will be severely limited in its potential if the infrastructure was not developed with technical, economical and environmental efficiency in mind.

The most efficient on-farm conveyance system will therefore be one that:

- Is planned in size and lay-out with the lowest capital and operating costs in mind to supply and remove water to and from the in-field irrigation systems,
- Is designed according to sound principles that will result in the most economical solution to the irrigator,
- Consists of quality equipment with high inherent energy efficiencies,
- Is operated according to the design specifications and the flow and pressure requirements of the in-field irrigation systems,
- Is maintained according to the equipment manufacturers' and / or irrigation designer's recommendations, and
- Is regularly evaluated to assess the level of performance and detect problems as early as possible.

This module therefore provide guidelines on how these aspects of system development and management can be addressed, through different methodologies and examples of where they have been applied in South Africa.

2 Planning

The most efficient on-farm conveyance system will be one that is planned in size and lay-out with the lowest capital and operating costs in mind to supply and remove water to and from the in-field irrigation systems. Systems should be planned within the limitations of lawful water supply and known reliable supply, as this can have an effect on the system flow rate available on the farm. Correct selection and placing of the different on-farm conveyance system components will have an effect on the energy required to operate the system – using farm dams to balance supply and demand, the amount of energy required to supply water to the hydraulically most remote point on the farm, pressure required to flush filters, and flow rates required by fertigation systems are some of the aspects that should be taken into account. Improved system operation by means of automated controls as well as improved sustainability through the installation of drainage systems should also be considered.

2.1 System lay-out

The planning and design of the in-field irrigation system components will result in the flow rates and operating pressures required at different locations on the farm to be known. The on-farm conveyance system should consequently be planned and designed so that the most economical main line pipe sizes can be used without excessive energy requirements at the pump station.

Irrigation blocks and/or systems should be arranged in a practical manner, applicable to the farmer's operating practices, as these decisions will have an effect on the size of the mainlines required:

• Specific operational practices often compel the grouping together of blocks involved. Newly planted crops usually consist of crops and cultivars which are grouped together for obvious reasons. It is also easier to control the operation of one valve, as well as maintenance activities, which are limited to a single area. However, this practice should be implemented with caution, especially when the farmer insists upon it without first considering other options.

• Non-adjacent distribution of blocks or systems to be operated simultaneously has the result that the water, which flows to the blocks or systems at any time, is conveyed in different directions through the distribution network. This has the effect that less water flows through each pipe section and that diameters can accordingly be sized smaller and cheaper. Such a group of blocks or systems will obviously utilise multiple valves operating simultaneously. The cost incurred with this approach must therefore be compared to the cost of groups of adjacently situated blocks, which are often supplied by only one (larger) valve.

• Automation also plays an important role, as described further below. This role can have a drastic impact on group composition and should likewise be taken into account at this stage.

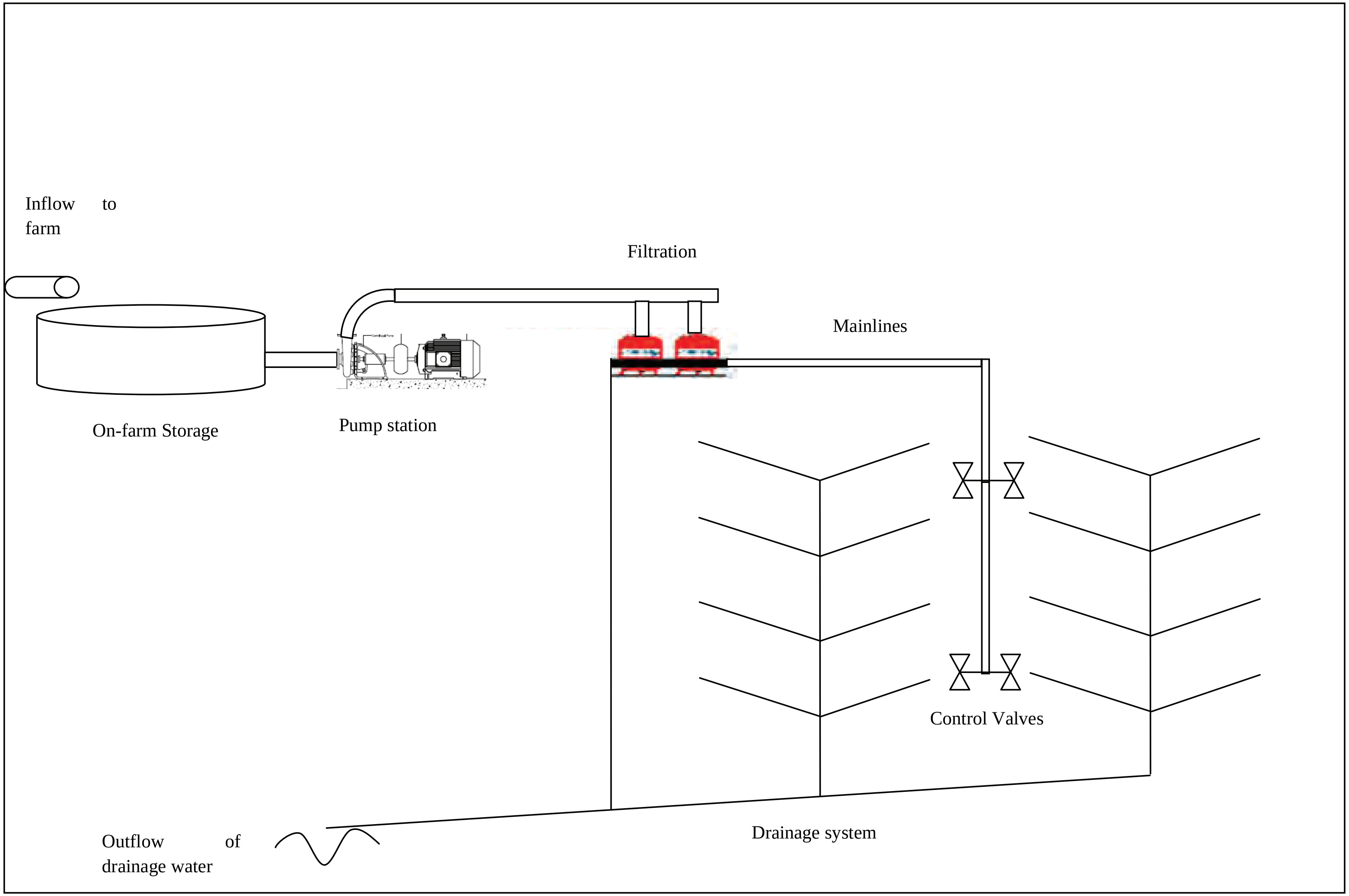


Figure 1: Typical components of the on-farm conveyance system

The irrigator can also decide on whether on-farm balancing dams should be used, or whether the water from the source will be pumped directly into the irrigation system. The use of balancing dams provides the irrigator with security and flexibility. If water is pumped directly into the irrigation system, the irrigator may be limited to a certain number of hours (if, for instance, he/she is part of an irrigation scheme), or certain irrigation intervals. In the other hand, if a balancing dam is to be used, there should be space on the farm for it in a suitable location, there is a significant cost involved when building the dam, and there may be additional water losses (seepage and evaporation) due to the water being stored. The situation therefore need to be analysed and the cost benefit determined.

2.2 Water sources

Both surface and ground water sources are used extensively for irrigation in South Africa. Water can be taken for irrigation directly from a river, or via a canal or shared pipeline, or from a groundwater aquifer.

The allocation of water and the use thereof by individual users from the different sectors is regulated by legislation. The act currently in force, is the National Water Act (Act 36 of 1998), which determines that the government is the official custodian of the country’s water. This described in detail in Module 1.

The water user should ensure that the planned irrigation system will not require more water than what he/she is lawfully entitled to, or what the source can sustainably provide, whichever may be less. Bore holes should be tested and the results interpreted by a hydrogeologist to prevent over extraction of groundwater.

2.3 Pump stations

If the location of the pump station can be selected, it should be as near as possible to the centre of the design area. As the purpose of the on-farm distribution system is to distribute water as economically as possible from the farm edge to the field edge, the efficient use of energy and economical pumps and motors becomes important.

Distributing water economically requires the system to have the lowest possible energy need. The energy (or kilowatt) requirement of the system depends on the following aspects:

2.3.1 The flow rate of the irrigation system

The higher the flow rate required, the greater the amount of power needed to supply it, and therefore the higher the energy cost. The flow rate of a system is influenced by the irrigation requirement of the crop, the application efficiency of the system applying the water, the effectiveness of the irrigator’s scheduling strategy, and the number of hours per day that the system is used. For example, a system that is in poor condition with many leaks will have a higher flow rate requirement, and therefore a higher energy requirement.

The flow rate of the system is simply the volume of water to be applied in one irrigation cycle (which is the product of the depth required for the cycle and the area on which is to be applied) divided by the time available to do so. The number of hours available within an irrigation cycle to apply the required amount of water therefore has a major impact on the flow rate for which the system has to be designed. The recommended maximum number of hours per week (ARC-IAE, 2003) that could be used to irrigate, are:

- Micro and permanent sprinkler systems: 144 hours
- Centre pivots systems: 144 hours
- Portable sprinkler and other portable systems: 110 hours
- Flood irrigation systems: 60 hours

However care should be taken to use these values when the irrigation cycle is less than one week in length, as non-irrigating days over weekends, for instance, can increase the requirement to be applied by the system (because the time available is less). These hours also does not take into account electricity tariff periods (see section 2.4).

The flow rate of the system determines what portion of the total area can be irrigated at any given time in the cycle. The whole area is therefore divided in groups, which are irrigated one at a time on a rotational basis. More time available in the cycle means a larger number of smaller groups, which means smaller flow rates and therefore smaller mainline pipe sizes.

2.3.2 The pressure requirement of the irrigation system

Similarly to the flow rate, the higher the pressure required to operate the irrigation system, the higher the energy requirement of the system. The pressure requirement of the system is influenced by the operating pressure of the selected irrigation system, the topography of the farm, the pipe sizing strategy used to design the distribution system, the length of the pipes distributing water on the farm, and friction loss through the other system components such as valves, filters, etc. The greater any of these factors are on a farm, the greater the pressure requirement will be and therefore the higher the operating cost will be.

2.3.3 The efficiency of the pump and motor

The higher the pump efficiency, the lower the energy requirement. Different pump brands and types of pumps can have quite different efficiencies even though they are pumping the same amount of water. This efficiency depends on the design of the pump. Likewise, different motor brands have different efficiencies. The energy cost of running the system depends on both of these factors.

The key to an efficient pumping system is to select the best motor/pump combination at the design stage. If the better combination is more expensive, an economic evaluation should be made to determine if the possible savings in energy outweigh the additional capital cost.

Operating a pump at a flow at or beyond its maximum efficiency point will reduce the cost per cubic metre of water pumped. As pumps wear, they become less efficient. Monitoring performance with pump tests will tell one whether or not loss of performance is significant enough to warrant repairs.

ESKOM launched its Energy Efficient Motors Programme in 2007, in which a subsidy is paid to electricity users who replace older, inefficient motors with premium efficiency (Efficiency 1) motors. More details are available at www.eskom.co.za/dsm

2.3.4 Total energy requirement

The total power requirement of the pump station is therefore calculated as:

$$P = \frac{H \times Q}{0.036 \times \eta_p \times \eta_m} \qquad \textbf{Equation 1}$$

Where P = Power (kW)

H = Pressure head (m)

Q = Flow rate (m^3/h)

η_p = pump efficiency (fraction)

η_m = motor efficiency (fraction)

2.4 Energy supply

2.4.1 Sources

The types of drives being considered for irrigation mainly include electric motors and to a lesser extent internal combustion engines. The choice between these two main types of drive systems is usually based on economic considerations. The cost of electricity in proportion to that of fuel for an internal combustion engine is such that electricity is usually preferred, except where the cost of supplying electricity at a specific point is very high. Electric motors are consequently usually preferred to internal combustion engines and internal combustion engines are normally only used where three-phase power is unavailable, variable speed is required (which is very unlikely), or where the pump has to be portable. It is, however, also possible to make use of an electric motor for portable pumps, but then every pump station has to be provided with a three-phase power point.

Other sources of energy such as solar power may in future be applied for this purpose, but due to economic considerations and the fact that the best time to irrigate is at night, when the sun doesn't shine, and because the intensity of the sun is changeable, it is not yet being applied for irrigation purposes. Solar power is currently only being used for pumping water for domestic use and stock watering, where the delivery of the pump is very small and may also be variable.

Before a power source is selected for a pump, both the pump speed and the required power on the pump shaft must be known, as well as at the operating point and any variations there upon in case anything unexpected should happen. With centrifugal pumps the required power will always rise if a pipe should burst because the pump will then be operating at a lower pump head and pumping a larger volume of water, which always goes hand in hand with an increase in power requirements, and it may damage the motor. With positive displacement pumps, just the opposite occurs, which is not so critical. It is also necessary to acquire some knowledge of the environmental conditions and what type of protection the installation will enjoy. Will it, for e.g., be housed in a pump house or installed out in the open.

Irrigators can take steps to utilise the waste generated through normal farming operations to create energy. Harnessing the power of the sun can also save energy costs – over the years, these can add up to considerable savings and transform the way business is done.

Where considerable amounts of animal waste are present, the possibility of using biogas installations to generate heat and electricity can be investigated. These installations take the heat generated by animal waste and enable it to be piped into feedlots and piggeries for use as heating, or used for the production of cheap electricity

There are a number of options available to utilise solar power. Solar panels can be used to supply electricity for pumping, charging batteries for lights and any other low wattage use. However, they can be expensive, have a lifespan of approximately ten years and are vulnerable to hail and theft. They also need to be cleaned regularly as dust can reduce their efficiency.

Effective water heating can be provided through a network of black polythene and copper piping through which water is pumped. This can be installed on a roof and used to heat water for the house and/or swimming pool.

Wind energy can be used to charge batteries that can supply power to low wattage equipment in households.

Where water flows constantly from a high point, the water flow can be used to generate electricity.

2.4.2 Tariff structures

Irrigators do not have much influence over electricity prices or the reliability of supply. There is a trend for some electricity supply companies to tailor tariffs to suit irrigation, or to offer load management options, but these are not yet common.

Where cheaper night rate electricity options are available, there is a temptation to design irrigation systems to only operate within those hours, even during peak irrigation periods. For a ten-hour night rate period, irrigation systems have to be designed with over twice the capacity, compared to a system that is operated over a full day (24 hours). This means bigger pipes, pumps and system components, and a much higher cost system.

Given that irrigation systems only need to operate at their peak capacity for part of the season, it is usually much cheaper overall to design systems to operate over the whole day (24 hours), operate at night whenever possible, and extend irrigation into day time rates when demand requires it. A full economic analysis is recommended in the case of new systems, taking into account envisaged tariff increases from ESKOM.

There a various energy cost saving options available from ESKOM. All tariff options included a fixed cost, for the use of infrastructure irrespective of whether electricity was used or not, and variable costs for the actual consumption of electricity. The Landrate option consists of a flat rate, dependant on the size of supply, for both fixed and variable costs. The Ruraflex and Nightsave options, however, were designed to promote the use of electricity during low demand season and off peak hours, as shown in Figure 2. For this reason the variable costs for energy consumption are differentiated according to the time of use. In other words use of electricity during low demand and off-peak periods were rewarded with lower tariffs and charges. The two tariffs for each options, for the 2008/2009 season, are displayed in Table 1. The table only represents a summary of the cost breakdown and is presented to demonstrate the tariff structure for a pre-selected supply size. The full list of current tariffs and charges can be obtained from ESKOM website, www.eskom.co.za

In previous years, the cost of electricity in South Africa was rated amongst the cheapest in the world (Jumman, 2009). This has changed in recent times. Due to the increase in population, the increase in costs for fossil fuels and difficulties with infrastructure, the countries energy supplier, ESKOM, has struggled to meet the electricity demands. As a result, a number of increases in the electricity tariffs have been affected to mitigate the situation. Increases included: 14.2% effective from 1st April 2008, 34.4% effective from 1st July 2008 and finally a further 33.6% increase on 1st July 2009 (ESKOM, 2008 & 2009), another increase of 24, 8% in 2010, 25% in 2011 and 25, 8% in 2012 have been approved. The increase in 2009 also included an environmental levy of 2c per kilowatt hour (ESKOM, 2009). In light of the economic climate, largely attributed to the cost of fuel and agrochemicals, the increase in electricity tariffs has significantly impacted on the profitability of farmers. Planners and water users should therefore investigate all possible energy tariff options and select the most effective one for the specific scenario.

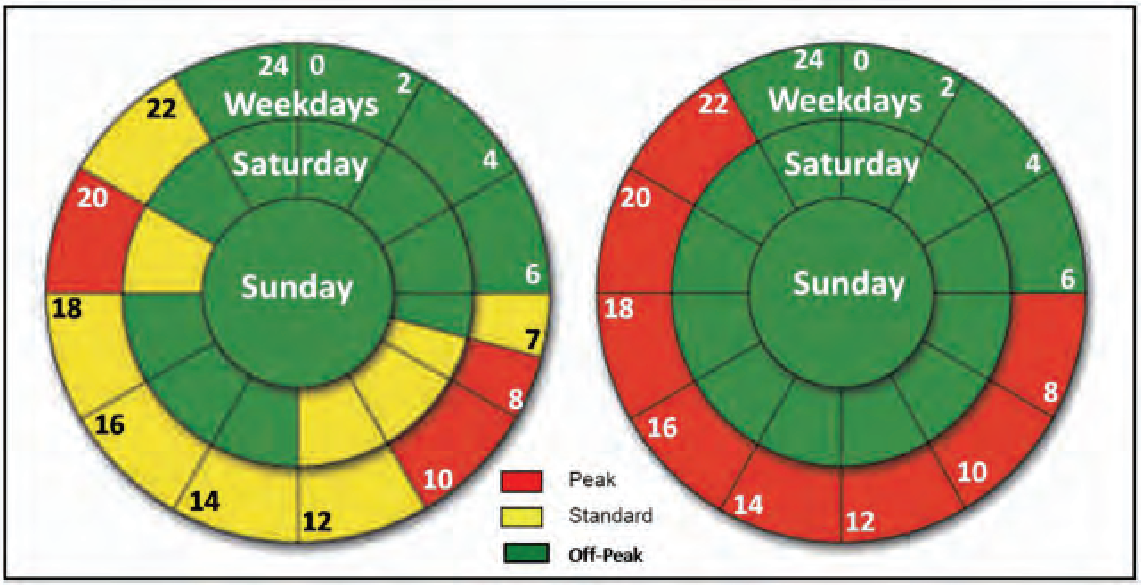


Figure 2: Tariff periods for Ruraflex (left) and Nightsave Rural (right)

Jumman (2009) found that although Ruraflex usually offered greater cost reductions than Landrate, as shown for the graphs for 2007 to 2009 below but as result of the latest tariff hikes, these differences have almost disappeared.

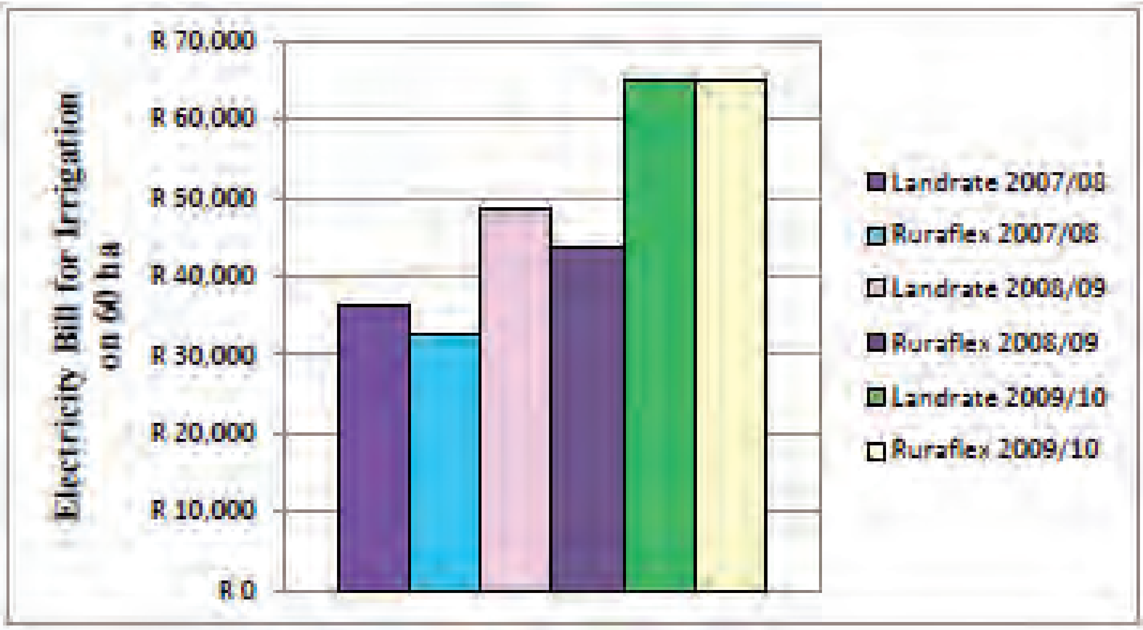


Figure 3: Difference in energy costs on Landrate and Ruraflex (Jumman, 2009)

Table 1: Components of energy tariffs effective from July 2008(ESKOM, 2008)

Options	Supply	Fixed Charges				Variable Charges					
Landrate		Network Access	Service				Active Energy				
	25 KVA	R 9.04/day	R8.60/day				40.63 c/kWh				
Ruraflex	Supply	Administration	Service	Network Access		Reactive Energy	Active Energy			Voltage Surcharge	Transmission Surcharge
	<100 KVA	R8.11/day	R5.54/day	R5.56/KVA		2.82 c/Kvarh	Peak c/kWh	Standard c/kWh	Off-Peak c/kWh	10.07%	1%
							139.84	39.16	19.22	High Demand	
							38.74	23.63	16.45	Low Demand	
Nightsave	Supply	Fixed Charges				Variable Charges					
		Administration	Service	Network Access	Energy Demand	Reactive Energy	Active Energy			Voltage Surcharge	Transmission Surcharge
	<100 KVA	R7.92/day	R5.54/day	R4.22/KVA		-				10.07%	1%
				High Demand	R85.79/KVA	-	19.60c/kWh				
				Low Demand	R56.50/KVA	-	13.50c/kWh				

Notes: Voltage Surcharge – Determined as a percentage of network access and active energy charges dependent on supply voltage.
Transmission Surcharge – Determined as percentage of network access, active and reactive energy charges dependent on the distance from a central point in Johannesburg
High Demand Season – June to August
Low Demand Season – September to May

2.4.3 On-farm electricity distribution

In order to ensure all electrical motors are operating correctly and efficiently, adequately sized electrical cable should be used to distribute electricity from the transformer to the motor. Cables should be designed to conform to SABS 0142-1981, Regulation 4.3.4. This regulation dictates that the maximum voltage drop under full-load conditions may not exceed 5%.

If the cable size is too small, the voltage [V] decreases excessively over the length of the cable and this causes the electric motor to draw a higher current. The motor may thus overheat and the energy loss will also increase. It is therefore very important not to use cables that are too small.

2.5 Control and Automation

Water control infrastructure is required at both the point of water supply into the on-farm conveyance system (usually the pump station) as well as the points where water is delivered to the in-field irrigation system (usually control valves at the block or system inlet) to manage flow and pressure.

Pressure management at the pump station can help to control energy requirements and also protect pipelines, and therefore reduce operating costs. The use of variable speed drives (VSDs) to match supply to demand is becoming more common, and although the drives are expensive to install, it negates the use of certain other system components such as a star-delta starter and pressure regulating valves at the irrigation system or block inlet.

There are various valves available to control flow and/or pressure at block or system inlets. Mechanical valves such as butterfly, gate or ball valves are mostly operated manually although they could be fitted with a gearbox for automatic or remote operation. Hydraulic valves are more versatile and can more easily be automated. The hydraulic control system makes use of pipeline pressure to open and close the valve. External energy sources (e.g. air pressure) may also be used to close the valve, while certain types (double chamber) can also be opened by these forces. The hydraulic control mechanism may be equipped with a pilot valve, solenoid or relay for automatic valve control.

Automation of the control system should be considered during the planning stage, even if it is not implemented immediately, as it can have an effect on the lay-out of the system, for example when considering where to place valves. It offers various advantages that support efficient water management:

• Manual control of systems, especially in the case of micro irrigation, is hampered by the long working hours and the complicated grouping systems generally encountered in the systems. Management expertise and abilities can be strengthened with a sensible automation system.

• Reliable labour is also getting scarcer and more expensive. This leads to inconsistencies which often result in over or under irrigation with the consequential unavoidable damage.

• More accurate control over the scheduling of irrigation can bring about moderate and even dramatic increases in both the quantity and quality of the yields, and can therefore contribute to higher profits.

• A reliable and accurate control system inevitably creates peace of mind and security with the farmer.

• Systems that were designed from the outset with automation as basis may save enough on capital layout to completely cover the costs of automation.

Automation can be implemented in different ways, depending on the requirements of the irrigator and the funds available.

The simplest way of automating the delivery of water, is by the use of metering valves, where the amount of water to be applied is set on the valve, which will close automatically when the volume has been delivered.

More commonly though, automation is being centralised, with valves at the irrigation block or system inlet being controlled hydraulically, electrically or with radio signals from a central point, usually the pump station. The computer from which the valves are controlled could simply act as a timer, or have more built-in intelligence to accommodate sensors for feedback into the system.

A well-planned control system will help the irrigator to have better control over his/her operations, and thereby reduce operational losses.

2.6 Drainage systems

Soils that do not have drainage problems under dry-land conditions may however become waterlogged when irrigated. This may occur as a result of over-irrigation, shallow soils or low quality water and/or salts. If economically justifiable, artificial drainage may be considered, or irrigation should be withdrawn from the specific field. Before a soil is drained, it is essential that all possible factors causing the waterlogging have been improved or removed. Leaking earth dams, blocked natural drainage channels or water courses, dense soil layers (resulting from tilling) with low infiltration rates as well as over-irrigating, can all play a considerable role in this regard, (Koegelenberg et al., 2003).

2.6.1 Assessment

The cause of the waterlogging and free water can be determined by means of a detailed soil survey. Once this has been done, a decision on the most suitable type of drainage system can be made.

2.6.2 Optimisation

Depending on the cause of the waterlogging, different approaches must be followed regarding the method of drainage. Two main types are distinguished in practice:

i) Cut-off drainage

This is used where free water moves under gravity from a higher lying to a lower lying position in porous, sandy or gravelly layers on dense soils. The cut-off drain is made more or less perpendicular to the flow direction of the free water. The cut-off drain must however have a gradient great enough to remove the water that accumulates in the drain, fast enough from the landscape. Over its full length, the drain must be made at least 300 mm deep in the dense underlying layer. It is essential that the lowest drainage level is continuous and has a consistent gradient. It is also recommended to build this drain as an open sough to get an idea of the amount of water to be removed (stream strength). When the stream strength is known, the minimum pipe diameter for removing the water can be determined if permanent pipe drains are considered.

ii) Subsurface drains

Actual soil water-levels occur on flat, low-lying landscape positions in sub-humid and humid regions. The height of the water-level is, in many cases, controlled by the water-level in adjacent river(s) or marshes. Because the laterally movement of such free water is very slow, cut-off drains cannot be used. In such cases a network of connecting drains is needed.

The maximum depth of installation of subsurface drains is determined by the height of the water – level in the river or marsh where the drains deposit their water. In the case of high river water levels, the possibility of making the channel or river deeper must be considered. If the soil to be drained has a relatively high permeability, it is economically beneficial to install the drains as deep as possible.

The shallower the drains are placed, the greater the length of drains per unit surface will be needed in order to obtain the same reduction of the free water-level in the soil as with a deeper placing. There are many cases where relatively shallow, static water levels on impermeable layers with a great extent occur. The problem of waterlogging can sometimes be overcome in such cases by relinquishing the limiting layer through deep soil preparation along the slope. The deeper such preparations are, the deeper the new drainage level. This action is especially successful if tilling is done through the limiting layer, into the underlying material with inherent better permeability, or which will remain open longer.

However, many soils are subject to waterlogging as a result of their inherent low permeability and/or physical instability that cannot be successfully drained by means of one of the above methods. The practice followed in these cases is known as “banking up” or beds. The main purpose of beds or banking-up walls is to remove excess rain-water or irrigation water collecting on the ground surface, as fast as possible from the field.

Since an in-depth discussion of the different drainage systems and materials to be used is not the purpose of this chapter, only a summary of the mentioned methods are given below.

The spacing of subsurface drains is dependent on the hydraulic conductivity of the soil, as well as the drain depth. Because the hydraulic conductivity of the soil is mainly determined by the texture thereof, texture and drain depth can be used as a broad guideline for drain spacing. Drainage can also be applied for reclamation of soils such as brackish soils. If excess water cannot drain naturally from a soil profile, the installation of a artificial drainage system can be considered. Well-drained soil is essential if the soil or water requires that leaching of undesirable salts must take place.

3 Design

The most efficient on-farm conveyance system will therefore be one that is designed according to sound principles that will result in the most economical solution to the irrigator. The most economical solution to any design is one that takes into account the total life cycle cost of the equipment. Selecting small pipes, filters and other equipment because they are cheap, results in higher energy demands from the pump and motor, a cost that the irrigator must carry for the rest of the system's lifetime.

Furthermore, the most efficient on-farm conveyance system will be one that consists of quality equipment with high inherent energy efficiencies. Forward-thinking manufacturers of pumps, motors and switchgear have developed and can supply the irrigator with technologies that are more efficient and therefore provide more output relative to input than older (or cheaper) technologies. In the long term, this reduces system operating cost. Correct installation and initial set-up of equipment is imperative for effective operation.

A qualified irrigation designer will be able to supply his/her client with the required information on different options to make the most appropriate selection of equipment for the specific situation.

3.1 Design Norms

The design norms as presented here are based on those of the South African Irrigation Institute (SABI), and is available on the website www.sabi.co.za.

3.1.1 Allowable friction loss in pipes

The filling up of pipelines and examples of mainline design must be according to industry standards, which are covered in manuals specific for designers. The designer must take into account the possible affect of water quality on pipes as well as the deterioration of pipes with age during the design process. The following values for allowable pipe friction in mainlines are proposed as norms:

The following applies for pipelines with a diameter of 200 mm or smaller:

- Rising pipeline: Maximum 1,5% (m/100 m) friction.
- Gravity pipeline: Maximum allowable flow velocity of 3,0 m/s.

If the above figures are exceeded, the designer must show that the chosen pipe diameter's total cost (capital and annual running cost) has been optimised and is the best of the available options. For pipelines of larger diameter, the effect of water hammer is critical and must be investigated and optimised.

3.1.2 Filters

Ring/mesh filter openings must be smaller than 1/5th of the emitter orifice diameter. The appropriate micro emitter manufacturer’s recommendations must be used for flow path openings of ≤ 1 mm. The following norms are recommended (ARC-IAE, 2003):

Maximum allowable pressure drop over ring/mesh filters:

- Recommended pressure drop over a clean ring filter is ≤ 10 kPa.
- Recommended pressure drop over clean filter bank ≤ 30 kPa.
- Maximum allowable pressure drop over a filter bank before backwashing ≤ 70 kPa.

When using a **sand filter**, a 200µm control mesh or ring filter must be placed on the downstream side of the sand filter to catch the impurities in case of damage to the sand filter. The drip manufacturer’s recommendations must be followed when using a ring/mesh filter. The present norms should be adjusted as follows (Van Niekerk et al., 2006):

The maximum allowable flow rate through a clean sand filter: Flow rate ≤ 50 m^3/h per m^2 with a maximum pressure drop over the sand filter of ≤ 10 kPa. The maximum allowable pressure drop over a sand filter with ring/mesh filters: Total pressure drop over a clean filter bank (including sand and ring filter) ≤ 40 kPa. The maximum allowable pressure difference over the filter bank before back-washing should be ≤ 60 kPa.

For sand filters, a minimum of 50% of the maximum filtration rate (50 m^3/h per m^2 sand surface area) is required to backwash the filters. The maximum backwash rate must not exceed 1.2 times the filtration rate. A minimum of 6 m inlet pressure is required during backwashing. The backwash time of sand filters can be between 90-180 seconds. Remembering that as the flush process starts, the raw water is above the sand bed, and at first appears to be clean. Thereafter the dirty water, which was trapped in the sand bed, is then expelled. During the flushing process the water will gradually appear cleaner. Thus it is so important to allow sufficient time during the backwash operation to ensure all impurities are removed from the filter.

3.1.3 Pump design margins

These values are added to the calculated system capacity and are used to indicate the duty point (pressure and flow) when selecting a pump. The present norms are accepted:

- Discharge: 10%
- Pressure head: 5%

Where an irrigation pump is also used for the mixing and application of fertilisers, then an additional 20% pump capacity must be provided for.

3.2 Equipment

(SABS codes, quality, quantities)

The use of good quality equipment from reputable, established suppliers that conform to locally recognised standards (such as SANS or ISO), contribute to system efficiency as less maintenance and repairs are needed, less water is lost through breakdowns and better after-sales service can be provided. Irrigation designers and irrigators should guard against using cheap imported equipment from unknown manufacturers. SABS 1200 is a quality control system for construction of medium pressure pipelines in the civil engineering industry but contains many clauses that are applicable and useful for the irrigation designer.

3.2.1 Pipelines

For the typical sizes and classes of pipes used for irrigation mainlines, there are various plastic pipe solutions that offer the most appropriate solutions in terms of economy, durability and handling.

Most on-farm conveyance pipelines are buried, in which case PVC (polyvinylchloride) are the best to use. If pipes have to be above ground, high density polyethylene (HDPE) pipes are more suitable due to their UV resistance properties. The development of special process techniques and improvement of production equipment have led to even better resins with which well-finished products are continuously being produced, to ensure quality and functionality.

The product specifications that PVC pipes should conform to, are described in SABS 966. SABS specifications exists for unplasticised PVC (uPVC) and modified PVC (mPVC). mPVC offers advantages over uPVC due to its greater flexibility and thinner wall thickness (which makes handling easier and also require less material to be manufactured, therefore an environmental consideration). In addition, manufacturers have also introduced their own non-SABS products, such as oPVC and tPVC. When considering which type of PVC pipe to use, irrigation designers or irrigators should carefully consider the manufacturers' recommended applications of the different types of pipe and how it agrees with the conditions under which the pipe will be used, before making a selection.

HDPE pipes are more expensive than PVC pipes and should therefore only be used if the installation conditions require it. Pipes approved by the SABS should conform to the ISO 4427 specifications. Development of new materials have led to improvement in strength properties with new grades of HDPE. Older PE materials were referred to as PE63 or more recently PE80, but now PE100 is available that achieves a saving of approximately 35% on wall thickness and therefore is more economical to manufacturer and easier to handle.

Plastic pipes that are manufactured from virgin material will last longer and have a smoother finish (reducing friction losses and therefore energy requirements) than pipes made from recycled material. Irrigation designers and irrigator should use pipes from reputable manufacturers, some of whom are members of SABI and of which the names can be found on at www.sabi.co.za.

The correct fittings should always be used to limit leaks and system down time due to repairs.

3.2.2 Valves

Valves are expensive items on the schedule of quantities of any irrigation system but correct placement can improve the ease of operation of a system and reduce maintenance costs dramatically, as described in the Irrigation Design Manual of the ARC-IAE.

Control valves are needed at the irrigation block / system inlets as well as at the water supply (usually the pump station) of the whole system. As discussed earlier, hydraulic valves are more suited to automated systems and this should be kept in mind when planning a new system. Control valves at the water supply is often forgotten or left out due to cost considerations but can save large volumes of water if pipes or even dams have to be drained for repairs or maintenance because there is no valve in place to isolate the section to be repaired. Manufacturers' recommendations regarding installation should always be followed, especially in the case of mechanical valves as incorrect installation practices can lead to valves not being able to open or close. The correct size of valve should be selected on the basis of the flow rate that the valve must be able to handle. Selecting a valve that is too small, will result in excessive friction losses, while selecting a valve that is too big, especially hydraulic valves, will result inaccurate operation, especially at low flows.

Air valves are also an absolute necessity on mainlines, as it protects the pipeline from damage due to air. Air valves can be designed to let air out (as when filling an empty pipeline), or to met air in (to prevent negative pressures when a pipe is drained or a pipe burst occurs). The design and installation of large diameter pipelines is a specialist field and knowledgeable designers should be consulted.

3.2.3 Filters

In systems where filtration or other forms of water treatment (oxidation, settling, etc.) is required, a well-designed and correctly operated filtration unit is key to the water use efficiency of the irrigation system. Such as system will:

- Remove all identified impurities from the water and thereby reduce the chances of blockages in the system;
- Not cause excessive pressure loss in the supply pipeline, which could increase operating cost;
- Be located in a position where there is enough pressure available for flushing;
- Not cause excessive amounts of backflush water to be produced, and
- Have a drainage system for the backflush water.

The most comprehensive information on filter selection and management is documented in the WRC publication "Guidelines for the Selection and Use of Various Micro-Irrigation Filters with Regards to Filtering and Backwashing Efficiency" (WRC Report No. 1356/1/06) compiled by Van

Niekerk; Koegelenberg; Reinders and Ascough on behalf of the ARC-IAE in 2006. The guidelines gave detailed information regarding to:

- Matching the filter type with the water quality and the irrigation system
- Choice of equipment
- Design of the upstream side of the filter station
- Design principles with respect to:
    - Commissioning of the filters
    - Filtration
    - Backwashing
    - Sizing of a filter
- Filter operation, and
- Maintenance of filters

3.2.4 Pump stations

Pump efficiency

An economical pump station takes into account the life cycle cost of the pump: i.e. the cost of purchasing, installing, operating, maintaining and disposing of a pump during its life time. The following components are taken into account (Grundfos, 2004):

- Initial cost (purchase price)
- Installation and commissioning costs
- Energy costs
- Operating costs (labour)
- Environmental costs
- Maintenance and repair costs
- Down time costs (loss of production)
- Decommissioning / disposal costs

It is estimated that around 20% of the world's electricity is consumed by pump systems. If all the different components of the life cycle are taken into account during a life cycle costing (LCC), a more sophisticated system such as one with a variable speed drive (VSD) that costs more initially may actually have a lower life cycle cost than a cheap pump that lacks the advantages of better energy management. In the majority of cases, energy consumption is the most significant life cycle cost of a pump system, particularly where pumps run more than 2000 hours per year.

The factors that influence the energy consumption of a pump include:

- Load
- Pump efficiency
- Motor efficiency
- Pump sizing (design round ups)
- Other system components in the system (pipework and valves)
- Using speed controlled solutions (such as Variable Speed Drives), which can reduce energy consumption up to 50% under certain conditions, such as steep topography where water have to be pumped to different heights.

An example of LCC analysis where the most significant cost components are used (initial costs, energy costs, maintenance costs) is shown in **Figure 3** (Grundfos, 2004).

Life cycle cost example for multistage centrifugal pump operated at a fixed speed (after Grundfos, 2004)	
Average power consumption, kW	18.76
Operating hours per day, hours	12
Working days per year, days	220
Calculation period, years	10
Total energy consumption, kWh	495 264
Electrical power price, R/kWh	0.7
Pump price, R	36 020
Maintenance costs, R	14 170
Energy costs, R	346 685
Total cost over 10 years, R	396 875

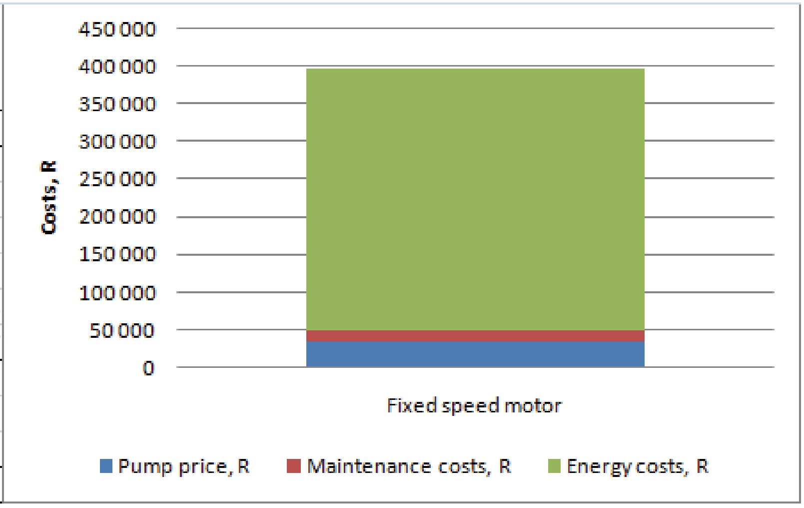


Figure 4: Example of life cycle costing (Grundfos, 2004)

Motor efficiency (Grundfos, 2004)

IEC 60034-2 Efficiency standards

Worldwide, there are several standards in existence for testing electrical machinery. For induction motors, the most important ones are IEEE Standard 112, JEC 37 (Japan) and IEC 60034-2. The efficiency value obtained from the different testing standards can, however, differ by several percent. This seems to be in contradiction to the theoretical definition of motor efficiency, η:

$$\eta = \frac{power\ out}{power\ in} = 1 - \frac{overall\ losses}{power\ in}$$

The losses for an induction motor are distributed as follows (Grundfos, 2004):

1. Stator winding loss P_{cu1} – approximately 40-45%
2. Rotor winding loss P_{cu2} – approximately 15%
3. Friction loss P_{fric} – approximately 15%
4. Iron loss P_{fe} – approximately 20%
5. Stray loss P_{stray} – approximately 10%

The main difference between the standards lies the way in which the 5th loss component, i.e. stray loss, (P_{stray}) is treated.

Efficiency performance standards

Motor manufacturers have used the designation “high-efficiency motor” for many years. However, it was difficult for customers to determine which motors actually were energy saving, because the motor manufacturers all claim to manufacture high-efficiency motors.

EPAct

In response to this, the American Congress introduced a new Act: The Energy Policy Act of 1992 (EPAct), which came into effect on the 24 October 1997. The objective of the EPAct is to reduce the energy consumption in the USA. To attain this objective, EPAct prescribes that imported or US-manufactured foot-mounted motors for the industry comply with the minimum standard requirements as to efficiency stated in the EPAct list.

MEPS

Minimum Energy Performance standards (MEPS) in Australia. From 2001 all three-phase motors from 0.73kW to 185kW have had to meet the MEPS. The new standards are described in Australia/New Zealand standards AS/NZ 1359.5:2000 which are mandatory state regulations. MEPS prescribes that products which are unacceptable because of their low energy efficiency are removed from the market. MEPS also define minimum efficiency levels for high-efficiency motors.

CEMEP

In Europe, a similar initiative has been taken to reduce energy consumption. The European agreement on the classification of electric standard motors came into force in 1999. The agreement is a result of the cooperation between the European Commission and the European Committee of Manufacturers of Electric Machines and Electronics (CEMEP). The objective is to reduce industrial energy consumption by using more efficient motors. The agreement is non-compulsory.

Today, CEMEP and EPAct requirements for motor efficiency are accepted as the global standards for 50 and 60 Hz high efficiency motors. CEMEP covers 50 Hz whilst EPAct covers 60Hz motors.

Motors covered by the CEMEP agreement include:

- Totally enclosed fan-cooled(normally IP54 or IP55 protected) 3-phase squirrel-cage induction motors
- Motors from 11 kW up to 90kW
- 2- and 4 pole motors
- Motors with a rated voltage of 400V
- 50 Hz motors
- Motors for duty range S1 operation
- Standard design motors (Design N according to EN600 34-12)

Motors ***not*** covered by the CEMEP agreement include:

- Certain three-phase motors
- Explosion-proof motors
- Braking motors
- Single phase motors

Motor manufacturers who have decided to comply with the requirements stated in the CEMEP agreement have committed themselves to:

- Classify their motors within the three efficiency classes:EFF1, EFF2, EFF 3
- Specify motor efficiency in percentage of full-load and ¾ load in catalogues
- Indicate the efficiency class on the motor's nameplate
- Reduce the number of motors in the lowest efficiency class EFF3
- Supply statistical data on the sales of motors for CEMEP countries every year.

A motor's efficiency is determined according to CEMEP on the basis of the loss-summation method according to EN60034-2 and A1: 1996 and A2:1996 and the following:

- Tolerances have to comply with EN60034-2 and A1: 1996
- For motors with thermal protection where the winding temperature rise during normal operations is 10k below the permissible limiting value the following reference temperature can be applied as a guideline: The actual rise in temperature is +15k
- For motors made to operate in a voltage range between e.g. 380 and 420V, the classification of the motor has to be based on the European voltage of 400V

- To ensure a representative test result of friction and windage loss, the test has to be carried out under stable bearing lubrication conditions and in accordance with common practice. If the motor is fitted with seal rings, they have to be removed before testing.
- The same reference temperature (winding temperature) is used in connection with ¾ load and full load.

Table 2: CEMEP and EPAct efficiency criteria (Grundfos, 2004)

HP	kW	Efficiency (%)					
		CEMEP				EPAct	
		2-pole	4-pole	2-/4-pole		2-pole	4-pole
		EFF1	EFF1	EFF2	EFF3		
1	0.75					≥75.5	≥82.5
1.5	1.1	≥82.8	≥83.8	≥76.2	≥76.2	≥82.5	≥84.0
2	1.5	≥84.1	≥85.0	≥78.5	≥78.5	≥84.0	≥84.0
3	2.2	≥85.6	≥86.4	≥81.0	≥81.0	≥85.5	≥87.5
	3	≥86.7	≥87.4	≥82.6	≥82.6		
5	4	≥87.6	≥88.3	≥84.2	≥84.2	≥87.5	≥87.5
7.5	5.5	≥88.6	≥89.2	≥85.7	≥85.7	≥88.5	≥89.5
10	7.5	≥89.5	≥90.1	≥87.0	≥87.0	≥89.5	≥89.5
15	11	≥90.5	≥91.0	≥88.4	≥88.4	≥90.2	≥91.0
20	15	≥91.3	≥91.8	≥89.4	≥89.4	≥90.2	≥91.0
25	18.5	≥91.8	≥92.2	≥90.0	≥90.0	≥91.0	≥92.4
30	22	≥92.2	≥92.6	≥90.5	≥90.5	≥91.0	≥92.4
40	30	≥92.9	≥93.2	≥91.4	≥91.4	≥91.7	≥93.0
50	37	≥93.3	≥93.6	≥92.0	≥92.0	≥92.4	≥93.0
60	45	≥93.7	≥93.9	≥92.5	≥92.5	≥93.5	≥93.6
75	55	≥94.0	≥94.2	≥93.0	≥93.0	≥93.0	≥94.1
100	75	≥94.6	≥94.7	≥93.6	≥93.6	≥93.6	≥94.5
125	90	≥95.0	≥95.0	≥93.9	≥93.9	≥94.5	≥94.5
150	110					≥94.5	≥95.0
200	150					≥95.0	≥95.0

Switchgear

Mainly two types of starting methods are used, namely

- Direct-on-line and
- Star-delta

Direct-on-line starters are normally used for smaller motors (< 2kW) and star-delta where the starting current is excessively high and thus has to be reduced. Star-delta starters are usually used for irrigation purposes, but direct-on-line starters can be used at very small installations. The provider of electricity will also set his standards, because excessively high starting currents may impair the power supply to other consumers. It is important to entrust the connection of electrical equipment to a qualified electrician.

3.2.5 Cables & Transformers

Cables should be designed to conform to SABS 0142-1981, Regulation 4.3.4. This regulation dictates that the maximum voltage drop under full-load conditions may not exceed 5%. It implies 19V between phase and phase and 11V between phase and neutral if the voltage is 380V. The cable size must, however, be based on the voltage drop [ΔV] of 5% maximum between phase and neutral, i.e. 5% of 220V = 11V.

The full-load current of a motor is the maximum current that an electric motor can draw before overheating. For the designing of cable sizes it is better to use this current, except in cases where the power rating of the electric motor is much larger than the required power.

If the cable size is found to be greater than 25 mm^2, in general it is recommended that step-up step down transformer systems are used, where the electricity is conducted at 1000 V rather than 400 V, which means that smaller cable sizes can be used. An electrical specialist should be consulted to design the system.

Due to theft of copper cables, aluminium cables are being used instead. Irrigators and designers should note that the conductive properties of the two metals differ greatly, and that sizing tables developed for copper cables cannot be applied to aluminium cables.

3.2.6 Life cycle costing of irrigation systems

The investment in a new irrigation system cannot be done by simply comparing different price quotations – the annual operating cost of the specific irrigation systems are becoming increasingly important, and should be considered thoroughly when acquiring such a system. The IRRICOST program (Meiring, Oosthuizen, Botha & Crous, 2002) was developed to estimate both the annual fixed and variable costs. The primary aim with the development of the IRRICOST program, was the establishment of a computerised cost-accounting program for the satisfactory calculations of the cost of different types of irrigation systems. The secondary purpose is to facilitate and enhance the execution of economic analyses regarding irrigation. If the annual irrigation costs that have been difficult to estimate thus far are known, the economy of irrigation can be analysed more readily.

IRRICOST is most widely used when analysing centre pivot and hand line irrigation. The scope of IRRICOST's field of application is wide, and the program can be used to compare the costs of alternative system designs, to evaluate annual costs and to estimate irrigation costs. The flexibility of IRRICOST ensures that changing situations in various localities can be dealt with. For example, users can do cost calculations for a unit that comprises more than one centre pivot or hand line with a shared pumping station, if the input values, such as area, pumping rate and head are interpreted correctly. Cost calculations can even be done for other types of irrigation systems, including flood irrigation, if the cost items such as labour cost are dealt with correctly. Additional equipment or assets, together with the life span, salvage value and annual repair and maintenance cost can be entered to calculate interest, depreciation and cost of repairs. Thus even the annual cost of a storage dam can be calculated.

Irrigation cost results of IRRICOST are estimated cost figures. The reliability of these values is vested in the accuracy of the inputs and assumptions made. With accurate input IRRICOST is a valuable instrument to facilitate irrigation cost calculation.

The IRRICOST program uses the paradox database system as well as binary files. The user manual and a demonstration programme can be downloaded from the University of the Free State website (Meiring, Oosthuizen, Botha & Crous, 2002).

3.2.7 Example – economic pipe sizing

A sugarcane farmer requires a water supply system for a 40ha centre pivot. Water has to be conveyed over a distance of 1000 m and the point of water delivery is located 50 m higher than the point of abstraction next to a river. Calculations have shown that a flow rate of 267 m^3/h is required.

Economical pipe diameter

For an interest rate of 11.5% and a repayment term of 5 years, the annual repayment for pipe sizes varying from 160 mm to 355 mm can vary from R25 151 to R123 015 per year. Bigger pipe sizes are more expensive but offers much lower friction losses, and therefore lower operating costs. For an assumed pump efficiency of 80% and a motor efficiency of 94% (Eff1), the power requirements may therefore vary from 111kW to 40kW and the pumping costs therefore from R149 556 to R54 303. The combined total cost will be lowest for the 200 mm pipe (R120 790).

Table 3: Economical pipe sizes – Example 2009

Pipe size (ND), mm	160	200	250	315	355
Pipe ID, mm	152	192	240	302	341
Pipe cost, R/m	R 68.90	R 100.36	R 158.91	R 269.45	R 336.98
Interest rate, fraction	0.115	0.115	0.115	0.115	0.115
Repayment term, years	5	5	5	5	5
Capital cost, R/year	R 25,151.15	R 36,635.71	R 58,009.56	R 98,362.51	R 123,014.53
Friction, m	74.50	24.43	8.42	2.81	1.57
Pump eff, %	80	80	80	80	80
Motor eff, %	94	94	94	94	94
Power, kW	110.78	62.34	46.85	41.42	40.22
Pumping hours	2700	2700	2700	2700	2700
Energy cost, c/kWh	50	50	50	50	50
Pumping cost, R/year	R 149,556.04	R 84,154.11	R 63,244.96	R 55,919.10	R 54,303.20
Total cost, R/year	R 174,707.19	R 120,789.82	R 121,254.52	R 154,281.61	R 177,317.73

If expected ESKOM tariff increases of 35% per year are taken into consideration, together with a 15% pipe price increase, the picture changes as shown in Table 4. The higher than inflation electricity cost increase, then results in the 250 mm pipe being the most economical solution.

Table 4: Economical pipe sizes – Example 2010

Pipe size (ND), mm	160	200	250	315	355
Pipe ID, mm	152	192	240	302	341
Pipe cost, R/m	R 79.24	R 115.41	R 182.75	R 309.87	R 387.53
Interest rate, fraction	0.115	0.115	0.115	0.115	0.115
Repayment term, years	5	5	5	5	5
Capital cost, R/year	R 28,923.97	R 42,131.22	R 66,711.14	R 13,117.03	R 41,466.86
Friction, m	74.50	24.43	8.42	2.81	1.57
Pump eff, %	80	80	80	80	80
Motor eff, %	94	94	94	94	94
Power, kW	110.78	62.34	46.85	41.42	40.22
Pumping hours	2700	2700	2700	2700	2700
Energy cost, c/kWh	67.5	67.5	67.5	67.5	67.5
Pumping cost, R/year	R 201,900.66	R 113,608.05	R 85,380.69	R 75,490.79	R 73,309.32
Total cost, R/year	R 230,824.63	R 155,739.26	R 152,091.84	R 188,607.82	R 214,776.18

Analysis of the effect of energy tariffs on decision-making during irrigation design and management should be carried out before selecting the pipe size (Jumman, 2009).

3.3 Documentation

A professional irrigation designer should provide the irrigator with a design report that contains at least the following information:

- Layout plan

This should comprise of the layout of the blocks and detailed plans of each block. Two copies are required, one for installation purposes and one for the producers records.

- List of quantities

A list of the items required for each block or system is needed so that quotations can be obtained from irrigation equipment suppliers. The list of quantities can also be used as a checklist for the equipment that is delivered by the irrigation equipment supplier.

- Detailed drawings of equipment to make installation easier

Valve connections: Drawings of the valves with the desired accessories.
Filter banks: Drawings of the complete filter installation with manifolds and valves.
Pumps: Drawings of the pump with necessary equipment.

- Pump curve

The producer uses a pump curve, on which the duty point is indicated, to easily read off the efficiency and power requirement of the pump. The pump curve is also needed in case the existing irrigation scheme is expanded in the future.

- Maintenance and management manuals

A thorough manual is required to ensure that the performance of the installed irrigation system is not adversely affected by incorrect practices.

- SABI peak design form

Technical design specifications that the design meets. The required operating flow rate and pressure for the irrigation system at critical points and many other parameters are included here to help the irrigator manage the system.

- Cost estimation

An estimate of the cost for the whole project must be made and for each phase, if applicable. The cost estimation should include both the envisaged capital and operating (energy and maintenance) costs.

3.4 Installation

Even the best designed system cannot operate correctly if not installed according to the equipment manufacturers' or irrigation designer's specifications.

3.4.1 Laying of PVC pipes

It is very important when laying PVC-U pipes to ensure that the pipe is laid in accordance with the manufacturer's recommendations and in accordance with SABS 1200 specifications (Petzetakis, 2004). Pipes must be backfilled immediately after laying, leaving the joints exposed for testing. Where this is not possible, cover the pipe with selected backfill prior to the actual backfilling operation.

Trenches

During installation of piping, footing and sand bedding are of vital importance for higher safety of pipelines. The reasons are as follows:

a) weaken the stresses acting upon the pipe to increase its safety.

b) prevent the pipe from moving at the flowing of water to impede generation of heavy forces which may rupture the pipe.

c) protect the pipe to prevent occurrence of external damage by stone or rock and generation of heavy stresses, and

d) form a uniform footing for longer retention of piping functions.

Execution of the work in accordance with the following specifications is therefore imperative.

- Depth of trench

Depth of trench is normally determined by the Consulting Engineer after extensive investigation of

routes and suitability of ground conditions has been undertaken. Consideration should also be given to pipe deflection under buried conditions before the pipe is installed under buried conditions before the pipe is installed.

- Excavation

The width of the trench at the crown of the pipe should be as narrow as practicable but not less than the outside diameter of the pipe plus 300 mm to allow proper compaction of the side fill. Above the crown of the pipe, the trench may be any convenient width. Excavation of the trench should be carried out in accordance with the following recommendations or SABS 058. The trench should not be opened up too far in advance of pipe laying.

- Width of trench and depth of cover

For most purposes a trench 300 mm wider than the diameter of the pipe allows enough room for jointing. Depth of cover should be at least one meter from top of pipe to ground surface. (It is wise to consider in early planning stages how future road widening plans could affect this depth of cover).

- Normal subsoil

On normal subsoil, replace more than 100 mm thickness of the excavated ground with suitably sifted sand to be used as bedding. It necessary river sand should be used if the excavated sand is not suitable.

- Backfilling around the pipe

Backfill soil should be free of stones and rocks and filled into both sides of the pipe evenly to prevent displacement of the pipe. The soil should be filled and tamped using hand tampers to firmly compact the soil around the pipe. This operation should be continued until the backfill has reached a height of 300 mm above the crown of the pipe. Care should be taken not to strike the pipe with the tampers.

- Backfilling to the ground level

The remainder of the trench (but not the pipe joints) should be filled (in layers of encompassed thickness of approximately 300 mm) over the full width of the trench with the excavated trench material, each layer being individually firmly tamped. If the excavated material is such that subsequent subsidence may occur selected material may be required (e.g. in cases where pipelines are laid under roads). Mechanical tamping may be used on the second and all subsequent layers.

- Cares for backfilling

(a) After assembly of piping check that all joints are correctly made.

(b) Remove all supports used in assembling the line.

(c) Before backfilling, pump any accumulated water from the trench.

(d) Backfill evenly ensuring the haunch of the pipe is also backfilled: Do not tip fill directly into trench from dump truck.

(e) As a rule, backfill after assembling every few pipes in a line or, where this is not possible, cover the pipe with selected backfill prior to the actual backfilling operation. As PVC-U pipe is flexible, it tends to adapt itself to the uneven topography of the trench bed thus producing stresses in the pipe. Backfilling a long pipeline in one operation could set up large stresses in the pipe.

(f) When assembly of a pipeline is suspended, do not leave tools, cement, lubricants etc. inside the piping. Cover the open ends of the line with fine wire netting to allow the line to breathe and to prevent the ingress of small animals.

(g) Make certain that no miscellaneous objects are buried in the trench with the backfill.

(h) Backfilling at joints. After completion of acceptance testing, the parts of the trench left unfilled must be backfilled in exactly the same manner as that used for the rest of the trench.

3.4.2 Flushing and commissioning

Following the installation of all system components, the system can filled with water under supervision of the designer or engineer. The first water available to the system should be used to flush all pipelines to remove any possible soil or other impurities that could have entered the system during installation.

It should be ensured that all air has been removed from the system, a function that should be performed automatically if adequate and correctly sized air valves had been installed at the correct locations in the system.

Once the system is under full pressure, any control valves that require adjustments should be set to provide the correct pressures at the various locations on the system. Pressures should be checked and compared with the design values.

4 Operation

The most efficient on-farm conveyance system will be one that is operated according to the design specifications and the flow and pressure requirements of the in-field irrigation systems. In order to make best use of the on-farm infrastructure, the irrigator should operate the system as intended by the designer. In the case of large commercial farms, the use of software programmes to optimise the scheduling of different irrigation blocks or systems will assist the irrigator to make the best decisions and keep record of water applied.

Monitoring of flows and pressures at strategic locations in mainlines, at filter and pump stations is necessary not only for volumetric recordkeeping but also to detect performance problems within the system such as blockages or leakages. Modern technologies can be built into the switchgear to send out messages via GSM networks and thereby limit losses due to breakdowns. Water quality can be monitored in a similar manner.

4.1 Optimisation

Irrigators can limit the cost of energy by employing energy-saving practices into their irrigation management strategies.

For the reasons as mentioned section 2.4.2, the irrigation system should always be designed as if it will be operated 24 hours.

In order to provide irrigation designers and water users with guidelines to estimate expected energy costs more accurately, an analysis was done in which 4 scenarios were used to calculate the cost of electricity per kWh, for a specific kW installation.

The following four scenarios, for both high (June to August) and low (September to May) demand periods, were used:

Scenario description	Number of operating hours per week
7 days/week; 22 h/day =	154 h/week
6 days/week; 24 h/day =	144 h/week
6 days/week; 12 h/day =	72 h/week
5 days/week; 10 h/day =	50 h/week

The scenarios cover a range of energy use levels from 50 hours per week (distributed as 10 hours per day across a 5 day working week) to 154 hours per week (distributed as 22 hours per day across a 7 working day week). The scenarios cover typical situation in the field, from manual systems limited to daylight hours and weekdays, to fully automated systems being operated at night and over weekends.

The results of the calculations are shown in Figure 5, covering all the scenarios and demand periods as discussed, for both the 2008/2009 and 2009/2010 tariffs.

As can be seen on the graphs, the cost of energy per kWh that a water user has been paying in 2008/2009, varied from 54c to R1.21 in high demand period, and from 27c to 75c in low demand period, depending on the number of operating hours. From 1 April 2009, the costs increased to between 74c and R1.63 per kWh in high demand period, and to between 38c and R1.02 in the low demand period.

It can also be seen that for installations below 20 kW, the energy cost per kWh is higher, due to the surcharges (fixed costs) payable on the installation. Water users with small pump stations therefore seem to be paying higher prices per kWh in all cases.

Furthermore, as was expected the scenarios with fewer operating hours per week have higher energy costs per kWh in all cases.

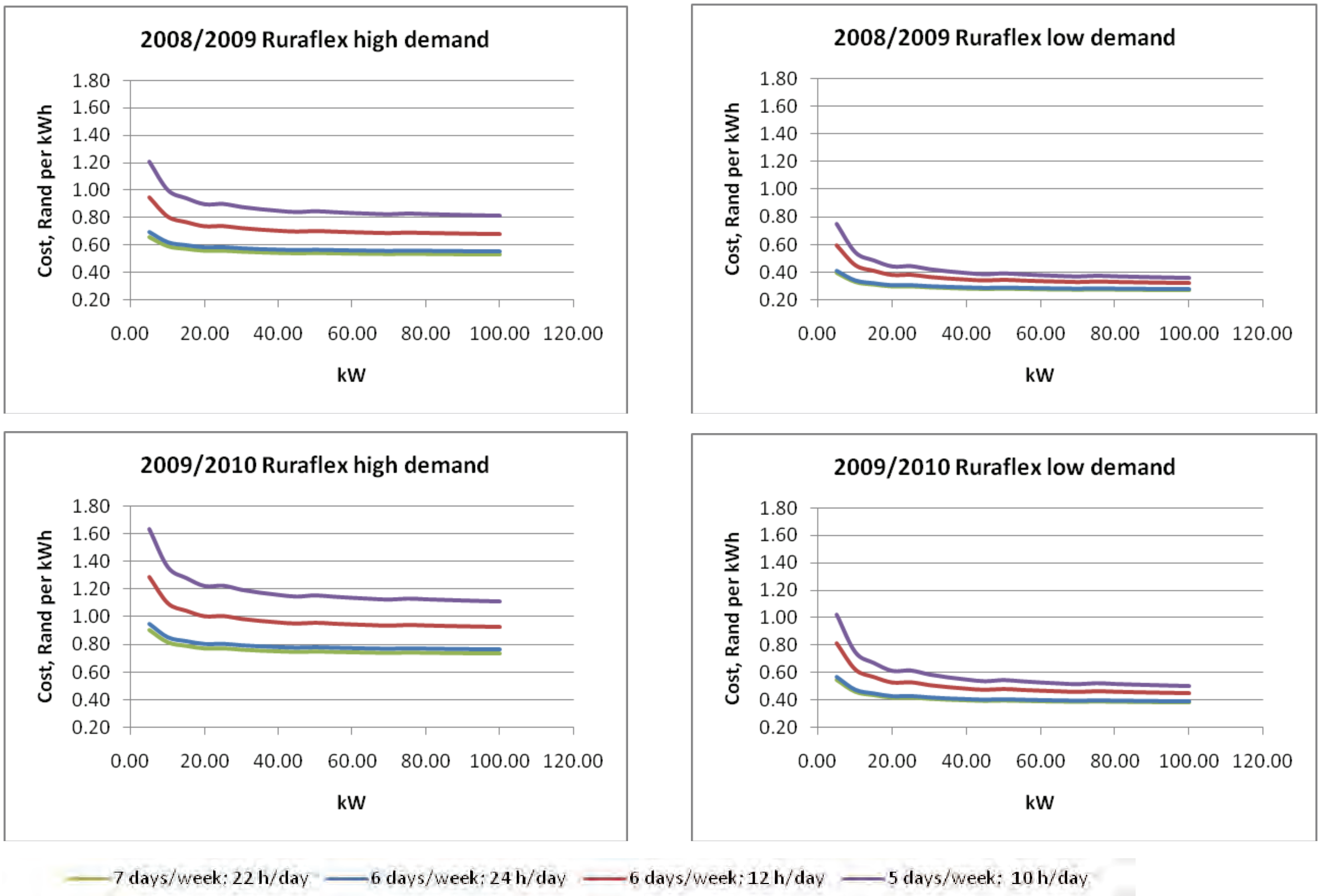


Figure 5: Energy cost per kilowatt – 2008 to 2010

4.1.1 Reducing Pumping Hours

Reducing pumping hours has an immediate effect on electricity use. This can be achieved by reducing the seasonal depths of irrigation applied, or by improving irrigation efficiency, and is possible without physically changing the irrigation system.

Separating out the effects of irrigation efficiency and application depth is difficult. However, efficient irrigation scheduling can significantly reduce the amount of irrigation water pumped, and through that, energy use.

The biggest opportunity for reduced pumping is through better use of rainfall. Managing the irrigation system to use as much of the rainfall that occurs in a season as possible has direct benefits, because that water does not have to be pumped.

4.1.2 Improving Irrigation Efficiency

Improving application efficiency reduces the gross water applied and reduces energy use.

The net water used by the crop is climatically driven, and is independent of the irrigation system. The gross irrigation depth applied that is necessary to maintain plant growth depends on irrigation system type and the irrigation management practices used. However, except perhaps for systems that apply large fixed depths of water, irrigation efficiency depends more on management than on the irrigation system. Irrigation efficiency changes during the irrigation season. For systems with limited system capacity, efficiencies may be lower at the beginning of the season because of the need to totally fill the soil profile. As the soils dry out as the season develops, irrigation efficiency increases, because the system does not have the capacity to fill the soil profile completely.

Poor irrigation efficiency depends primarily on four inter-related factors. These are:

irrigation timing, which is a function of soil moistures before irrigation;

the depth applied, which is a function of soil moistures after irrigation;

application uniformity, which affects how much of the water will be lost to deep drainage; and

application rate, which if excessive, causes poor uniformity because of surface redistribution.

Opportunities for improving irrigation efficiency are specific to each site. These can range from minor improvements to the irrigation system through to major equipment changes. Simple changes to management such as adjusting application depths through nozzle size changes and covering the area more quickly (if equipment allows), may result in significant efficiency improvements. Close monitoring of irrigation applications through soil moisture measurement can result in significant reductions in water pumped. Proper maintenance of the system, for example by replacing worn sprinklers and nozzles, or blocked emitters, will improve efficiency.

Major changes, such as changing the type of irrigation, for example from flood irrigation to pressurised sprinkler irrigation, could result in significant improvements in irrigation efficiency. However, the benefits in terms of energy use may not be realised if the flood irrigation system was previously a gravity supply system that did not involve pumping.

These aspects are discussed in greater detail in Module 2.

4.1.3 Reducing Pump Pressure

There are a number of ways of reducing the pump duty required for an irrigation system, but most require large physical changes to the system.

Changing to low pressure spray nozzles will reduce energy consumption, but may not result in significant savings because of the high application rates that occur, causing surface redistribution and run-off. Whether reducing the operating pressure of sprinklers is worthwhile depends on what percentage of the total pump head the sprinkler requirement makes up. For deep borehole pumps, most of the energy is used to lift water to the surface, and modifying the system at the surface will change little percentage-wise.

Replacement of pressurised systems with surface systems will certainly save energy, but if more water has to be pumped to make up for lower efficiency, the benefits may not be significant.

4.1.4 Improving Pump Efficiency

An efficiently designed pumping plant is necessary to minimise energy required for pumping. Different pump brands and types of pumps can have quite different efficiencies even though they are pumping the same amount of water. This efficiency depends on the design of the pump. Likewise, different motor brands have different efficiencies. The energy cost of running the system depends on both of these factors.

The key to an efficient pumping system is to select the best motor/pump combination at the design stage. If the better combination is more expensive, an economic evaluation should be made to determine if the possible savings in energy outweigh the additional capital cost.

Operating a pump at a flow at or beyond its maximum efficiency point will reduce the cost per cubic metre of water pumped.

As pumps wear, they become less efficient. Monitoring performance with pump tests will tell one whether or not loss of performance is significant enough to warrant repairs.

4.1.5 Electrical Load Management

As discussed earlier, full use should be made of the correct energy tariff plan but design hours preferably not reduced. Given that irrigation systems only need to operate at their peak capacity for part of the season, it is usually much cheaper overall to design systems to utilise the full day, operate at night whenever possible, and extend irrigation into day time rates when demand requires it.

4.2 Monitoring

4.2.1 Flow measurement

The pipes and canals that are used to convey water to the field are probably the most expensive component of the on-farm distribution system. They are usually sized according to a combination of hydraulic and economic requirements. Deterioration of these distribution channels can lead to a reduction in delivery capacity, through deposition inside the pipes or in canals, or the development of leaks where the material has become worn out. In either case, a higher energy requirement will be the outcome as more water (or water at a higher pressure) has to be pumped into the system to compensate for the flow and pressure loss in the system.

The water balance would typically be applied to this water use component in order to quantify the losses that occur in the system.

Although quantifying the losses in the system is an important part of assessing the effectiveness of the system, the bigger concepts of adequacy, equity, reliability and consistency should also be taken into account (Fairweather et al., 2003).

Losses that can occur in the system are the following:

- Operational

An appropriate operating system with effective measuring devices and skilled operators is needed to make sure water reaches the intended destination at the correct flow rate and time. Sometimes it is not possible to avoid operational losses, e.g. when a system has to be drained or filled up.

- Leakage

This is a non-recoverable fraction of water use that needs to be kept at a minimum. Leakages usually result from aging systems and/or poor maintenance.

- Evaporation (in the case of canals)

As discussed in section 2.1

- Seepage (in the case of canals)

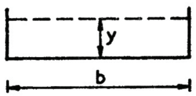
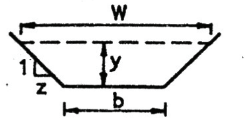
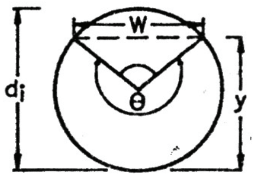
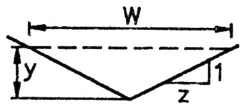
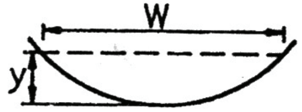
As discussed in section 2.1. Seepage losses are a function of the wetted perimeter and lining type of the canal. According to the "Guidelines for the design of canals and related structures" of DWA the following combined seepage and evaporation loss rates for canals should be used:

Concrete-lined canals: 1.9 l/s per 1000 m^2 of wetted perimeter
Earth canals in clay-loam soils: 2.3 l/s per 1000 m^2 of wetted perimeter
Earth canals in sandy-loam soils: 3.7 l/s per 1000 m^2 of wetted perimeter

According to the same publication, a properly lined canal should not lose more than 0.35 l/s per 1000 m^2 of wetted lining through seepage alone, although field measurements have shown that this value is usually exceeded.

The wetted area (m^2) of the canal can be calculated as the product of the wetted perimeter and the length of the canal. The wetted perimeter can be calculated for different typical canal cross sections as shown in Table 5.

Table 5: Properties of typical channels' geometrical characteristics (ARC-IAE, 2003)

Sketches					
Characteristic	**Rectangular**	**Trapezoidal**	**Circular (> ½ full)**	**Triangular**	**Parabolic**
Area (A)	$b\,y$	$(b + z\,y)\,y$	$\frac{d_i^2}{8}\left(2\pi - \frac{\pi\theta}{180} + \sin\theta\right)$	$z\,y^2$	$\frac{2\,yW}{3}$
Wetted perimeter (P)	$b + 2\,y$	$b + 2\,y\sqrt{1+z^2}$	$\frac{\pi\, d_i\,(360 - \theta)}{360}$	$2\,y\sqrt{z^2+1}$	$W + \frac{8\,y^2}{3\,W}$
Top width (W)	b	$b + 2\,z\,y$	$(\sin\frac{\theta}{2})\,d_i$	2zy	$\frac{3\,A}{2\,y}$
Hydraulic radius (R)	$\frac{b\,y}{b+2\,y}$	$\frac{(b+z\,y)\,y}{b+2\,y\sqrt{1+z^2}}$	$\frac{45\,d_i}{\pi(360 - \theta)}\left[2\pi - \frac{\pi\theta}{180} + \sin\theta\right]$	$\frac{zy}{2\sqrt{z^2+1}}$	$\frac{2\,yW^2}{3\,W^2+8\,y^2}$
Hydraulic mean depth (D_m)	y	$\frac{(b+z\,y)\,y}{b+2\,z\,y}$	$\frac{d_i}{8\,\sin\,(\frac{\theta}{2})} \times 2\,\pi - \frac{\pi\,\theta}{180} + \sin\,\theta$	$\frac{y}{2}$	$\frac{2\,y}{3}$

4.2.1 Measurement

The elements of the water balance that are assessed at this level usually require a combination of pressure and flow measurements to be done at various points within a system. The use of portable ultrasonic flow meters for both pipes and open channels is becoming more affordable as the technology becomes more freely available.

The components to be measured include:

- The inflow into the pipe or canal system

A variety of measuring devices for pipes and canals can be used to measure flow. If water is filtered, a greater variety of water meters can be used after the filtration system as the water will be clean enough to be fit for domestic water meters which are relatively cheap compared to raw water meters. If the WUA or other authority that the irrigator receives from does not have a flow meter installed at the farm edge, the irrigator should install his/her own measuring device.

- Any storage changes that occur

This could be due to filling up an empty pipe or canal system, and may require water depth rather than flow to be measured (for example the depth of water in a dam).

- All outflows from the system

At this location, flow measuring devices will also be needed. If the in-field irrigation system applies water accurately, it is possible to monitor water applications with simple pressure measurement, which is cheaper and requires less maintenance than volumetric flow meters.

To quantify these components therefore require flow to be measured volumetrically. When irrigation water use measurement was first institutionalised in the 1980s, the types of meters used were not very suitable for raw water – the accent was on accuracy. As a result, the devices didn’t last long and were deemed unreliable and more of problem than a solution. Today, more suitable devices are available and, together with remote sensing methods of data collection, offer much more affordable and sustainable solutions in the long term. Installation and maintenance have to be considered when making the final decision on the type of device to install. Some recommendations for devices suitable for different measuring conditions are made here; more detailed information can be obtained in the WRC report “Guidelines for Irrigation water measurement in practice” (WRC Report TT284/05).

If enough measurements are taken, a fairly accurate water balance can be compiled to determine the losses in the on-farm conveyance system. The water balance equation for the pipe or canal system would be:

$$Losses = Inflow - Storage\ change - Volume\ delivered\ to\ field - Unused\ deliveries$$

An example of the components of a water balance to assess the conveyance efficiency of a canal system is shown in **Figure 6** (Fairweather et al., 2003).

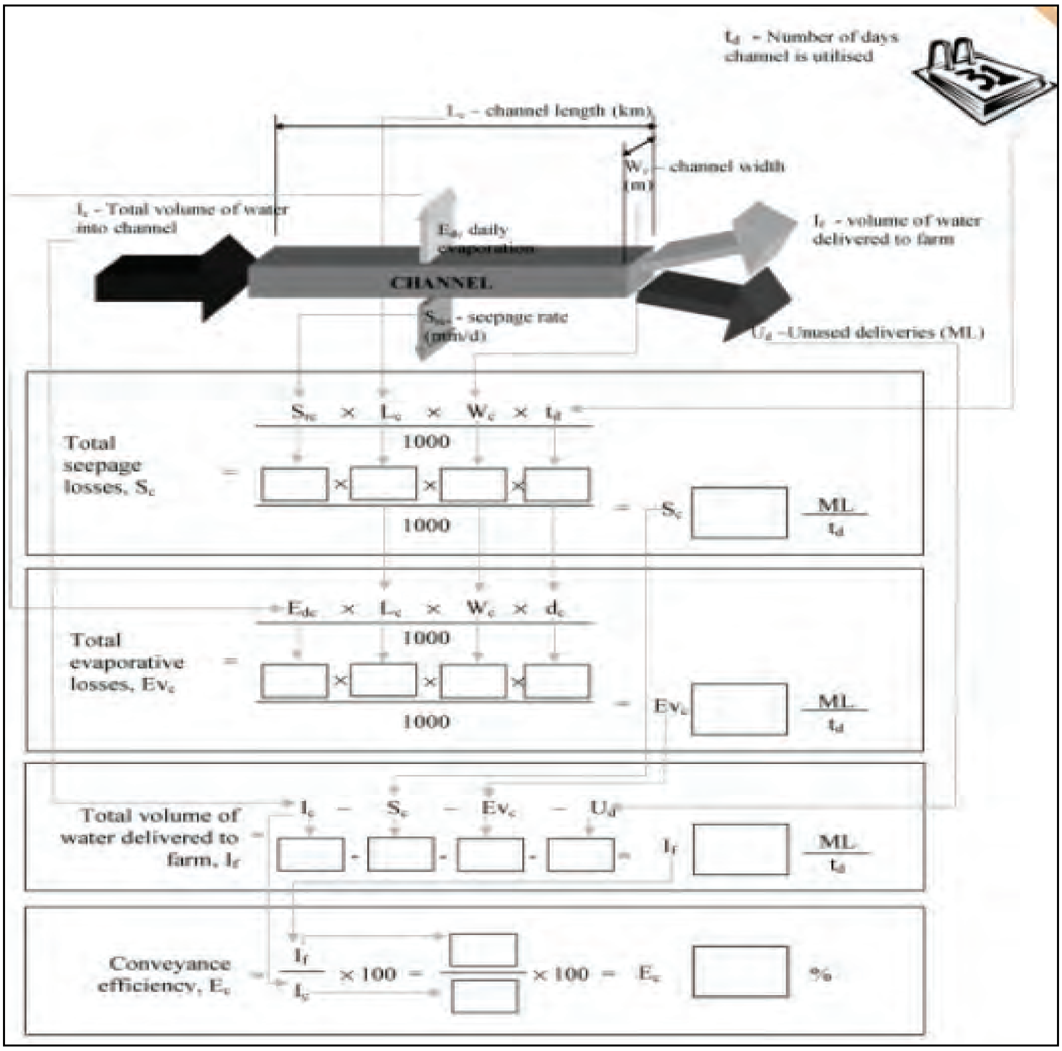


Figure 6: Example of a water balance on a canal system (Fairweather et al., 2003)

4.2.2 Pressure measurement

As with flow measurements, pressure should be monitored at both the water source (pump station) and the points of delivery (block or system inlets). In addition, pressure drop over the filter and other system components can be monitored.

Pressure at the pump must be sufficient to distribute the water, and pressure during operation at the different hydrants or block inlets should conform to the system design specifications as provided by the designer. The pressure-loss in main lines may not be larger than 1.5% per length as a result of the friction in the pipes of 200 mm and smaller diameter (Koegelenberg, 2003). That is, if a supply line is 800 m long, the pressure loss, as a result of friction, may not be more than 12 m (120 kPa). This principle is shown in Figure 7.

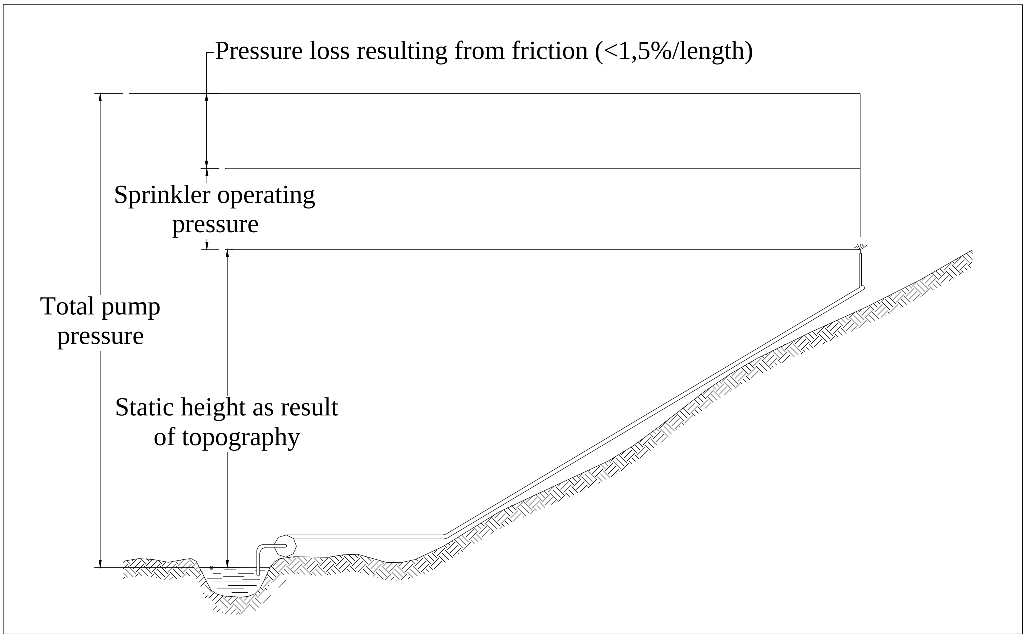


Figure 7: Pressure requirements of a pump

The following evaluation procedure can be followed during an inspection of the supply system. The information required may be obtained from the design, from the person who irrigates the crops, from installed meters or by physically obtaining measurements.

- Type of pipe
- Diameter of pipe
- Class of pipe
- Total pipe length
- Service pressure at the pump
- Service pressure at the hydrant
- Topographic height difference between the pipe and the hydrant

From the above information, the friction loss in a specific length of pipe can be calculated and must conform to the requirements mentioned above.

4.2.3 Water quality measurement

Irrigation water quality is classified according to the physical, organic and chemical impurities in the water. The quality of irrigation water influences the plant growth, soil characteristics, the biological balance of soils, and also influences the irrigation equipment. Water that contains much dissolved salts can still be used on soil with a good internal drainage pattern, if the salts are leached from the soil from time to time. The salt build-up in the soil must however be monitored continuously.

Physical, biological and chemical impurities that can cause blockages in micro systems are described in the Evaluation manual of the ARC-IAE.

Water quality can be monitored by taking samples and having it analysed but for more immediate results, the electrical conductivity (EC) and the pH can be measured with permanently installed or portable meters, to provide information on the salt content and acidity of the water, respectively.

Table 6 details the elements to be included in detail analysis and provides criteria for taking, handling and storing the samples.

Table 6: Sample taking and handling requirements

Element	Container	Minimum sample size (mℓ)	Storage	Maximum recommended storage period
Alkalinity	P, G	200	Refrigerate	24 hours
Electrical conductivity	P, G	500	Refrigerate	28 days
Hardness	P, G	100	Add HNO_3 to pH<2	6 months
Metals	P, (A) G (A)	_	For dissolved metals, filter immediately, add HNO_3 to pH<2	6 months
Ammonia	P, G	500	Analyse as soon as possible or add H_2SO_4 to a pH <2, refrigerate	7 days
Nitrates	P, G	100	Analyse as soon as possible or Refrigerate or freeze at –20°C	48 hours
Nitrates and Nitrites	P, G	200	Add H_2SO4 to a pH <2, refrigerate	None
Nitrites	P, G	100	Analyse as soon as possible or freeze at 20°C	None
pH	P, G	-	Analyse immediately	2 hours
Sulphate	P, G	-	Refrigerate	28 days
Sulphides	P, G	100	Refrigerate, add drops 2N zinc acetate/100 mℓ	28 days
Suspended solids	P, G	1 000	Refrigerate	7 days

Conversions

1 dS/m = 100 mS/m = 100 mmhos/m = 1 mmhos/cm = 1 000 µmhos/cm

1 mg/ℓ = 1 ppm

equivalent weight = atomic weight / number of charges of particular ion

meq/ℓ = mg/ℓ / equivalent weight

mmol/ℓ = meq/ℓ / number of charges of particular ion

Sum of cations/anions: (meq/ℓ) = EC (dS/m) $\times$10

Refrigerate = storage at 4°C in the dark

P = plastic (polyethylene equivalent): G = Glass (A) or P (A) = rinsed with 1+1 HNO_3

Ensure that the ion balance in milli equivalents per litre (me/ℓ) of the anions and the captions balance (ΣCations = ΣAnions), since water is normally electrically neutral. If not, the test laboratory must be requested to repeat the analysis.

4.2.4 Electrical measurements

As more system components are being automated, and as the quality of electricity supplied to rural areas decrease, the irrigator and irrigation designer should be able to do simple measurements and tests on electrical equipment. When working with electricity, especially alternating current, all safety precautions should be adhered to at all times to prevent injury or death.

A multimeter can be used to measure voltage and current, which are in most cases enough for simple problem solving. The most common problem in the pump house is low supply voltage, or one of the supply phases being down. Other possible problems include broken wires or contactors due to age or damage by rodents. At the block or system inlets, solenoids may need to be checked it valves are not opening correctly, although often it could also be a hydraulic blockage problem. In wire based automation systems, damage to communication wires are also often a problem.

5 Maintenance

The most efficient on-farm conveyance system will therefore be one that is maintained according to the equipment manufacturers' and / or irrigation designer's recommendations. Regular maintenance (routine or emergency) will reduce operating costs and water losses in the on-farm conveyance system. Timely fixing of leaks, checking of valves (especially hydraulic ones) and filters and maintenance of pumps and motors will ensure that water is supplied to the intended destination in the most energy (and therefore cost) efficient manner. Complete guidelines for different system components are available from the manufacturers and should be adhered to. Some general maintenance guidelines as included in the *ARC Institute for Agricultural Engineering's Irrigation User Manual* are shown below.

5.1 Pump Maintenance

The pump manufacturer usually provides a maintenance schedule that indicates the maintenance to be done. As with any type of equipment, it is very important that the necessary maintenance is done regularly to ensure that the installation can function efficiently and that the life span of the installation is prolonged. The pump must always run smoothly without any vibrations. The water depth on the suction side as well as the power consumption must also be regularly monitored.

Over and above the manufacturer's schedule, the following can serve as directives for the maintenance of the centrifugal pumps:

- Check the alignment every six months
- Replace the oil every six months if applicable. If the oil level drops, new oil must be added
- Check and clean the bearings every 1 000 operating hours
- Inspect all wearing parts regularly and do a hydraulic test. A simpler test can also be done by just closing the sluice valve and taking a reading on the pressure meter that is installed upstream of the sluice valve. If the pressure drops in relation to when the pump was initially installed, it indicates excessive wear. This test should be sufficient for maintenance purposes. If there is a suspicion that the installation does not function correctly, the complete test can be done, as described in Section 6. By monitoring the ampere reading, it can be determined whether the pump's service point changes with time.
- Inspect the gland leakage regularly. It must leak slightly, because it is lubricated by water. Also feel the pump for excessive vibrations.
- It is also worthwhile to dismantle the pump sometimes and to concentrate on the following:
    - Impeller clearance at collar – skim the impeller neck to give clearance and mount the correct wear rings.
    - Inspect the pump shaft for damage

Replace casings if necessary
Clean surfaces of impellers, pump casing, etc., paint if necessary
Replace gaskets and O-rings and bearings
Check all adapter parts.

Table 7 can be used as guidelines for maintenance of centrifugal pumps:

Table 7: Typical maintenance schedule for pumps

Monitor	Monthly	1 000 Operating hours	Bi-annually	Annually
Check alignment / settings			X	
Replace oil			X	
Inspect bearings and clean		X		
Inspect all parts for wear and do hydraulic test*	X			
Inspect the gland packing leakage (it must leak slightly, because it is lubricated by water)	X			
Replace the gland packing				X
Inspect cables and electric equipment			X	

*This test can be done by closing the stop valve and taking a pressure reading on the manometer mounted on the outlet of the pump. If the pressure drops, compared to the reading taken when the pump was new, it indicates wear (Section 6). As mentioned previously, the pump gland packing must have a slow leak when pumping is done. If the gasket can be compressed with the width of the gasket ring or more (as a result of the tighten up process), the gland packing must be replaced.

6 Evaluation

The most efficient on-farm conveyance system will be one that is regularly evaluated to assess the level of performance and detect problems as early as possible. Control valves should regulate pressure and flow correctly, filters should effectively remove impurities, and pump stations should supply water at the correct pressure and flow at the lowest possible power requirements. Evaluation differs from monitoring in the sense that it is performed periodically rather than continuously.

6.1 Methods

There are standard evaluation procedures that have been developed by the ARC – IAE. A summary of some of the basic procedures applicable to the on-farm conveyance system is shown in Table 8.

Table 8: Proposed basic evaluation procedure of on-farm conveyance system components

Subject / Item	Measurement/Evaluation	Action if measurements / evaluation does not conform to the design specifications
Inlet pressure of block	Determine the inlet pressure of the blocks with a pressure gauge and compare with the required pressured as specified on the peak design form	Contact designer and adjust set-up schedule if necessary
Equipment: model and manufacturer	Compare the model/ manufacturer of the installed pump, electric motor, filter and emitters with the specifications as per design report.	Contact designer for replacement of faulty equipment
Pump suction side fittings	Examine if the measurements of the suction pipe is according to plan and if the shape of the reducer, bend and adapters are as described in Section 4.1.	Contact designer for replacement or re-installation of faulty equipment
Pump duty point	Determine the pump pressure by reading the pressure from the pressure gauge at the delivery side of the pump and compare with the pump pressure height specified on the peak design form. Determine the pump delivery by	Contact designer for fault detection

Subject / Item	Measurement/Evaluation	Action if measurements / evaluation does not conform to the design specifications
	comparing the reading on the flow meter and compare with the design flow rate.	
Pump cavitation	Determine whether the pump cavitates by listening and feeling for excess vibration	Contact designer for fault detection.
Schedule of blocks/ movable sprinklers in simultaneous operation	Compare the blocks / sprinklers that are in simultaneous operation, with the specification as suggested in design report.	Change the blocks / sprinklers that are in simultaneous operation, by either opening the correct taps or reprogramming the irrigation computer.
General installation	Examine if any leakages occur in the system	Repair leaks
Operation of equipment	Examine operation of filters (e.g., pressure loss and back flushing action), air and pressure control valves	Contact designer for fault detection
System capacity	Determine system flow rate by taking the reading from the flow meter/ measuring notch	If a flow rate deviation of more than 10% from the average occurs, as specified in the peak design form, contact the designer.

If a complete system evaluation is required, an irrigation consultant can be approached to execute the evaluation as described in *Manual for the evaluation of irrigation systems*. Approved system evaluators who are also SABI approved irrigation designers are listed on the SABI website www.sabi.co.za.

6.2 Trouble shooting

The results of a system evaluation will highlight any possible areas where repairs need to be made or the system upgraded.

Tables 9 to 11 provide trouble shooting advice for supply systems in general, as well as uPVC and polyethylene pipes.

Table 9: Trouble shooting table for supply systems

Problem	Possible causes	Solution
Capacity of canal reduces	Canal is silted up	Clean canal
	Leakages occur as result of damaged canal	Repair
	Outflow sieve blocks	Clean sieve
	Damage to outflow structure	Repair
Delivery of pipeline reduces	Burst pipeline	Repair
	Blockage as result of bacterial growth/ lime deposit/iron sediment	Chlorinate/apply acid
	Air collection	Check operation of air valve or install air valve if absent
	Build-up of sand in low-lying areas	Replace flush valve or flush the valve
	Pump problems	See **Chapter 6: Pumps and driving systems**
	Negative pressure in the pipeline	Replace and install air valve/s

Table 10: Trouble shooting table for uPVC pipes (De Villiers, 2002)

Problems	Possible causes	Solutions
Pipe splits	Surge pressure exceeding the pressure class of the pipe	Replace pipe with a higher class Control the pressure
	Waterhammer in system	Put in air valves Reduce flow velocity Change the operational sequence of the system
	Poor quality	Replace pipe
	Damaged pipe	Replace or repair damaged portion
Pipe bursts in a herringbone fracture along its entire length	Waterhammer in the system, usually induced by the rapid recolution of air in the system	Investigate air entrapment in the system and install air relief valves
Pipe flattens causing stress cracking	Negative pressures in the line	Provide air valves to allow air into the system. Provide a non-return valve.
Joint leaks – seal pushed into the pipe	No lubrication during jointing	Use Gel lubricant
	No chamfer on the pipe spigot	Chamfer pipe to 15^o
	Seal inserted the wrong way round	Insert seal correctly
Joint leaks – seal extruded out of the pipe	Air in the line trying to escape	Purge the line at low pressure during commissioning.
	Poor alignment of the joint	"Ease" the alignment horizontally and/or vertically
Joint leaks – constant dripping	Sand/grit behind the joint	Remove and clean properly
	Pipe spigot over-inserted into the socket not allowing movement	Ensure pipe is only inserted up to the depth of entry mark.
	Poor quality of housing	Cut out joint and repair
	Pipe diameter under size	Replace pipe

Problems	Possible causes	Solutions
Solvent cement joint pulls out	Surface not prepared properly	Use sandpaper and a solvent cleaner.
	Solvent cement is “old” and does not “bite” into the surface	Use new pressure cement that has a strong smell and is not too thick
	Pipe too small or socket too big	Replace pipe or socket
	Solvent cement not cured properly	Allow longer curing time, especially at low temperatures.
Pipe splits near a solvent weld joint	Too much solvent cement in the joint area, softens the pipe	Only use sufficient to just cover both surfaces.
Small hole appears in the pipe wall	Foreign particles in the raw material	Repair hole or replace pipe

Table 11: Trouble shooting table for low density polyethylene pipes (De Villiers, 2002)

Problem	Possible causes	Solution
Stress cracking at joints	Insert fitting too big	Use reputable suppliers
	Pipe material is of poor quality	Replace pipe with SABS quality pipe
Pipe crumbles like a biscuit	Excessive Ultra Violet exposure	Bury the pipeline
	Poor quality of pipe, usually from regrind material	Purchase pipe from reputable manufacturers
Pipe bubbles and splits	Under specification wall thickness on one side	Cut out and replace pipe
	Pressure class of pipe is exceeded	Use higher class of pipe or reduce pressure
Small hole appears in the wall of the pipe	Foreign particles or unmelted pellet in the side wall	Cut out and repair
Joints "pull out"	Not clamped properly	Use hose clamps
	Pipe too big or fitting too small	Replace pipe or fitting
	No allowance for expansion or contraction	Provide expansion loops in long lines exposed to the sun

Valves

Correctly operating control valves also contribute to the effectiveness of a system. The following principles apply at hydraulic control valves:

- To open the valve, water must be released from the control chamber. This can be done by means of a three-directional switch, which is usually marked "open, close, auto". Ensure that when "open" is selected, water is released from the control chamber of the valve.

- A solenoid consists of a coil that pulls a shaft up as soon as electricity flows through the coil. If a solenoid is used, the water must be released as soon as the computer activates the solenoid.

- If the valve must carry out pressure control function, the three-directional switch must be set to the position that connects the control chamber of the control valve to the pilot valve. The water must then release through the pilot valve. If any combination of equipment is used, the switch must be directed to the position that releases water through the solenoid or pilot valve.
- To close a control valve, water must flow into the control chamber from the upstream position. Ensure that the three-directional switch is in the correct position.
- The pilot valve controls the pressure in the system by controlling the pressure in the control chamber. If water flows out of the pilot valve, the pilot valve is faulty, or the diaphragm of the control valve is damaged. (Some pilot valves, however operate on the principle that there must be a constant flow of water through the pilot valve, in order to execute the control function).
- Stones, sticks and other dreg can damage a control valve and cause it to leak or to not open at all.
- Control valves must however be chosen correctly for the flow and/or pressure conditions in the system.
- Control valves require a minimum pressure to function correctly. It varies between the different manufacturers. If the pressure is too low, the valve cannot open enough or close tightly.

Tables 12 to 15 show troubleshooting tables for different valves:

Table 12: Troubleshooting table for pressure relief / pressure sustaining valves

Problem	Possible causes	Solution
Valve does not open	Pilot valve spring is set too tight	Turn adjusting nut to (-) minus until the valve opens.
	No pressure in system	Switch on pump/ Open shutoff valve
	Hand control set incorrectly	Make sure of setting
	Worn pilot valve	Replace/repair pilot valve
Valve does not close	Control filter blocked	Remove and clean filter
	Internal ports in pilot valve blocked	Clean pilot valve
	Hand control set incorrectly (if applicable)	Make sure of setting
	Dirt in main valve	Remove valve or moving parts and check for damage
	Diaphragm faulty	Test for damage: **Single chamber**: Open plug on top of diaphragm chamber. Disconnect all pipes to diaphragm chamber. If water flows out constantly, replace diaphragm. **Double chamber:** If water flows out from bottom chamber constantly, with pilot valve connected, but stops as soon as pilot valve is disconnected, replace diaphragm.

Table 13: Troubleshooting table for electrical control valves

Problem	Possible causes	Solution
Valve does not open	No electricity supply	Check/switch on
	No pressure in system	Switch on pump/ Open isolator valve
	Solenoid: a) Shaft is stuck b) Ports blocked c) No activation click or coil is damaged	 a) Check and clean b) Check and clean c) Replace spool. Ensure that supply current is the same as solenoid specifications.
	Hand control set incorrectly	Check
Valve does not close	Control filter blocked	Remove and clean filter
	Hand control set incorrectly	Check
	Solenoid: a) Remains switched on b) Ports blocked	 a) Switch power off b) Check and clean
	Dirt in main valve	Remove valve or working parts and check for damage
	Diaphragm faulty	Test for damage: **Single chamber:** Open plug at top of diaphragm chamber. Disconnect all pipes to diaphragm chamber. If water flows out constantly, replace diaphragm. **Double chamber:** If water flows out of bottom chamber constantly with pilot valve connected, but stops as soon as pilot valve is disconnected, replace diaphragm.

Table 14: Troubleshooting table for pressure reducing valves

Problem	Possible causes	Solution
Valve does not open	No pressure in system	Switch pump on / Open valve
	No flow in system	Switch pump on / Open valve
	Pilot valve set incorrectly	Turn adjusting nut to (+)plus
	Hand control set incorrectly	Check
	Pilot valve blocked	Remove and clean filter
Valve does not close	Control filter blocked	Remove and clean filter
	Hand control set incorrectly	Check
	Dirt in main valve	Remove valve or working parts and check for damage
	Diaphragm faulty	Test for damage: **Single chamber**: Open plug on top of diaphragm chamber. Disconnect all pipes to diaphragm chamber. If water flows out constantly, replace diaphragm. **Double chamber**: If water flows out constantly with pilot valve disconnected, replace diaphragm**. Take care:** This test will cause the valve to go to fully open position. Ensure that no damage will be done to the system.
Valve does not control pressure	Pilot valve is worn	Check/Replace/Repair
	Valve constantly opens and closes	Control valve too large/Pressure difference too great/Flow too low – Replace control valve, delay operating speed or use another type of pilot valve
	Air trapped in control chamber	Loosen seal at highest point of control chamber and let air escape

Table 15: Troubleshooting table for sluice valves

Problem	Possible causes	Solutions
Valve leaks	Packing gland faulty/loose	Tighten packing gland, replace packing
Valve does not function	Screw thread damaged	Replace nut and/ or shaft
	Bush on sluice broken	Replace bush
	Sluice has corroded and rusted	Dismantle and clean
	Valve has difficulty functioning – turns heavily	Relieve tension on packing gland, lubricate screw-thread

7 Summary

The guidelines for on-farm conveyance systems provide information to convey the water from farm edge to the field at the lowest possible energy requirements – operational economy and conveyance efficiency of the system components are of importance.

The following guidelines should be adhered to when planning, designing and managing on-farm water conveyance systems:

- The system should be laid out and designed with capital as well as operational costs in mind
- The most efficient pumps and motors should be used as far as possible
- Infrastructure should be designed using SABI design norms
- Electrical cables should be correctly sized
- High quality equipment should be selected and correctly installed
- Flow rate, pressure, electrical current and water quality should be monitored regularly at strategic locations and assessed against the design values.

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Standards and Guidelines for Improved Efficiency of Irrigation Water Use from Dam Wall Release to Root Zone Application

EFFICIENT WATER USE GUIDELINES

Module 4

DEVELOPING AND MANAGING EFFICIENT IRRIGATION SCHEMES

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List of Acronyms and Abbreviations

BC	Beneficial consumption
CI	Confidence Interval
CMA	Catchment Management Agency
CV	Coefficient of variation
DWA	Department of Water Affairs
ECA	Environment Conservation Act (Act 73 of 1989),
ECSA	Engineering Council of South Africa
FWACS	Fractional water allocations and capacity sharing/water banking
GWCA	Ground Water Control Area
IB	Irrigation Board
ICID	International Commission on Irrigation and Drainage
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
NBC	Non-beneficial consumption
NEMA	National Environmental Management Act
NGA	National Groundwater Archive
NGDB	National Groundwater Database
NRF	Non-recoverable fraction
NWA	National Water Act (Act No.36 of 1998)
NWCDMS	National Water Conservation and Demand Management Strategy
NWRS	National Water Resources Strategy
PEL	Potential economic loss
PLL	Potential loss of life

RF	Recoverable fraction
SC	Storage change
WAS	Water Administration System
WC/WDM	Water conservation and water demand management
WMP	Water Management Plan
WUA	Water Users Association

1 Introduction

On an irrigation scheme, where irrigation water users are grouped into organisations that share a water source such as a canal, river or groundwater aquifer, the management authority have an important role to play in conserving water and managing demand.

To the farmer, good water management means getting the right amount of water to the crops at the right time with minimum labour and expense. If this can be accomplished without creating other problems, such as a build-up of salt in the soil or losing water to spills and seepage, so much the better.

To the irrigation scheme, good water management means meeting the water needs of its customers as efficiently as possible, with minimum waste or loss. Good water management is, therefore, fundamentally important to good overall scheme management.

To society, good water management means having adequate supplies of good quality water for all municipal, industrial, agricultural, recreational, and environmental needs. Those in charge of operating water supply and delivery systems bear the greatest burden of responsibility for promoting and achieving the good water management demanded by society (USBR, 1996).

1.1 Co-operative governance and institutional development

In terms of the National Water Act there is a hierarchy of measures in place for the control of water use. This hierarchy is linked to the risk of impact of that use – the higher the risk, the stricter the conditions are for the use (see Figure 1). Depending on the level of risk, certain management interventions need to be put in place. In stressed water resources such as the Sandveld and Steenkoppies aquifers, Inkomati and other water management areas, higher levels of management interventions such as the validation and monitoring of water use need to be put into place.

Validation of registered groundwater abstraction must be done in accordance with the Verification Guidelines of the Department. Once completed, compulsory licensing will be possible in the stressed area.

1.2 System management (Operation and Maintenance)

Monitoring devices such as flow meters and groundwater level metering should be adequately operated and maintained. Calibration of these instruments must be done through a third party and on a regularly base.

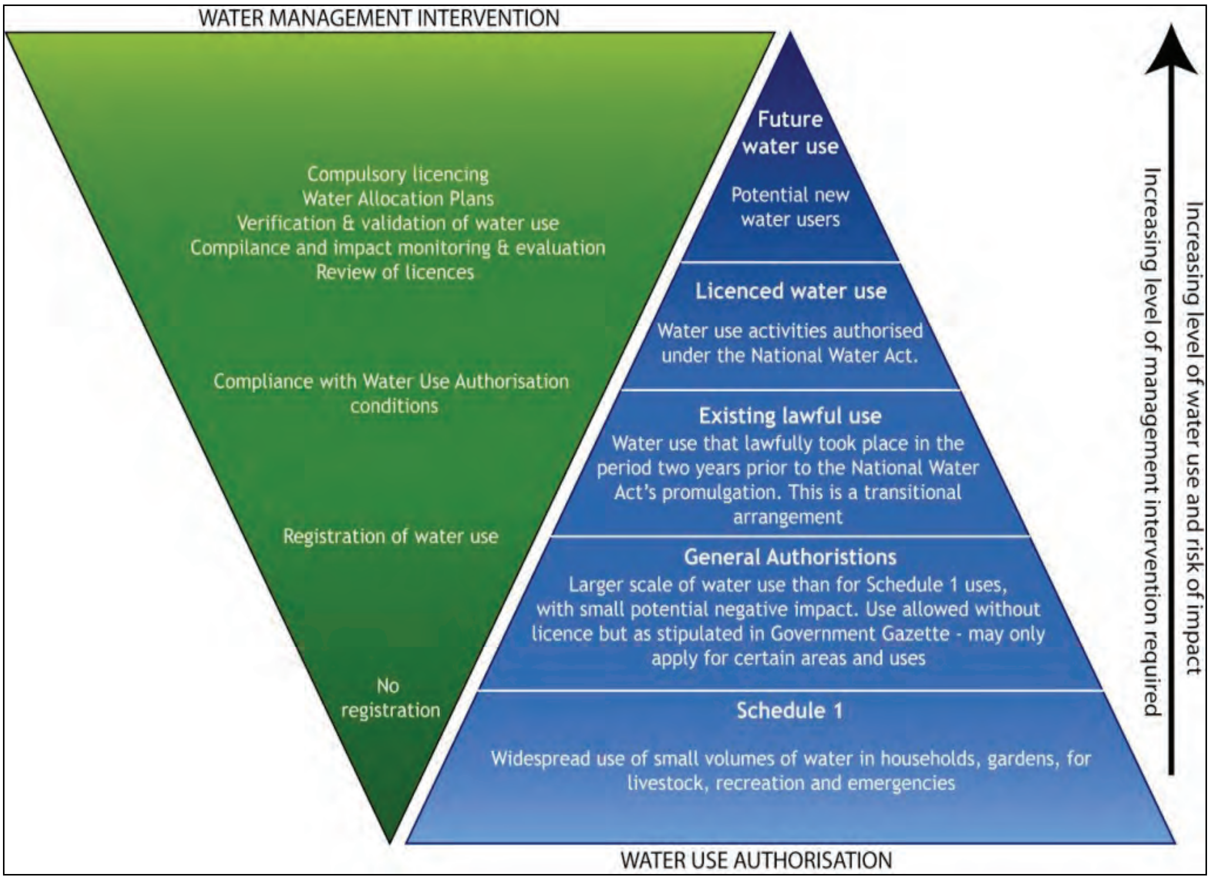


Figure 1: The water use authorization hierarchy (NWA)

1.3 Water Conservation and Water Demand Management

Improved efficiency through water conservation and water demand management (WC/WDM) could potentially save a significant volume of water. For the agriculture sector the optimum water needs for the specific crops grown in the area must be established and adhered to. For urban or informal settlements, water losses from the water supply system should also be monitored and managed.

1.4 Environmental management

1.4.1 Solid waste management

Poorly managed disposal of refuse and other waste products can severely impact on the surrounding environment and biodiversity, mainly through pollution effects. The disposal of waste is controlled by the Environment Conservation Act (ECA) (Act 73 of 1989), National Environmental Management Act (NEMA) (Act 107 of 1998), and the National Water Act (NWA) (Act 36 of 1998) and is administered jointly by DEADP and DWA.

1.4.2 Ecosystems

Groundwater management plans should take into consideration ecological needs of a groundwater system, for example the groundwater dependant ecosystems in Sandveld and Reivilo have been identified as having unique plant species.

In general, three broad classes of ecological issues affecting the biodiversity and ecological health can be distinguished:

- Altered flow regimes - increased abstraction from groundwater resources influence baseflows and therefore its contribution to surface water.
- Reduced water quality (through increased water resource abstraction, resulting in decreased freshwater input and recharge, saline intrusion and nutrient loading).
- Habitat modification and loss (through land clearing and water abstraction).

1.5 Water use pricing

The possibility to use water pricing as a mechanism to encourage the efficient and optimal use of the resource in groundwater areas should be investigated.

1.6 Scheme level water management

Therefore to manage irrigation schemes with water use efficiency in mind, it is necessary that:

- The water available to all the users on the scheme is known to both the scheme management and the water users, and the information is accessible,
- The water use on the scheme is planned on a weekly, monthly, seasonal or annual basis, as applicable, to match the expected crop water requirements but not exceed the supply available from the resource,
- The scheme has accurate and reliable measuring devices installed at the identified strategic points on the conveyance system,
- The scheme is operated and maintained according to the design specifications and sound operational rules, as captured in a regularly updated water management plan and supported by a water pricing policy that encourages efficiency, and
- The scheme management system is regularly evaluated to assess the level of performance and detect problems as early as possible.

This module therefore provides guidelines on how these aspects of irrigation scheme development and management can be addressed, through different methodologies.

2 Water availability

The water available to all the users on the scheme should be known to both the scheme management and the water users.

As discussed in Module 1, the allocation of water and the use thereof by individual users from the different sectors, is regulated by legislation. The act currently in force is the NWA, which determines that the government is the official custodian of the country's water.

The scheme management has an important role to play in assisting water users to comply with the legislative requirements of water use for irrigation. Scheme managers should be knowledgeable on matters of water use registration, transfers, verification, validation and compliance monitoring.

A major part of scheme water management is the administration thereof – keeping records of water users, their details, allocations, transfers and financial management. The Water Administration System (WAS) is designed to be a management tool for irrigation schemes and water management offices that want to manage their water accounts and water supply to users through canal networks, pipelines and rivers. WAS is developed and maintained by NB Systems cc. Financial contributions for the development of WAS were made by the Water Research Commission (WRC) and the Department of Water Affairs (DWA).

The WAS program is currently in use at all the major irrigation schemes and a number of smaller irrigation boards throughout South Africa.

2.1 The WAS program

The WAS is designed to be a management tool for irrigation schemes, Water User Associations (WUAs), Catchment Management Agencies (CMAs) and water management offices that want to manage their water usage, water distribution and water accounts. WAS can handle any number of abstraction points and measuring stations on canal networks, pipelines, rivers and groundwater aquifers.

2.2 Application areas

WAS is an integrated database driven system with many water management capabilities. WAS can be implemented in a small water office that manages a few abstractions and measuring stations up to a CMA level that manages thousands of abstractions and measuring stations. WAS is used for the efficient administration of:

- Address information.
- Scheduled areas.
- Water quota allocations.
- Water delivered through pressure-regulated sluice gates, measuring structures and water meters.

- Water transfers between users (Automatic and manually).
- Water use calculations for planted areas based on crop water use data.
- Date and time related flow data collected from electronic loggers or mechanical chart recorders.
- Discharge tables (DT) to do conversions between water depth and flow rate for measuring structures or visa versa.
- List of rateable areas (LRA) information.
- Calculation of scheme water balances.
- Calculation of water releases for water distribution through canal networks, pipelines and rivers taking lag times, evaporation, transpiration and seepage into account.
- Billing system that links to the water usage information.
- Flexible tariff sets based on water usage, a flat rate or scheduled area.
- Images and photos that can be linked to different types of information in the database.
- Mail merge facility for sending letters to clients.

2.3 Benefits

The WAS program saves all information in a Firebird database that can be installed on a single PC or on a server for use over a network. This makes it possible for the manager, accounts personnel and water office personnel to access the database from PCs in their own offices. There is no limitation on the number of PCs that can be linked to the database.

What makes the WAS program unique is the fact that it is an integrated system that includes the water allocations, water use, water distribution and billing information. WAS will generate monthly invoices automatically using water usage or scheduled areas information captured in the database.

Different user names and passwords can be used to control access to certain information in the database. Using the WAS program have many benefits including:

- Minimise water losses
- Maximise water usage
- Saving time and improve productivity
- Better financial control
- Improve overall management of a scheme

2.4 *WAS Modules*

WAS consists of seven modules (see figure 2) that are integrated into a single program that can be used on a single PC or a multi-user environment. These modules can be implemented partially or as a whole, depending on the requirements of the specific scheme or office. The seven modules are:

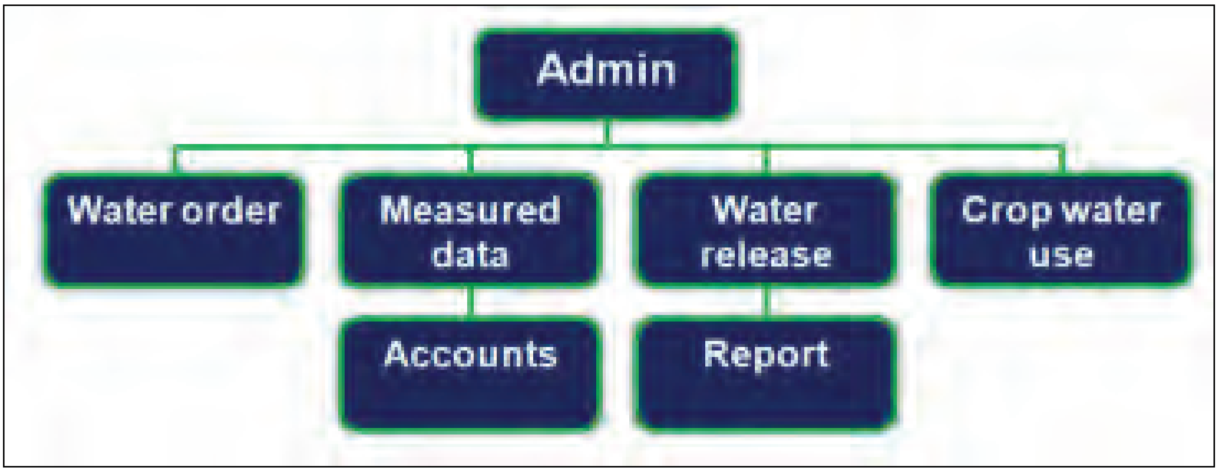


Figure 2: WAS program modules

2.4.1 Administration module

This module is used to administer the details of all water users on an irrigation scheme. Information managed by this module includes addresses, notes, cut-off list, images/photos, list of rateable areas, scheduled areas, household and livestock pipes installed on canals, industrial water quotas, crops and areas planted and crop yields. The administration module must be implemented before any other module.

2.4.2 Water order module

This module is used to administer water abstractions from canal networks, pipelines and rivers and it keeps track of water quota allocations and water usage. Water abstractions can be captured in four different ways.

- Standard water order forms such as the ones currently used by DWA and a few irrigation boards and water user associations. Provides for original orders, additional orders and cancellation of water.
- Water orders based on a flow rate, starting date and time and duration.
- Meter readings that can be captured on a weekly or monthly basis. The end reading of the previous period is automatically transferred to the start reading of the current period.
- Date and time related data that can be imported from electronic data loggers. Water usage can be calculated between specified date and time ranges.

The water order module also has extensive water reporting capabilities such as:

- Water balance sheet per abstraction.
- Water balance report that can summarise the water usage per abstraction and all the abstractions per farmer.
- Water usage per month report.
- Operator defined water reports to compile weekly, monthly, quarterly and yearly water usage reports.

Most of the water reports have extensive find, sort and filtering capabilities. Abstraction points can be linked in such a way that water is transferred from a master to an extension automatically. There is no limit to the number of extensions that can be linked to a master.

2.4.3 Crop water use module

The main function of the Crop water use module is to calculate the water usage per crop between two specified dates for all the planted crops on a scheme based on the plant date, the area planted and the crop water use curve. The crop yield (ton/ha) can be captured at the end of a growing season which is used to calculate the total yield (ton) and the yield in (g/m^3). A summary of water used for a specified period can easily be generated per crop type. All the crop water use information can easily be linked to a geographic information system (GIS) via ODBC and the Land ID field in the crop water use module.

2.4.4 Measured data module

The measured data module is used to capture date and time data into the WAS database. The data can be from graphs, electronic loggers, measuring plate readings, dam levels or meter readings. Integrated into this module are discharge tables that are used to convert water levels to discharges and vice versa. Data can also be imported electronically into the WAS database.

This module is also used to capture inflows and outflows for river systems and to generate discharges for stations that are linked to an indicator site. Volumes can easily be calculated between dates and converted to meter readings if necessary. Measure station data also integrates with the user defined water reports and the disposal report in the WAS program. All readings and discharges can be represented graphically with user-defined date and time ranges.

2.4.5 Report module

The report module includes an extensive range of water and financial reports. Water balance sheets, distribution sheets, disposal reports and various other operated defined reports can be generated.

2.4.6 Accounts module

This module links with the administration and water order modules and administers all water accounts for an irrigation scheme or water management office. The water accounts module is a full debit system, from which monthly reports can be printed, including invoices on pre-printed stationery, reconciliation reports, age analysis and audit trail reports.

2.4.7 Water release module

This module links with the water order module and calculates water releases for the main canal or river and all its branches and tributaries allowing for lag times and any water losses and accruals. A schematic layout of the total canal network or river system is captured with detail such as the cross-sectional properties, positioning of sluices or pumps, canal or river slope, structures and canal or river capacities. Discharges are converted to the corresponding measuring plate readings where needed. Water distribution sheets and water loss analysis reports can be printed for canal or river systems.

2.5 Special features

- Data capturing screens are consistent and easy to use
- WAS combines water management, water distribution and an accounting system
- The Firebird database is robust and easy to maintain
- The data handling capacity is only limited to the size of the hard drive
- WAS can be used in a multi-user environment
- Extensive error checking capabilities for data capturing are standard
- Where possible data or results are represented graphically
- WAS was developed for users, by users
- Additional features are included as part of an ongoing development, installation and training programme

2.6 User requirements

WAS requires at least a 486-PC running Windows 95/98/NT/XP/Vista. At least 512 Mb RAM must be available to run the program, but 1024 MB is recommended. WAS is written in the programming language Delphi and uses Firebird (SQL-based) as the underlying database. Firebird is a relational database management system (RDBMS) that provides rapid transaction processing and data sharing in a single- or multi-user environment.

3 Planning

The water use on the scheme is planned on a weekly, monthly, seasonal or annual basis, as applicable, to match the expected crop water requirements but not exceed the supply available from the resource,

Planning of water use – to predict expected abstractions by users from the shared water resource – is probably the most important aspect of water management. It is not enough to try and control or monitor water use after it has taken place without having an expected or predicted figure to compare it against.

The irrigation boards or WUAs in South Africa that have managed to implement practical and accurate planning functions into their management systems, have succeeded in establishing water management systems that are effective, useful and considered fair by all involved – an imperative factor if the water users are expected to respect and accept the system.

Good planning relies on an understanding of the supply of water from the source, as well as the behaviour of the water use abstracting water from the system. Understanding the hydraulics of a canal system, or the hydrology of a river, or the recharge of a groundwater aquifer are specialised fields of water management but there are South African models that help water managers to plan and predict the behaviour of the supply system they have to manage.

Predicting the behaviour of the water users require knowledge of and information on local conditions, crops and practices that can be used to estimate irrigation requirements and therefore expected water withdrawal patterns.

Good planning practices will provide the scheme manager with the necessary quantified information of supply and demand against which actual measured volumes can be assessed.

3.1 Canal schemes

The purpose of the on-scheme canal conveyance system is to convey the water from the source (usually a dam) to the farm edge so that the right amount of water reaches the right destination at the lowest possible energy requirement and with the least amount of losses – conveyance efficiency and operational economy of the system components are therefore of importance.

The canal conveyance system include the canal inlet works, main, secondary and tertiary canals, sluice gates and other control mechanisms, automation thereof, and drainage system, if applicable. Optimisation of the performance of any component of the system requires careful consideration of the implications of decisions made during both development (planning and design) and management (operation and maintenance) of the component. Optimisation through management alone will be severely limited in its potential if the infrastructure was not developed with technical, economical and environmental efficiency in mind.

Although it is unlikely that more new canal schemes are to be developed in South Africa in the near future, expansions and upgrades do take place from time to time and some comments on the planning and design of canal systems have to be made. Many existing schemes have aging infrastructure that need to be improved and modernised to improve conveyance efficiency, and WUAs are encouraged to seek finance or budget for these changes as early as possible.

The Department of Water Affairs (DWA) Guidelines for the design of canals and related infrastructure (1980) provide sound planning and design norms that are still valid. However, planners should take into account demands to be made on systems due to changes in water legislation and the water availability situation. Specifically, the accurate measurement of water has become more important, and together with a reduction in water quality in general, this poses new challenges to designers when selecting suitable equipment. Other demands include building more flexibility and capacity into canal systems so that water can be supplied within times when electricity tariffs are lower and to facilitate trading of water on-scheme. Scheme infrastructure should also be supported by sound operational rules and a sensible WUA constitution that encourages water conservation and demand management. Finally, when planning a new scheme, opportunities for automating the monitoring and control functions should be considered at the outset as it is more cost effective to plan for this from the beginning than to make changes to infrastructure at a later stage.

Improved operation and maintenance of existing canal schemes offer numerous opportunities for improving conveyance efficiency. Proper planning of water releases and deliveries, as well as effective administration and record-keeping, using suitable computer programmes such as the WAS is considered a best management practice and should be implemented.

This can be supported by implementing management technologies such as telemetry and automation that makes it possible for scheme managers to obtain the information needed to make decisions and to implement the decisions much faster than older, manual methods. Although some of the technologies are capital intensive, the cost is usually recovered within a few years and the benefits recognised by the water users when delivery improves. More accurate monitoring practices also makes it possible to assess losses more regularly and take the necessary action.

Due to deteriorating water quality in many of our rivers, water quality monitoring has also become a necessity, and various technologies are available to improve water quality problems that have negative impacts of water management in the canals.

3.2 River systems

A river system that supplies water to irrigation water users abstracting water through individually operated abstraction points, can be controlled, in which case water is released from a dam or weir into the river, or uncontrolled, in which case the irrigation water users are dependent on the natural stream flow that occurs in the river and there is no dam or weir (”run of river” system), and have little influence over the management of the conveyance system.

The purpose of the river conveyance system is to convey the water along the river to the abstraction points so that the right amount of water reaches the right destination with the

least amount of losses and impact on the environment – conveyance efficiency in the river system is therefore of importance.

The river conveyance system includes the dam(s) or weir(s) in the river from where water releases are controlled, the river section along which water is conveyed, the abstraction points, and automation of any component. Optimising the performance of any component of the system requires careful consideration of the implications of decisions made during both development (planning and design) and management (operation and maintenance) of the component. Optimisation through management alone will be severely limited in its potential if the infrastructure was not developed with technical, economical and environmental efficiency in mind.

3.2.1 Planning and design

The most efficient river conveyance system will be one that is planned and designed with the requirements of the users (supply versus demand), the hydrology of the system (physical characteristics of the terrestrial environment) and the requirements of the ecological environment taken into account.

Most irrigation water users in South Africa obtain their water from rivers, and the users can be organised in different ways – either into WUAs (or previously established irrigation boards) or they fall under the management of DWA regional offices, some of which are destined to become CMAs. The NWA calls for greater responsibility in managing our rivers, and water is suppose to be allocated firstly to the Reserve, which consists of the environmental requirement of the river system and water for basic human needs. The pressure is therefore increasing on irrigation water users depending on river flow to manage their water better and keep record of their consumptive use.

Opportunities for new dams/weirs are limited and permission must in most cases be obtained from DWA; opportunities for improved water use efficiency therefore lies mostly with the improved management of existing river supplied areas. A good understanding of the hydrology of the river is needed, and practical models used to improve this understanding.

Infrastructure in rivers should take the natural state and requirements of the rivers into account, such as passing of sediment and allowing passage for fish to pass through, and should also be supported by sensible operating rules and WUA constitutions. Abstraction points should be properly protected, and provision made for automation of control and data collection as far as possible.

Hydrology

Hydrology can be broadly defined as the technical field encompassing the occurrence of water on, above, or within the earth. Therefore it resolves around understanding and describing the physical components of the hydrological cycle. This hydrological cycle is the actual pathway of water as it moves in its various phases through the atmosphere, down to the earth, over and through the land, to the ocean, and back to the atmosphere.

For an irrigation practitioner making use of naturally generated runoff from the hydrological cycle, an understanding of hydrology is important for both the design and operation systems which are directly linked to hydrology, and components of the hydrological system (i.e. rivers conveying surface runoff).

Integrated Water Resources Management

Integrated Water Resources Management (IWRM) is an approach which promotes the co-ordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Global Water Partnership, 2000). With irrigation often being the largest user of water in river systems, it is important for irrigators to acknowledge that IWRM principles need to be upheld to ensure that social and ecological water needs are met for sustainable commercial development. These principles should be considered during planning phases, and always reviewed and upheld in the actual management and operation of catchments.

The NWA and the National Water Resources Strategy (NWRS) define how water and water resources are to be managed and utilised in South Africa. A brief description of how this act influences irrigation water use was presented in Module 1.

3.2.2 Construction of Dams

A dam or weir that is constructed in the river will, depending on the hydrology and existing level of infrastructural development, increase the volume of utilizable water in a river system.

Water Resources Infrastructure Development projects are expensive, and often have conflicting implications and benefits for different water use sectors or groups. Therefore, careful planning is required to achieve optimum utilisation of river basins as a whole, as well as for specific projects within them. A simple example of this would be constructing a dam to increase utilisable yield for irrigation water supply, but without comprising ecological systems downstream of the dam which require relatively natural flow regimes to be sustainable. The planning process is typically completed in three phases:

- **Preliminary/Pre-Feasibility Study** The preliminary study should be regarded as a where a number of alternatives may either be supported or rejected based on rough data and short cut/desktop analyses. The preliminary study will either result in the project being abandoned, or in a recommendation to advance to a full feasibility level study
- **Feasibility Study** A project plan is developed in sufficient detail to determine whether or not the project should be implemented. The plan should be technically and economically feasible, as well as environmentally acceptable. This is completed for a number the best sites identified in the pre-feasibility stage. A decision is made whether to advance to a final study level.

- **Final Study** Detailed designs, specification of construction plans and cost benefit estimates are finalised

Planning considerations for dam constructions will always include, but are not limited to:

- **Hydrological data** Data for the river that the dam is to be constructed on are analysed to determine flood and drought flows, in order to determine required capacity and operational procedures
- **Geological data** Geological data is required to investigate the structural ability of foundation material, and its ability to withstand leakage and erosion problems
- **Reservoir data** A complete analysis of the area to be inundated by the reservoir must be made to estimate the cost of land acquisition and relocation of infrastructure
- **Environmental Assessments** Environmental Impact Assessments (EIAs) are required to assess if unique environments may be inundated and also the general environmental impact caused by the dam and reservoir

Dams are classified according to their material composition (e.g. earth, rock, or concrete dams) and the configuration and manner in which they resist the forces imposed on them (e.g. gravity, buttress, or arch dams).

In South Africa, the construction of dams and weirs is regulated by DWA, which is guided by the NWA. Dam safety legislation attempts to set certain safety standards and, in so doing, limit potential loss of life and infrastructural damage.

1984 saw the inclusion of Article 9C, which deals with “Safety of dams”, in the Water Act. It is also known as the Water Amendment Act, 1984 (Act 96 of 1984), which was published in Government Gazette no 9339. Regulations arising from this act were implemented in 1986 and comprised the conditions and requirements which had to be met regarding the classification, design, construction, registration, commissioning, operation, maintenance and abandonment of a dam with a safety risk. This has been further reviewed and draft regulations regarding the safety of dams under section 123(1) of the NWA are currently being finalised. A number of conditions and requirements are set according to different dam sizes and threat potential.

Definitions and requirements

The following three definitions are listed as part of the regulations:

- A dam may be defined as any structure within which water may be stored.
- A “dam with a safety risk” may be defined as a dam which has a storage capacity in excess of 50 cubic metres and a vertical wall height, measured on the downstream side, in excess of five metres. Furthermore, any dam not fitting the above description may be declared a dam with a safety risk if, in the Minister’s judgement, the structure is such that it poses a threat to human lives or public safety.

- An "approved professional engineer" may be defined as a professional engineer who has been approved by the Minister in consultation with the Engineering Council of South Africa (ECSA), for the purposes of this article.

Requirements arising out of the Act are the following:

- An owner of a dam which was built before the implementation of the act must register the dam within 120 days of that date.
- An owner of a dam which was completed after the implementation of the act must register it within 120 days of the date at which it is ready to store or release water.
- An owner of a dam must comply with all the regulations, as specified by the act, regarding the design, construction, commissioning, modification, enlargement or use thereof.

Dam classification

Every dam with a safety risk must be classified by the Director General as a category I, II, or III dam in terms of the size (maximum wall height) and the potential threat thereof. For this purpose, the threat potential may be defined as the indication of the potential loss of life (PLL) and the potential economic loss (PEL) that could result from the collapse of the dam. The separate consideration of the PLL and PEL is accepted as the highest resultant value. Table 1 summarises the categories of dams with safety risks.

Table 1: Dam safety risk classifications

Size classes (h = max. wall-height in metres)	**Threat potential**		
	Minor (PLL = 0 and PEL: minimal)	**Considerable ($0 < PLL \leq 10$ or PEL: considerable)**	**High (PLL > 10 or PEL: high)**
Small (5 < h < 12)	Category 1	Category II	Category II
Medium (12 < h < 30)	Category II	Category II	Category II
Big (h > 30)	Category III	Category III	Category III

Before work starts on the construction of a new dam, or on modifications to an existing dam, the local Water Affairs office must be contacted for the necessary application forms and permits. The maximum wall height (h) is the height measured from the surface of the river or stream up to the top of the wall. This measurement is done on the downstream side of the wall. More detailed information, forms and regulations can be obtained from the Dam Safety Office at DWA (http://www.dwa.gov.za/DSO/guidelines.aspx).

3.2.3 Outlet works

The capacity of outlet works (not taking power generation into account) should be designed for general operation requirements of downstream water user and environmental requirements. Energy dissipation of released water also needs to be taken into account to prevent possible detrimental effects to the environment as well as the integrity of the dam for dam safety requirements. The outlet works should be to accommodate a range of flow rates, and flow measurement should be included at the outlet works. It is important that a dam operator can accurately determine the flow rate being released while changes are being made at the outlet works.

3.2.4 Abstraction points

The design and construction of abstraction points in terms of health and safety, and the reduction of head loss is detailed in the Irrigation Design Manual and the SABI norms. These documents stipulate design requirements and characteristics of pump stations which help ensure pump stations are safe, efficient and cost effective to operate. Please refer to these information sources for specific details.

Water Level Fluctuations

Water level fluctuations which will drastically affect the delivery side hydraulics of the pump leading to a reduction in efficiency of the pump need to be considered. If such water level fluctuations occur, either a floating, rail mounted, construction of low level sump should be considered. Water level fluctuations due to flooding, and the subsequent damage also need to be planned for.

Sediment Load

Excessive sediment loads caused by locating an abstraction point at the incorrect position relative to the river morphology will result in pump wear, reduced efficiency and higher maintenance costs. Planning this aspect of the pump station design will reduce these risks. If placement of the pump station alone is not sufficient to reduce sediment load, structures and mechanisms to reduce the impact will need to be planned and designed for.

River Bank Erosion

Erosion of the river bank needs to be considered when choosing a location for an abstraction point. Relocation of an existing pump station due to bank erosion, or excessive measures to prevent further erosion are expensive and best avoided by proper planning in the location and design of the abstraction point.

3.3 Groundwater aquifers

A groundwater system is a groundwater aquifer in which the water source is shared by individual water users and includes the abstraction points, water distribution network, management structure of the aquifer and automation of any of the components.

The exploitation of a shared groundwater system is typically a problem of common property, since the resource is limited. If the goal of each water user (e.g. an irrigation farmer) is to maximise profit, a private solution to manage the groundwater system is inefficient due to the following reasons:

- Because groundwater supply is limited, each unit extracted by a specific water user is no longer available to other users and the only way to lay claim to a unit of groundwater is to pump it. Therefore the incentive to save water is inadequate, since other water users have the same access to the groundwater.
- Pumping costs depends on groundwater depth and extraction cost will increase with the lowering of the groundwater level. Individual water users do not consider the detrimental effect of their pumping on other water users, so again the incentive to save water is limited.
- If an aquifer is susceptible to contamination resulting from the users' actions, then additional externalities occur. Each user will only consider his own polluting impact on the groundwater, imposing external costs on all other water users.

Therefore if the objectives of a groundwater scheme are to:

- Ensure sustainable use of water,
- Protect the resource,
- Effectively monitor and manage the resource,

then the source must be managed collectively with all stake holders' needs and expectations taken into consideration.

Optimisation of the performance of any component of the system requires careful consideration of the implications of decisions made during both development (planning and design) and management (operation and maintenance) of the component. Optimisation through management alone will be severely limited in its potential if the infrastructure was not developed with technical, economical and environmental efficiency in mind.

As the river water supplies in South Africa come under more pressure, more and more water users are developing groundwater sources for irrigation. It should be kept in mind though that groundwater supplies are not unlimited and need to be managed as carefully as surface water sources, both in terms of quantity and quality.

Determining the boundaries of an aquifer, its reliable supply and behaviour when used by more than one irrigator is a specialist field and geohydrologists should be consulted. Abstraction points should be fitted with flow measuring devices and aquifer water levels monitored continuously. It is important that the water users that share the aquifer should agree on operational rules and centralise management if possible.

3.3.1 Assessment of area

Physiography

Location

The boundaries and sub compartments of the aquifer must be well defined and illustrated on a map to include all relevant water users and stake holders on the aquifer. However, for management purposes this area can be expanded to include the catchment area and/or groundwater users adjacent to the aquifer that may influence the aquifer, as in the case of the Steenkoppies aquifer in Tarlton, West Rand.

Ecologically sensitive areas, such as the camel thorn trees of the Kathu forest (Reivilo, Kgalagadi district), Maloney's Eye (Tarlton, West Rand), threatened endemic plant species in the Sandveld (Sandveld, Western Cape) or the many wetlands that are found across South Africa, must be identified and incorporated in the planning and design of a groundwater system to protect these areas.

Local Government
The boundaries of more than one local government may extend over the aquifer, as in the case of the Reivilo (Kgalagadi District) and Steenkoppies (Tarlton, West Rand) groundwater management areas. Because local government is a stake holder that must be represented on the management committee of a groundwater association, all relevant local governments need to be identified.

Water users
The National Water Act prioritise water use between different sectors and therefore it is important that the different sectors, their water use and the socio-economic impact of water on these sectors (e.g. number of households, mining, agriculture, etc.) are identified and incorporated into the planning and design of a groundwater system.

Climate/Precipitation
Precipitation plays an important role in recharging groundwater aquifers and precipitation data from both Reivilo and Steenkoppies groundwater management areas indicates cyclic behaviour, where periods (3-9 years) of below and above average rainfall patterns can be distinguished. Drier conditions normally result in a greater demand for groundwater and therefore historical data on climate and precipitation should be taken into account in the planning and design of a groundwater system.

Soils
Irrigation schemes should be established in areas where the soil is suitable for irrigation. Comprehensive soil surveys may be necessary if large adjacent areas of suitable soil is needed for development. For more information, see Module 1 of this series of reports.

Geology

It is important to have a good understanding of the geology of a groundwater system due to the fact that dewatering or over abstraction may result in the formation of sink holes, especially on dolomite aquifers. Knowledge of the geology of a groundwater system is also imperative to the understanding of the geohydrology of the aquifer.

Geohydrology

Description

For a groundwater system to be managed in a sustainable manner it is necessary to quantify the different components of the water balance in order to solve the water balance (equation 1) for the aquifer.

$$I - O + Re - Q = S\,\frac{\Delta V}{\Delta t} \qquad \textbf{(Equation1)}$$

Where:

- I mean lateral inflow (m^3d^{-1})
- O mean lateral outflow (m^3d^{-1})s
- Re recharge to groundwater (m^3d^{-1})
- Q abstraction
- S storativity
- V change in saturated volume
- T time interval ($t_2 - t_1$)

Specialists in the field of geohydrology must be involved in developing a conceptual framework for a groundwater aquifer. Different scenarios (climatic conditions, increased abstraction, etc.) can be modelled to assist with the planning and management of a groundwater system.

Groundwater levels

The measuring of groundwater levels is imperative to the planning and design of a groundwater system. Lowering of the groundwater level may influence energy costs, availability and quality of groundwater. On the Steenkoppies aquifer the lowering of the groundwater below a critical point will result in a decrease of flow at Maloney's Eye (natural spring), which will lead to implementation directives that will restrict the abstraction of groundwater. In the Sandveld a lowering of the groundwater level will result in the deterioration of groundwater quality due to saline intrusion from the sea along the Sandveld coast.

Groundwater quality

Groundwater quality will be influenced by most sectors, whether it is agro-chemicals leaching to the groundwater from the agricultural sector or biological contamination of the groundwater from untreated sewage spills from private or informal settlements or contamination of the groundwater by mine activities. Therefore, groundwater quality must be monitored continuously to ensure the sustainable use of a groundwater system. The identification of monitoring sites should be done in consultation with the necessary specialists.

Groundwater/surface water interaction

Springs and baseflow must be taken into consideration with the planning and development of a groundwater scheme. Some ecosystems are dependent on groundwater, for example in the Sandveld. In the case of the Magalies River that receives part of its water from the Steenkoppies aquifer, surface water users depend on the flow of the spring.

3.3.2 Abstraction points

Groundwater depth, volume and tempo of abstraction are key elements for the effective planning and design of a groundwater system. Therefore, a borehole survey of the groundwater scheme needs to be done to determine the following:

- Location (GPS coordinates) of all abstraction points on the aquifer
- Size and depth of all abstraction points
- Yield of the different abstraction points
- Pump size and maximum pump capacity of the different abstraction points
- Type of water usage e.g. household, feedlot, irrigation, industrial, etc.

This information is used to determine the amount, size and accuracy of flow meters that need to be installed to monitor abstraction rates from the aquifer

3.3.3 Data storage and management

A detailed geodatabase, which includes the capture of numerous GIS feature layers, is essential for groundwater schemes. As an integrated component of the geodatabase, all groundwater levels (including both hand measurements and automatically logged data), abstraction information and groundwater chemistry must be included. This database must be designed in such a way that data can easily be uploaded to the National Groundwater Archive (NGA) and/or the National Groundwater Database (NGDB) for inclusion in the DWA corporate database systems.

3.4 Water use planning

The second aspect of scheme management as discussed above, is to be able to predict expected water abstractions from the shared source for irrigation use.

The WAS has a crop water use module that can be used but the SAPWAT3 program is more widely used to estimate irrigation requirements.

3.4.1 SAPWAT3

Sapwat3 provides the capability to import regional crop data from an outside source and to estimate irrigation requirements of the imported crops as an automated function for a field, farm, WUA or even WMA. Year-on-year crop water and irrigation requirements are estimated, and the user can export average crop irrigation requirements with and with-out the effect of rain to a spread-sheet, if so required.

This module is based on the South African approach where cropping patterns of quaternary drainage regions are stored in data files designed by the Department of Water Affairs. It further requires a weather station for each quaternary, typically named after the quaternary as “A24f”, in which "A" represents the primary drainage region, "A2", the secondary drainage region, "A24" the tertiary drainage region, and "A24f" the quaternary drainage region.

Each combination of field, with its soil characteristics and irrigation system, crop, crop option and planting data is seen as a "crop". Therefore a crop planted on three different planting dates on the same field is seen as three crops for purposes of estimating irrigation requirements.

Estimating irrigation requirements of the imported crops is automated. Sapwat3 will go through the list of imported crops and estimate the irrigation requirements of each. This process could take time; on a weather data set of fifty years of daily data calculation time per crop averaged out at about 40 seconds. Calculation time could be highly variable, depending on computer speed and crop characteristics.

Preparing data for importation

Field verification of data extracted from existing data bases is advised.

Data from an existing data table must be exported to a DBF table structured as shown in Table 2:

Table 2: The DBF data structure for crop importation into Sapwat3

Name	Type	Width	Decimal	Remarks
Quat	Character	9	0	
S3Systemid	Numeric	11	0	
S3Crop	Character	30	0	
S3Cropid	Long	4	0	
S3Option	Character	50	0	
S3Optionid	Long	4	0	
PlantDate	Date	8	0	mm/dd/yyyy
ActualCove	Numeric	12	0	
WettedArea	Numeric	11	0	

All cells in the table must contain data, otherwise importation will be aborted.

The DBF table will be identified as the import table into Sapwat3.

The crops editor allows exportation of crop data from which the cropid and optionid can be read. Irrigation system IDs are shown in Table 3.

Table 3: Table of irrigation systems showing the ID of each system

Irrigation System ID	Irrigation System
1	Centre pivot
2	Drip (trickle)
3	Flood: basin
4	Flood: border
5	Flood: furrow
6	Linear move
7	Micro spray
8	Micro sprinkler
9	Sprinkler: big gun
13	Sprinkler: boom
14	Sprinkler: dragline
15	Sprinkler: hop-along
16	Sprinkler: permanent
17	Sprinkler: quick coupling
18	Sprinkler: side roll
19	Sprinkler: travelling boom
20	Sprinkler: travelling gun
21	Sprinkler: Subsurface drip
22	Sprinkler: permanent (floppy)

Calculation approach

Each combination of field, with its soil characteristics and irrigation system, crop, crop option and planting data is seen as a crop. Irrigation requirements will be estimated for each, taking into account the system efficiency of the specific irrigation system but not making provision for poor system uniformity (in other words, keeping the DU setting at 100%). Crop growth and development characteristics of the nearest Sapwat3 crop planting date to the actual planting date will be used in the calculations.

All data is saved, which allows the user to visit individual data items afterwards and make adjustments, if so required.

Analysing irrigation strategies

The Dundee example

Figure 3 is the default irrigation management screen for maize planted near Dundee and presents the average situation for the full 50 year period. The default assumes that the soil profile is replenished every 7 days to 10 mm below the upper limit (field capacity) during the growing season. Irrigation applications supplement rain shortfalls and are scheduled to ensure that the crop is provided with the exact water quantity required to match demand. While soil texture, rooting depth and system efficiency are taken into account the amount applied weekly is not limited and may be impractical.

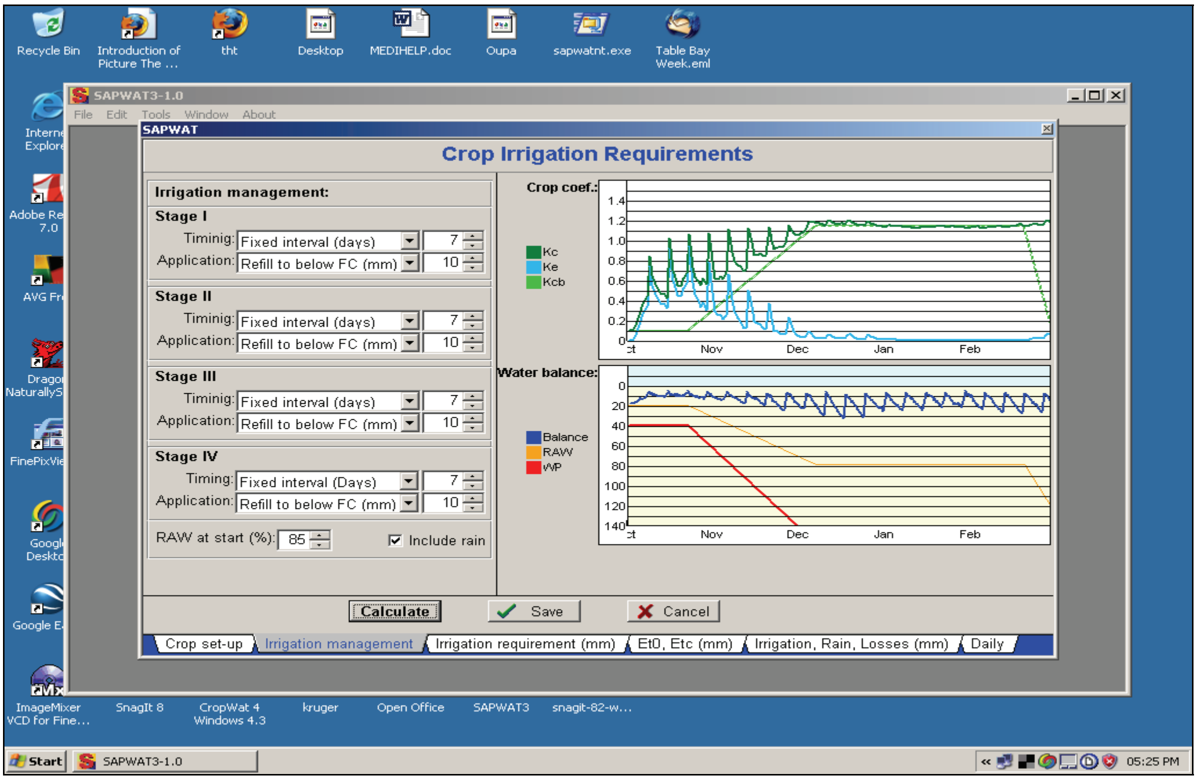


Figure 3: Screen depicting the result of an irrigation requirement estimation run for maize planted near Dundee

As shown in Figure 4 the estimated average irrigation water requirement is 467 mm of which 89 mm is due to evaporation. In order to simplify scheduling the run was repeated assuming that an irrigation system capable of applying up to 35 mm on a 10-day cycle was utilised and that irrigation be continued even when it rained! The applications every 10 days during stage one was 10 mm, during stage two 30 mm and from then on 35 mm. What sort of result could be anticipated? The average crop irrigation requirement at 455 mm is very similar as is the evaporation at 93 mm. It is possible to follow a season long mechanistic programme within the capacity of the system but in very dry seasons there will be years when the crop will be stressed.

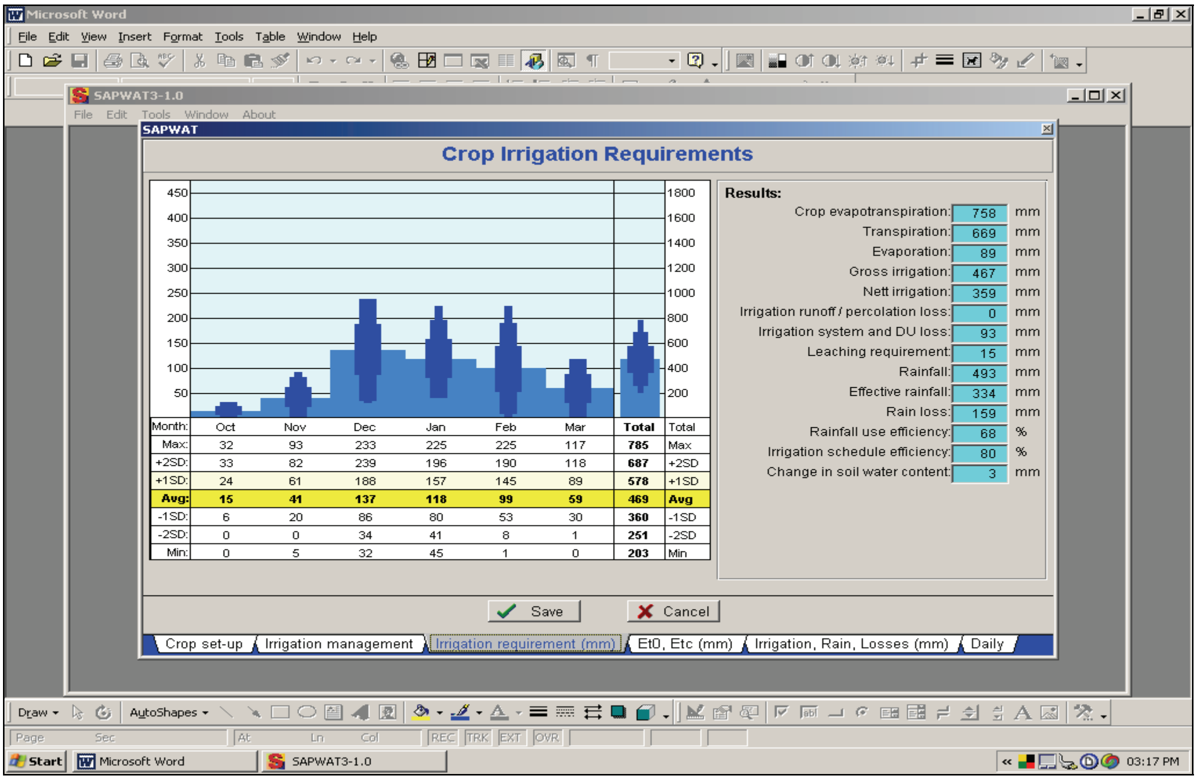


Figure 4: Average water balance of the maize shown in Figure 3

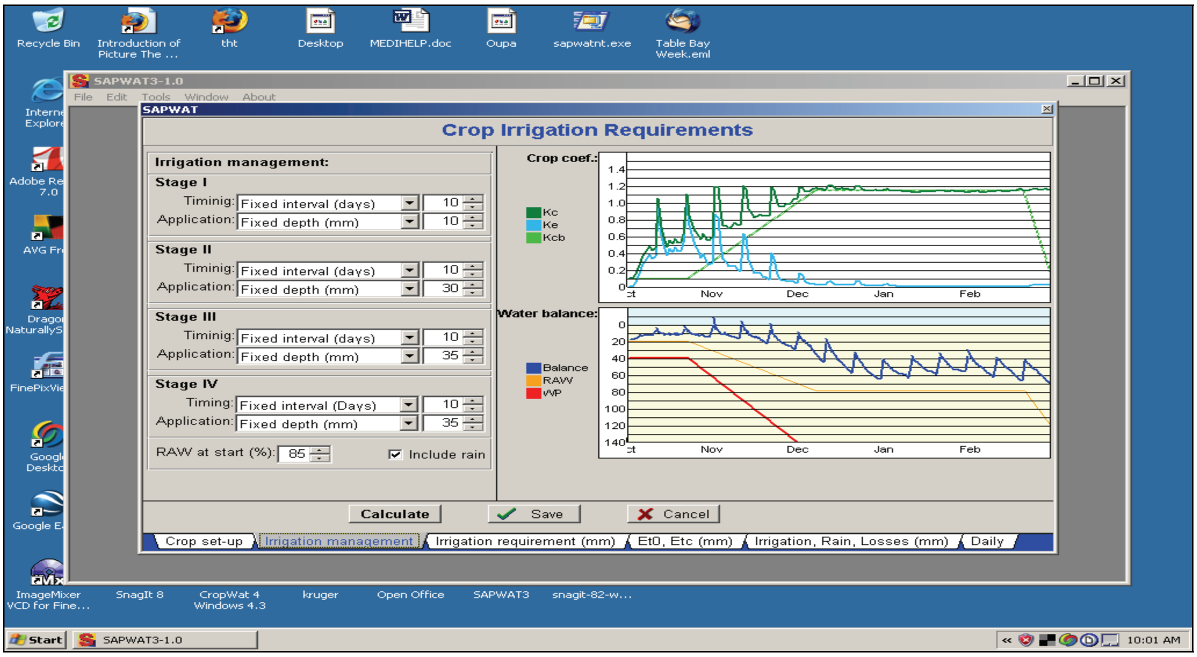


Figure 5: The same maize as in Figure 3, but with a different irrigation strategy

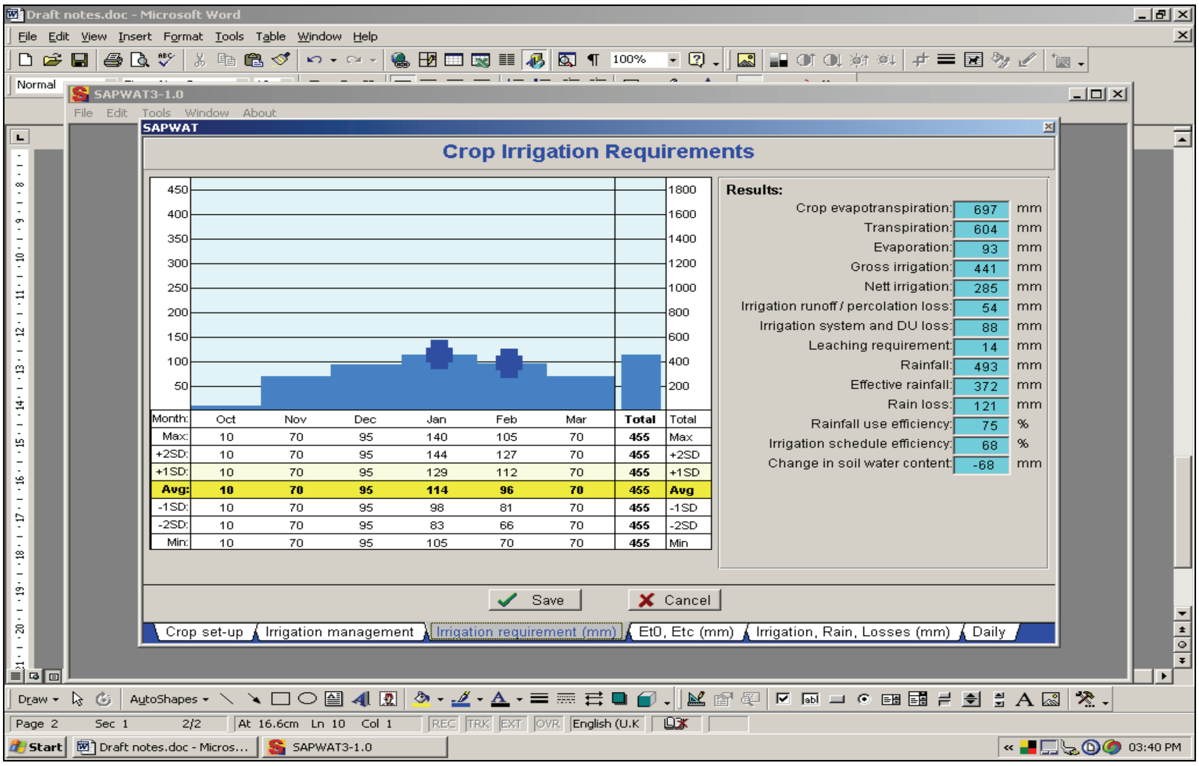


Figure 6: The result of the irrigation strategy shown in Figure 5

The driest season was 1950/51 when only 300 mm of rain fell during the growing season. In Jan, Feb and Mar the water content of the profile fell well below the RAW level (Figure 6). In order to cater for this the farmer would need to increase irrigation in these months (always presuming that water is available!)

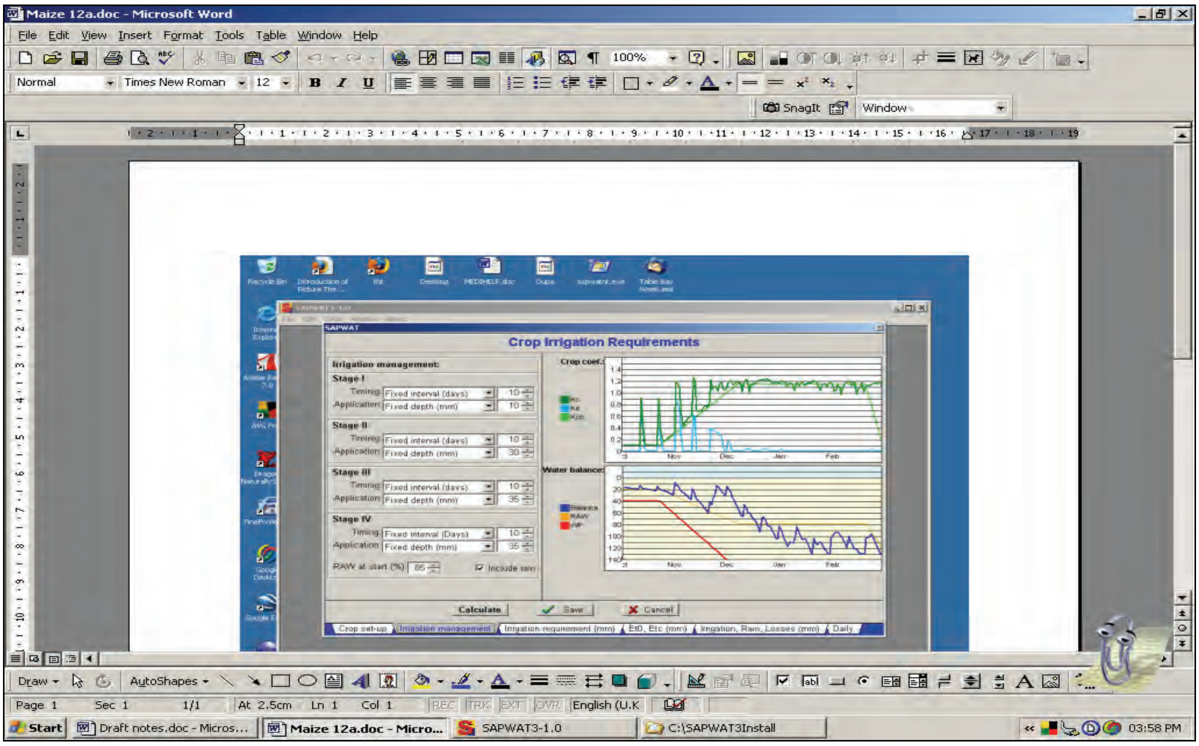


Figure 7: The result of a dry year for the same irrigation strategy as shown in Figure 5

Applications were increased after doing "what-if" runs from 35 mm to 50 mm in the third stage (Figure 8). This is sufficient to fully compensate, the profile water content is above the RAW line. The irrigation requirement is now in the order of 575 mm (Figure 9) virtually equal to the value of one standard deviation (Figure 4) on the original default estimation that in theory would be enough for 84% of the possible irrigation requirements.

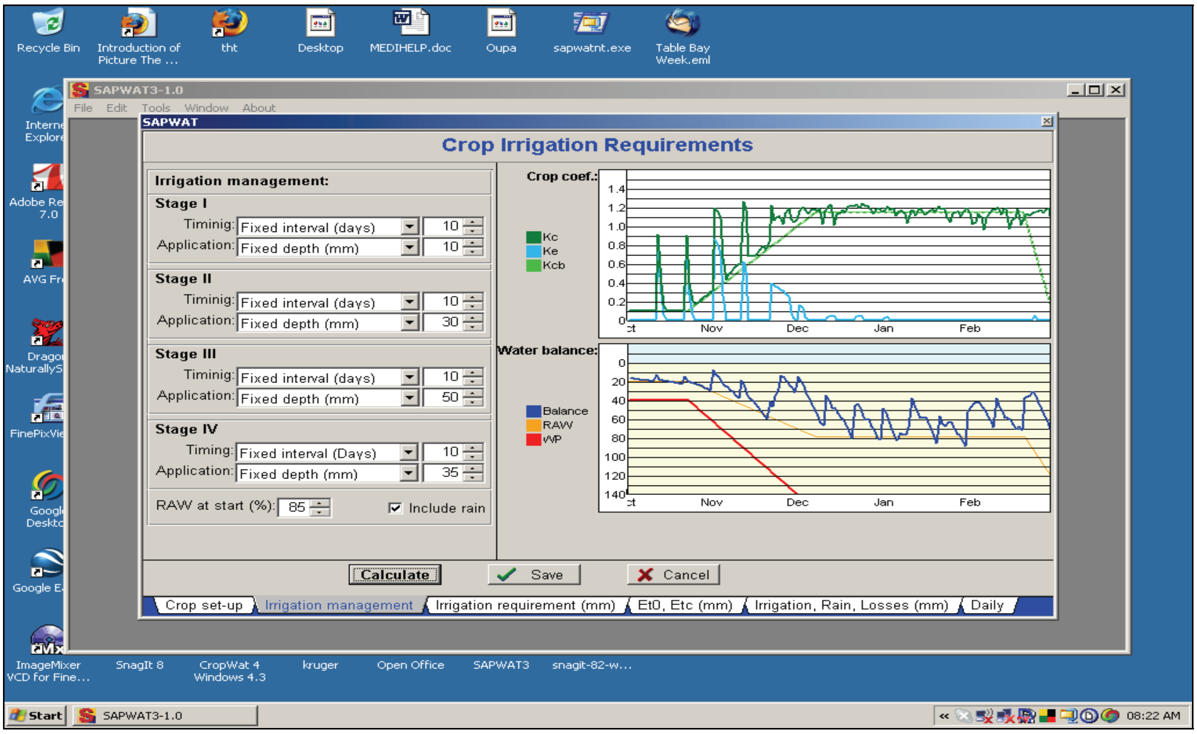


Figure 8: Result screen with increase irrigation application to counter the effect of the dry year indicated in Figure 5

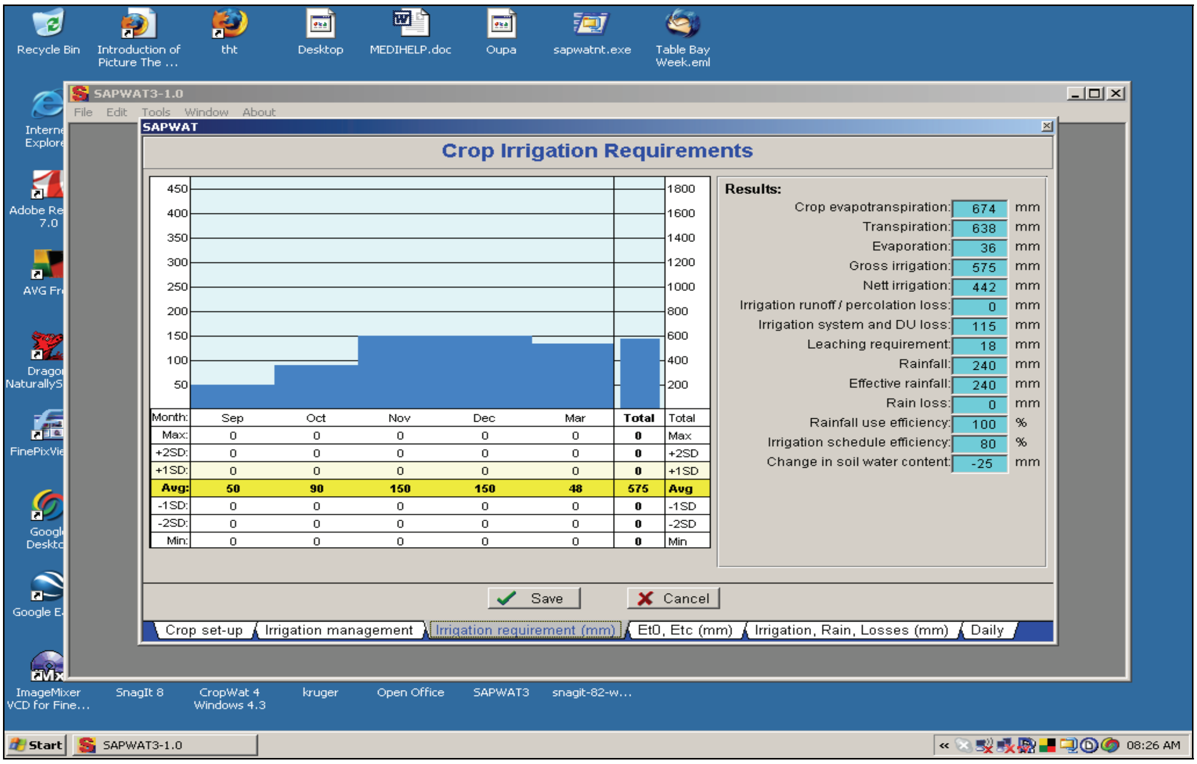


Figure 9: Result page for irrigation strategy depicted in Figure 8

It is for the designer and farmer to decide on the capacity and characteristics of the irrigation as well as on management strategies. This process is further facilitated by examination of the detailed daily water balances provided for the full 50 years as seen in Figure 10

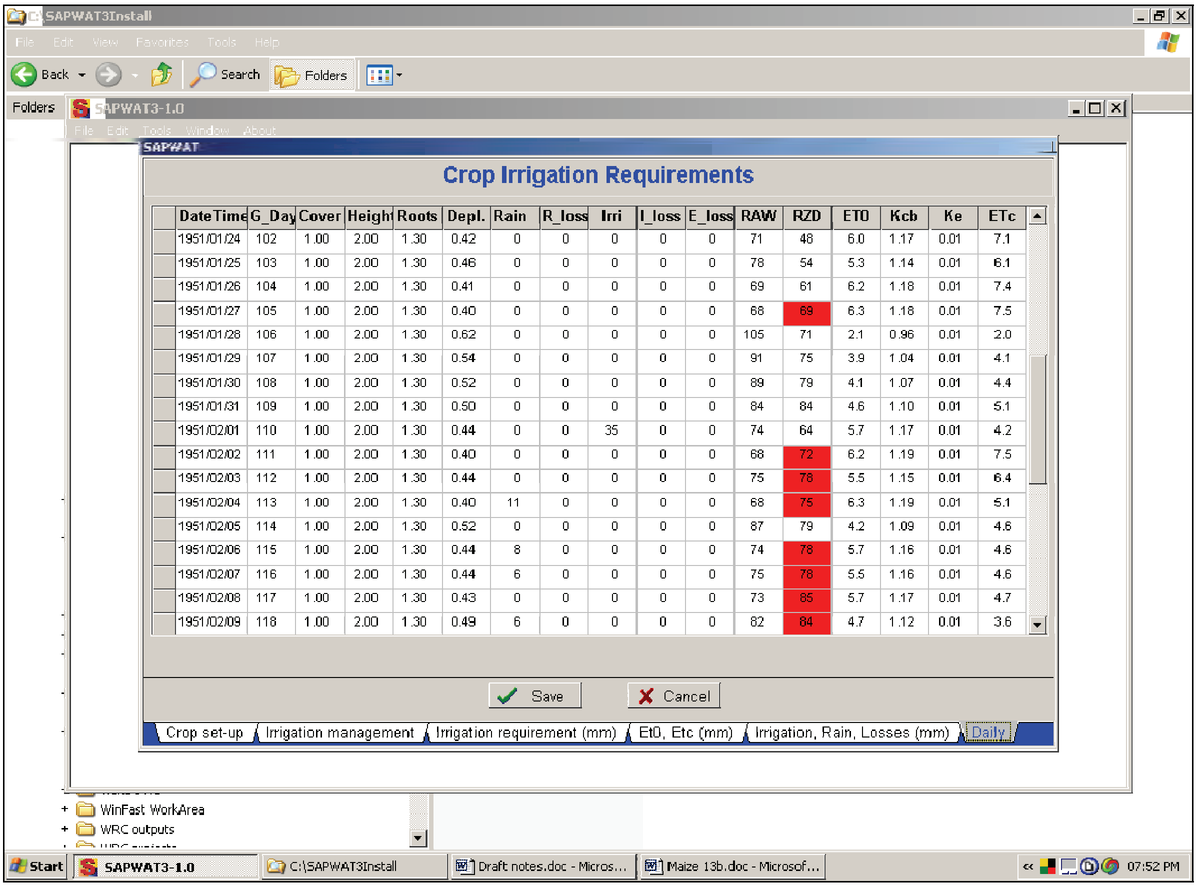


Figure 10: Daily water balances. The marked areas indicate stress

The low rainfall season 1950/51 is selected showing the details of the water balance for the original pre-season programme. The application of 35 mm/10 days was inadequate in the third stage and the RZD (Root Zone Depletion) exceeded the RAW (Readily Available Water) marking the initiation of stress in early February. This is immediately noticeable by highlighting when scrolling through the full year. Other years when problems may arise in dry years can be identified by judicious scrolling.

The Douglas example

In this case the irrigation application was fixed at a more practical value – in the Dundee example the amount given per time was not always practical – and applied when soil water level reached a specific level.

Figure 11 and Figure 12 show the result of a rooting depth of 1200 mm, while Figure 13 shows the result on a rooting depth of 600 mm.

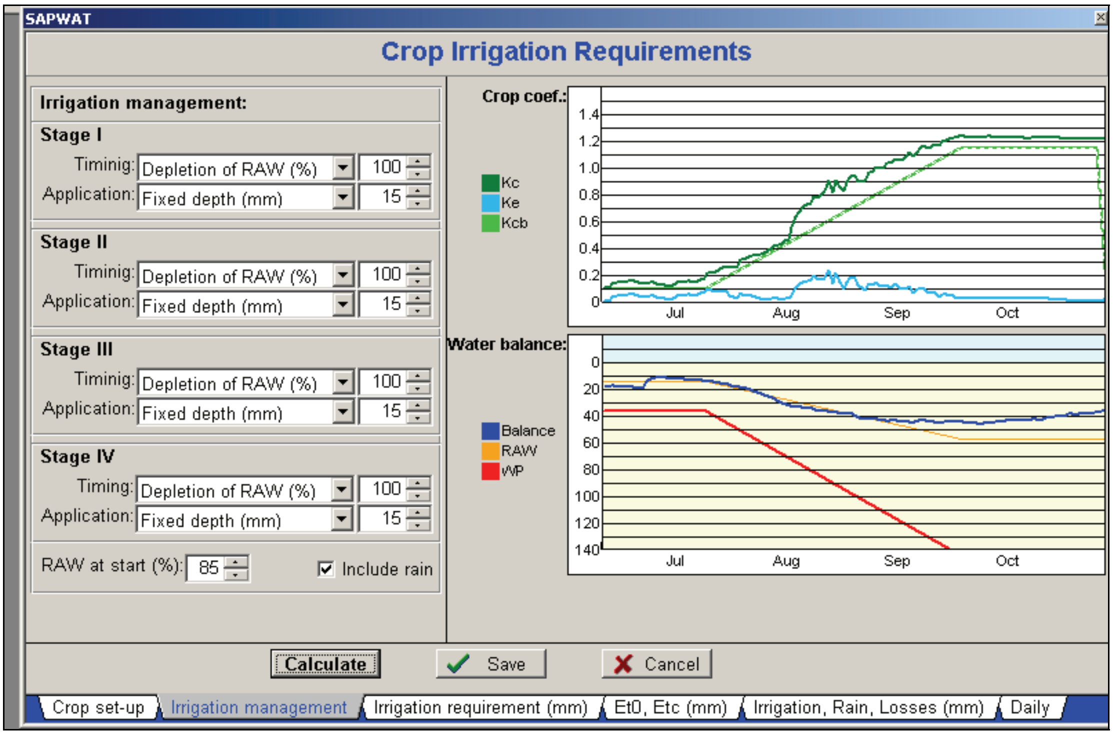


Figure 11: Results of a fifty year run on maize in the Douglas area. Rooting depth = 1200 mm

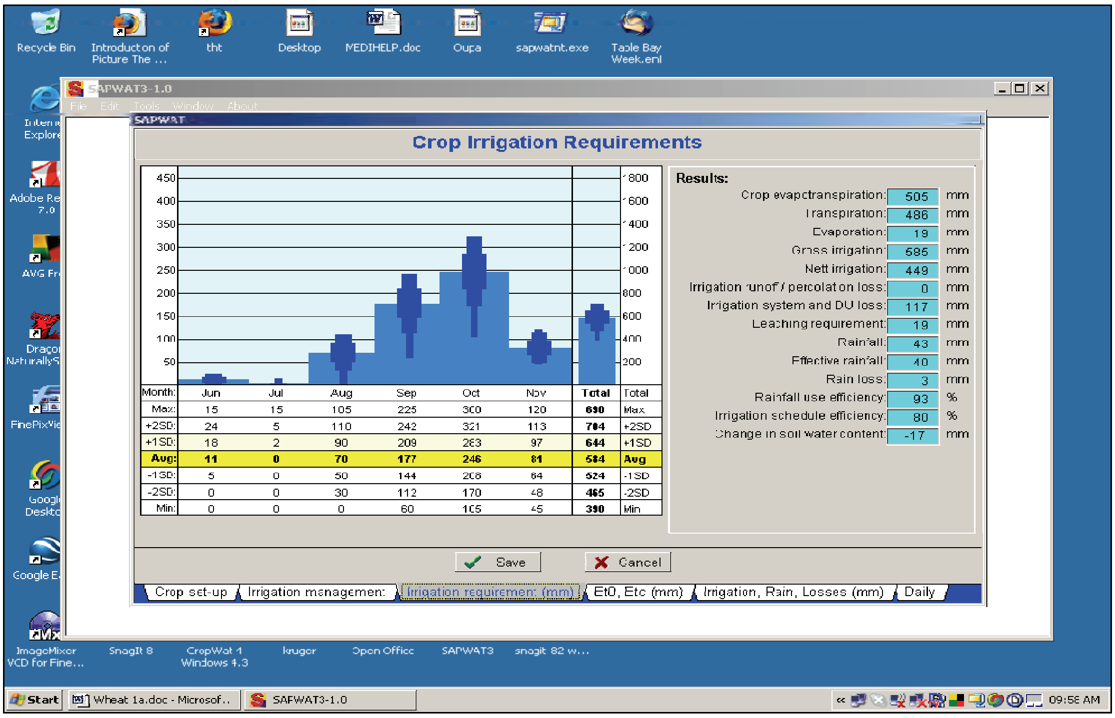


Figure 12: The result of a fifty year irrigation estimate run in Douglas on a strategy shown in Figure 11

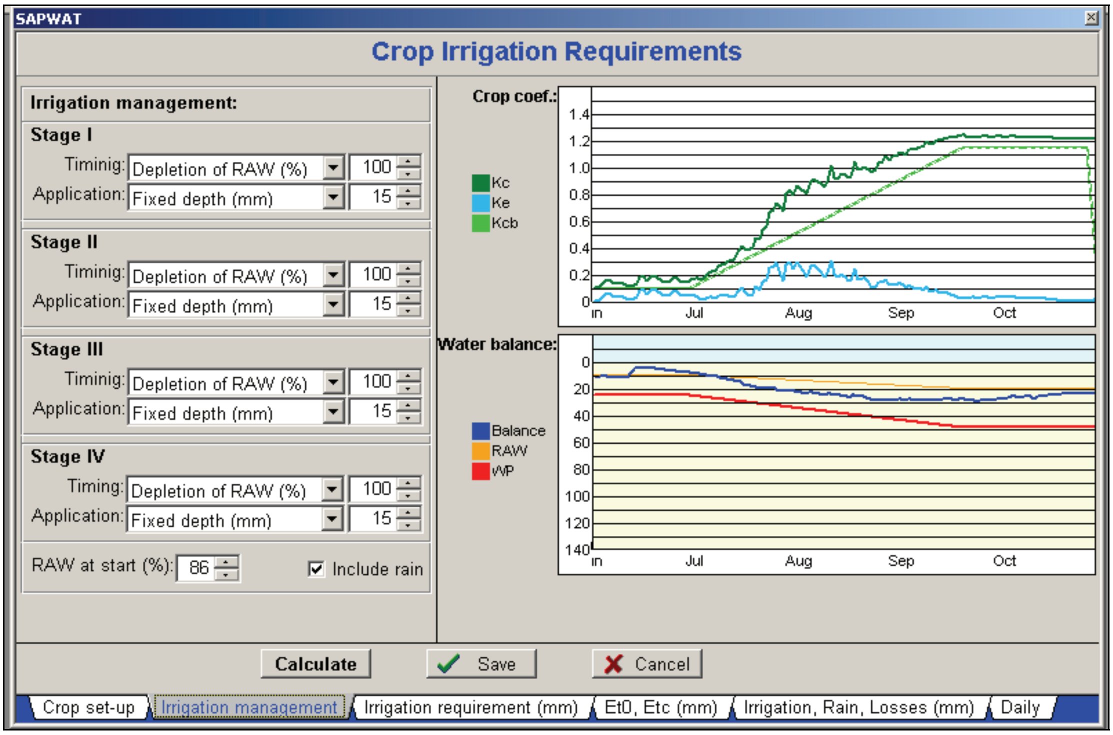


Figure 13: Results of a fifty year run on maize in the Douglas area. Rooting depth = 900 mm

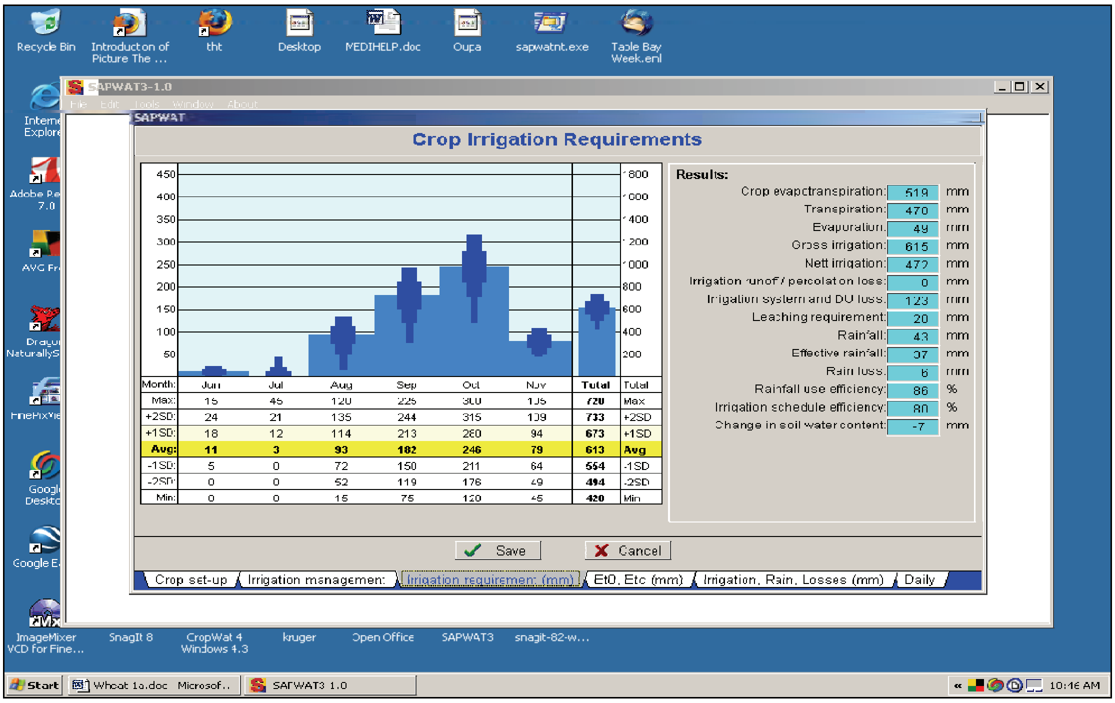
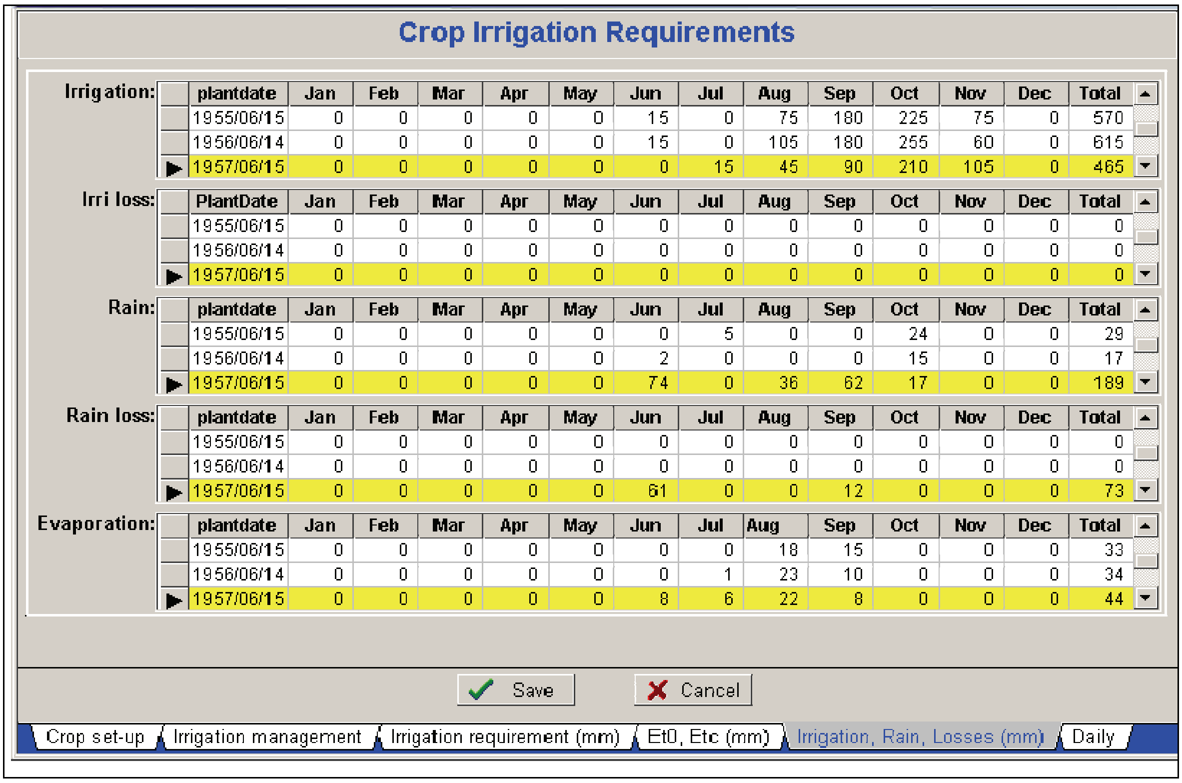


Figure 14: The result of a fifty year irrigation estimate run in Douglas on a strategy shown in Figure 13



Crop Irrigation Requirements

Irrigation:

plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1955/06/15	0	0	0	0	0	15	0	75	180	225	75	0	570
1956/06/14	0	0	0	0	0	15	0	105	180	255	60	0	615
1957/06/15	0	0	0	0	0	0	15	45	90	210	105	0	465

Irri loss:

PlantDate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1955/06/15	0	0	0	0	0	0	0	0	0	0	0	0	0
1956/06/14	0	0	0	0	0	0	0	0	0	0	0	0	0
1957/06/15	0	0	0	0	0	0	0	0	0	0	0	0	0

Rain:

plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1955/06/15	0	0	0	0	0	0	5	0	0	24	0	0	29
1956/06/14	0	0	0	0	0	2	0	0	0	15	0	0	17
1957/06/15	0	0	0	0	0	74	0	36	62	17	0	0	189

Rain loss:

plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1955/06/15	0	0	0	0	0	0	0	0	0	0	0	0	0
1956/06/14	0	0	0	0	0	0	0	0	0	0	0	0	0
1957/06/15	0	0	0	0	0	61	0	0	12	0	0	0	73

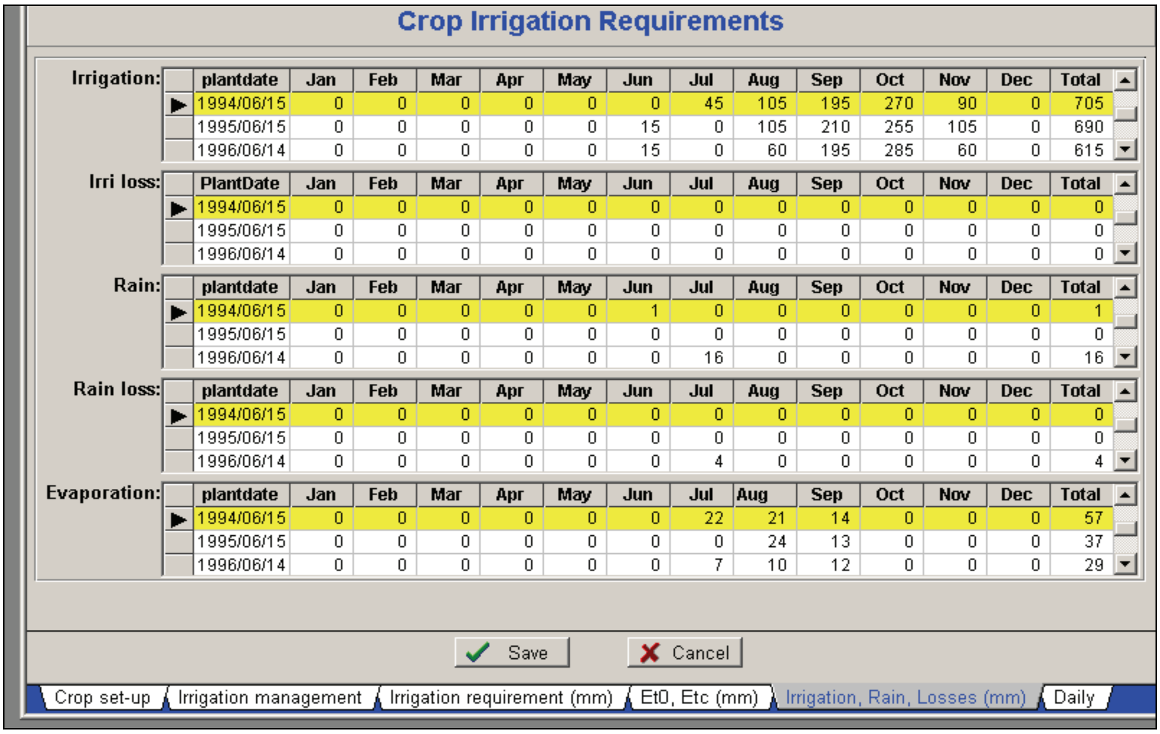
Evaporation:

plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1955/06/15	0	0	0	0	0	0	0	18	15	0	0	0	33
1956/06/14	0	0	0	0	0	0	1	23	10	0	0	0	34
1957/06/15	0	0	0	0	0	8	6	22	8	0	0	0	44

Save | Cancel

Crop set-up | Irrigation management | Irrigation requirement (mm) | Et0, Etc (mm) | Irrigation, Rain, Losses (mm) | Daily

Figure 15: Results of a wet year (1957)



Crop Irrigation Requirements

Irrigation:

plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1994/06/15	0	0	0	0	0	0	45	105	195	270	90	0	705
1995/06/15	0	0	0	0	0	15	0	105	210	255	105	0	690
1996/06/14	0	0	0	0	0	15	0	60	195	285	60	0	615

Irri loss:

PlantDate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1994/06/15	0	0	0	0	0	0	0	0	0	0	0	0	0
1995/06/15	0	0	0	0	0	0	0	0	0	0	0	0	0
1996/06/14	0	0	0	0	0	0	0	0	0	0	0	0	0

Rain:

plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1994/06/15	0	0	0	0	0	1	0	0	0	0	0	0	1
1995/06/15	0	0	0	0	0	0	0	0	0	0	0	0	0
1996/06/14	0	0	0	0	0	0	16	0	0	0	0	0	16

Rain loss:

plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1994/06/15	0	0	0	0	0	0	0	0	0	0	0	0	0
1995/06/15	0	0	0	0	0	0	0	0	0	0	0	0	0
1996/06/14	0	0	0	0	0	0	4	0	0	0	0	0	4

Evaporation:

plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1994/06/15	0	0	0	0	0	0	22	21	14	0	0	0	57
1995/06/15	0	0	0	0	0	0	0	24	13	0	0	0	37
1996/06/14	0	0	0	0	0	0	7	10	12	0	0	0	29

Save Cancel

Crop set-up | Irrigation management | Irrigation requirement (mm) | Et0, Etc (mm) | Irrigation, Rain, Losses (mm) | Daily

Figure 16: Results of a dry year (1994)

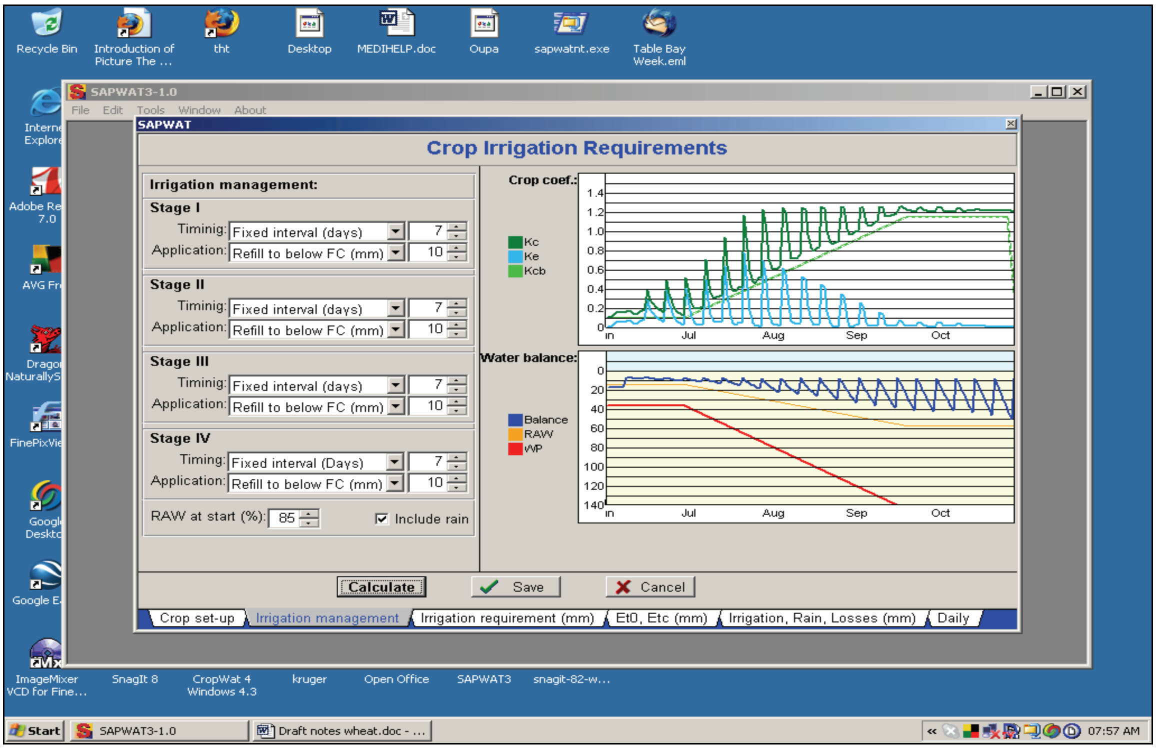


Figure 17: Result on default irrigation strategy. Compare with Figure 11.

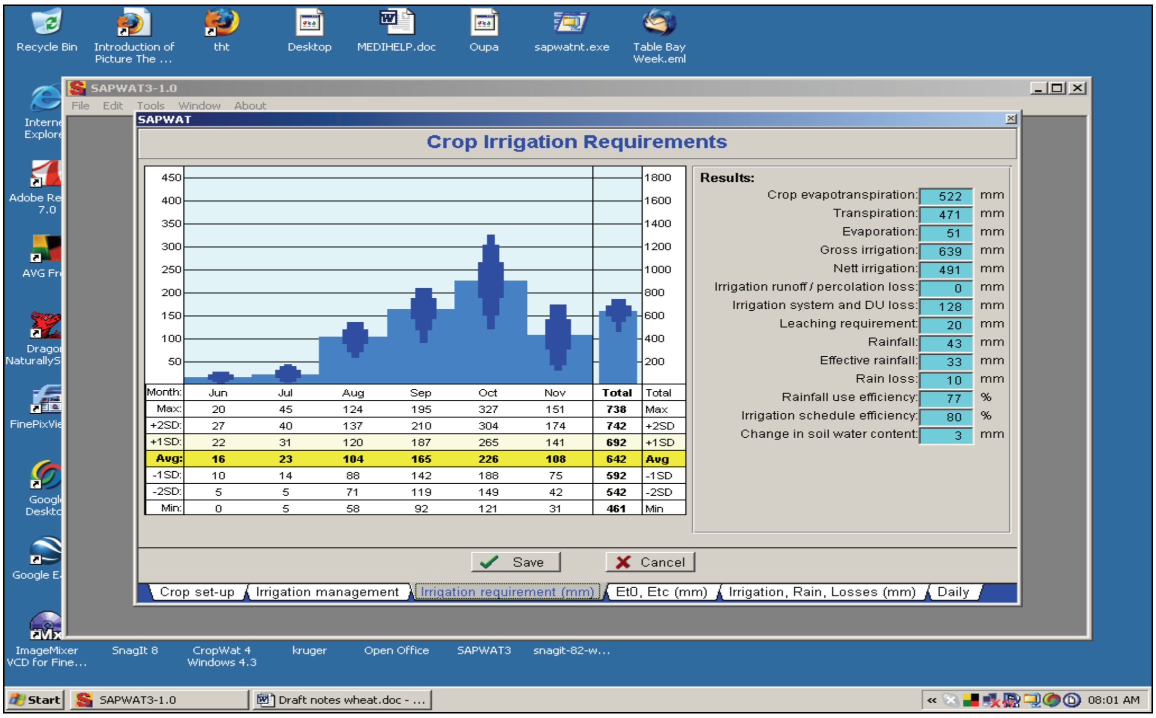


Figure 18: Result of strategy as in Figure 17. Compare with Figure 12.

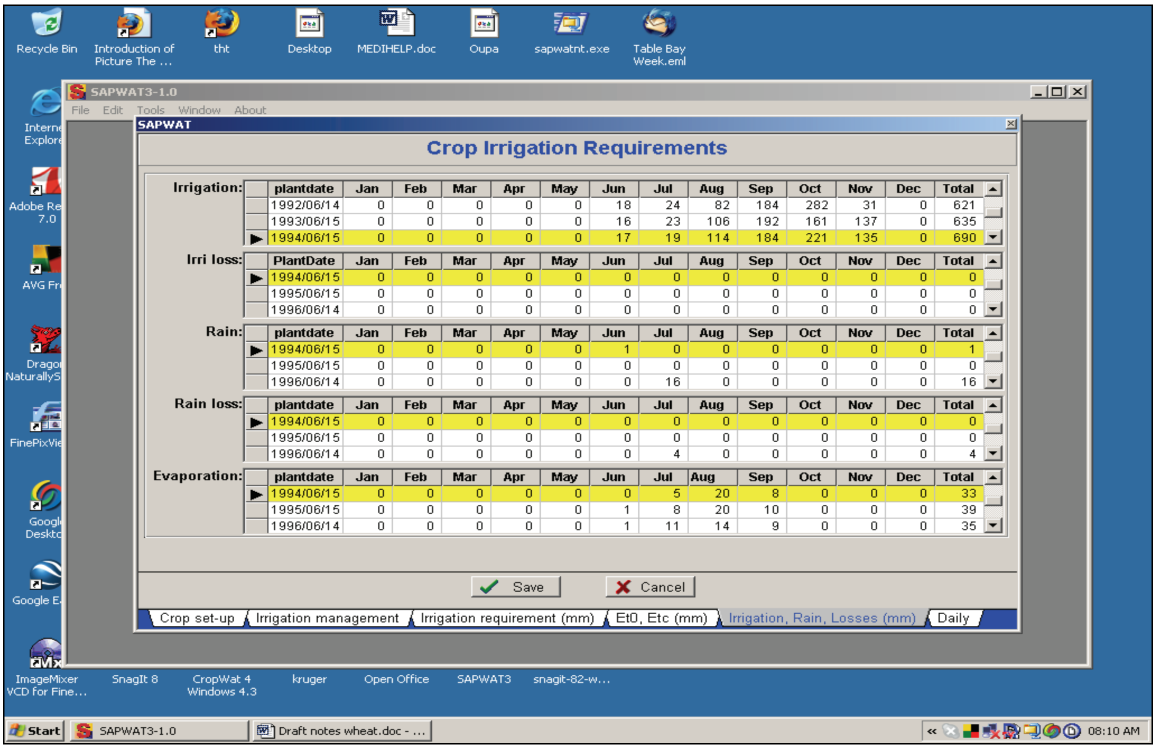
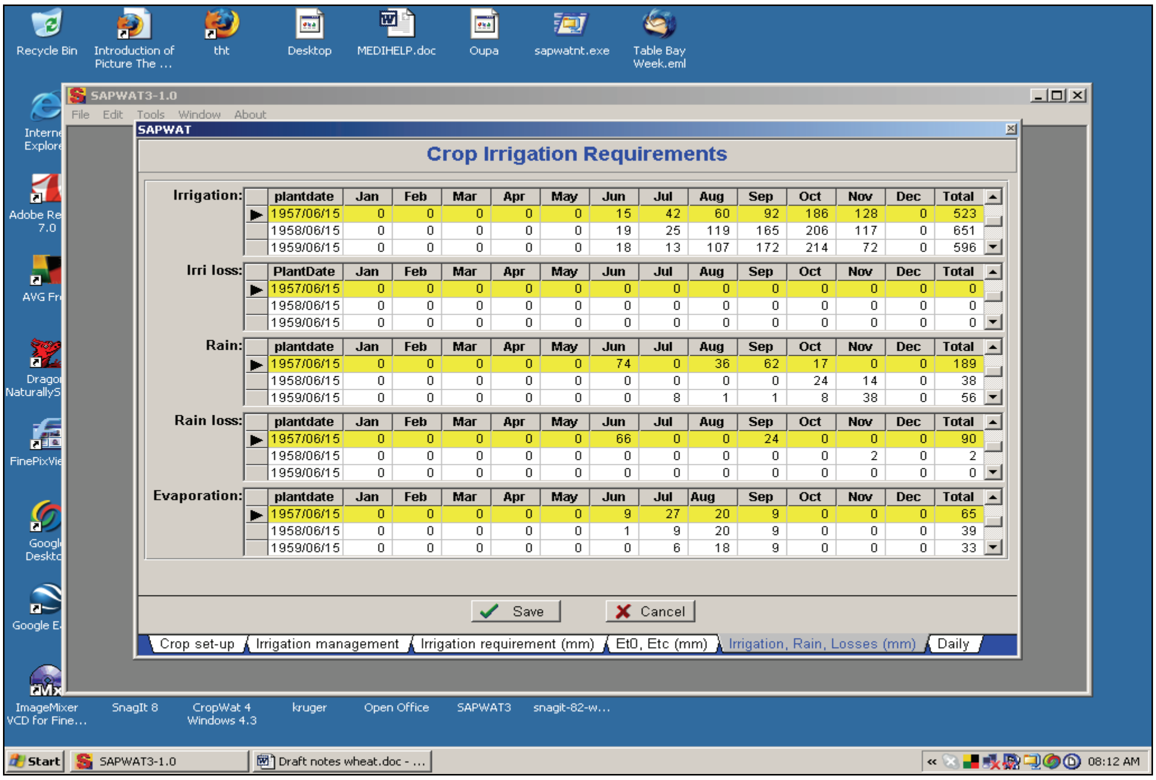


Figure 19: Result of default irrigation strategy. Compare with Figure 15 and Figure 16



Irrigation:

plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1957/06/15	0	0	0	0	0	15	42	60	92	186	128	0	523
1958/06/15	0	0	0	0	0	19	25	119	165	206	117	0	651
1959/06/15	0	0	0	0	0	18	13	107	172	214	72	0	596

Irri loss:

PlantDate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1957/06/15	0	0	0	0	0	0	0	0	0	0	0	0	0
1958/06/15	0	0	0	0	0	0	0	0	0	0	0	0	0
1959/06/15	0	0	0	0	0	0	0	0	0	0	0	0	0

Rain:

plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1957/06/15	0	0	0	0	0	74	0	36	62	17	0	0	189
1958/06/15	0	0	0	0	0	0	0	0	0	24	14	0	38
1959/06/15	0	0	0	0	0	0	8	1	1	8	38	0	56

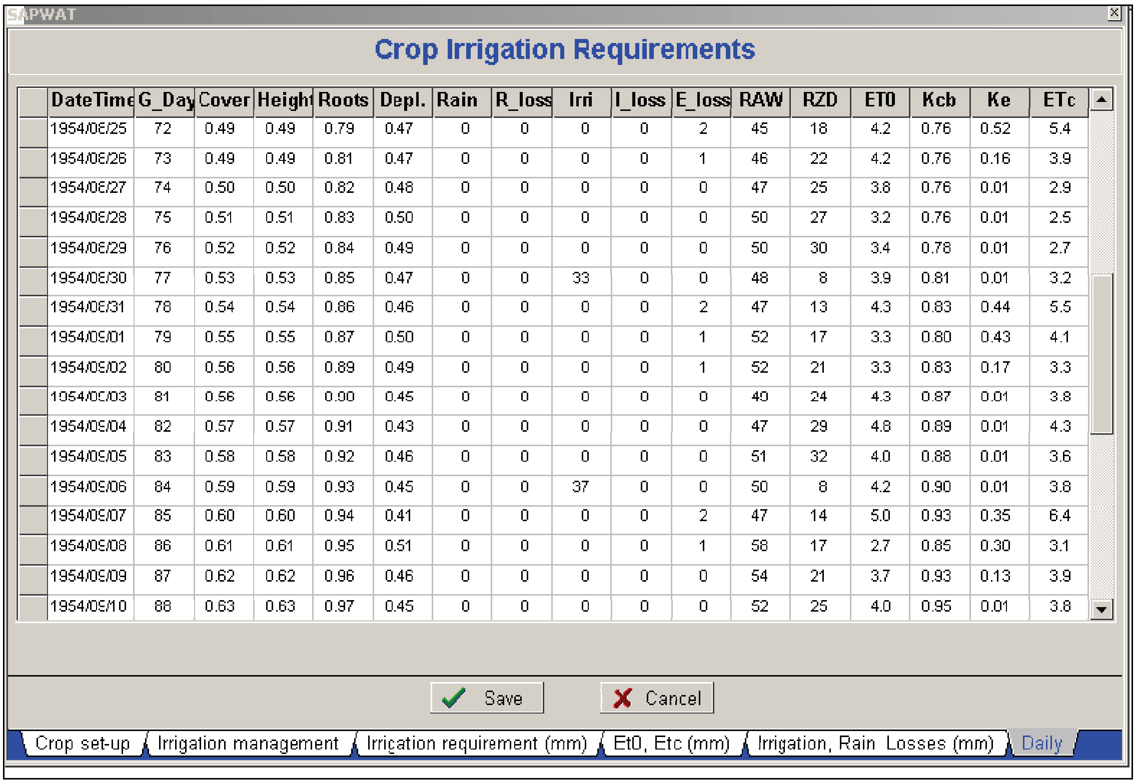
Rain loss:

plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1957/06/15	0	0	0	0	0	66	0	0	24	0	0	0	90
1958/06/15	0	0	0	0	0	0	0	0	0	0	2	0	2
1959/06/15	0	0	0	0	0	0	0	0	0	0	0	0	0

Evaporation:

plantdate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1957/06/15	0	0	0	0	0	9	27	20	9	0	0	0	65
1958/06/15	0	0	0	0	0	1	9	20	9	0	0	0	39
1959/06/15	0	0	0	0	0	0	6	18	9	0	0	0	33

Figure 20: Result of default irrigation strategy. Compare with Figure 15



DateTime	G_Day	Cover	Height	Roots	Depl.	Rain	R_loss	Irri	I_loss	E_loss	RAW	RZD	ET0	Kcb	Ke	ETc
1954/08/25	72	0.49	0.49	0.79	0.47	0	0	0	0	2	45	18	4.2	0.76	0.52	5.4
1954/08/26	73	0.49	0.49	0.81	0.47	0	0	0	0	1	46	22	4.2	0.76	0.16	3.9
1954/08/27	74	0.50	0.50	0.82	0.48	0	0	0	0	0	47	25	3.8	0.76	0.01	2.9
1954/08/28	75	0.51	0.51	0.83	0.50	0	0	0	0	0	50	27	3.2	0.76	0.01	2.5
1954/08/29	76	0.52	0.52	0.84	0.49	0	0	0	0	0	50	30	3.4	0.78	0.01	2.7
1954/08/30	77	0.53	0.53	0.85	0.47	0	0	33	0	0	48	8	3.9	0.81	0.01	3.2
1954/08/31	78	0.54	0.54	0.86	0.46	0	0	0	0	2	47	13	4.3	0.83	0.44	5.5
1954/09/01	79	0.55	0.55	0.87	0.50	0	0	0	0	1	52	17	3.3	0.80	0.43	4.1
1954/09/02	80	0.56	0.56	0.89	0.49	0	0	0	0	1	52	21	3.3	0.83	0.17	3.3
1954/09/03	81	0.56	0.56	0.90	0.45	0	0	0	0	0	49	24	4.3	0.87	0.01	3.8
1954/09/04	82	0.57	0.57	0.91	0.43	0	0	0	0	0	47	29	4.8	0.89	0.01	4.3
1954/09/05	83	0.58	0.58	0.92	0.46	0	0	0	0	0	51	32	4.0	0.88	0.01	3.6
1954/09/06	84	0.59	0.59	0.93	0.45	0	0	37	0	0	50	8	4.2	0.90	0.01	3.8
1954/09/07	85	0.60	0.60	0.94	0.41	0	0	0	0	2	47	14	5.0	0.93	0.35	6.4
1954/09/08	86	0.61	0.61	0.95	0.51	0	0	0	0	1	58	17	2.7	0.85	0.30	3.1
1954/09/09	87	0.62	0.62	0.96	0.46	0	0	0	0	0	54	21	3.7	0.93	0.13	3.9
1954/09/10	88	0.63	0.63	0.97	0.45	0	0	0	0	0	52	25	4.0	0.95	0.01	3.8

Figure 21: Frequency and amount of irrigation can be seen in the daily table.

In this case, a normal year.

Summary

By developing irrigation strategies that are typical of the crops and irrigation practices on a specific irrigation scheme, the scheme management can estimate the expected water use on a weekly basis for the whole area under their control. Running SAPWAT3 in this manner, of course then requires that the planting programmes of the farmers are known – in areas where there is little variety in the crops being planted (such as along the Komati River in Mpumalanga where sugarcane is produced for the local mill), it is easy to estimate water use figures as the crop and climate is known, and the cutting dates per field can be obtained from the farmers or the mill. In other areas where there are a greater variety of crops planted, the scheme management have to draw up a list of all possible crops and planting date combinations and set the irrigation requirements in agreement with the farmers. This has been done successfully in the Douglas area in the Northern Cape.

4 Measuring devices

The most irrigation scheme will be one that has accurate and reliable measuring devices installed at the identified strategic points on the conveyance system.

In order to perform a water balance on the whole or part of the canal scheme, flow measurements are needed. Wide-scale implementation can be expensive but a phased approach can help manage expenditure. At the very least, the flow into the canal system, and all outflows from the system (including deliveries to farms) should be measured to ensure fair and equitable distribution of water. Thereafter, more interim measuring locations can be identified and equipped to assist the WUA with on-scheme efficiency.

There are many measuring devices available, ranging in cost and capability. Devices should be suitable for the water quality and installation conditions under which they are expected to function. The WRC publication 'Guidelines for irrigation water measurement in practice (WRC Report nr TT 248/05) can be consulted. While permanently installed devices with continuous data logging is the ideal, there are various portable or manually operated alternatives available to the WUA.

4.1 Locations

Most important is the accurate measurement of water released into the system and the farm off takes. All other measuring locations are a bonus and will help with effective water distribution management. It is normally impractical (and too expensive) to measure all tail ends and the focus should therefore be on the major tail ends where most of the losses can be quantified.

Major secondary canals are also important measuring locations because it can then be treated as a separate scheme with its own water loss information.

4.2 Devices (fixed and portable)

The device at the release into the system should be fixed and very reliable. It is also important to have an electronic logging device which logs the water level in a measuring structure and/or the flow rate in the canal.

Pressure regulating sluices at farm off takes are the norm for canal networks and flow meters in the case where pipes are used to deliver water to a farm. Off takes to farms must be fixed.

Portable devices can be used to do spot checks in the system and to calibrate fixed installations.

4.2.1 Measuring flows

Flow measurement can assist the irrigator to optimise irrigation water management by reducing losses caused by leaks occurring in the pipelines, pipe bursts, and wear of nozzles. Different flow meters are available for flow measurement, but the choice of the correct flow meter for a specific set-up is important.

When irrigation water use measurement was first institutionalised in the 1980s, the types of meters used were not very suitable for raw water – the accent was on accuracy. As a result, the devices didn't last long and were deemed unreliable and more of problem than a solution. Today, more suitable devices are available and, together with remote sensing methods of data collection, offer much more affordable and sustainable solutions in the long term. Installation and maintenance have to be considered when making the final decision on the type of device to install . Some recommendations for devices suitable for different measuring conditions are made here; more detailed information can be obtained in the WRC report "Guidelines for Irrigation water measurement in practice" (WRC Report TT 284/05).

Measurement of water use at individual off-takes

River distribution systems: Poor quality water and remote locations necessitate robust and reliable devices to be used to measure water abstracted from river systems. Robust mechanical meters, battery operated electromagnetic or ultrasonic water meters, or indirect electronic metering (Electroflo meter) are the most suitable, and can be fitted with modems for telemetric data collection. The cost per meter sometimes depends on the pipe size in the case of the electromagnetic and ultrasonic devices (if flanged units are used) and can vary from R12 000 to R50 000 for typical irrigation off-take sizes (up to 315 mm, installation included). Electroflo meters' cost does not increase significantly with system capacity and vary from R12 000 to R15 000 per installation.

Pipeline distribution systems: IOs distributing water through a central pipeline system usually have a central filtering system as well, resulting in less physical impurities in the water. Mechanical water meters can therefore be used successfully under these circumstances. A calibration facility will make regularly checks easier; alternatively, a clamp-on type ultrasonic flow meter can be very useful to check meters in the field. Telemetric data collection will only be possible if there is power supplied to the measuring locations; alternatively the meters will have to be read manually. Mechanical flow meters cost between R7 500 and R25 000 per flanged unit, installation included. Clamp-on ultrasonic flow meters cost between R50 000 and R100 000, depending on accuracy and measurement method.

Canal distribution systems: Most lined canal systems in South Africa have some type of measuring device at the off-takes – either a pressure controlled sluice gate, measuring flume or weir. Unlined canals on the other hand, are not usually fitted with measuring devices and lack of upstream flow depth control render sluice gate settings inaccurate. Passing of sediment is usually the main concern. Fitting canal systems with continuously recording measuring devices, though possible, is expensive and management intensive, and it is recommended that existing infrastructure should rather be maintained and regularly calibrated to ensure functionality and accuracy. Portable ultrasonic canal flow meters can be used to undertake in field calibration of measuring structures, and cost between R40 000 and R100 000 depending on brand and measurement method.

Groundwater areas: Borehole water is generally free from physical impurities and mechanical water meters can be used. Water quality should however be assessed beforehand to ensure that water chemistry cannot damage the devices.

Measurement of bulk flows

Open channel systems (rivers and canals): Measuring structures are still the most common device used, with Crump weirs are preferred to Parshall flumes due to the greater ease of installation and less sensitivity to submerged conditions. Combination Crump/V-notch weirs work well in rivers and can measure of a wide flow range. In canal systems, ultrasonic devices are much easier to install as they do not restrict the flow and therefore do not require additional head and freeboard. Although the devices seem expensive at first, they do offer good value for money if one compares installation cost with concrete measuring structures and the continuous logging functions that are often included in the unit. They can also be removed easily and re-used at other locations. Due to the fluctuating nature of our rivers, ultrasonic devices cannot be used as easily in rivers. Prices vary depending on the brand and measuring method, from R40 000 to in excess of R100 000.

Closed conduit systems (pipelines >315 mm): The most appropriate device for raw water measurement in large diameter pipelines are ultrasonic and electromagnetic devices, with the ultrasonic devices becoming more economical at large pipe sizes. Offering the advantages of no obstruction to the flowing water and the ability to measure flow in both directions, the only limiting factor may be the velocity of the water, with especially electromagnetic meters requiring a minimum velocity of 1.5 m/s. The cost of devices vary according to housing, type of measuring method and installation, from R60 000 to in excess of R100 000.

4.2.2 Measurement errors

Once the water balance components have been identified and quantified, an estimate of the confidence interval (CI) for each value should be made (Burt, 1999). A CI of “6” indicates that one is 95% certain that the correct value lies between plus or minus 6% of the value stated in the water balance. The purpose of using CIs on figures and tables is to reinforce the fact that we rarely know many values with precision, even though discussions of those values often seem to assume that we do know them as absolute values. It is better to include all water components in the water balance, even if they have a large confidence interval rather than ignore them because they are perceived to be inaccurate.

4.2.3 Flow rate and volumes(locations, equipment/methods)

The use of a permanent electronic device to measure the flow rate as the primary means of measurement is not recommended. Electronic devices will fail at some time and it is therefore important to have a manual system like a measuring plate installed that can be used as a backup.

Although there are many electronic measuring devices on the market that can calculate the total volume released for a specified period, it can just as easy be calculated from flow rate data or water level measurements through the use of discharge tables.

4.2.4 Water depth

The water level measurement in a measuring structure is still the most reliable and cost effective method to use. The measurement of flow rate and volume is normally calculated using the water level anyway.

Vaalharts WUA is still using OTT chart recorders to measure water levels at a number of locations with great success. The charts are then digitized using a digitizing tablet and the WAS to capture the water levels accurately and in a short period of time. At their main release into the scheme they use an electronic logger which logs the water level and a chart recorder as a backup.

5 Operation and maintenance

5.1 Canal Systems

The most efficient canal conveyance system will be one that is operated and maintained according to the design specifications and sound operational rules, as captured in a regularly updated water management plan.

Improved operation and maintenance of existing canal schemes offer numerous opportunities for improving conveyance efficiency. Proper planning of water releases and deliveries, as well as effective administration and record-keeping, using suitable computer programmes such as the WAS is considered a best management practice and should be implemented.

This can be supported by implementing management technologies such as telemetry and automation that makes it possible for scheme managers to obtain the information needed to make decisions and to implement the decisions much faster than older, manual methods. Although some of the technologies are capital intensive, the cost is usually recovered within a few years and the benefits recognised by the water users when delivery improves. More accurate monitoring practices also makes it possible to assess losses more regularly and take the necessary action.

Due to deteriorating water quality in many of our rivers, water quality monitoring has also become a necessity, and various technologies are available to improve water quality problems that have negative impacts of water management in the canals.

Finally, Water Management Plans (WMPs) are the primary tools with which the agricultural sector is expected to implement the NWCDMS, and a requirement of the DWA to be met by WUAs. The development of a WMP is not an end in itself but should be a process with an annual cycle which can assist WUAs in realising the economic and social benefits of improved water use efficiency. DWA has guidelines available for the compilation of WMPs.

5.1.1 Releases and deliveries

The WAS release module provide the opportunity to capture and calculate channel data to determine releases and deliveries.

5.1.2 Monitoring and control:

Telemetry/Automation, SCADA (data, software)

Advances in the industrial and process engineering fields have led to the development of automatic monitoring and control systems. This technology makes it possible for an industrial plant to be supervised and operated by programmed electronic controllers, reducing the need for 24 hour human monitoring. If these functions are performed from a central point some distance from the infrastructure that is being managed, it is referred to as remote sensing and/or control systems.

Automatic monitoring and control systems are well adapted for use in irrigation water supply and distribution applications, and some basic information on the typical system lay-out and components are presented here.

Other terms that are often used to refer to automatic monitoring and control systems are telemetry, Supervisory Control and Data Acquisition (SCADA) and Automatic Meter Reading (AMR).

Telemetry can be defined as the remote recording or indication of measurements and signals from plant or supply infrastructure, by means of telecommunication, as well as the remote control and management of such infrastructure via the same means (Wolhuter, 2004).

Supervisory Control and Data Acquisition (SCADA) refers to a system whereby computers are used to collect real-time data from plant machinery to provide central monitoring, control and process visualisation of the plant and its facilities. A SCADA system is built around programmable logic controllers (PLCs) receiving inputs from measuring devices, and specialised PC-based software as the interface (Adroit Technologies (Pty) Ltd, 2000).

Automatic Meter Reading (AMR) refers to systems that collect the data from flow meters automatically, usually consisting of a combination of telemetry and datalogging technology. Two examples of sophisticated yet useful AMR systems are "walk-by" and "drive-by" systems. A walk-by system utilises a meter interface unit which automatically transmits the meter reading to a handheld computer. All the meter reader has to do is to walk by within a certain distance of the meters and the readings will automatically be picked up when the handheld device is within range of a meter interface unit. Drive-by systems are similar, except that a data collection unit is fitted inside a vehicle which is then driven past meters fitted with interface units. The technologies' obvious advantages are the reduced amount of time required to collect readings as well as easier collection from meters in hard to reach places.

Telemetry is a specialised field of electrical engineering and it is advised that knowledgeable and experienced consultants are approached to assist the WUA in planning a telemetric system. The information presented here is therefore only aimed at providing a WUA with some insight into the basic composition and possible functions of a telemetry system.

The process of selecting suitable data retrieval technologies is similar to the one outlined for selection of the measuring devices. The intended purpose of the system should be defined, as well as a range of design considerations, for example (Wolhuter, 2004):

- Number and type of inputs from measuring devices
- Data arrival rate
- Single or multi channel communications
- Required and/or available bandwidths
- The existing (if any) and ultimately required network topology
- Communications medium to be used

- Physical infrastructure at the different areas of intended installation (power, security, etc.)
- Standard of service required (reliability and accuracy)

Losses (methods, benchmarks)

The WUEAR in WAS is a simple and effective way to keep track of water losses on a scheme or part of a scheme for that matter. It is important to keep the reporting on water losses simple because past experience has shown that complicated reports such as the previous disposal report from the DWEA was either incorrectly used or not used at all. The calculation of water losses on a scheme should add value to water distribution management and be used as a tool to minimise water losses.

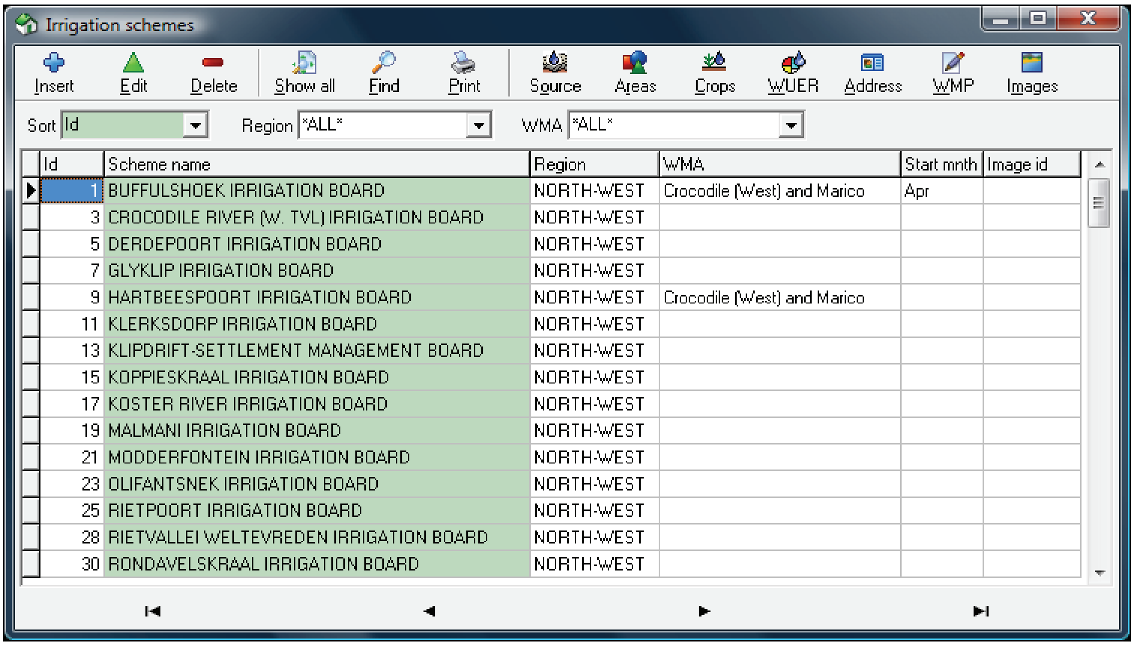
The simplest way to do this is to subtract the water orders from the total water released on a weekly basis. It is common practice to assume that water ordered is water delivered. If this loss is unacceptable high, the water management personnel can go on a fault finding mission by making use of measuring stations (permanent or temporary) and better management practices to locate the problem. It is also important to know that the weekly water losses calculated (as described above) can vary substantially from week to week (and even be negative) due to on scheme storage, but the average loss should stabilise after a few weeks.

iScheme

iScheme is an information system for irrigation schemes that contains a list of all irrigation schemes throughout South Africa. Every irrigation scheme is linked to a specific Water Management Area (WMA) and a region. This feature makes it possible to filter the information in the database according to scheme, WMA, region and nationally. One of the uses of iScheme is to archive WUEA reports for all schemes on a national basis. This part of the iScheme manual focuses on the importing and management of WUEA reports.

The following information can be captured in the iScheme database:

- Scheme name
- Region name of the scheme
- WMA of the scheme
- Address and contact information of each scheme
- Water source/s name, type and capacity feeding into a specific scheme
- Water allocation information and number of irrigators
- Crops and planted areas per year
- Locality maps
- An unlimited number of images that can be linked to a specific scheme
- WUEA reports which are imported from the WAS



Id	Scheme name	Region	WMA	Start mnth	Image id
1	BUFFULSHOEK IRRIGATION BOARD	NORTH-WEST	Crocodile (West) and Marico	Apr	
3	CROCODILE RIVER (W. TVL) IRRIGATION BOARD	NORTH-WEST			
5	DERDEPOORT IRRIGATION BOARD	NORTH-WEST			
7	GLYKLIP IRRIGATION BOARD	NORTH-WEST			
9	HARTBEESPOORT IRRIGATION BOARD	NORTH-WEST	Crocodile (West) and Marico		
11	KLERKSDORP IRRIGATION BOARD	NORTH-WEST			
13	KLIPDRIFT-SETTLEMENT MANAGEMENT BOARD	NORTH-WEST			
15	KOPPIESKRAAL IRRIGATION BOARD	NORTH-WEST			
17	KOSTER RIVER IRRIGATION BOARD	NORTH-WEST			
19	MALMANI IRRIGATION BOARD	NORTH-WEST			
21	MODDERFONTEIN IRRIGATION BOARD	NORTH-WEST			
23	OLIFANTSNEK IRRIGATION BOARD	NORTH-WEST			
25	RIETPOORT IRRIGATION BOARD	NORTH-WEST			
28	RIETVALLEI WELTEVREDEN IRRIGATION BOARD	NORTH-WEST			
30	RONDAVELSKRAAL IRRIGATION BOARD	NORTH-WEST			

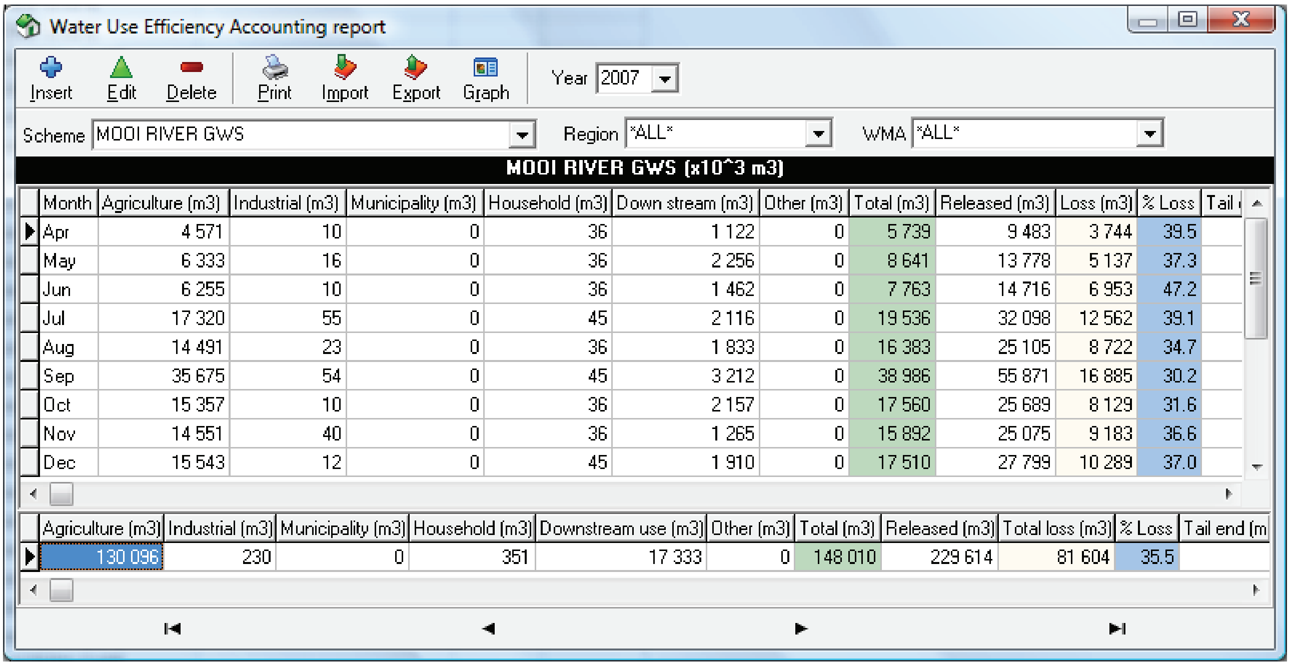
Figure 22: iScheme - Irrigation schemes form

The iScheme database is ideally suited to import, manage and report on WUEA reports on a scheme, WMA, region and national levels.

iScheme - Water Use Efficiency Accounting Reports (WUEAR)

The WUEA report section in iScheme is accessed through the 

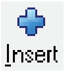
button on the Irrigation schemes form. Clicking on this button will open the following form.



Month	Agriculture (m3)	Industrial (m3)	Municipality (m3)	Household (m3)	Down stream (m3)	Other (m3)	Total (m3)	Released (m3)	Loss (m3)	% Loss	Tail (
Apr	4 571	10	0	36	1 122	0	5 739	9 483	3 744	39.5	
May	6 333	16	0	36	2 256	0	8 641	13 778	5 137	37.3	
Jun	6 255	10	0	36	1 462	0	7 763	14 716	6 953	47.2	
Jul	17 320	55	0	45	2 116	0	19 536	32 098	12 562	39.1	
Aug	14 491	23	0	36	1 833	0	16 383	25 105	8 722	34.7	
Sep	35 675	54	0	45	3 212	0	38 986	55 871	16 885	30.2	
Oct	15 357	10	0	36	2 157	0	17 560	25 689	8 129	31.6	
Nov	14 551	40	0	36	1 265	0	15 892	25 075	9 183	36.6	
Dec	15 543	12	0	45	1 910	0	17 510	27 799	10 289	37.0	

Agriculture (m3)	Industrial (m3)	Municipality (m3)	Household (m3)	Downstream use (m3)	Other (m3)	Total (m3)	Released (m3)	Total loss (m3)	% Loss	Tail end (m
130 096	230	0	351	17 333	0	148 010	229 614	81 604	35.5	

Figure 23: iScheme: Water Use Efficiency Accounting Report

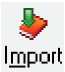


Insert a new WUEA report for the selected water year.

Change the description of the current WUEA report record.

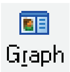
Delete the current WUEA report.

Print the current WUEA report.



Import WUEA reports from *.csv files that were exported from the WAS

Export the current WUEA report to a *.csv file



Open the WUEA report graph form.

Graphs that can be printed are:

- Released & Total
- Total loss
- % Loss
- Cumulative Released & Total
- Water allocation used & Available
- % Water allocation used & % Available
- Released & Crop used
- Total & Crop used

The year filter which is used to display the WUEA report for a specific year.

The scheme filter which is used to select a specific scheme.

The region filter which is used to summarise the WUEA report data according to the selected region.

Water management area filter which is used to summarise the WUEA report data according to the selected WMA.

All the filters can be used together. If you want a specific filter to be ignored, select the *ALL* option if it is available. All the volumetric values in the WUEA report are divided by 1000. All the values in the report can be edited. The WUEA report consists of the following fields:

- Month — The corresponding month within the actual year.
- Agriculture (m^3) — Water used for agriculture for the specific week which can be captured manually or imported.
- Industrial (m^3) — Industrial water used for the specific week which can be captured manually or imported.
- Municipality (m^3) — Water used by municipalities for the specific week which can be captured manually or imported.
- Household (m^3) — Household water used for the specific week which can be captured manually or imported.
- Downstream (m^3) — Water volume that is released for a specific user downstream of the scheme.
- Other (m^3) — Other water use for the specific week that does not belong to any of the previous water usage types. This water usage type can be captured manually or imported.
- Total (m^3) — Total water used per week which is the sum of all the different water usage types. This value is calculated automatically and cannot be captured manually.
- Released (m^3) — The total water released per month can be captured or imported.
- Total loss (m^3) — The total loss is calculated by subtracting the total water used from the total water released per month.
- % Loss — The % Loss per month is calculated automatically using the following equation: (Water released – Water used/Water released)*100.
- Tail end loss (m^3) — Water volume that passes over the tail end of a canal. This water can only be considered as a water

use if it is released for a specific user downstream otherwise it should be considered as a loss.

- Tail end loss (%) The tail end loss calculated as a percentage loss.
- Crop water use (m^3) Total crop water used for the specific month.
- Water allocation used (m^3) Total water allocation used for the specific month.
- Water allocation avail (m^3) Water allocation available for the specific month.
- % Used Water allocation used calculated as a percentage.
- % Available Water allocation available calculated as a percentage.

5.1.3 Maintenance methods and equipment

Canals require regular maintenance as canal failure can lead to extensive damage to the canal, structures, top soil and crop yields, both from direct damage as well as water supply interruptions to the scheme (Jensen, 1981). Canals should be inspected regularly and the maintenance requirements assessed. The timing of inspections will depend on the type of canal (lined, unlined, type of lining), the underlying soil, the water quality and the climate at the scheme. As a minimum however, annual inspections of the whole system should be made.

Maintenance consists mostly of cleaning the canal of deposits, and controlling grass or weed growth as well as rodents. Furthermore repairs will be needed to ensure the canal stays in an efficient operational condition.

Canals need to be cleaned at least once per year, for which a dry period have to be scheduled, to remove sediment deposits and excess vegetation, and to reshape the profile of the canal, in unlined cases. Vegetation growth on the canal banks must be controlled to prevent interference with the canal operation and canal capacity. Due to the steep terrain surrounding the canal, grass is usually cut by hand but it is recommended that the canal banks and access road are maintained in such a way that tractors can be used where possible. As weeds along canal banks can be a major source of weed infestation in the fields, they should not be allowed to go to seed along the canal. Weeds can be burned in extreme cases or herbicides applied; if chemicals are used however, they should be chosen carefully to prevent accidental damage to crops, animals or aquatic life.

Rodents are a major cause of damage to unlined canals, eventually leading to leaks and therefore water losses, and should be controlled. Rodent activity near structures can sometimes be discouraged by mixing course sand and gravel with the backfill.

Unlined canals should be inspected every year for erosion, bank scouring, weak or low spots in the banks, structure cracks and deterioration, or other conditions that may need repairs. Canals should be stable – if erosion is occurring, additional slope control measures or energydissipating structures may be needed, and next to structures, rip-rap or gabions (rock-filled wire baskets) may need to be placed.

Cracks in concrete and masonry structures should be caulked to prevent water entry. In the case of very cold climates, water in cracks can freeze and cause further damage. Metal structures of parts should be painted or a protective coating applied to prevent rusting, and rubber-type seals should be replaced when they perish. Metal sluice gates should be lubricated and the whole system preferably drained if there is a non-irrigating season to prevent gates from getting stuck and dirt build-up.

The material needed to perform repairs should be kept in stock by the WUA or irrigation board to ensure timely repairs can be made and water supply continue as uninterrupted as possible. The lifespan and annual maintenance costs of a canal lining will vary depending on site conditions and the quality of the initial construction and materials used. According the Jensen (1981), a lifespan of 15 years and annual maintenance costs of 5% of the installation costs are recommended for non-reinforced concrete and flexible membrane linings.

Costs of repairs in 2010 were reported by Matthee (2010) as follows:

Plaster repairs (15 mm thickness) R150.00/m^2

Gunite (100 mm thickness) - R776.00/m^2

Concrete packaging (100 mm thickness) - R618.00/m^2

Water quality may also require additional maintenance to be undertaken. In the case of aggressive water (see Module 2), concrete experts should be consulted to determine the most appropriate maintenance or repair methods to be followed.

If the growth of algae or water grass occurs in canals, chemical treatment need to be undertaken, a practice that can be very expensive for the irrigation organisation to repeat regularly. Water treatment specialists should be consulted to obtain information on suitable products and mixing concentrations that will provide an acceptable term of treatment without causing damage to crops or aquatic life in drainage systems down-stream of the canal system.

5.2 Rivers

The most efficient river conveyance system will be one that is operated and maintained according to a suitable hydrological model and sound operational rules, as captured in a regularly updated water management plan.

Improved operation of river schemes offers numerous opportunities for improving conveyance efficiency. Proper planning of water releases and deliveries, as well as effective administration and record-keeping, using suitable computer programmes such as the WAS is considered a best management practice and should be implemented. Planning to satisfy demand within the constraints of water availability needs to be considered for two different horizons, namely:

- **Short Term,** which is meeting the current demand by making releases from reservoirs; or ensuring equity of water use by imposing short term restrictions on water abstractions
- **Long Term,** which involves a water resources planning assessment with is a risk analysis to investigate whether current water storage in reservoirs, is capable of meeting the demand of users at an acceptable level of risk based on historical or stochastic hydrology for the catchment.

These two functions need to be supported by implementing management technologies, software frameworks, and even aspects such as telemetry and potentially automation to makes it possible for scheme managers to obtain the information needed to make decisions and to implement the decisions much faster than older, manual methods. Although some of the technologies are capital intensive, the cost is usually recovered within a few years and the benefits recognised by the water users when delivery improves. More accurate monitoring practices also makes it possible to assess losses more regularly and take the necessary action.

Due to deteriorating water quality in many of our rivers, water quality monitoring has also become a necessity, and various technologies are available to improve water quality problems that have negative impacts of water management in the canals.

5.2.1 Releases and deliveries

The decision on the amount and manner with which to release water from reservoirs is a function of:

- Downstream water demands (both water losses and actual water user requirements) which are distributed in space and time in the downstream network.
- Downstream hydrology (both recently observed and an indication of forecasted/predicted hydrology), this also need to have spatial and temporal variations included in the estimates.
- Physical characteristic of the conveyance channel (i.e. longitudinal channel profile, bed resistance, channel shape)
- Current state of water available (distributed in space and time) in the rivers, this will affect the lag and attenuation of any additional releases that are made to supplement water availability in the short term.

The end goal of the short term operations for handling these aspects is to provide a decision support and operational platform which is capable of estimating or accounting for all of these aspects listed and provided decision support to managers responsible for making short term water release decisions.

Planning/Hydrological Modelling

A water resources and hydrological planning assessment needs to be completed to determine what longer term operation rules need to be enforced The DWA has platforms and tools to use and apply for water resources planning and hydrological assessments. There are also many different other platforms available which are specifically designed to meet specific user/operational requirements. These types of assessments often involve statistical representations of plausible hydrology to increase the confidence of the water resources planning process. These statistical representations are referred to as stochastic hydrology and the following extract is taken from a WRC publication entitled: Monthly Multi-Site Stochastic Streamflow Model" (Van Rooyen and McKenzie, 2004) and provides an excellent description of why stochastic hydrology is often used in the water resources management in Southern Africa.

> "Stochastic hydrology is a process that is applied to determine the reliability of supply of water resource systems and is a standard technique used by the Department of Water Affairs and Forestry of South Africa since the early nineteen eighties. The need for stochastic hydrology originates from the requirement to estimate the assurance of supply, at say a recurrence interval of a failure of 1:200 years, when the available recorded streamflow data rarely exceeds 40 years and that, through rainfall-runoff simulation, a maximum period length of only 80 years can be derived. Stochastic hydrology provides the capability to synthetically increase the available data in order to evaluate the behaviour of water resource systems using alternative, but statistically plausible, streamflow conditions. This gives the opportunity to assess the probability of occurrence of critical periods that can be as long as nine years, which is difficult given the relative short historical time series"

These water resources assessments are often the responsibility of the DWA and do not need to be undertaken at a WUA level. However, decisions that are made based on these assessments have large impacts on irrigators and therefore the WUA needs to be heavily involved in the process. This includes supplying information on demand and risk profiles of their water users, and ensuring that the water resources models and simulations correctly reflect the manner in which the system is operated.

Software – WAS/Other

Currently there are software tools capable of meeting these requirements. The WAS software has functionality to account for all aspects of determining what releases need to be made from dams to meet water user demands and account for losses. Other platforms have also been developed, and new tools which meet specific predefined needs can also be hypothesized and implemented. These tools are also capable of determining what short term restrictions are required to ensure equitable use of water amongst all users in a river system.

Regardless of whether software is being used to estimate releases or restrictions, an important element is to monitor the compliance of water abstractions according to two specific elements:

- Is the amount of ordered/requested water in line with lawful allocated water amounts?
- Is the water abstracted equal to the amount which was ordered/requested?

Effective management cannot be instituted if these to criteria are not satisfied. Therefore, management platforms should also be capable of assessing these two criteria.

Software and management systems should also be able to disseminate and distribute meaningful information at different levels of detail to stakeholders. This is required to encourage and develop a participatory approach to water management between the WUA and the individual irrigators.

Water quality

Water quality monitoring is important to ensure that ecosystems are maintained, health and safety of workers in contact with water (irrigation water in-field), sustainability of irrigation land (from a salinity perspective) and to ensure quality of produce.

5.2.2 Maintenance methods and equipment

All aspects of used to manage and operate a river distribution network need to be maintained to ensure that systems are operated in an efficient and sustainable manner. These maintenance procedures are especially important for measuring equipment which will need to be periodically tested to ensure that they are still functioning according to manufacturers' specifications.

5.3 The Water Management Plan

A legislative requirement, WMPs are the primary tools with which the agricultural sector is expected to implement the National Water Conservation and Demand Management Strategy (NWCDMS). This strategy derives from the National Water Act (Act 36 of 1998) and it is important to note that both these documents define strategic outputs which they expect the water management and use system to deliver.

The development of a WMP is not an end in itself but is a process with an annual cycle, which can assist WUAs in realising the economic and social benefits of improved water use efficiency. Specific financial benefits flow from this. Depending on the crop type, markets and water supply costs, these include any or all of the following:

- Improved yields ·
- Improved quality of produce, especially for the export markets which pay large premiums for quality,
- Reduced water supply costs,
- Saving in water wastage, therefore extra water for sale and increased income to the WUA, and

- Easier management, especially with automated systems

In addition, the development of the plans provides an opportunity to improve agricultural water management by stimulating self-analysis and forward thinking on the part of farmers, their water suppliers, CMA, officials, consultants and advisors. The plans can be used as a management tool for WUAs, DWA and the CMAs to compile catchment databases and determine national water balances. They offer a means of planning, measuring and demonstrating progress in WCDM and to share experience between WUAs. WMPs can form the basis for negotiation with other institutions, including WUAs, CMA, and DWA etc. and for international water negotiations.

Developing a WMP and reviewing it annually is a major stimulus to efficiency, provides input to the business planning process, promotes coordinated action and facilitates negotiations with the CMA and other stakeholders. The process involves analysing current water use, setting targets for improved efficiency and planning a realistic means of reaching these targets. In light of all these benefits, and since they form the basis of the statutory Business Plan, WUAs are now required to submit WMPs to their CMAs or DWA, in default of a CMA.

6 Evaluation

The most efficient irrigation scheme will be one that is regularly evaluated to assess the level of performance and detect problems as early as possible.

Except for the continuous monitoring of infrastructure performance as part of day-to-day operation of the canal system, a WUA also have to evaluate performance from time to time. On a canal scheme, the most important evaluations are the assessment of measurement device accuracy.

Except for the continuous monitoring of the groundwater aquifer and abstractions as part of day-to-day operation of the system, a WUA also has to evaluate performance of the management system from time to time. In a groundwater system, the most important evaluations are the assessment of measurement device accuracy and aquifer management. DWA, as stipulated in the NWA, can make decisions based on the best available technical information. There will always be uncertainties related to understanding how water resources function, for example in determining the groundwater recharge or the water use. Uncertainty is not an excuse for inactivity, lack of decision-making, or lack of management. Water resources need to be managed through an adaptive management approach, using the latest available information. This information can or should be improved as better information becomes available. Uncertainties can be dealt with by taking a precautionary approach.

6.1 Benchmarks

A history of average losses for the scheme and parts of the scheme is an excellent benchmark to use. This is the only way to monitor improvement or to get an early warning sign of bad management or a deteriorating canal.

6.2 Trouble shooting

Divide and conquer which means evaluate smaller parts of a scheme to locate a problem.

7 Summary

To conserve water manage demand, the management authority have an important role to play, especially on an irrigation scheme, where irrigation water users are grouped together.

The following guidelines should be adhered to when planning, designing and managing irrigation schemes:

- All legal requirements as specified in the NWA should be met, especially regarding institutional arrangements and water use
- The SAPWAT3 program should be used when planning irrigation demands, adapted if necessary for local conditions
- The relevant modules of the WAS program should be used to operate irrigation schemes on a daily basis and keep records
- Water abstraction and distribution should be measured at an appropriate level of accuracy with suitable measuring devices at strategic points on the irrigation scheme
- The iScheme program (implemented by DWA as the Water Use Efficiency Accounting Report) should be used to monitor and evaluate irrigation scheme performance

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