Irrigation methods for efficient water application: 40 years of South African research excellence

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Abstract

The purpose of an irrigation system is to apply the desired amount of water, at the correct application rate and uniformly to the whole field, at the right time, with the least amount of non-beneficial water consumption (losses), and as economically as possible. We know that irrigated agriculture plays a major role in the livelihoods of nations all over the world and South Africa is no exception. With the agricultural water-use sector being the largest of all water-use sectors in South Africa, there have been increased expectations that the sector should increase efficiency and reduce consumption in order to increase the amount of water available for other uses.

Studies and research over 40 years, on the techniques of flood-, mobile- and micro-irrigation have contributed to the knowledge base of applying irrigation methods correctly. In a recent study on irrigation efficiency, the approach is that irrigation efficiency should be assessed by applying a water balance to a specific situation rather than by calculating various performance indicators. The fraction of the water abstracted from the source that is utilised by the plant is called the beneficial water-use component, and optimised irrigation water supply is therefore aimed at maximising this component. It implies that water must be delivered from the source to the field both efficiently and effectively. Optimising water use at farm level requires careful consideration of the implications of decisions made during both development (planning and design), and management (operation and maintenance), taking into account technical, economic and environmental issues. An exciting, newly-developed South African Framework for Improved Efficiency of Irrigation Water Use covers 4 levels of water-management infrastructure: the water source, bulk conveyance system, the irrigation scheme and the irrigation farm. The water-balance approach can be applied at any level, within defined boundaries, or across all levels to assess performance within the entire water management area.

Keywords: irrigation methods, water-use efficiency; water-balance approach, beneficial water use, South African framework

Introduction

Irrigated agriculture plays a major role in the livelihoods of nations all over the world and South Africa is no exception. With irrigated agriculture being the largest user of runoff water in South Africa, there have been increased expectations from government that the sector should increase efficiency and reduce consumption in order to increase the amount of water available for other uses, in particular for human domestic consumption. Irrigation in South Africa is currently practised on 1.6 x 10^6 ha. In 2000 it used 62% of the runoff water that was used by all sectors, or 39.5% of the exploitable runoff water (DWAF, 2004). Studies and research over 40 years, on flood-, mobile- and micro-irrigation techniques contributed to the knowledge base of applying irrigation methods correctly to improve the efficient application of water. The different irrigation systems vary in terms of individual components, cost and performance and generally they can be classified into 3 groups:

- Flood-irrigation systems by which water that flows under gravity over soil while infiltrating is applied to the farm lands. This includes basin, border, furrow and short furrow.
- Mobile irrigation systems which move over the farm land under their own power while irrigating. These include centre-pivot, linear and travelling-gun systems.
- Static systems include all systems that remain stationary while water is applied. We distinguish between 2 types:
  - Sprinkler by which water is supplied above ground by means of sprinklers or sprayers. This includes permanent or portable like quick-coupling, drag-line, hop-along, big-gun, side-roll and boom irrigation systems.
  - Micro-systems which include micro-sprayers, mini-sprinklers and drip-irrigation systems.

Aspects that have been addressed in the research were layout, design, selection, management and a number of other factors that can improve the efficiency of the irrigation system. However, great emphasis has been placed lately on how an increase in efficiency will lead to reduced water consumption by agricultural users and thereby ‘release’ some of the annual water yield for use by the domestic sector. Recommended actions to improve efficiency include measurement of the quantity of water distributed and applied at specific times; preparation of water-use efficiency and risk-management plans; and a reduction of the quantity of water used for irrigation by existing farmers through investment in appropriate technology.

Various research projects funded to date by the Water Research Commission (WRC) demonstrate how improvements can be made to efficiently manage water in South Africa.

Improved flood-irrigation approach

Increasing the efficiency of flood irrigation has been intensively researched in South Africa since 1972 by engineers of the

This paper was originally presented at the Water Research Commission 40-Year Celebration Conference, Kempton Park, 31 August - 1 September 2011.
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Department of Agriculture – Division of Agricultural Engineering and implemented as such. It was only in the late 80s and early 90s that, through a WRC-supported project, aspects such as the upgrading of the layout, the management and design of the systems were addressed and a model was developed to simulate the hydraulics of flood irrigation more accurately (Du Rand and Kruger, 1995). In a WRC-sponsored project Russell (1982) studied infiltration under flood-irrigation conditions on a typical crusting soil of the Eastern Cape. He found that infiltration under dynamic (flood) conditions on this soil was very high and remained so over the medium term, in sharp contrast to the quick surface sealing and very low infiltration under static conditions.

Computerised irrigation design

An Israeli computerised irrigation design package was introduced in South Africa in 1983. The International Commission on Irrigation and Drainage (ICID) predicted in 1985 that an integrated computer process will be the norm for the future and indeed since then a number of computer-aided design routines have been developed and reported on. In 1987 MBB Inc completed a WRC-supported project titled 'The development of procedures for design and evaluation of irrigation systems' (MBB Inc., 1987). Irrigation design principles and procedures were studied in depth and evaluated critically. Different design algorithms were developed that were based on the well-known principles of the PolyPlot software. The research eventually resulted in the development of the IDES irrigation design and evaluation program which was the front-runner for the popular design program ModelMaker that was only introduced towards the end of the century. Today a range of excellent computer programs are available for modern-day design of efficient irrigation systems.

Containing losses during centre-pivot irrigation

During the period 1970-1982 the efficiency of centre pivots was estimated at 80%. A research project was supported by the WRC to investigate, identify and quantify the spray losses between the emitters on a centre pivot and the plant canopy (Van der Ryst, 1995). Apart from technical measurements, meteorological and other factors influencing irrigation losses were identified. It was found that the average losses rarely exceed 10% of the pumped water if the emitter package is properly designed and the wind speed is less than 6 m/s. From the results obtained with single nozzles it was clear that droplet size has an important effect on spray losses. This research provided valuable guidelines in terms of emitter selection, application depth and management of centre pivots. The WRC also sponsored a project aimed at deriving criteria for the adaptation of overhead irrigation systems, including centre pivots, to the infiltrability of different soils, so as to minimise water losses through runoff and/or evaporation due to ponding (Bloem et al., 1992; Bloem and Laker, 1993; 1994a; b). The energy flux (or kinetic energy), given by a combined effect of drop size, falling height and application rate was found to be a key factor. Equations were derived for predicting the maximum allowable kinetic energy (MAKE) for different scenarios (Bloem and Laker, 1994a).

Performance of 2 types of sprinkler irrigation emitters

In a WRC-supported project, 2 types of sprinklers operating on a dragline and a floppy sprinkler (*Floppy Sprinkler* (Pty) Ltd) on a permanent layout was evaluated (Simpson and Reinders, 1999). The individual sprinklers were evaluated on the sprinkler test bench of the ARC Institute for Agricultural Engineering, and the installed systems were evaluated in-field. The performance of the coefficient of uniformity (CU), distribution uniformity (DU) and the scheduling coefficient (SC) were determined. The importance of this is that high CU values and DU values in-field have a direct influence on the potential yield of the crop. In this research it was illustrated that layout, pressure variation, droplet size and maintenance of sprinkler systems have a significant impact on the irrigation system's performance.

Managing surface- and subsurface drip-irrigation systems

Drip irrigation is considered to be one of the most efficient irrigation systems available, but through a WRC-supported research project evidence was obtained from the literature as well as from on-farm and in-field testing that even this system can be inefficient, as a result of poor water quality, mismanagement and maintenance problems (Reinders et al., 2005). Apart from the research on the performance of various types and ages of drippers (Koegelenberg et al., 2002) and filters under different water quality and typical farming conditions (Van Niekerk et al., 2006), guidelines were developed to make the correct dripper and filter choice. Through this research excellent guidelines were provided for proper choice, maintenance schedules and management of filters and drip-irrigation systems.

The water-balance approach

In a recently completed WRC research project on irrigation efficiency (Reinders et al., 2010), the selected approach is that irrigation efficiency should be assessed by applying a water balance to a specific situation, rather than by the calculation of various performance indicators, based on once-off measurements of samples. The purpose of an irrigation system is to apply the desired amount of water, at the correct application rate and uniformly to the entire field, at the right time, with the least amount of non-beneficial water consumption (losses), and as economically as possible. When applying water to crops, it should be considered both as a scarce and valuable resource and 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 is utilised by a planted crop is 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 volume for production along the supply system) and effectively (at the right time, in the right quantity and at the right quality). Optimising water use at farm level requires careful consideration of the implications of decisions made during both development (planning and design), and management (operation and maintenance), taking into account technical, economic and environmental issues.

Perry (2007) presented a newly developed framework for irrigation efficiency as approved by the ICID. He describes in detail the history and subsequent confusion surrounding the calculation and interpretation of so-called irrigation or water-use 'efficiency' indicators. The framework and proposed

http://dx.doi.org/10.4314/wsa.v37i5.13
Available on website http://www.wrc.org.za
ISSN 0378-4738 (Print) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011
ISSN 1816-7950 (On-line) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011

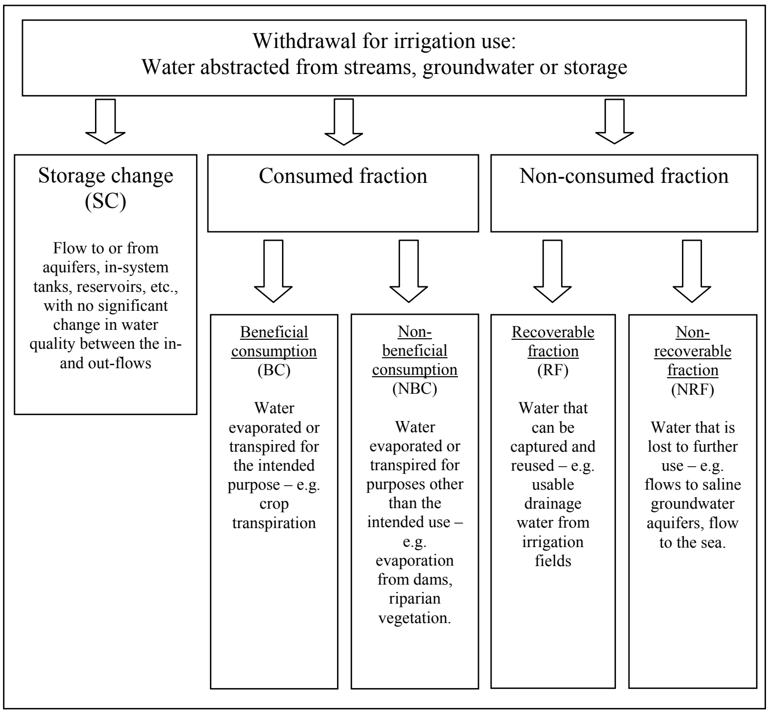

Figure 1
ICID water-balance framework for irrigation water management (Perry, 2007)

terminology are scientifically sound, being based on the principle of continuity of mass, and promote 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 using the calculation of input-output ratios as done in the past.

The basis of the framework is that any water withdrawn from a catchment for irrigation use contributes 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 reuse) or non-recoverable (lost to further use).

In order to improve water availability in a catchment, the relevant authority needs to focus its attention on reducing non-beneficial consumption and non-recoverable fractions; the activities undertaken to achieve this result can be called best management practices. The ICID water-balance framework, based on Perry's model, is shown schematically in Fig. 1.

In order to apply this framework to irrigation areas, typical components of the water-infrastructure system are defined wherein different scenarios may occur. In South Africa, most irrigation areas make use 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 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.

The South African framework covers 4 levels of water-management infrastructure (Table 1), i.e.:

- The water source
- The bulk conveyance system
- The irrigation scheme and the irrigation farm
- The relevant water-management infrastructure.

TABLE 1
Four levels of water management infrastructure (Reinders et al., 2010)

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		
	In-field irrigation system		

The different components of the water-balance framework system and their classification according to the ICID framework, for whichever agricultural water-management system, have been developed as a guide to identify the different areas were water losses can occur. In order to improve water-use efficiency in the irrigation sector, actions should be taken to reduce the non-beneficial consumption (NBC) and non-recoverable fraction (NRF). Desired ranges for the NBC and NRF components have been developed to assist the practitioner in evaluating the results obtained when first constructing a water balance.

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 water user association (WUA) or other responsible organisation. Acceptable ranges need to be set, and agreement obtained with the Department of Water Affairs (DWA) as to where in the system provision should be made to cover losses.

The fieldwork undertaken in the course of the WRC project, 'Water Use Efficiency from Dam Wall Release to Root Zone Application' (Reinders et al., 2010), comprised various

http://dx.doi.org/10.4314/wsa.v37i5.13
Available on website http://www.wrc.org.za
ISSN 0378-4738 (Print) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011
ISSN 1816-7950 (On-line) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011

TABLE 2 **Irrigation schemes where fieldwork took place and system components were assessed** **(Reinders et al., 2010)**					
Irrigation scheme	**Bulk convey-ance**	**On-scheme distri-bution**	**On-scheme return flow**	**Irrigation system (appli-cation)**	**Irrigation manage-ment (soil storage)**
Breede River	X	X	X	X	
Dzindi	X			X	
Gamtoos	X			X	X
Hartbeespoort	X			X	
Hex River				X	
KZN scheme	X	X		X	X
Loskop	X			X	
Nkwalini	X			X	
ORWUA	X	X	X	X	X
Steenkoppies					X
Vaalharts	X		X	X	
Worcester East				X	

approaches and strategies applied at each of the irrigation schemes that were investigated (Table 2) aimed at quantifying some of the water-use components mentioned. As the application of water-balance approach was an outcome of the research rather than anticipated solution at the outset, the fieldwork was not initially designed to produce results to which the water-balance approach could be readily applied. However, at many of the schemes where fieldwork was undertaken, at least some of the system components could be assessed using the water-balance approach.

The research activities undertaken and the outcomes implemented were done in 4 phases:

- **Baseline study phase**
  The various performance indicators previously available were reviewed, and irrigation systems evaluated to obtain information on the current status of irrigation schemes and systems. The outcome of this phase was a decision to introduce the water-balance approach in which the framework components have to be defined and quantified for the boundary conditions selected, using standardised measurements rather than the performance-indicator approach.
- **Assessment phase**
  During this phase, existing best management practices were used to assess the current status of irrigation schemes and systems and to identify which components of the water-balance framework improvements can be made. This may be at water management area (WMA) scheme or farm level where different sources of information are available for assessment.
- **Scenario development phase**
  During this phase, alternative scenarios were developed for the components requiring change, and the feasibility of implementing the changes was assessed from technical, environmental and economic perspectives. Models were used for feasibility assessment, making use of available computer programs and data sets.
- **Implementation phase**
  In this phase recommendations were made for implementing feasible changes, and guidelines were developed. These guidelines should be promoted amongst all levels of stakeholders (WMA, scheme and farm), as a means of influencing the way in which water-use efficiency is reported at the different management levels, for example, in water-use efficiency accounting reports, water-management plans and water-conservation plans.

Within this phase the main outcome was developed, viz. ‘Standards and Guidelines for Improved Efficiency of Irrigation Water Use from Dam Wall Release to Root Zone Application’ (Reinders et al., 2010). The structure and content of the Guidelines are based on the lessons learnt locally and internationally during the course of the project. Hence, the conventional set of performance indicators with benchmarks was moved away from and a water-balance approach is instead being promoted as a more meaningful and sustainable approach to improving water-use efficiency in irrigation. These Guidelines are aimed at assisting both water users and authorities to achieve a better understanding of how irrigation water management can be improved, thereby building human capacity and allowing targeted investments to be made with fewer social and environmental costs.

The Guidelines comprise 4 modules:

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

The guidelines developed as part of this project contain information on aspects of irrigation water-use efficiency that is either new or supplements previously available information:

- The ICID framework was applied to re-assess the system efficiency indicators typically used by irrigation designers when making provision for losses in a system and converting net to gross irrigation requirement. A new set of system efficiency (SE) values for design purposes has been developed. These values are illustrated in Table 3 and are considerably more stringent than previous system-design norms.
- System efficiency defines the ratio between net 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.
- The new application efficiency values are shown in the ‘Norms’ column of Table 3**,** while the different water-use components and their losses at the point of application within a specific irrigation system have each been incorporated in the default system efficiency value. The approach makes provision for the occurrence of non-beneficial spray evaporation and wind-drift, in-field conveyance, filter and other minor losses.
- When an irrigation system is evaluated, the system efficiency value can be compared with these default values, and possible significant water loss components identified as areas for improvement. The approach is therefore more flexible and easier to apply than the original efficiency framework where definitions limited the applications.

It should always be kept in mind that a system’s water-application efficiency will vary from irrigation event to irrigation event, as the climatic, soil and other influencing conditions are never exactly the same. Care should therefore be taken when applying the SE indicator as a benchmark, as it does not make provision for irrigation management practices.

http://dx.doi.org/10.4314/wsa.v37i5.13
Available on website http://www.wrc.org.za
ISSN 0378-4738 (Print) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011
ISSN 1816-7950 (On-line) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011

TABLE 3 New default system efficiency values (adapted from Reinders et al., 2010)					
Irrigation system	Losses				New default system efficiency (net to gross ratio) (%)
	Non-beneficial spray evaporation and wind-drift (%)	In-field conveyance losses (%)	Filter and minor losses (%)	Total losses (%)	
Drip (surface and subsurface)	0	0	5	5	95
Micro-spray	10	0	5	15	85
Centre pivot, Linear move	8	0	2	10	90
Centre pivot, LEPA	3	0	2	5	95
Flood: Piped supply	0	3	2	5	95
Flood: Lined canal supplied	0	5	2	7	93
Flood: Earth canal supplied	0	12	2	14	86
Sprinkler permanent	8	0	2	10	90
Sprinkler movable	10	5	2	17	83
Travelling gun	15	5	2	22	78

It is recommended that system efficiency be assessed in terms of the losses that occur in the field. This can be determined as the ratio between the volume of water lost to non-beneficial spray evaporation and wind-drift, in-field conveyance, filter and other minor losses, and the volume of water entering the irrigation system, for a specific period of time. The losses can also be expressed as a depth of water per unit area, rather than a volume.

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. The traditional approach to accounting for the distribution uniformity of the lower quarter (DU_{lq}) has most likely resulted in the default irrigation efficiencies customarily referred to, e.g., that furrow irrigation is assumed to be 65% efficient and centre-pivot irrigation is assumed to be 85% efficient. Unfortunately, the rationale for these assumed efficiencies, i.e. the typical or assumed non-uniformity, is seldom well considered, and water is often thought to just ‘disappear’ with the assumed low efficiencies. However, once the water-balance approach is applied, it is realised that the water does not ‘disappear’ but could contribute to increased deep percolation which may eventually appear as return flow further along the drainage system.

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 therefore increasing the water applications accordingly.

If poor uniformity results in low crop yields, the uniformity needs to be corrected in order to improve system performance. Simply applying more water to compensate for the part of the field that is being under-irrigated is unlikely to result in improved crop yields, as large parts of the field will now suffer from over-irrigation, and the risk of long-term problems developing due to a raised water table will increase. The preferred recommendation in this case would be to deal specifically with the problem of poor uniformity. For planning purposes, the GIR at the field edge should therefore be calculated as the product of the NIR and system efficiency.

Conclusion and recommendations

Studies and research over 40 years on mainly the engineering aspects of the techniques of flood-, mobile- and micro-irrigation contributed to the knowledge base of applying irrigation methods correctly to improve the efficient application of water. In particular, the research that was carried out to improve irrigation-water management from dam-wall release to root-zone application has to a large extent consolidated and contributed to local knowledge on issues regarding irrigation water-use efficiency. The resulting approach of ‘measure; assess; improve; evaluate’, promotes an investigative approach to improving efficiency, rather than relying merely on water accounting.

The main output of the project was the compilation of guidelines for improved irrigation-water management from dam-wall release to root-zone application. The guidelines are aimed at assisting both water users and authorities to achieve a better understanding of how irrigation-water management can be improved, thereby building human capacity, allowing targeted investments to be made with fewer social and environmental costs. Using the lessons learnt during the WRC project, best practices and technologies were identified and then illustrated.

It is recommended that the research output, i.e. the guidelines for management advice on improved efficiency of irrigation-water use, should be further developed into a user-friendly package with supporting training material, targeting farmers, service providers and policy advisors. This will contribute to better understanding of the realities and potential for efficient irrigation water use across all levels of water management, and encourage the adoption of the water-balance approach.

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http://dx.doi.org/10.4314/wsa.v37i5.13
Available on website http://www.wrc.org.za
ISSN 0378-4738 (Print) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011
ISSN 1816-7950 (On-line) = Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition 2011