1. Introduction

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1.1 Refocusing irrigation water management

The world population grows at a pace of 1.3 % per year. By 2025, global population will likely increase to 7.9 billion, more than 80 percent of whom will live in developing countries (*UN*, 1998). This growth in population combined with the expected increase in prosperity will put enormous pressure on water resources. As a matter of fact, 36% of the 2025 world population is projected to be living in China and India alone, so water management in India will rank high on the national and international political agenda. Although there is quite some uncertainty imbedded in these numbers, it is obvious that the current per capita water availability cannot be maintained. These developments put an enormous demand on the land and water resources and in particular on irrigated agriculture, that is responsible for 70% of the global fresh water withdrawals (*Seckler et al.*, 1998).

The available surface water resources are all exploited to meet the growing water demands, and most river basins are now at the edge of being developed to their maximum capacity. The risks are that basins retain all surface water resources in small and large reservoirs, and that the outflow diminishes to virtually nothing (‘closed basin’). This is far from being adequate for maintaining wetlands, estuaries, lagoons and other biodiversity-rich ecosystems that are traditionally found in the lower ends of basins. It has been estimated that during the 20th century, more than 50% of the wetlands are lost (*Bos and Bergkamp*, 2001).

Water demand exceeding water supply is – already – common for rural areas in the vicinity of fast expanding super metropolitans. Alluvial plains in the semi-arid and arid climates are the potential water conflict hazards because irrigation systems and urban water users have to share the space and resources. A fierce competition for water between the urban, industrial, agricultural and environmental users has began, and irrigated agriculture will – undoubtedly – have to develop new strategies based on water conservation. Although there is more demand for food to feed the expanding population, there is less water available for boosting the agricultural production. As a consequence, the irrigation sector has to utilize water resources more productively.

Several basins exploit groundwater for irrigation as a remedy to surface water resources scarcity, but this leads to unsustainable developments. Water policy makers have, therefore, to work out strategies for integrated water and environmental management, which rely on a proper knowledge of the basin hydrological and pollution conditions. Without strong governmental control on water rights and well permits, groundwater pumping can lead to unacceptable, fast declines of the groundwater table. Hence, irrigation with groundwater can only be a solution to overcome the shortage of surface water resources as long as the recharge rate is in balance with the extraction rate. Ideally, the groundwater system should function as a natural storage to overcome surface water shortage during dryer years, while additional recharge will take place during wetter years.

The often promoted solution to combat water scarcity is the improvement of irrigation efficiency, i.e. reducing water losses between the point of water diversion and the root zone soil moisture storage. This is, however, not a proper solution everywhere, because percolating water from fields that are irrigated is not necessarily bad (it is not always good either). When farmers are using groundwater or drainage water for irrigation, recycling of water resources will increase irrigation efficiencies that are substantially greater than the nominal field scale values. The ballpark figure for field scale irrigation efficiencies is 45%, and several studies have indicated that the irrigation efficiencies for deltas or river basins as a total system with recycling of percolation water can be as high as 80 to 100%. This implies that improvements in efficiency will be next to impossible, and is basically false hope. However, in shallow groundwater areas, irrigation efficiency is important to protect an area that is prone to water logging or soil salinization. When good quality irrigation water becomes deteriorated by saline groundwater, recycling is not longer an attractive management option, and managing canal water losses becomes a highly relevant issue.

Improving irrigation system efficiencies and reductions in irrigation water applications are no guarantee for successful water conservation. Reducing irrigation water supply will cut off the field scale percolation rates, but the impact on evapotranspiration (*ET*) can be minimal. The reduction in irrigation water supply by improved conveyance and application efficiencies may aggravate the declination of the groundwater table, or it deteriorates the water availability to downstream stakeholders. Despite many possible misconceptions about using irrigation efficiency terms are pointed out before (e.g. *Molden and Sakthivadivel*, 1999), it is still the standard building block of irrigation management planning, probably because alternative solutions are not well known.

One of the alternative solutions in water utilization is the framework of water accounting (*Molden*, 1997), which distinguishes different water use categories such as process depletion, non-process depletion, non-beneficial depletion, committed outflow and uncommitted outflow (Fig. 9.1). Others referred to these users as comprehensive *ET*, beneficial *ET*, non-beneficial *ET* and consumptive use. The framework of performance indicators describes the various aspects of water management such as production, utilization, environment and economy (e.g. *Bos et al.*, 1994; *Willardson et al.*, 1994; *Burt et al.*, 1997; *Kijne et al.*, 2003) and it needs to get more attention. The bottleneck is that tools are absent to make quick scans of the systems.

In summary, the major obstacles that prompt for a refocus on irrigation management are:

- The water flows and return flows in irrigation systems are generally poorly understood; it is uncertain what the irrigation efficiencies are at the various spatial scales;
- A higher or lower irrigation efficiency can be good or bad and does not lead to clear cut conclusions and management strategies;
- Water saving programs usually ignore the impact of the intervention on the hydrology of the surrounding environment;
- The tools for a more comprehensive irrigation performance framework are absent.

Hence, irrigation efficiency related management is not straightforward to implement, and a paradigm shift is required to describe the utilization of the water resources in irrigation systems in a simple manner. Agricultural production has traditionally been expressed in kg crop per ha of land, assuming that land resources are the limiting factor. In some cases land is indeed the limiting factor, but with the current water crisis, sufficiently available fresh water resources are becoming the binding constraint for food production, and limited water should be use more productively. It is therefore logic to express the agricultural performance in terms of kg crop produced per m^3 water used. From a plant physiological point of view this is already referred to for decades as water use efficiency (e.g. *de Wit*, 1958) or 'the amount of organic matter produced by a plant divided by the amount of water used by the plant in producing it'.

The terminology on water use efficiency is often confused with various versions of irrigation efficiency, thus describing losses or other forms of water that are not available for root water uptake. As an 'efficiency' is per definition related to comparing input with output during a given process, the same units for input and output should be applied (which does not hold true for water use efficiency). The classical concept of efficiency as used by engineers omits production values. The International Water Management Institute (IWMI) has started a strong lobby to change the nomenclature from water use efficiency into water productivity, which is now also followed by other Consultative Group on International Agricultural Research (CGIAR) institutes and the Food and Agricultural Organization of the United Nations (FAO). This provides also a better basis to concern with non-agricultural products that originate from water such as industries, bird habitats and tourism.

A key element in the discussion on Water Productivities (*WP*) is the nominal values and the ranges of *WP* for certain cropping systems. If the range is narrow, than there is only little scope to improve *WP*. There exists a general opinion that crop yield is a simple derivative of *ET*, assuming that the ratio of yield and *ET* is quasi-constant. In fact, *Doorenbos and Kassam* (1973) have demonstrated that yield and *ET* can be scaled between zero and a maximum value, and be related mutually by a single crop yield response factor K_y (Eq. 5.1). Although this is an interesting concept, the maximum yield for certain irrigation and drainage systems is not constant which makes yield over *ET* variable. *Bastiaanssen* (2000) showed the results of a literature review of wheat and corn, and he came to the conclusion that *WP* per unit depletion for wheat ranges between 0.4 to 1.6 kg/m^3 and that for corn the range was 0.3 to 2.7 kg/m^3. This implies that there is a factor 4 to 9 between the lowest and highest levels, and that an enormous scope for improving *WP* exists. An increase of *WP* by for instance 40% implies that the same food production can be maintained with 40% less crop water consumption. This is a great opportunity for the irrigation sector that needs to get more attention by water resources planners, agronomists and irrigation engineers. It needs to be emphasized that the saving should be related to *ET* ('wet saving') and not to water supply ('dry saving'). If we are able to increase the water productivity in irrigated agriculture, water can be allocated for other users in the river basin. In an extensive study towards world agriculture in 2015/2030, the FAO (2002) stresses the importance of higher water productivity in irrigated systems in order to meet the food demands of this century.

Traditional agronomical and hydrological knowledge need to be pooled together for addressing the following major problems with regard to *WP*:

- What are the benchmark *WP* values under practical conditions for various crops and what are the spatial variations occurring within and among irrigation schemes?
- How can we improve *WP* at the different spatial scales so that agricultural production can be maintained and fresh water resources come available for competing sectors or for expanding the irrigated area?

1.2 General background of water productivity

The water productivity concept is based on "more crop per drop" or "producing more food from the same water resources" or "producing the same amount of food from less water resources". In a broad sense, productivity of water is related to the value or benefit derived from the use of water. Definitions of water productivity are not uniform and change with the background of the researcher or stakeholder involved. For example, obtaining more kilograms dry matter production per unit of transpiration is a key issue for plant breeders. At a basin scale, economists wish to maximize the economical value from water used. There are several definitions of water productivity, so we have to ask ourselves *which crop* and *which drop* are we referring to (see Table 1.1).

Table 1.1 Some examples of stakeholders and definitions in the water productivity framework.

Stakeholder	Definition	Scale	Target
Plant physiologist	Dry matter / transpiration	Plant	Utilize light and water resources
Nutritionist	Calorie / transpiration	Field	Healthy food
Agronomist	Yield / evapotranspiration	Field	Sufficient food
Farmer	Yield / supply	Field	Maximize income
Irrigation engineer	Yield / irrigation supply	Irrigation scheme	Proper water allocation
Groundwater policy maker	$ / groundwater extraction	Aquifer	Sustainable extraction
Basin policy maker	$ / evapotranspiration	River Basin	Maximize profits

If we concentrate on the productivity than we can express this as total dry matter production or as actual yield as a harvestable product. Productivity expressed in kg is less useful if we want to compare different crops or different regions and under these circumstances, a definition based on economic value is more appropriate. These economic values can be based on simple gross value, so kg yield multiplied by market prices, but it can include also a complete economic evaluation to get the net benefits. Fluctuations in prices (per region and/or between years) can influence the *WP* substantially and it is therefore practical to use average world prices.

Water managers tend to be more concerned with the total water input. Rainfed farmers in arid areas, for example, are extremely concerned with capturing and doing the most with limited rainfall. Where an additional supply is available as supplemental irrigation, maximizing the output from a small amount of additional irrigation supply is normally highly productive. For irrigation farmers, and managers of irrigation systems, water supply is a managerial factor and they will evaluate their own *WP* on the basis of canal water supplies in relation to crop yield, rainfall, supplemental irrigation, or full irrigation supplies.

Water that has been evaporated through *ET* is not longer available for reuse in the basin to other stakeholders, so it should be used as productively as possible; opportunities for recycling are absent. It seems therefore an advantage of expressing *WP* per unit *ET*, but, as referred to earlier, this is a strong field and agronomical approach.

1.3 Summary of earlier work in Northwest India

The Sirsa Circle pilot area in Haryana state has been selected for a number of reasons. In the central and north-western region of Haryana, where the groundwater is brackish and no drainage outlets are available, canal irrigation has led to problems of water table rise, water logging and flooding, and secondary salinization. In the eastern region and other areas with fresh groundwater the water table is continuously declining. At the same time, Haryana together with Punjab – being the wheat belt of Asia - play an important role in the food production for the more than 1 billion inhabitants of India.

In the past decades, Haryana witnessed an impressive increase of crop yields. For instance average wheat grain yields in India rose from 1350 kg/ha in 1975 to 2450 kg/ha in 1998. Haryana participated in the Green Revolution, and current wheat grain yields in irrigated farmer fields fluctuate around 3900 kg/ha. In an extensive farming system analysis and planning study for sustainable food security in Haryana, *Aggarwal et al.* (2001) found that the availability of water is a major constraint to further food production increase in Haryana. These researchers stress the importance of more reliable data on water resources and water use in Haryana in order to improve its water management and crop production.

Indo-Dutch Operational Research Project on Hydrological Studies

One of the major studies undertaken to improve water management in Haryana State is the Indo-Dutch Operational Research Project on Hydrological Studies (*Agarwal and Roest*, 1996). This over ten-years intensive research, training and awareness creating project took place in Sirsa Irrigation Circle from 1989 to 1996. The main partners were Chaudhury Charan Singh Haryana Agricultural University, Hisar, India and Wageningen University and Research Centre, The Netherlands. The long term sustainability objectives of the project were dealt with by developing the following technologies:

- efficient on-farm water management;
- conjunctive use of fresh and saline water;
- development of drainage criteria;
- development of on-farm and regional integrated simulation models.

Based on the SWAP model linked to a GIS and a multi-objective optimization procedure, 6 major crop rotations in combination with 4 water management alternatives were explored (*Bastiaanssen et al.*, 1996). Results indicate that sustainable water and salinity management is possible if drainage systems will be installed in 5 to 10% of Haryana and if canal water supply will be made variable, according to local soil physical needs and crop water requirements, incorporating contributions from shallow groundwater tables.

The regional water management analysis was also based on modeling approaches using SIWARE (*Boels et al.*, 1996) for the canal and on-farm water management and SGMP for the regional groundwater flows (*Boonstra*, 1996). Two options were explored to solve the problems of rising groundwater tables in some areas and declining ones in other areas. The key to solve this would be to reduce on-farm irrigation applications, which was tested by two alternatives: water pricing and demand driven operations. Both options were concluded to be effective, but the demand driven option is difficult to implement since this would require a complete change in the infra-structure and would mean to abandon the *warabandi* system.

Jacobs and de Jong (1997) conducted an interesting field inquiry towards the perception of farmers and irrigation managers in the Adampur division near Hisar. The vision of these stakeholders was converted into water management rules, and the impact of these rules was evaluated through Water Management Response Indicators including relative evapotranspiration, salinity hazard index, salt concentration change, moisture storage change, and several groundwater related indicators (Box 4.1). The best solutions comprise drainage in shallow groundwater table areas, more tubewell use, lining of canals and watercourses, cropping pattern adjustments and bio-drainage through planting of eucalyptus trees.

Jhorar (2002) used the SIWARE model to reduce canal water supply by about 25% during the rainy season in the areas facing rising groundwater levels. In addition he increased the capacity of groundwater extraction by 60 mm y^{-1}. The models results revealed that groundwater of relatively poor quality can be used, and that the sustainability of the system depends on the rainfall distribution. Sirsa district appeared to be vulnerable to drought.

According to all these studies, one of the most important issues in solving Haryana's problem is to create a drainage outlet for the inland drainage basin area. Unfortunately, ten years after the Indo-Dutch study, the drain is not constructed due to high costs.

International Water Management Institute studies in Haryana

The International Water Management Institute has completed a set of studies concentrating on water productivity analysis during the last five years.

Sakthivadivel et al. (1999) integrated wheat yield from remote sensing with GIS data on soil type, water table depth, groundwater quality, district level discharge, rainfall and *ET*. The conclusion was that although *WP* is high, especially for Indian standards, rising water tables and salinity threats the sustainability of the irrigation system. In other words, equal emphasis should be given to the rising and falling trends of groundwater levels.

Bastiaanssen et al. (1999) linked the SIWARE output with crop yield assessed from the Indian Remote Sensing satellite (*Thiruvengadachari et al.*, 1997) to estimate irrigation performance and *WP* for Sirsa irrigation district. One of their key findings is that the average *WP* of wheat is 0.88 kg m^{-3}, which was achieved at average crop yields of 3.76 t ha^{-1}. In terms of sustainability, average increase in groundwater storage is about 100 mm of water, which corresponds to a rise in groundwater level of about 80 cm y^{-1} if we use an average specific aquifer yield for Sirsa district of 0.12 (*Boonstra*, 1996).

A study based on intensive data collection over 216 farms in the Bhakra canal system was undertaken during the *rabi* season 2000-01 (*Hussain et al*, 2003). The study took place in the context of a major initiative, the Rice-Wheat Consortium for Indo-Gangetic Plains. This consortium strives to address the issues of productivity enhancement of rice and wheat in a sustainable fashion. Their study compared growing practices and production levels in the Punjab of Pakistan with these in Haryana, since the general assumption is that yields in Haryana would be almost double in comparison to the ones in Punjab, Pakistan. Some of their key findings with respect to wheat relevant for Haryana are:

- Average wheat yields are higher in India (4.48 t/ha) than in Pakistan (4.11 t/ha). However, the magnitude of yield difference is not as high as is generally perceived.
- There are significant differences in yields across farms and locations with yields ranging from 2.96 t/ha to 5.73 t/ha.
- Wheat yield differences are much higher across watercourses within a distributary than across distributaries.
- There is significant variation in total water (both surface and groundwater) applied. Per hectare water use varies from 746 m^3 to 4,322 m^3 averaging at 3,050 m^3 against crop water requirements of 3,300 m^3.
- Average productivity of consumed water is 1.36 kg m^{-3}. Average WP_{ET} is 1.47 kg m^{-3}.

Central Soil Salinity Research Institute studies

Various studies have been undertaken by the Central Soil Salinity Research Institute, Karnal, focusing on soil-water-plant interaction and salinity management options. A study on improving wheat productivity showed that improved crop varieties could indeed increase crop yields but would place a greater stress on soil and water management (*Tyagi and Sharma*, 2000). It was stated that the majority of research is still concentrating on farm irrigation scheduling, while the real problems are the inadequacies of the conveyance and distribution systems. Their results indicate also that the key option to increase wheat productivity lies in an improved drainage system to minimize water logging and secondary salinization.

A diagnosis and recommendation for improving water delivery performance in the Bhakra canal command area, to which Sirsa Irrigation Circle belongs, is given by *Tyagi* (1998). His analysis showed that canal water delivery, in terms of equity, timing and amount, was very poor. Three options were suggested for improvement:

- Improvement in water distribution equity and efficiency through the proper design of the unit command area size;
- Relaxing the rigidity of the delivery schedule;
- Improving reliability.

In fact, this would require substantial changes in the *warabandi* operational system and in the actual canal infrastructure.

Tyagi (2003) mentioned that irrigation with sodic water given after two turns of irrigation with fresh water, to rice as well as to wheat, helped in obtaining yields comparable to those with irrigation with fresh water. In the case of alternate irrigation with sodic and fresh water, crop yields were only marginally less than when fresh water alone was used.

A study by *Ambast et al.* (2002) on the rice-wheat crop rotation emphasized that canal water delivery is not a limiting factor during the *rabi* season (wheat) due to the low water requirement and high salt tolerance of the crop and the availability of groundwater. However, during *kharif* (rice) canal water is critical. From a series of scenarios they concluded that reducing the existing differences in canal water supply between head and tail farmers could increase average crop yields by 240 to 580 kg ha^{-1}.

Others

The option to use water pricing as a means to improve water productivity was explored by *Hellegers* (2003). The hypothesis tested was whether a mechanism of water pricing would be a feasible management tool to minimize seepage and percolation in saline, waterlogged areas and to minimize groundwater pumping in the declining groundwater areas. She concluded that since returns on water are on average about 100 times the price of delivery, a socio-political unacceptable increase in water price is required to achieve this. A solution proposed is to have reliable canal water supply in saline areas and, as a price, less reliable supply in fresh water areas.

Table 1.2 Water productivity values (kg m^{-3}) from Harayana (*ET* is evapotranspiration, *CW* is canal water supply)

Source	Scale	Crop and drop	Wheat	Rice	Cotton
Sharma et al. 1990	Field	Yield/*ET*	0.65	-	-
Bastiaanssen et al., 1996	Field	Yield/*ET*	1.27-1.43	-	0.46
Khepar et al. 1997	Field	Yield/*ET*	-	0.4 – 0.5	-
Bastiaanssen et al., 1999	Distributary	Yield/*ET*	0.83-1.18	-	-
Sakthivadivel et al., 1999	Distributary	Yield/*CW*	2.79	-	-
Bouman and Tuong, 2000	Field	Yield/ supply	-	0.2 – 0.4	-
Hussain et al., 2003	Field	Yield/*CW*	1.47	-	-
Hussain et al., 2003	Field	Yield/*ET*	1.36	-	-
Tyagi, 2003	Field	Yield / supply	1.2-1.8	0.36-0.67	-

1.4 The toolbox

An optimal water management planning relies on accurate knowledge of plant water consumption, water flows and salt transport throughout the growing season. This cannot be reconstructed from field measurements, so dynamic simulation models are deemed necessary to describe soil physical processes, the hydrology of the system and crop growth in order to extract *WP* values. As emphasized before, a thoroughly understanding of all the water flows enables the calculation of a set of *WP* values, each with its own comprehensions and usefulness.

In the past decades researchers devoted much effort to develop and calibrate field scale simulation models for water flow, salt transport and crop growth. In order to analyze crop water productivity, the different modules for simulation of vertical water flow, nutrient transport, salt transport, and crop growth were integrated in SWAP/WOFOST with close interaction between the processes. Clear and reliable calibration procedure were developed to extend the application of these integrated simulation models. Gradually these simulation models grew beyond the laboratory and plot scale and are now such mature that they can be very useful to analyze water productivity at farmer fields and, in combination with geographical information systems, at regional scale.

Over the last decade advances in remote sensing (RS) from satellites have resulted to practical applications of RS in water resources research and applications (*Schultz and Engman*, 2002). In the early days of RS, images were mainly used qualitative, but increase in accuracy of sensors, and especially a better understanding of processes, have evolved in the development of quantitative algorithms to convert raw data into useful information. Information on *ET*, yield and soil moisture helps water managers to adjust water allocation to ensure proper distribution between different users. These data are very useful to tune the simulation models on crop growth and soil transport processes. *Droogers and Bastiaanssen* (2002) have used a parameter optimization procedure to assess the planting dates and irrigation schedule of irrigated cotton in Turkey. *Ines and Droogers* (2002) have determined the irrigation water quality and irrigation schedule in Haryana. *Jhorar* (2002) found from inverse modeling techniques the hydraulic properties of irrigated soils as well as the groundwater extractions from the Ghaggar river belt.

After combining measured satellite data with crop growth and soil transport simulation models, a thorough analysis can be performed of current and future water productivities. The physically based integrated models are, once calibrated, perfectly suitable to study the effects of different water management options on *WP* and recommend the best scenarios for a productive and sustainable agricultural system that improves rural livelihoods.

1.5 WATPRO objectives

As one of the outcomes of the second World Water Forum in The Hague (2000), the Dutch ministry of Agriculture, Nature Management and Fisheries started the *Partners in Water for Food* action program. In the frame of this action program, various departments of Wageningen University and Research center, the International Water Management Institute and WaterWatch made plans to combine the operational knowledge in remote sensing and simulation of crop growth and soil transport processes to develop a general tool to assess regional water productivity in irrigated agriculture. The WATPRO project focussed on the following activities:

- integrate and apply advanced tools (remote sensing, improved simulation of crop growth, soil water flow and solute transport, geographical information systems);
- scale up from the local field scale to the regional scale;
- applying recent ideas from the international community on water productivity in river basins;
- survey future scenario's that improve water productivity in Sirsa district.

These 4 activities highlight the progress as compared to other studies conducted in the past and WATPRO. The innovative aspect is the diagnosis of the *current situation* by means of remote sensing technologies supported by field measurements, and of the *future situation* using simulation models that describe dynamic irrigation, drainage, salinity and crop growth processes simultaneously, in combination with geographic information systems.

The WATPRO project aimed at collecting the required water, crop and soil data at a large number of farmer and experimental fields and making them available in an accessible database These data were subsequently used to tune the simulation models for crop and soil water to current farmer practices.

Different organizations collaborated towards the successful implementation of the WATPRO project. The Water Resources Group of Wageningen University and Research centre (WUR) coordinated the project, and applied the generic water and salt transport model SWAP. Chaudhary Charan Singh Haryana Agricultural University (CCS HAU) implemented the project in Haryana, collected the data at experimental sites and farmer fields and developed the database. The Plant Production Systems Group of WUR analysed the crop experiments and applied the generic crop growth model WOFOST. Alterra Green World Research of WUR designed the regional data base and performed the regional water productivity analysis. WaterWatch analysed Landsat and NOAA satellite images for evapotranspiration and biomass production with the SEBAL model. The International Water Management Institute (IWMI) lead the discussion and analysis of water productivity. The WATPRO project has been financed by the Dutch ministry of Agriculture, Nature Management and Fisheries and lasted from January 2001 until November 2003.

In this report first a description is given of water management and crop production in Sirsa Irrigation Circle. The measurement program and database are described in detail in Chapter 3. The database is spread with the CD-ROM attached to this report. The water flow and salt transport at farmer fields is analysed with SWAP in Chapter 4. In Chapter 5 the model WOFOST is calibrated with the crop growth data at the experimental sites and applied to farmer fields in Sirsa Irrigation Circle. In Chapter 6 the remote sensing analysis of Landsat and NOAA images for evapotranspiration, biomass and water productivity is described. Chapter 7 contains the setup and results of the regional analysis with the SWAP-WOFOST combination. Chapter 8 shows the merit of combining disciplinary knowledge of crop growth, soil physics, hydrology, civil engineering, remote sensing, and computer science. This all comes together in Chapter 9 where the current water productivity in Sirsa Irrigation Circle at regional scale is discussed and viable options are given to use water in a more productive and sustainable way.