Food and Agriculture Organization of the United Nations

DOES IMPROVED IRRIGATION TECHNOLOGY SAVE WATER?

A REVIEW OF THE EVIDENCE

Discussion paper on irrigation and sustainable water resources management in the Near East and North Africa

Regional Initiative on Water Scarcity for the Near East and North Africa

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

CAIRO, 2017

ISBN 978-92-5-109774-8

Cover photos:
courtesy of ICARDA (left photo) and of prof. Don Slack, University of Arizona, Tucson, AZ, USA (right photo)

CONTENTS

TABLES

FIGURES

FOREWORD

The Near East and North Africa (NENA) Region has the lowest per-capita fresh water resource availability among all Regions of the world. Already naturally exposed to chronic shortage of water, NENA will face severe intensification of water scarcity in the coming decades due to several drivers related to demography, food security policies, overall socio-economic development and climate change. Irrigated agriculture in the Region, which already consumes more than 85 percent of renewable fresh water resources, will face strong challenges in meeting augmented national food demand and supporting economic development in rural areas.

Countries of the NENA Region promote efficient and productive irrigation as well as the protection and sustainable management of scarce and fragile natural resources, particularly water, in their national plans. Through the Regional Initiative on Water Scarcity, FAO is providing support and focus to efforts in confronting the fast-widening gap between availability and demand for fresh water resources. A key question to address is: how can countries simultaneously reduce this gap, promote sustainable water resources management and contribute effectively to food security and enhanced nutrition?

The traditional assumption has been that increasing irrigation efficiency through the adoption of modern technologies, like drip irrigation, leads to substantial water savings, releasing the saved water to the environment or to other uses. The evidence from research and field measurements shows that this is not the case. The benefit at the local "on-farm" scale may appear dramatic, but when properly accounted at basin scale, total water consumption by irrigation tends to increase instead of decreasing. The potential to increase water productivity—more "crop per drop"—is also quite modest for the most important crops.

These findings suggest that reductions in water consumption by irrigated agriculture will not come from the technology itself. Rather, measures like limiting water allocation will be needed to ensure a sustainable level of water use.

The present report provides the evidence needed to open up a discussion with all major stakeholders dealing with water resources management on the proper and scientifically sound framework required to address jointly water scarcity, sustainability and food security problems.

A discussion that has been disregarded for too long.

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ACKNOWLEDGEMENTS

The present report has been prepared following contacts with over two hundred individuals (including researchers, academics, experts and specialists) working in the field of water resources management and irrigation and with staff members of the World Bank, FAO, UNESCO-IHI, the Asian Development Bank, the International Water Management Institute (IWMI) and other Consultative Group for International Agricultural Research (CGIAR) institutions. The authors are grateful to all who provided their valuable contributions in terms of data, information and intellectual insights. A special thanks goes to Dr Abdullah Droubi (former director of Water Studies department at Arab Centre for the Studies of Arid zones and Dry lands (ACSAD) and to the FAO colleagues of the Water Technical Network for their valuable feedbacks during the reviewing phase of the manuscript, as well as to Elodie Perrat for her diligent and accurate management of the manuscript revision and editing.

Policy-makers, water resources managers, irrigation developers and financial institutions will benefit from the insights of this report and are invited to provide their views and feedback to our dedicated e-mail: WSI@fao.org. At the same time, FAO will be organizing workshops to discuss in an open and constructive manner the pathway for water resources sustainability.

ABBREVIATIONS AND ACRONYMS

ACSAD	Arab Centre for the Studies of Arid zones and Dry lands
AQUASTAT	FAO Agricultural Water Information System
APSIM	Agricultural Production Systems Simulator
CGIAR	Consultative Group for International Agricultural Research
DI	Deficit Irrigation
E_S	Soil Evaporation
ET	Evapotranspiration
ETc	Crop Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GEF	Global Environment Facility
ICID	International Commission on Irrigation and Drainage
IFI	International Financial Institutions
IWMI	International Water Management Institute
IWUE	Irrigation Water Use Efficiency
MDB	Murray Darling Basin
METRIC	Mapping EvapoTranspiration at high Resolution with Internal Calibration
NENA	Near East and North Africa
NRCS	Natural Resources Conservation Service
O&M	Operation & Maintenance
ORMVA	Office Régional de Mise en Valeur Agricole
PNEE	Programme National d'Economie d'Eau
RBMP	River Basin Management Plans
RCT	Resource Conservation Technologies
RW	Rice-Wheat
SATREPS	Science and Technology Research Partnership for Sustainable Development
SEBAL	Surface Energy Balance Algorithm for Land
SEEAW	System of Environmental-Economic Accounting for Water
SI	Supplemental Irrigation
T	Transpiration
TE	Transpiration efficiency
UNESCO	United Nations Educational, Scientific and Cultural Organization
WP	Water Productivity
WUE	Water Use Efficiency

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EXECUTIVE SUMMARY

Unsustainable water use (over-drafted aquifers, seasonally dry rivers, disappearing lakes and wetlands) is a problem across the world. This is especially true in the NENA region, which includes many of the most water-short countries in the world. These countries have always depended on human interventions to regulate water for food security, domestic and other uses. Historically, these developments were mostly small scale, locally managed and hydrologically independent. These systems were also hydrologically self-regulating, with annual rainfall, runoff and recharge setting the limits to annual use. However, in recent decades the proliferation of large scale storage-based systems and the development of deep tubewell technology have resulted in dramatic increases in water withdrawals and created interdependence and competition across new, mostly unregulated, boundaries—often based on exploitation of non-renewable resources. The governance of these new relationships goes much beyond the scope of traditional institutions.

The solution to these problems is apparently simple: less water must be consumed, treated waste water should be reused, and whatever water is available should be used as productively as possible. The politics of this simple solution are far from simple. Who should reduce water use? Which country, region, sector, or farmer? What are the economic, social and food-security implications of reducing water use?

As long as additional water was accessible, the tendency has been to develop additional use of these resources. More recently, as the environmental impact and unsustainability of current water use have become evident, solutions that appeared to avoid the difficulties of direct interventions to reduce water allocations have figured prominently in the agendas of planners, policy-makers and financial institutions. These solutions involve some form of modernisation or re-engineering of irrigation management. While institutional reform was often part of these programs, improved irrigation technology was invariably central to the package. Such technologies include mostly piped delivery systems, laser levelling of fields, conversion to pressurised systems for sprinkler, drip, or sub-surface drip. In each case, the objective is to replace traditional, "inefficient" irrigation with techniques that maximise beneficial water use by the crop, and improve the timing and reliability of water deliveries. These types of intervention are collectively referred to in this report as "hi-tech" irrigation.

These innovations are expected to generate two major benefits:

- water is "saved" and released to other uses
- more production is achieved per unit of water

Understanding how different interventions impact on resource use requires a clear set of accounting terminology because in the analysis of water systems, stakeholder perspectives (farmers in rainfed agriculture, farmers in irrigated agriculture, industrialists, system operators, basin managers, environmentalists, etc.) affect how different flows are labelled and valued.

The following, neutral set of labels, is applicable at any scale, to any type of water use:

All the water *Used* for any purpose goes to one or more of the following categories:

1. Consumptive use (conversion of water into water vapour), comprising
   - 1.1 *Beneficial Consumption* (crop transpiration; evaporation from wetlands; cooling towers)
   - 1.2 *Non-beneficial Consumption* (evaporation from free water surfaces and from wet soil; transpiration by weeds)
2. Non-consumptive use (water that remains in liquid status), comprising
   - 2.1 *Recoverable* flows (returning to a river or aquifer for potential reuse)
   - 2.2 *Non-recoverable flows* (flowing to the sea or other economically unviable sink)
3. Change in storage

These accounting terms allow a clearer definition of the issues and options we face in irrigated agriculture. Headlines claiming (say) 50 percent water savings through better technology invariably refer to a narrow "local" perspective of water *applied* to the field, failing to account for return flows that recharge aquifers or contribute to downstream river flows. If the underlying aquifer is saline, or outflow goes straight to the sea, then savings are real, but only a complete set of water accounts will reveal whether real water savings are achieved, so that water can be released to other users with no negative effects.

The impact of hi-tech irrigation on consumption, therefore, needs to be quantified: what changes occur in water consumption when areas are converted from traditional techniques to hi-tech drip and sprinkler?

This leads into the issue of water productivity. If hi-tech irrigation allows the same or higher quantity of (say) grain to be produced while water deliveries are reduced, then there is an apparent increase in bio-physical water productivity (*bio-physical* water productivity [WP]) when expressed in $kg{\cdot}m^{-3}$ *delivered*. If the water delivered remains constant and the area irrigated increases, then again there is an apparent increase in *bio-physical* WP. But if our concern is *water saving*, we need to measure production per unit of water *consumed* expressed in $kg{\cdot}m^{-3}$ *consumed*. This figure, especially for field crops (grains, fibre, forage, sugarcane) is widely reported in the literature to be "conservative" – in other words for a given crop and given agro-climatic conditions, the relationship between water consumed and crop production is linear. The important implication of this relationship is that if yield per unit area increases, then it is likely that water consumption also increases.

On the other hand, if hi-tech irrigation allows the farmer to grow higher value crops, we are interested in another indicator: economic water productivity (*economic* WP expressed in USD per m^3 *consumed*). Here the evidence is stronger that hi-tech (which often ensures more controlled and better timed irrigation supplies) is one of the various factors that encourages farmers to invest in higher return crops.

These questions about the impact of hi-tech irrigation are critically important in the NENA region because the introduction of hi-tech irrigation is central to the programmes that most countries (and most financial institutions) propose to address water scarcity.

Two diverging entities, pertinent to two different scales and interests, can be identified: the farmer (farm-scale; driven by its benefit/profit); the water resources manager (watershed, basin or national scale; that should be driven by sustainability).

In fact, hi-tech irrigation (broadly defined as any technical intervention designed to improve water delivery on farm) has many benefits: water application is reduced, pumping costs are reduced[1]; fertilisers and other chemicals are saved and pollution is reduced; labour costs are often lower; and cropping options are wider. Are these benefits, derived from improved irrigation technology, providing also 'water saving' at watershed or national scale? The answer to this question is relevant where water is scarce, and especially where aquifers are over drafted and rivers are drying.

In the process of writing this paper, more than 150 experts were addressed with requests for evidence of the impact of hi-tech irrigation on water consumption and water productivity. Those experts ranged from individual researchers to institutions such as IWMI, the World Bank, the Asian Development Bank, FAO, etc. The request was posted on the Global Water and Food Network website, which also has about 150 members (some overlapping with the first group) and on the Irrigation List.

This review indicates, somewhat surprisingly, that there are rather few examples of carefully documented impacts of hi-tech irrigation, while there are many examples of projects and programmes that *assume* that water will be saved and productivity increased. Such studies as do exist, are either inconclusive or, more often, show that water consumption actually *increased* (as science would predict) when irrigation systems were upgraded, and that productivity per unit of water consumed was more or less constant. The exception to these conclusions—included as an example of what can be achieved in tree crops, which are the most promising candidates for real water savings and increased water productivity—showed average reductions in water consumption of some 6 percent when comparing flood irrigated fields with drip, together with an increase in production.

The conclusion of this report is that restoring a balance between sustainable supply and consumption of water requires *first* physical control of the water resource by government or other agencies responsible for sustainable use, *followed* by interventions to reduce allocations. Within the allocated and controlled quotas, hi-tech irrigation will evolve and spread to the extent that it makes sense for the farmer who wishes to take advantage of the various benefits of hi-tech irrigation.

However, introducing hi-tech irrigation in the absence of controls on water allocations will usually make the situation worse: consumption per unit area increases, the area irrigated increases, and farmers will tend to pump more water from ever-deeper sources. This implies that controlled access to water must *precede* introduction of hi-tech irrigation.

These conclusions have important implications for key actors in the water sector: *Governments* have to take up their important and difficult responsibility in stewarding a critical national

[1] Though not always: in converting flood irrigation into drip or sprinkler, water must be pressurised and energy costs of irrigation increases.

resource, and *donors* should promote the sequence of actions defined above—avoiding funding for hi-tech modernisation projects in the absence of prior control over water allocations.

With this report, we advocate to open up a discussion with all major stakeholders dealing with water resources management on the proper and scientifically sound framework required to address water scarcity and sustainability problems. A discussion that has been disregarded for too long.

Policy-makers, water resources managers, irrigation developers and financial institutions are invited to provide their views and feedbacks to our dedicated e-mail: WSI@fao.org.

At the same time, FAO will be organizing workshops (in person or web-based) to discuss in an open and constructive manner the pathway for water resources sustainability.

CHAPTER 1

Introduction

Competition for water and unsustainable rates of use are evident across the world from California to the Near East and North Africa Region (NENA) to the North China Plain (Kendy *et al.*, 2003; Zamora, Kirchner and Lustgarten, 2015). Even temperate areas of Europe that are relatively well endowed with rainfall are now experiencing localized scarcity (OECD, 2015) that will require interventions to protect the environment and the long term sustainability of water use.

Focusing on the Middle East and NENA Regions, Table 1 summarizes the 2014 data from AQUASTAT[2] on the availability of water by country. Many of the most water-scarce countries in the world are in the NENA Region and only Iran, Iraq and Turkey (which already report serious local scarcity) are not in the top 50 of the 200 countries having yearly renewable water resources less than 1 000 m^3 per capita, the threshold for countries to be classified 'water scarce' (Falkenmark, Lundqvist and Widstrand, 1989).

Per capita fresh water availability, currently about 10 percent of the world average and which has already decreased by two-thirds over the last forty years, is expected to decrease of another 50 percent by 2050. Furthermore, there is an alarming trend observed over the last decades showing that the NENA Region is experiencing more frequent, intense and prolonged droughts as a consequence of Climate Change (IPCC, 2014).

Overall, the water systems of the NENA Region are considered 'fragile' and 'unsustainable' with the current management approach.

Irrigated agriculture is the major water user, withdrawing about 85 percent of all renewable water resources, impinging heavily on rivers and groundwater.

The trends for the future indicate that the NENA Region will be exposed to a severe intensification of water scarcity due to several drivers, including demographic growth, tendency to increase food self-sufficiency to reduce vulnerability to import and price volatility, changes in diets with higher, more water intensive, animal protein content, urbanization expansion, energy demand and overall socio-economic development (FAO, 2015).

Several measures are put in place to cope with water scarcity. From the supply side, focus is on reuse and recycling of treated wastewater, desalination of brackish and seawater and rainfall or storm water harvesting, conjunctive management of surface and groundwater, and storage. Special attention is given to water quality preservation and conservation. From the demand side, the focus is on increasing efficiency and productivity of water use, along with reduction of waste and loss of agricultural products in the supply chain.

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2 http://www.fao.org/nr/water/aquastat/data/query/index.html

There is increasing focus on trade, noting the contribution of virtual water and the importance of "sustainable" diets. However, the dominant component of investment programmes continues to be physically modernising irrigation systems mostly through interventions such as piped delivery systems, laser levelling of fields, and pressurized systems delivering water through sprinklers, or drip emitters (including sub-surface). The underlying assumptions supporting this approach are that:

- a lot of water can be "saved" because traditional irrigation methods have an irrigation efficiency of 50 percent or less
- yields per hectare will increase, so that the productivity of water will increase.

In short, modern irrigation (here indicated as hi-tech) is seen as a basic solution to water scarcity.

In this report, we argue that, due to the absence of control of quotas, these measures have actually contributed to worsen the water scarcity situation in the NENA Region. The insights obtained by sound water accounting (Batchelor *et al.*, 2016), a literature review, and project-result analysis will provide the evidence base for this argument.

Finally, the implications for sustainable water resources management are set out.

Table 1. **Renewable Water Resources in the Near East and North Africa (AQUASTAT)**

	Precipitation (mm/year)	Internal (million m³/yr)	External (million m³/yr)	Total (million m³/yr)	Per capita (m³/yr) in 2014	World Ranking (from lowest to highest)
Algeria	89	11 250	420	11 670	294	15
Bahrain	83	4	112	116	84	7
Egypt	51	1 800	56 500	58 300	637	22
Iran (Islamic Republic of)	228	128 500	8 500	137 000	1 732	54
Iraq	216	35 200	54 660	89 860	2 467	69
Israel	435	750	1 030	1 780	221	13
Jordan	111	682	255	937	123	11
Kuwait	121	0	20	20	5	1
Lebanon	661	4 800	- 300	4 500	770	26
Libya	56	700	0	700	112	9
Mauritania	92	400	11 000	11 400	2 802	76
Morocco	346	29 000	0	29 000	844	27
Occupied Palestinian Territory	402	812	25	837	179	12
Oman	125	1 400	0	1 400	312	16
Qatar	74	56	2	58	26	3
Saudi Arabia	59	2 400	0	2 400	76	4
Sudan	250	4 000	33 800	37 800	940	30
Syrian Arab Republic	252	7 132	9 670	16 800	908	28
Tunisia	207	4 195	420	4 615	410	18
Turkey	593	227 000	- 15 400	211 600	2 690	74
United Arab Emirates	78	150	0	150	16	2
Yemen	167	2 100	0	2 100	78	5

CHAPTER 2

From sustainable to unsustainable water use

The concept of “sustainability” has come to be associated with a variety of perspectives and dimensions – social, economic, environmental, ecological, etc. The focus of this report is water, and although water contributes significantly to several important aspects of sustainability, the analysis centres quite narrowly on physical indicators of sustainability, which is a fundamental point of departure for all additional considerations of sustainable development. From this perspective, the indicators of unsustainable use are progressively declining groundwater tables and seasonally or permanently dry rivers not reaching estuaries. These indicators are generally accompanied by deteriorating water quality, saline intrusion into coastal aquifers, and poor water quality in rivers.

In the arid environment that predominates in the NENA region, food security has always depended on the control of scarce water. Approaches varied, depending on the topography, geology and hydrology, but were largely locally designed and locally constructed. Operation and maintenance were similarly organised around local ‘institutions’ (formal and informal), so that the priorities for allocating water reflected the social and economic priorities of a relatively small and socially coherent group. Developments were mostly scattered and generally operating in hydrological independence of one another.

Here we report three examples of sustainable water management for irrigation developed in the Region before the introduction of large scale, modern irrigation systems, i.e. about up to the middle of the twentieth century.

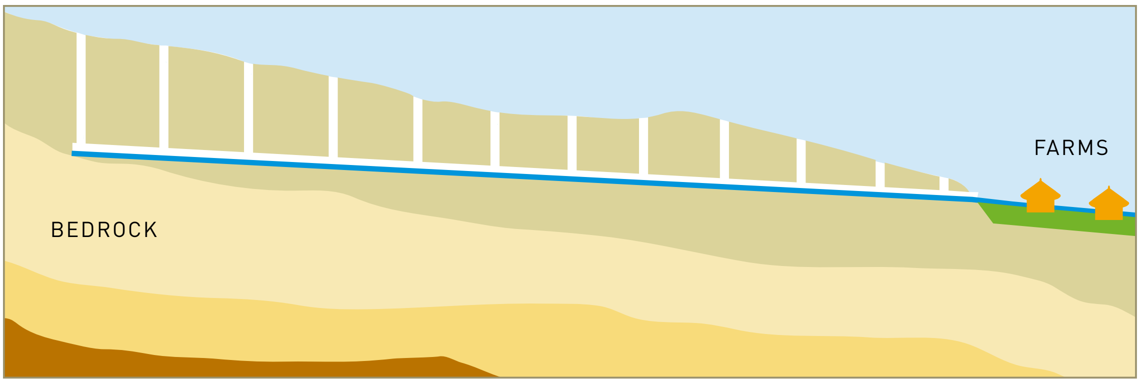
Example 1 - *Spate irrigation systems* have been significant in a number of Arab countries accounting for about 20 percent of the irrigated areas in Algeria and Yemen. These systems consist of earth dams—often temporary—that divert water from fast-flowing ephemeral streams after significant rainfall events. The farmers collectively owned the infrastructure and the land that can be irrigated is clearly demarcated—as is the land from which runoff is derived. Yemen has areas of land that provide runoff where (for example) grazing of animals is open to anyone, but planting crops or otherwise intervening to affect the natural rainfall/runoff relationship is prohibited.

Since spate irrigation occurs suddenly and unpredictably, the procedures for sharing water have to be correspondingly easy to apply and communicate. Typically, the area sanctioned for irrigation is defined; the allowed depth of application is a simple measure (e.g. up to the knee), and one method of indicating the end of a farmers turn is to fire a rifle into the air, which alerts the next farmer that he can open his outlet and start irrigating. While all this seems crude, it ideally suits the need in a spate system to share a very uncertain quantity on the basis of simple rules and quick communication. The outcome (see Figure 1) is an apparently rather uniform distribution of water among users.

Figure 1. **Spate system in Yemen**

Example 2 - *Qanats* (also variously known as *kareez, foggara, aflaj*, etc.) are found in many Arab countries, as well as in Afghanistan and in China to the east. North African communities took the technique to Spain, where some are still functioning and subsequently the Spanish took the technique to South America. They are still found in Mexico, Peru and Chile. A *qanat* (see Figure 2) consists of tunnel that starts at ground level at the foot of hills and is constructed towards the hill, sloping upwards at a lesser angle than the ground so that the tunnel becomes progressively deeper, eventually intersecting the water table in the hillside. *Qanats* are essentially man-made springs –providing a route for infiltration from higher areas to flow out at a single point. The vertical shafts allow access during construction – some *qanats* are several kilometres long.

Figure 2. **Cross section of a qanat**



Source: redrawn from www.livius.org, with permission

The owners of a *qanat* share the water. Examples in Oman have sophisticated procedures for prioritizing allocation—first to households, then to gardens and trees, then to field crops. Sundial-type instruments were used to time the allocations among users.

As well as the channel or diversion structures that deliver water, the infrastructure may also comprise facilities to assist in allocation, including stone water-dividing structures—where each channels is of a different width, reflecting different shares of the stream.

Example 3 - *Sakias* - In Egypt prior to construction of the Aswan Dam, inundation canals diverted the annual Nile floods. The government was nominally responsible for diversion of water into the canals – although in reality the rise and fall of the Nile River automated this process. Uniquely, the tertiary distribution canals to the farmers are below grade so that farmers had to pump water using animal-powered (*sakias*), which provided a natural incentive to minimize the water applied to the fields. The *sakias* were generally communally owned, and the farmers would agree on the procedures for sharing water from this common source.

Aside from these regionally important techniques for exploiting water, open dug wells capable of exploiting shallow aquifers were also widespread.

Two features are common to each of the irrigation technologies described above:

- Water exploitation was naturally limited to the annual renewable resource. Thus "sustainability" was ensured in each of these systems because what was available for exploitation was determined by precipitation, hydrology and hydrogeology.
- There is minimal interaction among systems, except at the most local level, so that "governance" at aquifer, basin, regional or national levels was not needed to ensure sustainability.

This situation changed dramatically in the latter half of the 20th century, driven by a familiar combination of factors: population increased so that the basic demand for food and fibre increased; rising living standards and changing diets further increased demand per capita; and industrialisation and urbanisation added new demands for water. Finally, and perhaps most decisive for the growing imbalance between demand and the renewable supply, was the technological change.

In surface systems, the development of large-scale reservoir and diversion systems converted flood events to storage. Controlled releases to irrigation often increased total consumptive use and eventually generated competition among geographically separated users within a river basin. In groundwater systems, the arrival of cheap, portable engines and submersible pumps vastly increased the potential to exploit water—pumping from rivers, streams, and most significantly from aquifers at rates that resulted in continuous falls in water tables.

Elsewhere in the region, and indeed across the world, submersible pumps allowed deepening of wells, exploiting deeper aquifers at rates that interfered with other users (Foster and Garduno, 2006) and the issue becomes a classic "tragedy of the commons" (Hardin, 1968). Similarly in surface systems, increased consumption in all "upstream" areas also reduced river flows, so that many rivers in the region now only reach the sea during exceptional rainfall events.

CHAPTER 3

A basic framework for analysing the impact of responses to water scarcity and high water demand

The combination of continuously increasing demand for water, the ability to access water in excess of the renewable supply, and new means of access that crossed the traditional "local" boundaries for mediating among competing demands, present completely new challenges to water resources management:

- *Governance* now requires institutions that set priorities, set rules and engage in system operations that reflect interdependencies at basin and aquifer scale.
- *Technically* it means ensuring that users are encouraged to operate within bounds that respect the rights of others, while minimizing physical losses and wastage.
- *Economically* it means maximising the socio-economic benefits derived from reduced water availability, including the re-allocation of water to the highest priority uses.

Understanding how technical and economic interventions impact on the demand for, and consumption of, water requires a consistent water accounting framework, which is set out below as the basis for the subsequent discussion of technical and economic issues.

3.1. PHYSICAL WATER ACCOUNTING

The most common use of the term "accounting" refers to financial record keeping. The principles on which financial accounting is based are common to any type of accounts: financial accounting is the application of a set of definitions and rules to incomes, expenditures, and other transactions so as to describe, for a given period of time, the financial flows, including increases and decreases in savings, profits and losses for a financial entity.

We are accustomed to many of the terms used in financial accounting – expenditure, income, savings, balances, etc. and can readily understand many associated concepts such as profit and loss. We are also accustomed to understanding that the procedures are independent of scale – each term has the same meaning whether applied to a child's pocket money, a corner shop, or a nation. Furthermore, the temporal frame of reference is relevant: sales in one season may be usually much higher or lower than sale in another season, so that accounts must be qualified in referring to relevant time periods. Most importantly, within the selected time frame and scale, all the flows of funds must be accounted for, and any difference between income and expenditure must be reflected by an increase or decrease in savings.

Historically, the science of hydrology and the practice of water engineering have developed at different scales and with different objectives. In consequence, there is no common set of definitions on which a compatible accounting system can be based. When irrigation becomes a significant component of basin hydrology, the divergence of terminology poses at least a difficulty, and sometimes a threat, to the understanding of irrigation and other categories of water use within the overall hydrological context.

At the global scale and in the long term, evaporation from water bodies plus evaporation and transpiration from the landscape must equal precipitation. However, when the frame of reference is less than the global, long-term scale, careful attention must be paid to the flows across the borders of the area being analysed, and to changes in storage within that area.

When analysing how best to respond to unsustainable water use, it is essential to adopt appropriate, unambiguous terminology. The first important clarification is to distinguish between "using" water (for example to generate hydro-power or to wash clothes) and "consuming" water (for example in an irrigation system by evapotranspiration (ET) through crops). In the former case, the vast majority of the water used returns directly to the same hydrological system from which it was abstracted, perhaps at a different location, perhaps polluted in some way, but *physically* the water remains available for re-use. When water is consumed through evaporation and transpiration, however, it is no longer available.

The second clarification relates to the engineering perspective, which is entirely valid and appropriate for planning, designing and operating irrigation facilities. This perspective tends to treat water that flows beyond the boundary of the scheme as losses. An environmental analyst, on the other hand, might be very interested in these "losses" as a source of recharge to aquifers or flows into wetlands, i.e. the engineer's "loss" is the environmentalist's "source".

The following framework (Perry, 2007; Batchelor *et al.*, 2016) differentiates the various flows that are associated with any type of water use, and can be applied to any sector, at any scale, without modification:

Water use: any application of water to a defined purpose (irrigation, diversion through a power station, domestic washing, industrial processes, etc.).

All *Water Use* goes to one or more of the following categories:

1. Consumptive use (conversion of water into water vapour), comprising:
   a) *Beneficial Consumption* (crop transpiration; evaporation from cooling towers)
   b) *Non-beneficial Consumption* (evaporation from free water surfaces and from wet soil; transpiration by weeds)
2. Non-consumptive use, comprising:
   a) *Recoverable flows* (returning to a river or aquifer for potential reuse)
   b) *Non-recoverable flows* (flowing to the sea or other economically unviable sink)
3. Change in storage

The law of conservation of mass requires that:

$$\text{Water Use} = 1a + 1b + 2a + 2b + 3$$

When the impact of an intervention is evaluated, each flow component must be defined pre- and post-intervention to ensure a complete description of the impact. Partial descriptions, as will be exemplified later, can be very misleading.

The majority of interventions designed to address scarcity have focused on technical options that improve the "efficiency" of physical water distribution (reducing "losses") and/or improve the productivity of water delivered to users (e.g. increasing "crop per drop").

Irrigation efficiency is traditionally defined as the ratio between water available at separate points in an irrigation system – for example, water delivered to farmers divided by water delivered to a scheme, or water retained in the root zone divided by water delivered to the farm. Irrigation efficiency is a dimensionless ratio (for example, m^3:m^3) or percentage. For traditional flood irrigation systems, delivering water through earthen channels, the ratio of water consumed by the crop and water delivered to the project is often as low as 40 percent. The common inference from this figure is that 60 percent of the water is "lost", and that lining and improved on-farm water management (drip, sprinkler, laser levelling, etc.) can "save" large quantities of water.

However, translating this scenario into the accounting framework set out above, it is readily apparent that until we know where the "losses" are going, we cannot be clear as to the extent of water "savings". For example, percolation from "inefficient" irrigation (item 2a, above) is often a major source of aquifer recharge. If a farmer is able to *increase* the irrigated area (and hence also increase beneficial consumption, item 1a above) while *reducing* percolation to a usable aquifer or return flows to downstream users, the overall impact is increased local water consumption and less water available for other users or at other times in the year.

None of this is to recommend inefficient irrigation, but rather promote clarity in the reporting and evaluation of the physical impact of improved irrigation technology. Thus, when proponents of drip irrigation argue that the technique can "double the irrigated area", we should interpret this as "doubling the proportion of water delivered to the farm that is consumed", and hence dramatically decreasing return flows to the environment or to other users.

3.2. WATER PRODUCTIVITY ACCOUNTING

Water productivity (WP) can be defined in two ways – bio-physical water productivity (kg of produce per unit of water consumed; $kg \cdot m^{-3}$) and economic water productivity (value of produce per unit of water consumed; USD per m^3).

Bio-physical water productivity is conventionally also referred to as *Water Use Efficiency* (WUE), and is crop- and location-specific. For common field crops (food grains, forage crops, fibres, sugar) the relationship between biomass (yield) and water consumption (transpiration - T) is essentially linear (Howell, 1990; Fereres and Soriano, 2007; Steduto *et al.*, 2012) over a wide range of intermediate yield levels. If water availability is low and erratic, controlled increments of irrigation can produce large increments in yield; at very high levels of management, controlled stress during non-sensitive growth stage can somewhat improve bio-physical WP – but where yields are moderate, an increase in yield typically is associated with an increase in crop water consumption.

The slope of the relationship between biomass production and transpiration is also affected by the local climate: the hotter and drier the climate, the more transpiration required per unit of biomass production—but again, this is essentially a locally "fixed" relationship.

An agronomic practice that has shown some influence on the biophysical WP is *Deficit Irrigation*. The practice of *deficit irrigation*[3] (DI) consists in applying less water than the crop water requirements on crop evapotranspiration (ETc). As a result, two situations may develop. In one case, stored soil water and/or rainfall supply the deficit and the crop does not experience ET deficits, thus there are no savings in water consumption. This scenario is often desirable to make best use of stored soil water, but requires precise management and water accounting to ensure that ET deficits do not develop. The second situation occurs when the irrigation supply is deliberately kept low enough to create deficits and actual crop ET is less than ETc. In this second case, given the close association between production and transpiration, crop yields would generally be less than those obtained under full irrigation.

Some crops (trees and vines are the most common examples) react positively to ET deficits offering opportunities for using Deficit Irrigation (DI) to increase biophysical WP. For the major cereals, however, the opportunities are extremely limited. For maize, many experiments have shown that full irrigation is the best economic option, and if water is limited it should be concentrated in less area. For wheat, the evidence from supplemental irrigation research in the Middle East and other areas shows that, while you can achieve higher irrigation water productivity, there is almost always some yield penalty. An optimal level of deficit may be found if water is very expensive/scarce but it would be at around 80 to 90 percent of ETc. Among other field crops, cotton and grain sorghum are good candidates for DI.

For most field and vegetable crops, DI has limited prospects and needs to be assessed through an optimization exercise based on local data. Even then, from the practical standpoint, managing small reductions in ET is very difficult, risky, and also tends to lead to salinization of the soil. In the case of woody perennials (fruit trees and vines), DI is a viable option to save water and to optimize the use of limited water resources (Steduto *et al.*, 2012).

Another agronomic practices that has been shown to influence the biophysical WP is *Supplemental Irrigation* (SI). Even though SI has several meanings in different environments, it is generally considered a form of deficit irrigation in which small water amounts are applied to supplement rainfall. Although the term has been used in the past in humid areas, the SI concept has been primarily developed in the arid areas of the Middle East for improving winter

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[3] The authors greatly appreciate the advice of prof. Elias Fereres (University of Cordoba, Spain) in drafting this section on DI and SI. Partial root drying (the alternate wetting and drying of both sides of the row/tree line) is a form of deficit irrigation which has been shown not to differ from other forms of deficit irrigation, thus it is not considered independently here.

cereal production. It is often promoted in conjunction with rainwater harvesting (Oweis and Hochum, 2006). Many experiments have shown that relatively small amounts of water applied to winter cereals around flowering have dramatic effects on yield and on water productivity ($kg \cdot m^{-3}$). The explanation is that the maintenance of adequate water status during that time has a positive effect on maintaining the crop harvest index under the drought conditions of those water-limited environments. However, despite the positive results at the experimental level, SI has not been widely adopted by farmers so far.

The reasons for the limited adoption of SI have to do with the difficulties in the implementation of the technique. Main limitations are: a) uncertainties in the return of the investments required for the collection and application of the irrigation water; b) variations in the timing of water deficits relative to the limited irrigation supply available; and c) once a supply of water is made available, there is a tendency to concentrate it to maximize production per unit irrigated area (often of high-value crops such as vegetables) rather than spread it over a larger area as SI of cereals. For the reasons above, the application of the SI concept in practice has a niche that has turned out to be smaller than the experimental results have suggested. There are, however, a few cases in fruit tree production such as the olive where it has been practiced with success.

In sum, for a given crop and a given climate, increases in production are associated with increases in water consumption by the crop, and for most field crops, bio-physical WP ($kg \cdot m^{-3}$) is highest when water consumption and yield per hectare are maximum, because some degree of (non-beneficial) evaporation from wet soil or foliage is unavoidable but comprises a smaller proportion of total consumption when T is at its maximum potential level.

Economic water productivity (USD per m^3) is more complicated than bio-physical WP. Ready access to markets and the availability of suitable seeds, agro-chemicals and credit are among the factors that allow a farmer to opt for higher value crops such as fruit, vegetables, orchards, and so on. Such choices involve increased expenditure on inputs. The product is often more perishable with a less stable market. Controlled and reliable access to water are often critical elements of a farmer's decision to seek higher but riskier returns from all his resources (land, labour and capital) that such crops offer. Hi-tech irrigation contributes substantially to reliable, adequate and timely water supply, and hence is seen as a necessary prerequisite for secure investment in other inputs for higher economic water productivity. Allocating a general increase in value added among all the various complementary inputs, and adjusting for risk and variability in price, is not simple – but when average farm income is expressed solely in relation to water consumption the apparent increase in economic water productivity from hi-tech irrigation is often substantial.

To summarise, the following are the components of the analysis that must be made to assess the impact of changes in irrigation technology:

- *Water accounts* must report how consumption of water changes, and how any return flows are affected
- *Bio-physical* increases in production must be related to changes in crop water consumption
- *Economic* increases in production should be reported separately.

CHAPTER 4

The reported impact of technical interventions. A review of the evidence

The evidence summarised below was identified from a wide variety of sources including experts and technical specialists in international donor organisation; international research centres, and other high profile agencies in the water sector; individual researchers with special interest in water and irrigation; editors of relevant journals; and personal contacts of the authors with known interests in irrigation, including manufacturers of hi-tech irrigation equipment. In addition, the authors reviewed relevant published literature.

Some 120 individuals were contacted directly[4] and requested to provide data or reports and publications that quantify the impact on water consumption and water productivity of improved irrigation technology. Some individuals provided useful data; some forwarded the request to others, such that in total about 150-200 people were made aware of this exercise.

The criteria for inclusion among the examples listed below were that the case in question provided data on (a) water consumption, and/or (b) production per unit of water consumed, and (c) that the data related to field crops (rice, wheat, maize, cotton, sugarcane, forage, etc.). Every source of information that met these criteria has been included among the examples that follow. No filtering has been applied to favour examples supporting the general conclusions of this paper, or to exclude examples that refute those conclusions. It cannot be claimed that the evidence presented is exhaustive, but despite the wide-ranging search for examples among interested parties, all the evidence suggests that the introduction of hi-tech irrigation tends to increase local water consumption, and that any increases in yield are usually associated with increased crop water consumption.

While this outcome may be surprising, the common assumption that hi-tech "saves" water and increases water productivity is due to the continuing confusion between local effects (on-farm water savings are not necessarily basin water savings), and the focus on applied rather than consumed water as an indicator of improved productivity. A paper on this topic (Perry, 2011) reviewed two submissions to Agricultural Water Management where claims of significant water savings and water productivity were presented, and the data were sufficiently detailed to allow re-analysis of claims in the original submissions of water saving and increased water

[4] Those contacted included multiple staff members of the World Bank, FAO, the Asian Development Bank, the International Water Management Institute , IRRI, IFPRI, the Water for Food Institute, Water Accounting.org, and many scientists in Universities and Research Centres.

productivity. The revised analysis showed much more modest levels of water saving (due to reductions in evaporation) and almost no change is water productivity.

In this section, relevant field cases from all over the world are reported to test the 'null hypothesis' that the law of conservation of mass, and the known relationships between crop yield and water consumption would predict, namely, that hi-tech irrigation results in: an *increase* in water consumption, due to increased areas irrigated and/or higher yield per hectare, while *bio-physical water productivity* ($kg \cdot m^{-3}$) remains more or less constant and *economic water productivity* (USD per m^3) often increases (Perry *et al.*, 2009).

None of this is to deny that hi-tech irrigation (broadly defined as any technical intervention designed to improve water delivery on farm) has many benefits: water application is reduced, pumping costs are reduced; fertilisers and other chemicals are saved and pollution is reduced; labour costs are often lower; and cropping options are wider. But where water is scarce, and especially where aquifers are over drafted and rivers are drying, reducing water consumption in agriculture should be the primary aim of policies and investments.

The following pages summarise those reports where quantitative information about the impact on consumption and water productivity of hi-tech interventions is available. The cases are reported by country, alphabetically.

4.1 AUSTRALIA

Document(s)

System of Environmental-Economic Accounting for Water (SEEA-Water) (United Nations Statistics Division, 2012); Water Account Australia 2004–05, (Australian Bureau of Statistics, 2006); *Drought and the rebound effect: A Murray–Darling basin example (Loch and Adamson, 2015); Understanding irrigation water use efficiency at different scales for better policy reform: A case study of the Murray-Darling Basin, Australia* (Qureshi *et al.*, 2011); *Water Reform and Planning in the Murray–Darling Basin, Australia (Grafton, 2017)*

Context

Australia has led the world in the introduction of water rights in a context of extreme resource variability. This in turn has provided the basis for managed trading between sectors and locations, and valuable lessons regarding potential problems as previously under-utilized entitlements are sold and used, and of "stranded assets" if significant volumes of water are traded out of an area. More recently, evidence suggests that subsidy programmes to "save" water seem to have been ineffective, poorly conceived and un-prioritized.

Highlights

The Murray Darling Basin (MDB) is widely recognized for its advanced standards in water resources management—in particular the system of tradable water rights that allows transfer of water on short-term or permanent leases subject to evaluation of third party impacts by the regulatory authorities.

Australia participated in the formulation of the United Nations (UN) System of Environmental-Economic Accounting for Water. This framework accounts for water withdrawn from "the environment" (rivers, aquifers), use of that water in various sectors, including transfer between sectors (for example a water utility supplying a factory or town), consumption through ET, and direct and indirect return flows to the environment and to sinks. Trial implementation of the framework was planned in Australia, and the Australian Bureau of Statistics had already in 2006 issued guidelines referencing the System of Environmental-Economic Accounting for Water (UN- System of Environmental-Economic Accounting for Water (SEEAW) system), which was to be applied to the reporting of the 2004-5 national water accounts.

However, the following statement from the introduction to Chapter 4 of the 2004-5 National Water Accounts for Australia[5] is apparently at variance with one critical element of the SEEAW approach—namely the distinction between consumptive and non-consumptive uses:

This chapter examines the use of water within the AGRICULTURE industry in Australia. Water used by this industry includes livestock drinking water and water applied through irrigation to crops and pastures. Since the AGRICULTURE industry does not use water in-stream, or supply water to other users, ***total water use is equal to water consumption.***

Elsewhere in the Accounting Standards it is stated that:

It is believed that leakage to landscape from surface water resources such as rivers and storages occurs in the MDB region; however, reliable volumes are not available, and currently there is no suitable quantification approach to estimate these volumes.

[5] http://www.water.gov.au/Publications/ABS_Water_Account_2004-05_Chpt4.pdf

Does this assumption of zero return flows matter? Indeed it does: Australia is now embarked on a massive (AUS$ 10bn) programme to save water for the environment, including subsidies to farmers for hi-tech on farm investment. Savings are estimated on the basis of typical application efficiencies (e.g. flood irrigation 50 percent, drip 90 percent), so a farmer with a water entitlement of 100 water units, switching from flood to drip would be assumed to consume 50 units at present, which would require a delivery of only 50/0.9 (55.5) units after conversion. The "saving" of 44.5 units are then divided between the farmer and the environment. Of the 22.25 units going to the farmer, he consumes (with the new technology) approximately extra 20 units. So on-farm water consumption is expected to increase from 50 units to 70 units (and return flows are diminished by approximately the same amount), in apparent direct contradiction to the programme objectives. In some cases, such return flows will be non-recoverable outflows to saline groundwater; in other cases, where irrigation is close to rivers or where groundwater is usable, the return flows are recoverable and cannot be counted as "savings". However, the current evaluation of investments includes no apparent basis for assessing whether subsidized introduction of hi-tech systems will actually release water to alternative uses, or simply increase consumption by the extra amount allocated to the farmer. A more comprehensive implementation of UN-SEEAW—where return flows to the environment are specifically accounted for—would have addressed this problem.

Other authors have identified the issue. Qureshi *et al.* (2011) point to the problem of ignoring return flows, and the danger of focussing on local "efficiency", while Loch and Adamson (2015) go on to identify the "rebound effect" whereby when water deliveries to the farm are more valuable, the demand for water actually increases.

Most recently, writing in a Special Issue of Water Economics and Policy that addressed many of the complexities of managing water scarcity in the Murray Darling basin, Grafton (2017) made the following key observations regarding the Australian experience with providing subsidies for on-farm improvements in irrigation technology:

- About USD 2.5 billion of taxpayers' funds used for improving farm irrigation has primarily benefitted private individuals;
- These investments have had no discernible impact in terms of reduced water use on a per-hectare basis, or release of water to alternative users;
- The buyback of water rights from willing sellers was the most effective use of taxpayer funds to release water to alternative uses;
- Investments in irrigation to raise "crop-per-drop" productivity had failed to deliver water savings on a basin scale.

4.2 CHINA

Document

Policies Drain the North China Plain: Agricultural Policy and Groundwater Depletion in Luancheng County, 1949 – 2000 (Kendy *et al.*, 2006)

Context

This analysis demonstrates in a well-documented environment how hi-tech irrigation has contributed to overdraft of aquifers, distinguishing carefully between water applied, and water consumed.

Highlight

The Hai Basin in the North China Plain is of considerable importance to China's food security, but is widely recognized as under threat due to continuous over-exploitation of groundwater. The study reviews some 50 years of data on groundwater levels and pumping rates in Luancheng county, and reports that while the total volume of water pumped has been steadily decreasing since the mid-1970s, the water table has continued to decline at a more or less constant rate. Part of the explanation of this situation is that the government (and the farmers) have invested heavily in improved irrigation technologies, such that a much larger proportion of the water extracted is consumed—in other words, consumption has remained constant, or increased, while water applied per hectare has decreased.

Document

Basin-wide evapotranspiration management: Concept and practical application in Hai Basin, China (Wu *et al.*, 2014)

Context

This analysis uses remote sensing to estimate the extent to which consumption of water in the Hai Basin exceeds the renewable supply, and recommends to shift the focus onto "ET Management" to restore balance.

Highlight

Based on China's unsuccessful experience in reducing water consumption through the introduction of hi-tech irrigation, the concept of "ET Management" has been developed and introduced through a number of World Bank administered projects. The approach focuses on water consumption, setting limits to sustainable water use based on the major elements of the water balance—precipitation, evapotranspiration, and outflow. This study assesses the current components of the water balance, concluding that irrigation consumption must fall by about 20 percent ($6x10^9$ $m^3 yr^{-1}$) to restore equilibrium. The study refers to the Global Environment Facility (GEF) Hai Basin Integrated water and Environment Management Project[6], which is based on the ET Management principle. Where it has been applied (in the Hai Basin, and elsewhere in World Bank projects in China) the key intervention to reduce ET has been changes in the cropping pattern, including a reduction in the irrigated area.

Document

Assessing potential water savings in agriculture on the Hai Basin plain, China (Yan *et al.*, 2015)

Context

The report is a simple arithmetical projection of research results of potential water savings through mulching, crop pattern changes, deficit irrigation, and cultivar changes compared to the identified water deficit in the region. It is shown that even if farmers fully adopted such techniques, overdraft of aquifers would continue, so that grain production will have to be reduced to re-establish equilibrium.

[6] http://www.worldbank.org/en/results/2013/04/09/china-improving-water-resource-management-pollution-control-in-hai-basin

Highlight

The report assesses the theoretical potential to close the gap between consumption and renewable supply in the Hai basin, which is estimated at $6x10^9$ $m^3 yr^{-1}$ or some 20 percent of total consumption. The analysis assumes that the water saving and yield-enhancing reported from research stations could be replicated on farmers' fields. Research results indicate that mulching can significantly reduce consumption (5-10 percent) while also increasing yields for winter wheat (up to 18 percent) and maize (5 percent). The very positive result for wheat is largely due to the long period prior to emergence of winter wheat, when evaporation is minimised by mulching and moisture is retained for transpiration by the plant. Potential water savings through deficit irrigation are also evaluated, and show that while small gains in water productivity ($kg{\cdot}m^{-3}$ of water consumed) are achieved, this is always based on a reduction in yield associated with a larger reduction in water consumed—so that from the farmers point of view, total production (and hence income) tends to fall. The paper draws the conclusion that interventions such as mulching are attractive to farmers, because production is increased. Deficit irrigation is less attractive to farmers because extra management effort is required, while production is reduced.

Document

Towards groundwater neutral cropping systems in the Alluvial Fans of the North China Plain (van Oort *et al.*, 2016)

Context

Using simulations with the *Agricultural Production Systems Simulator* (APSIM) cropping systems model the paper explores production opportunities in an area within the North China Plain with intensive cropping and no access to surface irrigation. Production levels for wheat and maize were estimated if average aquifer abstraction was reduced to equal recharge through changes in crop sequence, irrigation practices and water conservation technologies (e.g. mulching with plastic film).

Highlight

Restoring a balance between aquifer recharge and abstraction would result in a fall in total grain production by 44 percent compared to current practice. Water conservation by plastic film could limit this reduction to 21–33 percent.

4.3 EGYPT

Document

The new era of water resources management (Seckler, 1996)

Context

Egypt presents a unique context for water accounting. Rainfall is practically zero; irrigation is served by controlled releases from Aswan, and inland return flows all return to the Nile system. This means that increases in irrigation efficiency are extremely unlikely to save real water, except than for the potential reduction of some non-beneficial water consumption (i.e. free water surface and wet soil evaporation). At the coast, the situation is more complex: excess freshwater deliveries to irrigated areas serve to control saline intrusion.

Highlight

Egypt is a unique irrigation environment. More than 95 percent of the country's water resources come from the Nile as inflow from upstream catchments; rainfall is negligible. Hydrologically, this makes analysis of water utilisation relatively simple: all return flows from excess irrigation applications go either to groundwater (which is in equilibrium in the surface irrigated areas, and over-drafted in newly developed areas in the western delta), or back via the drains to the surface system—except at the northern interface with the Mediterranean. In that area, saline intrusion is a problem, so that releases of fresh water to the sea are required to maintain equilibrium and to flush out pollutants. Egypt is thus a classic example of recoverable flows, and "on farm efficiency" is of modest relevance to water saving.

Despite this, many millions of dollars have been spent on on-farm irrigation development (e.g. Ministry of Agriculture – informal communications) designed to increase on-farm irrigation efficiency and, as late as 2015, the "On farm Irrigation Development Project" reports[7] that large quantities of water can be "saved" through increased "efficiency" from 50 percent to 80 percent in the old lands, allowing expansion of the irrigated area elsewhere.

Similarly, the Japanese-funded *Sustainable System for Food and Bio-energy Production with Water saving Irrigation in the Egyptian Nile Basin* (Science and Technology Research Partnership for Sustainable Development – (SATREPS))[8] programme suggests that on-farm techniques could "save" 20 percent or more of water applied—without any consideration of where the excess water is currently going.

These same ideas were assessed at a round-table meeting in Cairo some 25 years ago, concluding that the scope to save water was minimal (Keller, 1992).

4.4 INDIA

Document

Halting the groundwater decline in north-west India. Which crop technologies will be winners? (Humphreys *et al.*, 2010)

Context

The papers review interventions designed to improve water productivity and/or save water, applying a water accounting framework that distinguishes between consumption and use, concluding that there is very little evidence that ET is actually reduced. Water saving is best achieved with changes of planting date and short duration varieties.

Highlight

Many improved technologies are under development for Rice-Wheat (RW) systems, with multiple objectives including increased production, improved soil fertility, greater input use efficiency, reduced environmental pollution and higher profitability for farmers. These technologies include laser land levelling, alternate wetting and drying water management in rice, delayed rice transplanting, shorter duration rice varieties, zero till wheat, raised beds, and replacing rice with other crops. However, the

[7] Abdel-Ghany and El-Gindy (presentation)

[8] http://www.jst.go.jp/global/english/kadai/h2007_egypt.html

nature of the irrigation water savings has seldom been determined. It is often likely to be due to reduced deep drainage, with little effect on evapotranspiration.

More than 90 percent of the major rice-wheat areas in northwest India are irrigated at least partially from groundwater. Here, reducing deep drainage does not "save water" nor reduce the rate of decline of the water table. In these regions, it is critical that technologies that decrease ET and increase the amount of crop produced per amount of water consumed as ET are implemented. The best technologies for achieving this are delayed rice transplanting and short duration rice varieties. The potential for replacing rice with other crops with lower ET is less promising.

Document

The effect of rice straw mulch on evapotranspiration, transpiration and soil evaporation of irrigated wheat in Punjab, India (Balwinder-Singh *et al.*, 2011)

Context

Reductions in non-productive evaporation are expected as irrigation techniques improve and water is applied more accurately to the crop. Such results are often reported for orchard crops and vines – where the spacing between crops is large. This study looks at a more typical field crop – wheat – where the canopy closes relatively quickly and reports that reductions in evaporation were compensated almost exactly by increases in transpiration.

Highlight

Evaporation from wetted soil (E_s) is considered to be a non-productive component of evapotranspiration (ET). Reducing soil evaporation (E_s) should influence the amount of water available for transpiration (T), the productive component of ET. Field experiments investigating the effects of rice straw mulch on components of the water balance of irrigated wheat were conducted during 2006–2007 and 2007–2008 in Punjab, India, on a clay loam soil. Daily E_s was measured using mini-lysimeters. Mulch lowered total E_s over the crop growth season by 35 and 40 mm in relatively high and low rainfall years, respectively. However, much of this "saved water" was partitioned into T, which increased by 30 and 37 mm in the high and low rainfall years, respectively. As a result, total ET was not affected by mulch in either year. In both years, though, there was a trend for higher biomass production and grain yield with mulch. Transpiration efficiency (TE) with respect to grain yield was 1.88–1.91 $kg{\cdot}m^{-3}$ in 2006–2007, and 1.46–1.64 $kg{\cdot}m^{-3}$ in 2007–2008. While wheat grown in the presence of mulch tended to lower TE, this was only significant in 2007–2008. The results suggest that while mulching of well-irrigated wheat reduces E_s, it does not "save" water because the crop compensates by increased T and reduced TE.

4.5 ISRAEL

Document

Decoupling dependence on natural water: Reflexivity in the regulation and allocation of water in Israel (Gilmont, 2014)

Context

Israel has been successful in increasing agricultural production through hi-tech irrigation in a context of severe water scarcity.

The context is critical to this achievement: from the earliest days, Israeli state agencies managed and controlled water. The national water carrier, which carried water from the relatively water-abundant north to the arid but plentiful agricultural lands in the south, had a limited capacity, so that unconstrained access to water for irrigation was never an option. Similarly, groundwater was considered a national asset, with access limited by strict quantitative controls. All water deliveries were, and are, metered.

Land use was also determined by the state, so that increases in the irrigated area (potentially made possible by the impact of hi-tech systems described above) was only possible with the permission of the state. In sum, water resources are owned by the state, and can only be used with a licence; land is owned by the state, and its use, including the area permitted to be irrigated and its allocated water supply are controlled by the state. A farm is thus closely defined in terms of its irrigable area, and its "normal" water allocation.

Highlight

Water is allocated on the basis of an annually authorized volume per hectare, specified in relation to the "normal" allocation for an average year. Thus in a dry year, authorized volume may be 80 percent of the normal allocation, and in a wet year the authorized volume might exceed the normal allocation. Pricing plays a role in this system, but the basic approach is to assign an annual quota, and set steeply rising "block tariff" prices to encourage use at that level.

For many years, water allocations to agriculture increased, as infrastructure was developed to serve new areas and exploit the country's natural runoff and recharge—most importantly through the national water carrier, abstraction from internal rivers, and development of the mountain and coastal aquifers. In the period up to about 1970 allocations gradually stabilised, and in the following years, allocations of fresh water to agriculture were reduced—partly due to some severe droughts, and partly as policy reflecting the increased need for non-agricultural water and the need to stabilise and reverse the environmental impacts of water resources development. Despite this, agriculture production continued to grow.

Two separate factors explain this achievement. First, the continuous improvement in irrigation technologies and their widespread adoption resulted in an increase in on-farm irrigation "efficiency"—an increase in the proportion of water supplied to the farmer that is converted into crop ET. Well-managed flood irrigation typically has an efficiency of 50-55 percent (that is, roughly half of the water is converted to crop consumption) while advanced drip and sprinkler technology will easily exceed 80 percent even allowing for flushing of salts. Thus the supply of water for crop *consumption* was substantially increased over the period as technology was transformed from flood to drip and other hi-tech approaches, while the *withdrawals* of fresh water remained constant. Secondly, freshwater supplies in the last decade or so have actually decreased dramatically and have been replaced by treated wastewater. Paradoxically, while freshwater *allocations* to agriculture declined, hi-tech systems allowed crop water *consumption* in the sector to increase, which was the basis for increase in production—a phenomenon that has also been observed in the North China Plain (Kendy *et al.*, 2006). Correspondence with manufacturers of drip irrigation in Israel produced the following quotes:

- While in crops which are "mass" crops what you give is what you get, I know that in fruit trees, grapes, vegetables etc., you do get "more for less".[9]
- When given the same yield for drip and surface irrigation, the amount of water consumed by the crop is equal.[10]

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[9] Personal Communication, Naty Barak, Chief Sustainability Officer, Netafim

[10] Personal Communication, Dr Itamar Nadav, Project Manager, R&D Department, Netafim

Furthermore, Israeli towns and cities mostly disposed their effluent either into rivers that discharged into the sea, or through local treatment plants that released partially treated effluent to the local environment. More recently, and particularly as non-agricultural water use has become a major component of national demand, the potential to treat and recycle urban wastewater has been exploited, and has provided a major new "source" of water for agriculture. The construction of large-scale desalinisation plants in the last ten years has also vastly increased the basic availability of water to the country (600 mm^3 per year of a total supply of 2 000 mm^3 per year).

Israel's achievements in the irrigated agricultural sector are notable, and appear to have gone through the "usual" cycle of water resources development, expansion of agriculture, over-exploitation of aquifers and rivers (resulting in declining water levels, pollution and environmental degradation) and now emerging into a more unusual scenario where incremental supplies from desalinisation are affordable to augment urban supplies, while re-use of the consequent wastewater is an affordable source for hi-tech irrigation.

However, several components of this achievement are unique to Israel, and more importantly are preconditions for the model to work elsewhere:

- Central control of the surface and groundwater resource;
- Effective control of demand (setting volumetric quotas with a supporting tariff structure; control of the irrigated area);
- The availability of recycled water to substantially enhance allocations to agriculture;
- Sufficient surface and groundwater reserves to meet unplanned excess demand on a seasonal basis.

In other countries, similar to Israel in climate and water scarcity, the absence of controls over demand, inability to set, measure and enforce quotas for physical water allocation, and the inability to limit the area irrigated, pose very serious questions for the water-saving impact of introducing hi-tech irrigation. The increase in economic productivity of water that hi-tech allows will tend to increase immediate consumption, and also increase demand for more scarce water—the opposite of the desired effect.

4.6 IRAN

Documents

Irrigation Improvement Project, Islamic Republic of Iran, World Bank Staff Appraisal Report (World Bank, 1993); *Lake Uromiyeh. A concise Baseline Report* (Lotfi, 2012)

Context

The project aimed to restore, or at least stabilise a lake that was progressively drying-up as a result of irrigation development upstream. The main intervention was designed to increase 'irrigation efficiency'. No proper water accounting was prepared to assess whether pre-project return flows were in fact lost, nor to project the impact of water consumption of the proposed interventions.

Highlight

In 1993, the World Bank funded an Irrigation Improvement Project in Iran, in part covering areas around Lake Uromiyeh. The project addressed a number of problems, including the very low (20-30 percent) "irrigation efficiency", noting the potential to save large quantities of water by improving this parameter.

No details are provided as to the destiny of the presumed losses—whether to saline sinks, excessive evaporation, percolation, runoff to drains, etc.

Later, a very detailed analysis of the gradual disappearance of Lake Uromiyeh covered all aspects of the hydro-geology of the area around the lake, and documents the near threefold expansion in irrigated area and water use for agriculture in the period from 1970-2006. Reference is made in this report to the findings of the World Bank Appraisal, and the inefficiency of irrigation in the region. The report concludes (Lotfi, 2012) that "*there is a great potential to increase water application efficiencies at farm level and save considerable volume of water for restoring and sustaining the Lake without hampering agricultural productions and farmers' incomes. This potential source of water can even replace in part the need for constructing new storage dams.*"

Several aspects of this scenario are worrying: first, the failure to consider the overall water balance and the likely impact of improved irrigation efficiency; second, that the regional study states that the "alluvial aquifers are mostly recharged by the surface rivers and to a lesser extent by the precipitation", clearly implying that irrigated areas would also provide recharge if excess water is applied; third, failure to realise that the predominant reason for continued depletion of both the lake and underlying aquifers is the tripling of the irrigated area, and consequent similar increase in water *consumption* in irrigated agriculture.

4.7 MOROCCO

Document

Programme National d'economie d'eau en Irrigation (Morocco, Ministry of Agriculture and Fisheries, no date)

Context

Morocco's water resources are under severe pressure. Groundwater levels are falling rapidly in many areas, and most rivers do not regularly reach the sea. Tubewell development is largely uncontrolled. While it is recognised that water is over-exploited, and that percolation from irrigation schemes is a major source of recharge, subsidized conversion to drip irrigation remains a major element of addressing water scarcity – without analysis of potential impacts on groundwater levels.

Highlight

This national programme has many elements and policy suggestions, but is heavily dependent on the assumption that on-farm irrigation techniques can be dramatically improved, saving water for expansion of irrigation elsewhere, stating as a basic premise:

Among the different techniques of irrigation, gravity is the least efficient (generally reported to be 50-60 percent in Morocco). At the other extreme the drip irrigation is the most efficient (90 percent or more).

In several irrigation schemes, it is intended not to increase the allocation but rather increase the economic water productivity. The measured impacts of introducing drip instead of flood irrigation were reported in the following report.

Document

Satellite Based Evapotranspiration Mapping and Water Use by Rural Communes of Morocco, Riverside study for World Bank, (Riverside, 2009)

Context

The study attempted to assess ET in some 250ha of citrus fields in Morocco, some of which were irrigated by gravity, the rest by drip. ET was virtually identical in each case.

Highlight

Water resources in Morocco are scarce and unevenly distributed. Demand is increasing because the population is growing and urbanizing. Agricultural production is the dominant water use, consuming approximately 85 percent of available water resources. The government's programme compensates farmers for limiting consumption by modernizing infrastructure so that it provides water on-demand (rather than on a fixed rotation) and by helping farmers access markets for their crops and switch to higher value crops. The program's two indicators of success are thus value-added per unit of water consumed by the beneficiary farmers and level of groundwater consumption by the beneficiary farmers.

The area of study included three ORMVA (Office Régional de Mise en Valeur Agricole) districts (Tadla, Haouz, and Doukkala) in the Oum er R'bia basin. Analysis focused on pilot areas within the ORMVA's that have had some irrigation improvements or modernization implemented. Riverside was contracted by the World Bank to perform remote sensing and water balance analyses. The Mapping EvapoTranspiration at high Resolution with Internal Calibration (METRIC) algorithm (Allen *et al.*, 2007) was used to derive ET estimates from satellite data. METRIC is similar to Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen *et al.*, 1998), but employs different calibration procedures.

Of the approximately 9 million ha of cultivated area within Morocco, around 1.5 million are equipped for irrigation (AQUASTAT, Data 2004). It is estimated that about 70 percent of the irrigation is derived from surface water sources, with the remaining 30 percent supplied from groundwater (AQUASTAT, Data 2000). The common irrigation techniques include surface (flood/furrow) applications, which comprise approximately 83 percent of the developed irrigation, with sprinkler systems accounting for 10 percent of all irrigation, and other localized methods (drip, etc.).

The study evaluated ET on 12 sample fields covering a total of about 250 ha. All the fields were planted with citrus; 5 fields were irrigated by gravity; the rest by drip. Average water consumption for the drip-irrigated fields was 0.1 percent less than in gravity irrigated fields (947.9 mm compared to 956.3 mm). Yields are not reported, so no assessment of productivity impacts was possible. However, water consumption was virtually identical in each case.

A recent study (Molle, 2017) evaluates the investments in Morocco to upgrade traditional surface irrigation to drip, with the explicit primary objective of saving water. While up to 4 billion dollars have been slated for that policy, there is no evidence that water consumption has been reduced so far while it is observed that aquifers continue to fall at an alarming rate (with an estimated deficit of one billion m^3 per year). Even more worrying is the absence of effective monitoring and evaluation of these investments.

4.8 PAKISTAN

Document

Constraints and opportunities for water savings and increasing productivity through Resource Conservation Technologies in Pakistan [Mobin-ud-Din Ahmada, Ilyas Masih, Mark Giordano (2014). Agriculture, Ecosystems and Environment, 187: 106–115].

Context

Pakistan is generally water short. Large areas of Punjab Province are underlain by fresh groundwater, which is over-exploited. Other areas in Punjab, and most of Sindh are underlain by saline groundwater and prone to waterlogging and salinity. The report reviews interventions designed to "save" water, finding that these are aimed at reducing water applied without attempting to quantify actual reductions in consumption. In fresh groundwater areas, excess water would be recovered, while elsewhere-reduced applications have the benefit of reducing the threat of waterlogging.

Highlight

In the last 10 years, Pakistan's population has increased by over 25 percent, and is expected to reach more than 230 million by 2030[11]. This poses serious food security concerns as more than half the country is already categorized as food insecure. A key issue in efforts to keep food production rising, at least as fast as population growth, is the limited availability of fresh water for agricultural use. Various Resource Conservation Technologies (RCTs) are being promoted, in particular for rice and wheat which together make up 90 percent of the country's total food grain production. These technologies include zero tillage wheat, direct seeded rice, bed planting of rice and wheat, laser land levelling and crop residue retention.

Experimental studies on farmers' fields report various impacts of RCTs on a range of these factors, though with irrigation water application and crop yield as the two main performance indicators. Zero tillage, laser levelling and bed and furrow planting, reportedly reduced irrigation water *applications* between 23 percent and 45 percent while increasing yield. Zero tillage adopters in Pakistan's Punjab demonstrated reductions in irrigation *applications* of 5–15 percent and obtained similar yields compared to the conventional agricultural practices. Other studies have reported that land levelling resulted in about a 25 percent reduction in irrigation water *application* and an increase of about 30 percent in wheat yield as compared to conventional practices.

The study includes a review of other research in Pakistan on the impact of these technologies, concluding that while water *applied* can be significantly reduced, the impact on water *consumed* through ET is minimal and production per unit of ET is (for rice) substantially higher for traditional transplanting than for the "water saving" approaches; while for wheat, the traditional practices are marginally surpassed (in terms of yield and production per unit of ET) by zero tillage.

The paper additionally points out that reductions in water applied generate minimal real "savings" in Punjab – where groundwater is fresh and widely exploited. The excess irrigation applied during the monsoon season, when water is plentiful, contributes positively to groundwater availability in the rest of the year.

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[11] United Nations, Department of Economic and Social Affairs, Population Division (2015). *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables.* Working Paper No. ESA/P/WP.241

In Sindh Province, where groundwater is saline, reductions in percolation are a real benefit, so that the RTCs technologies are far more attractive.

The study also reported that where reductions in water *applied* are achieved, these are mostly used to expand the irrigated area, so that *consumption* actually increases.

4.9 SOUTH AFRICA

Document

Standards and Guidelines for Improved Efficiency of Irrigation Water Use from Dam Wall Release to Root Zone Application, (Reinders *et al.*, 2010)

Context

South Africa is moving towards adopting water accounting guidelines that distinguish between recoverable and non-recoverable return flows – having adopted a water law that explicitly recognises water uses that reduce stream flows (i.e. consumptive use). Scheme managers also seek to reduce losses that occur in areas distant from where recovery is possible.

Highlight

The Water Research Commission has published guidelines for the evaluation of irrigation system performance that closely follows the International Commission on Irrigation and Drainage (ICID) terminology set out in Section 3 of this report. The basis of the ICID 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 re-use) or non-recoverable (lost to further use). To improve water availability in the 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 the best management practices.

Implementation has proved difficult[12]; measurements and modelling so far make it very difficult to quantify the recoverable and non-recoverable component. The reason is that this obviously depends on the state of maintenance of the canals on an irrigation scheme i.e. earth or concrete lined and repairs /maintenance that limits leakages and seepage. It is argued that the non-consumptive/recoverable fraction will be anything between 90 percent and 50 percent.

Over time, water managers work towards reducing the volumetric difference between water releases and water abstractions—eventually establishing a (fluctuating) ceiling for volumetric losses, which are applicable to the specific irrigation scheme. This will enable more effective water management and reduction of volumetric losses to a practical level. The acceptable difference between release and abstractions should not exceed 20 percent. In addition, estimates should thereafter be made of the relative proportions of the recoverable and non-recoverable losses, which will then indicate the true savings which have been achieved, i.e. recoverable water that is available for the environment or other uses (irrigation or industrial or domestic) below the irrigation scheme.

[12] Personal Communication; Gerhard Backeberg.

4.10 SPAIN

Document

Literature Review on Rebound Effect of Water Saving Measures and Analysis of a Spanish Case Study (Berbel *et al.*, 2014)

Context

Spain has a number of severely water-stressed basins in the south of the country, where irrigation is highly developed. Conversion to drip and sprinkler has been subsidised, and this paper reviews the impact of these investments. In particular, they seek to demonstrate whether the increase in consumption and demand resulted from these changes. Though, it is difficult to interpret the results of the study unambiguously. Rainfall varied significantly, and perhaps contributed to reduce demand for water in the post-investment period; some areas clearly reduced water applied, but whether this reflected a reduction in consumption is not clear. The authors conclude that strictly enforced reductions in water allocations prevented an increase in consumption.

Highlight

This paper presents a case study with an overview of both modelling studies and empirical evidence. Only the empirical evidence is summarized below.

The "rebound effect" referred to in the title is also known as Jevons Paradox (York and McGee, 2015). In 1865, the English economist William Stanley Jevons observed that technological improvements that increased the efficiency of coal-use led to the *increased* consumption of coal in a wide range of industries. While common intuition suggested that if less of a particular input was required to achieve a given outcome, the demand for that input would fall, while the observed reality was that with the fall in the effective price of the input fell, demand increased.

Spain is for the most part a water short country with an important irrigation sector. More generally in the Mediterranean region, the problem of demand exceeding sustainable supply has been tackled recently with 'demand side' policies, particularly through investment in water saving technologies and reduction of losses in distribution networks associated to the promotion of water pricing.

The Spanish Government developed the National Irrigation Plan with the aim of converting the old open channel distribution infrastructure into pressurized pipe networks anticipating annual water savings of 3000 mm^3. These new pressurized pipe systems operate on demand, which allows high frequency irrigation, optimal crop irrigation scheduling, and the diversification of cropping patterns towards higher value. The modernization of irrigated systems and projected water savings is a key measure in the implementation of River Basin Management Plans (RBMP) in Spain. Once implemented, the water rights of beneficiaries of the improved systems are reduced by 25 percent.

The original research presented in the paper is based on data from Water User Associations covering 36 000 ha at various locations in the Guadalquivir basin. Data from 1999-2001 were compared with data from 2009-11, by which time modernized systems had been in place for 2-3 seasons. Government subsidies covered 60 percent of the costs of constructing improved delivery systems and on-farm investment in drip and sprinkler technology. The farmers agreed to cover the remaining capital costs, Operation & Maintenance (O&M) of the new system, accept a 25 percent reduction in water rights (to 6 000 $m^3\,ha^{-1}\,yr^{-1}$), to accept metering and volumetric billing, and not to increase the irrigated area.

Assessing the outcome is not simple, most importantly because average rainfall in the post-modernization period was more than 50 percent higher, accounting for 19 percent of crop demand in the first period and 28 percent of crop demand in the post-modernization period. Annual demand for irrigation water consequently fell from 6 526 $m^3 ha^{-1}$ to 5 159 $m^3 ha^{-1}$, even though the estimated crop water demand rose very slightly due to changes in cropping pattern (so there was no observed fall in *potential* consumption as a result of modernization). In both pre and post-modernization scenarios, the water allocation exceeded demand from the farmers. The data do show that the total water supply in the pre-modernization scenario was 98 percent of potential crop demand, falling to 90 percent post-modernization. Whether this difference is real water saving is unclear.

The authors conclude that the "rebound effect" of *increased* consumption as a result of modernizing with hi-tech irrigation is avoided *provided* the area under irrigation is controlled.

The authors, then, review a large number of modelling studies (see documents below), and four empirical studies from Spain that include estimates of changes in water *consumption* due to the introduction of hi-tech irrigation. In four cases (Playán and Mateos, 2006; Lecina *et al.*, 2010a, 2010b; Rodriguez Díaz *et al.*, 2012) *consumption* is reported to increase. Two other cases suggest a decrease in consumption, though without precise clarification as to the reasons. In one case (García-Garizábal and Causapé, 2010) there is a reduction in water requirements, presumably due to a change in the cropping pattern, while in another (Garcìa-Mollá *et al.*, 2013) there is a switch to higher value crops, and an improvement in water levels in aquifers.

Document

Effects of modernization and medium term perspectives on water and energy use in irrigation districts (Fernandez Garcia *et al.*, 2014)

Context

This study concludes that the Spanish modernisation programme reduced water applied significantly, but in the long run led to increased consumption due to changes in cropping patterns.

Highlight

This paper also assesses the impact of the programme to introduce hi-tech irrigation and reduce water allocations in southern Spain, using data from water users associations. The authors find that water *applied* fell by 23 percent following the introduction of drip systems. At the time of analysis, water *consumption* was marginally (2 percent) higher, but once the newly planted citrus trees are fully developed, *consumption* is expected to increase by about 9 percent.

Document

Modernizing water distribution networks: Lessons from the Bembézar MD irrigation district, Spain (Rodriguez Díaz *et al.*, 2012)

Context

While water supplies to irrigated areas has reduced significantly, consumption has increased due to the adoption of more water demanding crops. Energy costs of pressurized systems is also substantial.

Highlight

In this study, the modernization of water distribution networks is evaluated using performance indicators derived both before and after the modernization of an irrigation district (Bembézar MD) in Andalusia, southern Spain. The analysis shows a reduction of approximately 40 percent in water diverted for irrigation due to a more efficient distribution system. However, this has led to changes in crop rotation, with higher-value and more water-demanding crops being introduced. As a consequence, crop evapotranspiration has increased considerably (21 percent). Modernization has also led to a dramatic increase (fourfold) in management, operation and maintenance costs. Much of this cost is due to the high-energy dependency of the new pumped system (0.15 kWh per m^3). Such costs were negligible prior to modernization due to the scheme being gravity-fed.

Document

Water and energy consumption after modernization of irrigation in Spain (González-Cebollada, 2015)

Context

Spain has gone through a considerable programme of irrigation modernization in recent decades with expected significant results in 'water conservation' and 'water saving'. Given the importance of these main goals, it was expected an accurate assessment of water consumption 'before' and 'after' the various modernization projects. Similarly, it was expected that the water saved would be made available to the water authority in order to determine its new use, following for example the Water Framework Directives of the European Union. However, government response to 'Parliamentary Questions' (May 2013) was that "there is no assessment which can quantify the resulting water savings". The author, then, assembled scientific studies done by universities and research centres to provide the 'evidence' on changes in water (and energy) consumption following the irrigation modernization programme in Spain.

Highlight

The paper analyses several case studies in the Ebro, Tajo and Guadalquivir river-basins, providing the water consumption and energy consumption before and after modernization. The results of the analysis indicates that irrigation efficiency (expressed as water consumed divided water applied), in the case studies analysed, has increased noticeably, going from 67 percent of 1950 to 82.5 percent in 2007, as a result of the adoption of modern irrigation techniques. However, 'water use' by agriculture increased 2.4 times, over the same time period, while 'water consumption' has quadrupled.

Similarly, the results of the analysis show a nineteen-fold increase in energy consumption (for pumping) between 1950 and 2007. At present, irrigated agriculture is the largest electricity consumer in Spain with a share of 2.37 percent of the electricity nationally produced. The author indicated that agricultural production was expected to increase more than energy costs and initially the investments in irrigation modernization were clearly profitable, especially in the presence of substantial public funds. However, it is very difficult to forecast electricity prices (and other variables) over very long periods as those considered in modernization projects (e.g. the special electricity rate for irrigation ended in July 2008 when liberalization of the electricity market was introduced).

The authors concludes by stating that *"it can be observed that Spain's irrigation modernization policy, supported by billions of euros in public funding from Europe and the national and regional budgets, and justified socially by hypothetical water savings, has not in practice led to any water savings, but rather the reverse. No water resources have been freed up for environmental use, or any other kind"… "Productivity in modernized farms has increased thanks to modernization, but their energy costs and the costs of recouping the investments have also increased in most cases"*.

4.11 TUNISIA

Document

Water Balance and Evaluation of Water Saving Investments in Tunisian Agriculture (Zwart and Bastiaanssen, 2008)

Context

This is one of the most comprehensive studies of the field impact of hi-tech irrigation at a large scale. The results are entirely consistent with the analysis presented in the main text: water consumption increased somewhat; yields per hectare increased; the relationship between wheat yield and water consumption was linear.

Highlight

Tunisia, like other North-African countries, is affected by limited water supplies and faces a serious water deficit caused by low annual rainfall. For economic reasons, and to enhance food security, the Tunisian government promotes irrigated agriculture, thus putting more pressure on available fresh water resources. In 1995, the Government of Tunisia adopted the *National Water Savings Program* (PNEE). The PNEE programme was initiated to increase the economic value of water, and to maintain the balance between available water resources and water demand by irrigation.

The investments should lead to lower water consumption by irrigated agriculture at national level, and benefit other sectors such as industry and domestic use (drinking water). The investments in the irrigation sector can be divided into three categories:

1. Improved surface irrigation (construction of storage reservoirs, canal lining, irrigation equipment, etc.)
2. Installing sprinkler irrigation equipment
3. Installing drip irrigation equipment

The national total irrigated area at the end of 2007 was reported to be 414 000 ha. Between 1995 and 2007 approximately 330 000 ha of these irrigated lands were improved during the PNEE programme.

At the time of the study there had been no systematic evaluation at the national scale of changes in productivity, water consumption, effects on groundwater tables and impacts on downstream users. In order to provide initial insights, remote sensing data were used to make a country-wide analysis of Tunisian rain-fed and irrigated agriculture. A comparison was made of the 2000-01 and 2006-07 hydrological years using the SEBAL algorithm (Bastiaanssen *et al.*, 1998) to derive ET from satellite data.

The analysis was complicated by the fact that rainfall in 2006-07 was considerably higher than in 2000-01, so that irrigation demand was reduced quite independently of the improved technology. In irrigated areas, total crop water consumption was 11 percent higher in 2006-07, suggesting that the improved irrigation technology did not result in actual water savings.

Wheat yields were a linear function of ET, so that while total water consumed by wheat reduced by 10 percent, production fell by approximately the same proportion.

In irrigated mixed cropped areas, several objectives of the programme were achieved: yields per hectare and production per unit of water increased sharply, but water consumption also increased, so that no real water savings as a result of the investments could be demonstrated. The picture was similarly mixed in oases, while in orchard areas water consumption increased and water productivity fell.

4.12 UNITED STATES OF AMERICA

State of Arizona

Documents

The Sustainable Use of Water in the Lower Colorado River Basin (Morrison, Postel and Gleick, 1996); Water budget for agricultural and aquatic ecosystems in the delta of the Colorado River, Mexico: Implications for obtaining water for the environment (Carrillo-Guerrero, Glenn and Hinojosa-Huerta, 2013)

Context

These two reports present conflicting views of the impact of hi-tech irrigation. The first seems to be based on the simple assumption that on-farm efficiency increases automatically generate savings. The second carefully follows the path of these losses through the rest of the system, generating a complete water balances and concluding that the impact of hi-tech irrigation would be negative for the downstream wetlands.

Highlight

The agricultural sector uses almost two-thirds of the water in the lower Colorado River basin and offers the greatest opportunities for savings. The Pacific Institute estimates that improvements in irrigation efficiency can free significant amounts of water for environmental or other purposes. For example, in Arizona, it is assumed that upgrading half of all irrigated cotton and major vegetable and citrus crops to drip or other micro-irrigation techniques, would reduce consumptive losses from 30 percent to 5 percent (Table 19, p39 of Morison *et al.*, 1996). These assumptions are entirely at variance with carefully measured impacts of conversion from flood to drip from California (see next document of Thorenson *et al.*, 2013), where savings are found to average less than 6 percent.

In another study of this area, Carrillo-Guerrero *et al.* (2013), argue that higher efficiencies in agriculture per se would reduce water availability to the Colorado River delta wetlands. They argue that the reduction in the "operational releases" and "excess flows" discharged into the floodplain and the reduction of water applied to croplands would have a net effect of increasing water consumption in the irrigated areas.

State of California

Document

Drip irrigation impacts on evapotranspiration rates in California's San Joaquin valley (Thorenson, Lal and Clark, 2013)

Context

The study was designed to measure the difference between water consumption of various tree crops, at various stages of development, when irrigated with drip compared to flood-irrigated areas. On average water consumed through ET was reduced by less than 6 percent.

Highlight

This study applied remote sensing techniques to directly estimate ET from drip and flood irrigated fields of fruit trees and vines. The areas selected for study were screened to ensure that samples were not a mixture of more than one crop or the edge of a field; the technique used to estimate ET was uniform for all samples and the climatic data were identical for all sample areas. Tree crops and vines offer the highest potential for water saving through hi-tech irrigation, because the proportion of the field that is not shaded by foliage, and hence likely to "lose" water unproductively to evaporation, is much higher than for field crops such as rice, wheat or cotton. Generally, though not uniformly, the reductions in ET were higher for the less fully developed trees, which is consistent with the hypothesis that the main saving depends on reduced evaporation from unshaded soil. These measured results directly contradict the assumptions in the Pacific Institute study of Arizona, where reductions in total ET of 25 percent (4-5 times more than measured in this study) were assumed.

State of New Mexico

Document

Remote-Sensing-Based Comparison of Water Consumption by Drip-Irrigated Versus Flood-Irrigated Fields (Intera, 2013)

Context

This study was prepared for the New Mexico Interstate Stream Commission, and was designed to reveal the consumption impact of the introduction to drip irrigation. The study demonstrated that conversion resulted in an 8-16 percent increase in water consumption with consequent reduction in stream flows. Production and productivity were not measured.

Highlight

The New Mexico Interstate Stream Commission evaluated the water-saving effectiveness of converting from traditional flood irrigation to drip irrigation in agricultural fields in the Deming area, New Mexico. This evaluation was made by comparing the relative crop consumptive use of water in flood- and drip-irrigated fields using a remote-sensing-based technique combined with data collected in the field.

The study reported that on average drip-irrigated fields were cooler than flood-irrigated fields, indicating a higher consumption of irrigation water. This conclusion was supported by analysis using the METRIC surface energy balance algorithm: drip irrigated fields were estimated to consume 8-16 percent more water, depending on the crop.

More water consumption generally results in more biomass and hence higher crop yield and this too was confirmed by evaluating relative differences in the vegetation index—a proxy for biomass.

An important result of this study was that water consumption during the early season was higher with drip irrigation. When canopy cover is sparse, and the evaporation from wet soil is entirely unproductive, drip irrigation offers the possibility to localize deliveries to a much smaller area *provided it is carefully managed*. This does not appear to have happened, and the more frequent deliveries required in drip systems appears to result in higher losses.

State of Kansas

Document

Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence (Pfeiffer and Lin, 2014)

Context

The results of the study, based on a very large data set, show that water consumption increased both in terms of water consumed per unit land (the "intensive margin"), and also that the area irrigated expanded (the "extensive margin").

Highlight

The authors investigate whether the widespread conversion to more efficient irrigation technology (from conventional high pressure standard pivot systems to dropped nozzle centre pivots) had the effect of decreasing the total groundwater extracted for irrigation in western Kansas. At the beginning of the review period (mid-1990s) most farmers were already using centre pivot systems, with field application efficiency in the 80-90 percent range. Subsequently, farmers adopted dropped nozzles that reduce losses to evaporation and wind drift, increasing application efficiency to 95-98 percent. By comparison with most studies, this is a case of switching from "hi-tech" to "higher tech" irrigation, but is of particular interest because the farmers are expert irrigators, and they are concerned to conserve resources and energy costs (e.g. in this case the irrigation system is the 'Low Energy Precision Application' – LEPA).

State of Nebraska

Document

Furrow Irrigation Management with Limited Water (Schneekloth *et al.*, 2006)

Context

This report confirms the linear relationship between yield and water consumption for maize, and highlights the possibility to reduce irrigation water supplies if the crop can then exploit soil moisture. This is a viable option when the soil moisture will be replenished by rainfall.

Highlight

This paper investigates alternative irrigation schedules and practices for maize, reporting the results in terms of Irrigation Water Use Efficiency - IWUE - (that is, $kg{\cdot}m^{-3}$ water applied) and Water Use Efficiency - WUE - or Water Productivity ($kg{\cdot}m^{-3}$ water consumed). The report also estimates the impact on farm incomes of deficit irrigation strategies for various water prices.

The analysis demonstrates that IWUE can be significantly increased by deficit irrigation (typically by 50-100 percent, and even more in a drought year), while WUE is basically constant (±10 percent). The explanation for this is twofold: first, when the crop is subjected to deficit irrigation, it is able to compensate to some degree by utilizing residual moisture (so yield is less variable than irrigation water applied because the water available to the crop is stabilized by soil moisture); and second, the fact that WUE is constant once ET is above a certain threshold). This result further confirms the divergence between the farmer's objective (to maximize IWUE), and the broader societal objective (to maximize WUE).

State of Oregon

Document

Drainage reuse by Grassland area farmers: the road to zero discharge (Linneman *et al.*, 2014)

Context

This project had the objective of maximising consumption of drainage water from irrigated areas by grassland farmers in order to minimise outflows (and associated pollutants) to downstream areas. Maximum water consumption was thus the explicit objective of the programme.

Highlight

Beginning around 2004, growers within the Grassland Drainage Area began aggressively converting from conventional surface irrigation methods (like furrow and flood) to "high efficiency" irrigation systems such has sub-surface drip and micro-sprinklers. The cost of these systems is substantial, ranging from USD 1 000 to more than USD 1 500 per acre, and many growers took advantage of financial assistance programmes through the State of California (low interest loans), federal assistance through the Natural Resources Conservation Service (NRCS), and the local district programmes (including both loans and grants). By improving water application uniformity and more precisely controlling irrigation volumes, these systems reduce the quantity of water that percolates past the root zone and into the tile drainage systems.

The impact was dramatic. Outflows, though variable and dependent on seasonal weather patterns, approximately halved over the subsequent decade while the area irrigated with drainage water approximately doubled, including significant areas of higher value crops.

The introduction of hi-tech irrigation resulted in increased consumption, increased irrigated area, and crop diversification.

4.13 YEMEN

Document

Water Savings Report (Ministry of Agriculture and Irrigation - Yemen, 2011)

Context

This report highlights two issues: first, that water consumption is rarely evaluated, while "water savings" are reported, and second that in some circumstances – for example where aquifers are very deep or saline, percolation may indeed be a loss. Full water accounting would clarify these points and provide the basis for identifying priority locations for hi-tech irrigation.

Highlight

The project involved improvement to delivery channels (lining and piping), and improved on farm irrigation technology, including drip, sprinkler, and bubbler. Measurements were taken of quantities of water delivered at various points in the system before and after technology improvements. Savings were reported to be in the range of 15 percent for the improved delivery system, and up to 30 percent for the on-farm works. Crop yield increased, but generally expansion of the irrigated area was limited.

No actual measurements of water consumption were made. Thus the reported savings are unlikely to have been achieved in the narrow sense of reduced water consumption. Indeed, since crop yields increased it is likely (though not certain, as cropping patterns also changed) that crop water consumption also increased. However, the analysis fails to appreciate the importance of local groundwater conditions which vary from extremely deep, sometimes confined and over abstracted aquifers which percolation may never reach, to shallow aquifers where percolation directly contributes to recharge within a short period of time.

Where the aquifer is deep, the reported savings are indeed beneficial provided that abstraction is reduced in line with the reduction in seepage and percolation, because the possibility of recycling "losses" is quite uncertain. On the other hand, where aquifers are at shallow depths, it is unlikely that any real savings were achieved.

4.14 ZIMBABWE

Document

Simple micro-irrigation techniques for improving irrigation efficiency on vegetable gardens (Batchelor, Lovell and Murata, 1996)

Context

This is an example of demonstrated water savings. The technologies are labour intensive and not suited to large scale implementation; but the results show that for crops grown at garden scale, by comparison with flood irrigation techniques, water saving is possible.

Highlight

The authors experimented with various irrigation regimes, employing subsurface pipe irrigation and pitcher irrigation on maize, tomato, rape, and okra. The authors point out that these very labour-intensive techniques are not suited to large scale irrigation systems.

Compared to traditional flood irrigation, the increased water productivity (based on water applied) on maize and rape was dramatic (64 percent and 21 percent respectively); for tomato the impact was about 6 percent, and for okra -1 percent. The authors report both yield and water productivity (kg per ha and $kg{\cdot}m^{-3}$) so that savings in water consumption can be derived.

For maize, there were no water saving in terms of consumption—the increase in yield and WUE is the same; rape shows significant water saving—WUE increases by about 12 percent. For okra and tomato, the results are mixed.

CHAPTER 5

Concluding remarks

It is commonly assumed that the introduction of hi-tech irrigation will save large quantities of water from agriculture that can be then released to other uses. This assumption, often sustained by major manufacturer of drip and sprinkler equipment[13], needs to be substantiated.

The information compiled in this review found no documented examples of substantial water savings for field crops in terms of consumptive use, and very few cases where bio-physical water productivity increased (yield/ per m^3 of T). Some examples of increased water productivity (yield per m^3 of ET) were found (in China, though not in India), but the basis for these improvements were ascribed to mulching and not to hi-tech irrigation.

The fundamental cause of confusion about water savings and increasing water productivity lies in two legitimate but different perspectives on water scarcity. The farmer is trying to derive maximum returns from his resources, which in turn means consuming as much as possible of the scarce water available to him. Society, on the other hand, often wants scarce water to be released from agriculture to other sectors of the economy, including the environment. These two objectives are in conflict, and appropriate terminology to describe real water "saving" is central to informed debate on the issue.

In cases where the water accounting was well documented, there were important examples of water consumption increasing as farmers were able to expand the area irrigated per unit of water delivered to the farm (thus increasing consumption and reducing return flows), and/or where evapotranspiration increased along with biomass formation. In other cases, the water accounting was incomplete or not properly used to determine the impacts of interventions on water consumption and productivity.

The case study from California of tree crops is also revealing: because trees and vines expose relatively large areas of soil to direct sun, the potential to reduce non-beneficial evaporation is high. Yet the reduction in water consumed was on average less than 6 percent. For field crops, where the canopy is largely closed, even these meagre savings are unlikely to be achievable, as confirmed by the studies in India.

The cases analysed significantly tilt toward supporting the "zero sum game" hypothesis: the impact of (on-farm) hi-tech irrigation increases local water consumption and crop production *at the expense of* water availability and production elsewhere.

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[13] http://www.jains.com/irrigation/drip percent20irrigation percent20system.htm, viewed February 6, 2017

But beyond this rather disappointing first round impact, hi-tech irrigation has an additional effect that is more worrying. From the individual farmer's perspective, hi-tech irrigation makes water delivered to the farm more profitable: he or she can irrigate a larger area, obtain higher yields, and perhaps switch to higher value crops. These effects combine to make water an even more valuable input, making pumping more affordable, and increasing the incentives that the farmer has to obtain more water. In sum, the predictable impact of "more efficient" irrigation is to increase *current* consumption, and to increase *demand* for water—making scarcity both worse and more difficult to manage.

Among the case studies reported, the project in Oregon is particularly interesting: hi-tech irrigation was introduced explicitly to maximise water consumption and *minimise* return flows to the environment. Because these were the explicit objectives of the investments, the impacts were carefully monitored and accounted for. Hi-tech did exactly what science would anticipate – water consumption increased substantially, local biomass production increased and return flows decreased dramatically.

Hi-tech irrigation does have important benefits: it often saves labour; fertilisers and chemicals can be precisely and economically applied; leaching of nitrates and other pollutants is minimised; pumping costs may be reduced and energy may be saved[14]; and the farmer may be able to diversify into higher value crops. But the most commonly assumed benefit - that large quantities of water are "saved" - rests on two assumptions that are not evidenced by experience:

(i) *That traditional irrigation techniques are inefficient and wasteful of water, while modern techniques directly reduce losses.* Hydrology demonstrates that excess water applications do not "disappear". Even when some bare-soil evaporation occurs, most excess water returns to the groundwater or surface-water systems for re-use. Careful hydrological analysis of flow paths before and after system modernisation must be the basis for assessment of physical water savings, often revealing that savings are at most a fraction of the headline increase in "efficiency". Efficiency in irrigation may be required when water logging is a problem, as it is the case in several clay-soils of the Mediterranean, or to reduce the non-recoverable flows.

(ii) *That bio-physical Water Productivity (kg·m^{-3} of water consumed) increases significantly.* Crop science and experimental data for typical field crops suggest that biomass formation (yield) is essentially a linear function of water consumed by the crop, so that production increases are associated with commensurate increases in water consumption.

For the farmer, hi-tech irrigation allows some combination of increased irrigated area, increased quantity of production, and increased value of production. But in parallel with these benefits, current water *consumption* is likely to increase (with consequent decreases in return flows), and future *demand* for water will increase because water is a more valuable

[14] Though not always: when flood irrigation is converted to drip or sprinkler, the water must be pressurised, which increases the energy costs of irrigation.

input to the farmer. Jevons' paradox, predicting that improved efficiency of resource use tends to increase consumption and demand for that resource, applies also to water.

It cannot be claimed that exceptions to these general conclusions do not exist, and revisions to this paper incorporating such cases will be welcome. Meanwhile, this wide-ranging search for examples suggests that the conclusions stated above should be the default assumption—the null hypothesis—against which project and programme designs should be tested.

CHAPTER 6

Policy implications

These conclusions point to an essential ‘sequence of actions’ required to move towards sustainable water resources management. Historically the approach has been to promote (and often subsidise) hi-tech irrigation while expecting (or hoping) that demand for water would fall, and occasionally actually measuring the physical impact of the new technologies. In fact this sequence must be reversed:

- *first*, establish a water accounting system that provides quantitative estimates of the physical water balance (sources, diversions and withdrawals, consumption, return flows, changes to storage, etc.);
- *second*, set limits to water allocations (designed, based on the current water balance, to reduce consumption to sustainable levels);
- *third*, encourage and support all users to maximize the net benefit of allocated water. In this context, introduction of all possible measures such as hi-tech irrigation will find an appropriate place.

The process will be iterative. Estimates of the water balance will improve over time while allocations are adjusted accordingly—but information and control of water allocations are the essential first steps. This priority applies across all sectors, but is particularly significant in agriculture. Any changes in land use, whether converting forests to farmland, water-harvesting, modernising spate irrigation (van Steenbergen *et al*., 2010), or the more formal introduction of water storage and control for irrigation has implications for water availability elsewhere in the system and requires revision to projected water balances.

If the required transformational change towards sustainable water resources management is to occur, this revised ‘sequence of actions’ is critical. Countries need to enhance their ‘water accounting’ capacity, to be able to report and justify their proposed development trajectories towards future sustainable levels of water consumption, and set progressive and monitorable operational boundaries for water consumption. Finally, within those boundaries stakeholders should be encouraged, and typically will seek out ways to maximize the net benefit of water use.

In conclusion, it is hoped that this report will draw the attention on the path towards sustainable water resources management and stimulate discussion and the identification of any practical, alternative or complementary approaches to intervention and more positive outcomes.

Meanwhile, the evidence assembled so far has important implications for two of the key actors in the water sector: *Governments* have to take up their important and difficult responsibility in stewarding a critical national resource, and *donors/(* International Financial Institutions*) IFIs* should promote the use of the sequence of actions defined above—supporting governments who are addressing stewardship issues while avoiding funding for hi-tech modernisation projects in the absence of proper water accounting and prior control over water allocations.

A strong coordination between Ministry of Agriculture and Ministry of Water Resources is required, from planning to implementation of irrigation projects, to address the implication for water saving at the two major scales: on-farm and basin/watershed.

We invite all interested actors in the domain of sustainable water resources management and water scarcity to provide their feedbacks, documents and additional evidences on the issue of hi-tech irrigation and water saving at the following address WSI@fao.org.

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DOES IMPROVED IRRIGATION TECHNOLOGY SAVE WATER?

A REVIEW OF THE EVIDENCE

Regional Initiative on Water Scarcity
for the Near East and North Africa

The Near East and North Africa (NENA) Region has the lowest per-capita fresh water resource availability among all Regions of the world, consuming more than 85 percent of renewable fresh water resources through irrigation. Demography, food security policies, overall socio-economic development and climate change will accelerate the fast-widening gap between availability and demand for fresh water resources in the coming decades.

How can NENA countries simultaneously reduce this gap, promote sustainable water resources management and contribute effectively to food security?

Several measures are put in place. However, modernising irrigation systems remains dominant through typically converting the 'low-efficient' surface methods into the 'high-efficient' drip methods. The often underlying assumption is that increasing irrigation efficiency will allow to 'save' substantial amount of water that could be released for environment or other uses.

The evidence from research and field measurements shows that this is not the case. While the benefit at local "on-farm" scale may be dramatic, at basin scale total water consumption by irrigation tends to increase significantly.

The conclusion of this report is that restoring a balance between sustainable supply and consumption of water requires first physical control of the water resource by government or other agencies, followed by interventions to reduce allocations. Within the allocated and controlled quotas, irrigation technology will evolve and spread to the extent that it makes sense for the farmer. These conclusions have important implications for *Governments* and *Donors*.

With this report, we advocate to open up a discussion with all major stakeholders dealing with water resources management on the proper and sound framework required to address water scarcity and sustainability issues. A discussion that has been disregarded for too long.

Policy makers, water resources managers, irrigation developers and financial institutions are invited to provide their views and feedbacks to our dedicated e-mail:
WSI@fao.org

ISBN 978-92-5-109774-8

9 789251 097748

I7090EN/1/05.17