Managing the Real Water Consumer: Evapotranspiration

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1 Introduction

Water related problems are diverse and location specific, but water shortage is frequently the most pressing issue in many developing countries. Increasing international and intersectoral competition for scarce water, in the context of growing demand for food and uncertain impacts of climate change, is a central challenge for the next decades. In the context of achieving the Millennium Development Goals, water to sustain food production plays a key role. Access to water and irrigation is a major determinant of land productivity and the stability of yields.

However, in sub-Saharan Africa, only 4 percent of the area in production is under irrigation, compared with 39 percent in South Asia and 29 percent in East Asia. With climate change and reduced glacial runoff leading to rising uncertainties in agriculture, investment in using water more productively will be increasingly critical. With growing water scarcity and rising costs of large-scale irrigation schemes, opportunities to enhance productivity of water should be explored.

At the same time, agriculture, and more specifically irrigated agriculture, is often regarded as one of the main causes of water related problems. The 2008 World Development Report of the World Bank claims: “Agriculture is by far the largest user of water, contributing to water scarcity”. The very same report also concludes that “Without irrigation, the increases in yields and output that have fed the world’s growing population and stabilized food production would not have been possible.” In general, irrigated land productivity is more than double that of rainfed land.

However, policy makers and planners are often constrained, in this context of increasing complexity, by insufficient knowledge and tools to evaluate the consequences of alternative interventions, to make appropriate decisions. Furthermore, important misconceptions often underlie strategies proposed to address these problems.

In this paper the importance of focusing on evapotranspiration as the dominant water consumer (Figure 1) will be advocated. Methodologies to support policy makers and water managers to manage the evapotranspiration will also be discussed, and some practical examples will be given.

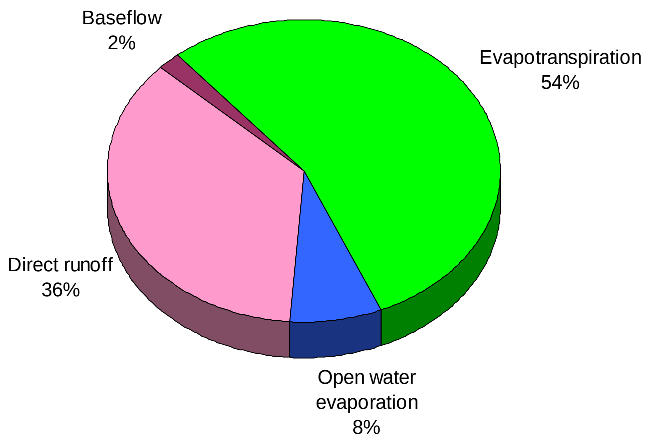

Figure 1. Global water use for land (source: Shiklomanov, 1999).

2 Evapotranspiration

2.1 Concepts

A persistent misconception is that irrigated agriculture is the main consumer of water (Figure 2). This misconception is mainly based on a combination of (i) ambiguous terminology and (ii) undefined domains. Regarding terminology, it is often unclear what is meant by “consumers”, “users”, “efficiencies”, “losses” and related terms. This has led, especially in irrigation science, to confusing policies (Allen et al., 2005; Seckler et al, 2002; Molden, 2007; Perry, 2008; Droogers et al., 2000).

A typical example is that irrigation science has traditionally focused on improving the “efficiency” while completely ignoring what happens with the “non-efficient” water. In many cases this “non-efficient” water is reused by downstream users, pumped from the groundwater, serves to reduce salt intrusion, or contributes to wetlands. It is quite common that a substantial amount of these “losses” is beneficial to the poorest in a region. From a discussion of these efficiency concepts, Perry (2007) showed that the following conclusions may be drawn:

- high efficiency reflects low losses;
- losses are a non-recoverable waste of resources;
- reductions in ‘‘losses’’ will mean that more of the input is available for alternative uses;
- high efficiency is ‘‘good’’.

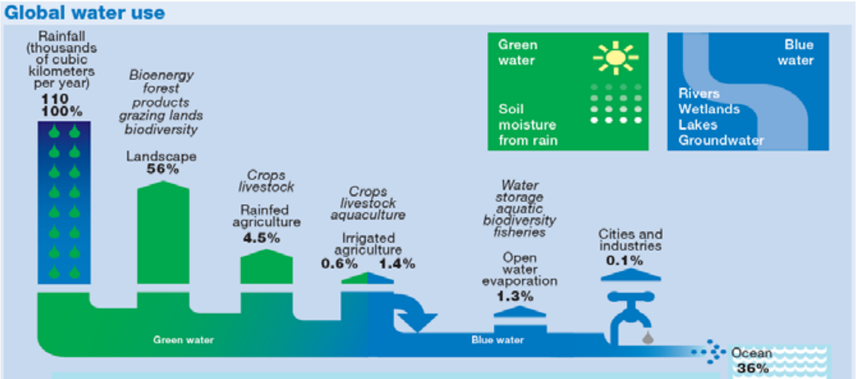

Figure 2. Global water use (source: Molden, 2008).

To overcome these misconceptions based on considering only the irrigation domain, the concept of “irrigation in the basin” has been promoted and partly put into practice over the last decade (Seckler, 1996; Kite and Droogers, 1999). This line of thinking is also reflected in the first of eight recommendations in the recently published result of the Comprehensive Assessment of Water Management in Agriculture (Molden 2007):
“*Change the way we think about water and agriculture. Thinking differently about water is essential for achieving our triple goal of ensuring food security, reducing poverty, and conserving ecosystems. Instead of a narrow focus on rivers and groundwater, view rain as the ultimate source of water that can be managed.*” (Policy action #1).

The basic concept put forward in this policy action is that one should realize that whatever policies are practiced, the ultimate restriction is always the total rainfall in a basin (provided that no inter-basin transfer occurs). Acknowledging that rainfall is the only source of water, one

could claim that there is effectively only one ultimate consumer of water: evapotranspiration. For water policy planning this can be summarized as:
In the same way as rain can be regarded as the ultimate source of water on the supply side of the hydrological equation, one could say that evapotranspiration is the only term on the consumer side.

This simple fact has tremendous impact on policies. In situations where the non-evaporated components of irrigation diversions return to the fresh water resource for reuse by others, conservation programs may not stretch water supplies or "save" water in the region, especially in the long-term. Water conservation programs should fundamentally be evaluated against the general principle that the only real loss of water from an irrigation project is by the process of evaporation from open water surfaces, evaporation from soil and wet foliage, transpiration from vegetation, and flows into saline sinks. In fact one should go back to the fundamental hydrologic concepts that were already recognized by the early Greek philosophers, and mathematically underpinned in the 18th century by Bernoulli and Chezy amongst others (Hubart, 2008).

The term evapotranspiration (ET) relates to three components: (i) interception evaporation, (ii) soil evaporation, and (iii) crop transpiration. The interception evaporation for agricultural crops is often around 10% of the total ET, while for forests this can go up to 80 to 90% depending on the prevailing climate conditions. Soil evaporation can be a substantial amount of the total ET, especially at the time of crop emergence when leaf cover is very limited. Crop transpiration is in fact the only term that can be considered as a productive use, since it supports vegetation growth. One should realize that less than one percent of the transpired water is actually retained by the vegetation. Carbon dioxide is the only carbon source for plants and in order to obtain this, plants have to open their stomata. During this process, water diffuses outwards and one could claim that plants have to transpire water to obtain the required carbon. In addition to this, some water might be transpired to maintain plants' internal temperature at acceptable levels.

Ignoring ET and simply reducing water diversions almost always results in a reduction in return flow back to the resource. Therefore, the quantity of net consumption by an irrigation system may be largely unchanged by a conservation program. To effectively create "new" water in a regional context, unless directly upstream of a salt sink, a conservation program must in some way reduce ET or improve return flow quality, and not simply reduce diversions. Reduction of crop ET will almost always reduce crop yields, unless evaporation from soil is reduced without reducing plant transpiration.

In fact one can only evaluate the performance of an irrigated area by examining the irrigation water when it leaves the defined boundaries of interest. The applied irrigation water can be placed into five categories (Clemmens and Allen, 2005):

1. Water consumed by the crop within the area under consideration for beneficial purposes.
2. Water consumed within the area under consideration but not beneficially.
3. Water that leaves the boundaries of the area under consideration, but is recovered and reused by the same party or by a “downstream” party.
4. Water that leaves the boundaries of the area under consideration, but is either not recovered or not reusable.
5. Water that is in storage within the area under consideration.

In practice much emphasis in irrigation engineering has been on category 3 using the concept of efficiencies, while category 2 and 4 are those that deserve greater recognition by policy makers and water managers.

A similar approach based on the diversion of water allocations was advocated by Perry (2007) who stated that all water that enters a certain domain (irrigation, streamflow and rainfall) can be classified into four terms:

1. Beneficial consumption: Water evaporated or transpired for the intended purpose – for example evaporation from a cooling tower, or transpiration from an irrigated crop.
2. Non-beneficial consumption: Water evaporated or transpired for purposes other than the intended use – for example evaporation from water surfaces, riparian vegetation, or waterlogged land.
3. Recoverable fraction: water that can be captured and reused – for example, flows to drains that return to the river system, percolation from irrigated fields to aquifers, or return flows from sewage systems.
4. Non-recoverable fraction: water that is lost to further use – for example flows to saline groundwater sinks, deep aquifers that are not economically exploitable, or flows to the sea.

Based on these discussions, it is clear that only by considering the basic concepts of hydrology, and continuity of mass can proper intervention options be explored. When water is scarce, key areas of attention would be to reduce non-beneficial consumption, and to reduce non-recoverable flows to the extent that proper hydrological analysis shows that no unintended consequences of such reductions occur. Based on this conclusion, it is essential that all terms of the water balance should be known.

2.2 Policy Support Tools

From the previous section it is clear that a focus on ET is justified and is required to understand water related issues and improve water management. The concept of ET management requires innovative and policy-oriented supporting tools. Figure 3 provides a conceptual framework highlighting that a clear distinction should be made between understanding and monitoring the past and the current situation on the one hand, and pro-active planning using modelling tools on the other hand.

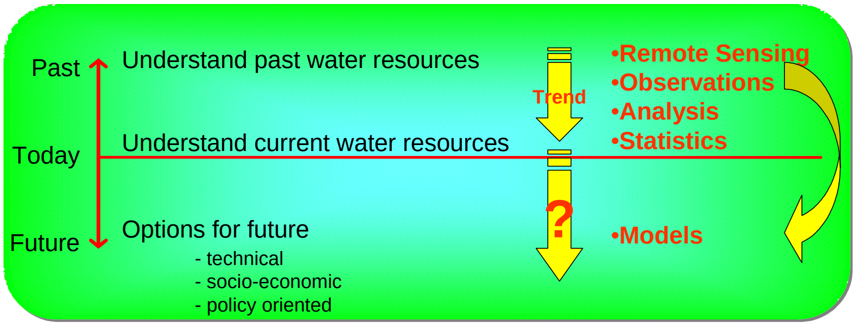

Figure 3. The concept of using policy oriented supporting tools.

In terms of monitoring ET, special emphasis should be put on remote sensing. One could safely claim that remote sensing is the only tool available nowadays to monitor ET over large areas.

Over the last decades various ET algorithms have been developed to make use of remote sensing data acquired by sensors on airborne and satellite platforms. The reported estimation accuracy of various methods varied from 67 to 97% for daily ET, and greater than 94% for seasonal ET, indicating that they have the potential to estimate regional ET accurately (Gowda et al., 2008). Only in the last decade have these tools made the transition from research to application. In particular, the SEBAL approach, introduced in 1998 (Bastiaanssen et al., 1998), and some successors (SEBS: Su, 2002; METRIC: Allen et al., 2007), have been influential in promoting acceptance of these remote sensing approaches into operational and strategic decision support systems.

All policy should be based on comparing different options (interventions) for the future, and requires appropriate planning tools in the form of simulation models (Droogers and Kite, 1999). Over the last decades models have been used successfully to support policy-making by firstly improving understanding of processes, and secondly by conducting scenario analyses. The main reason for the success of models in promoting understanding of processes is that they can provide output over an unlimited time-scale, at an unlimited spatial resolution, and for sub-processes that are difficult to observe (e.g. Droogers and Bastiaanssen, 2002). The most important benefit of applying models, however, is their use to explore different scenarios. These scenarios can capture aspects of the water management system that cannot directly be influenced, such as population growth and climate change (Droogers and Aerts, 2005). These model outputs are often referred to as projections. In contrast, management scenarios or interventions can be simulated where water managers and policy makers can make decisions that will have a direct impact. Examples of the latter are changes in reservoir operation rules, water allocation between sectors, investment in infrastructure such as water treatment or desalinization plants, and agricultural/irrigation practices.

A huge number of hydrological models exist, and applications are growing rapidly. The number of pages on the Internet including “hydrological model” is over 300,000 (Google, November 2008). Using the same search engine with “water resources model” results in 13 million pages. A critical question for hydrological model studies is therefore related to the selection of the most appropriate model. One of the most important issues to consider is the spatial scale to be incorporated in the study and how much physical detail needs to be included. Figure 4 illustrates the negative correlation between the physical detail of a model and the spatial scale of the application. This figure also indicates the position of commonly used models in this continuum.

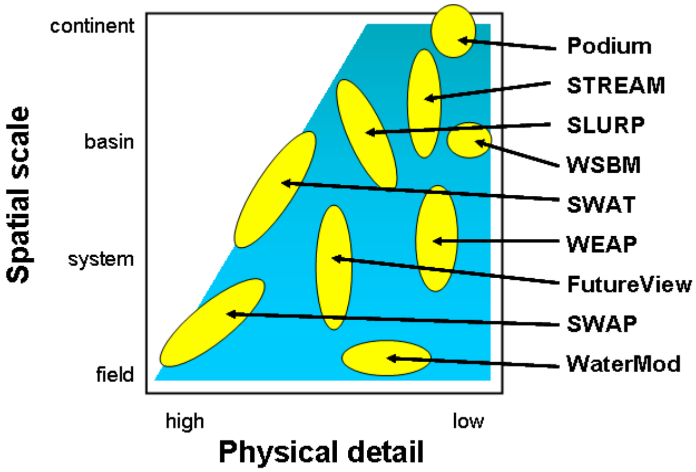

Figure 4. Spatial and physical detail of hydrological models.

3 Examples

Over the last years several projects have been started where ET was considered as a key component of the overall objective to improve water management. Three of these projects will be summarized in the following sections.

3.1 China's Hai Basin

The Hai Basin in P.R. China is experiencing groundwater overdraft, resulting in dropping groundwater levels and water shortages. The water balance shows a non-sustainable situation, with more water leaving the basin than water entering it. Outflow from rivers in the Hai Basin barely reach the Bohai sea, and most of the water leaves the area through ET.
Although much information is available on agricultural water allocation to individual fields, real water consumption (actual ET) is lacking. Moreover, water consumption at the basin scale is essentially unknown. The GEF World Bank project "Hai Basin Integrated Water and Environment Management Project" aims at managing ET to restore groundwater levels and maintain outflow to the Bohai Sea (Bastiaanssen et al., 2008).

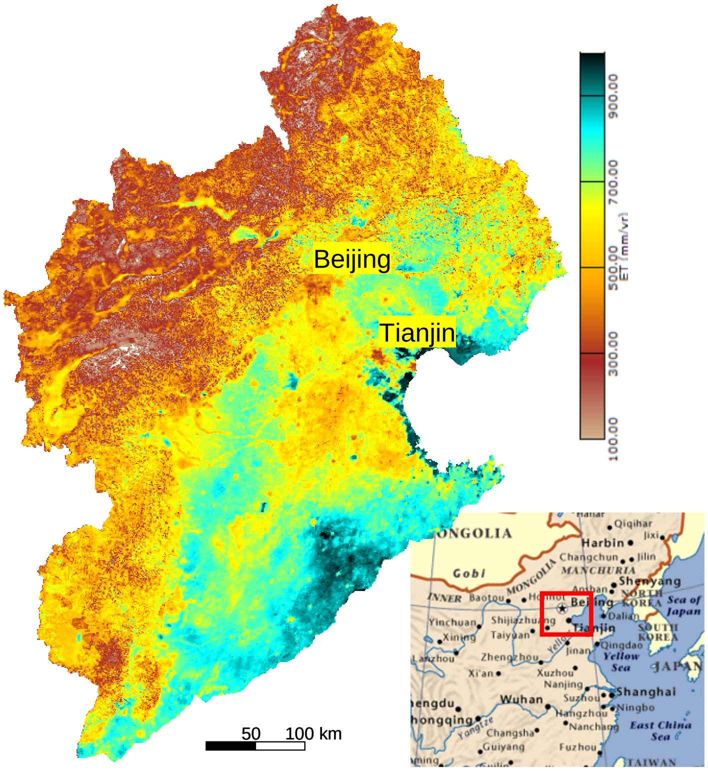

Figure 5: Actual annual evapotranspiration (2002) for the Hai Basin.

In this project, ET from the Hai Basin is calculated using remote sensing measurements. Based on these observations, allocation plans for each county are under development and by using various modeling tools, scenarios for the future to reduce ET are explored. A typical example of some of the policy-supporting tools is the basin-wide water consumption map shown in Figure 5. This map has been aggregated per county and is currently used to define water quotas. An innovative aspect is that these quotas will not be based on allocations, but on real water consumption (actual ET). A major advantage of this approach is that allocations that yield return flows to downstream counties are not considered as consumption.

To support county water managers to develop plans to reduce ET, various modeling tools have been setup. A typical example of exploring the impact of a certain intervention is shown in Figure 6. This example shows the impacts on ET and groundwater of reducing irrigation by 50%.

The Hai Basin project is ongoing, but the uptake of the concept of ET management is impressive. Chinese policy makers and water managers have developed their own remote sensing applications and suit of models to focus on real consumption rather than on allocations.

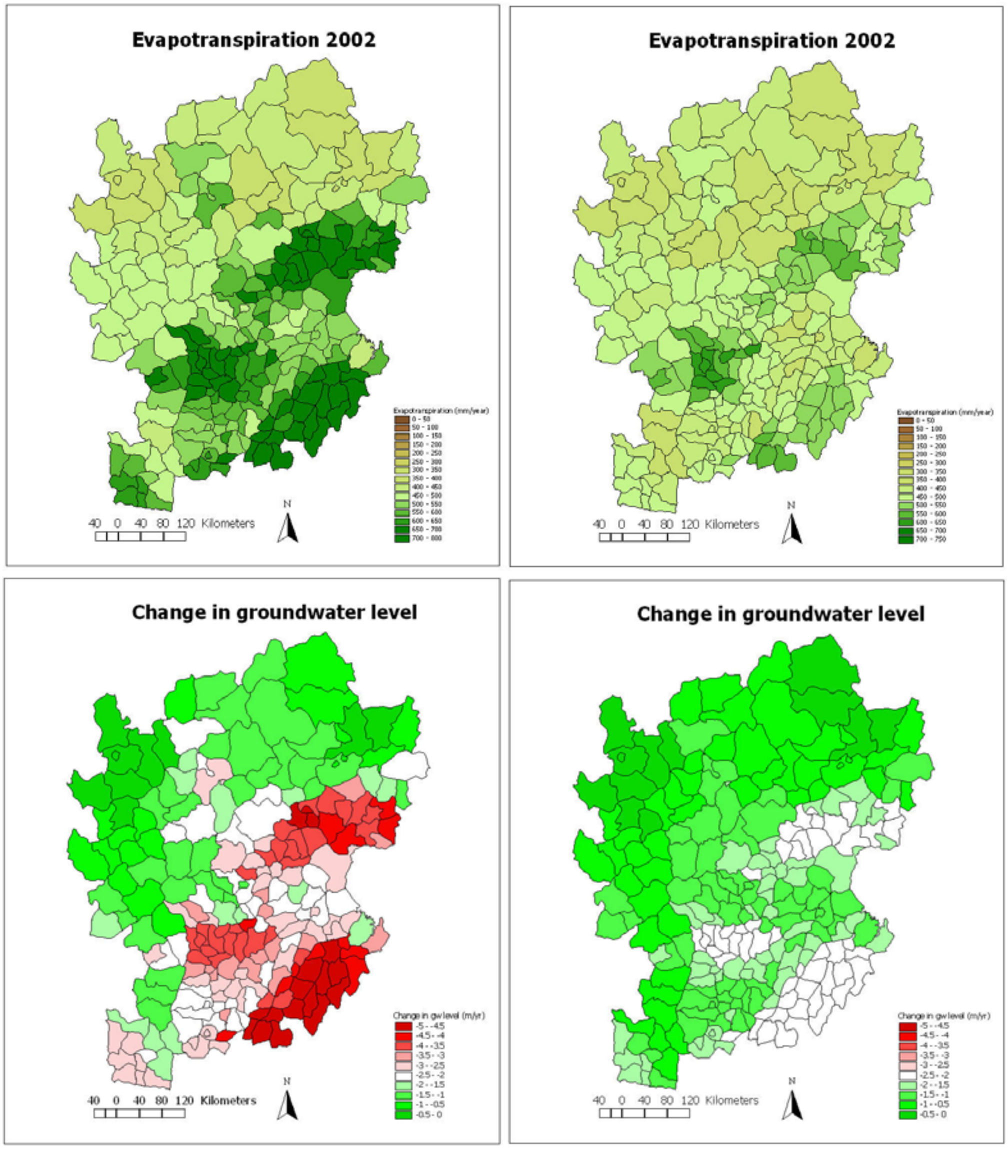

Figure 6: Scenario analysis applicable to counties in the Hai Basin, China: impact of reducing irrigation by 50% (right) compared to the current situation (left) on ET (top) and groundwater (bottom).

3.2 Egypt

Debates on the actual water balance of the Egyptian part of the Nile Basin have persisted over decades. The political sensitivity of the Nile Water Agreements of 1959 has made it virtually impossible to obtain realistic numbers on actual consumption. The agreed 55.5 km^3 entitlement is often equated to the total amount of water consumed. However, expansion of irrigated areas, large amounts of uncommitted flows to the sea, and water savings attempts have made the situation even more confusing. The main problem is that no information at all on real water consumption (actual ET) has been available.

A recent study (Droogers et al., 2008b) combined various completed studies focusing on the main question: how much water is actually used in contrast to the amount of water that is allocated. The cornerstone of the analysis were remotely-sensed ET estimates of the Nile (Bastiaanssen et al., 2003; Noordman and Pelgrum, 2004).

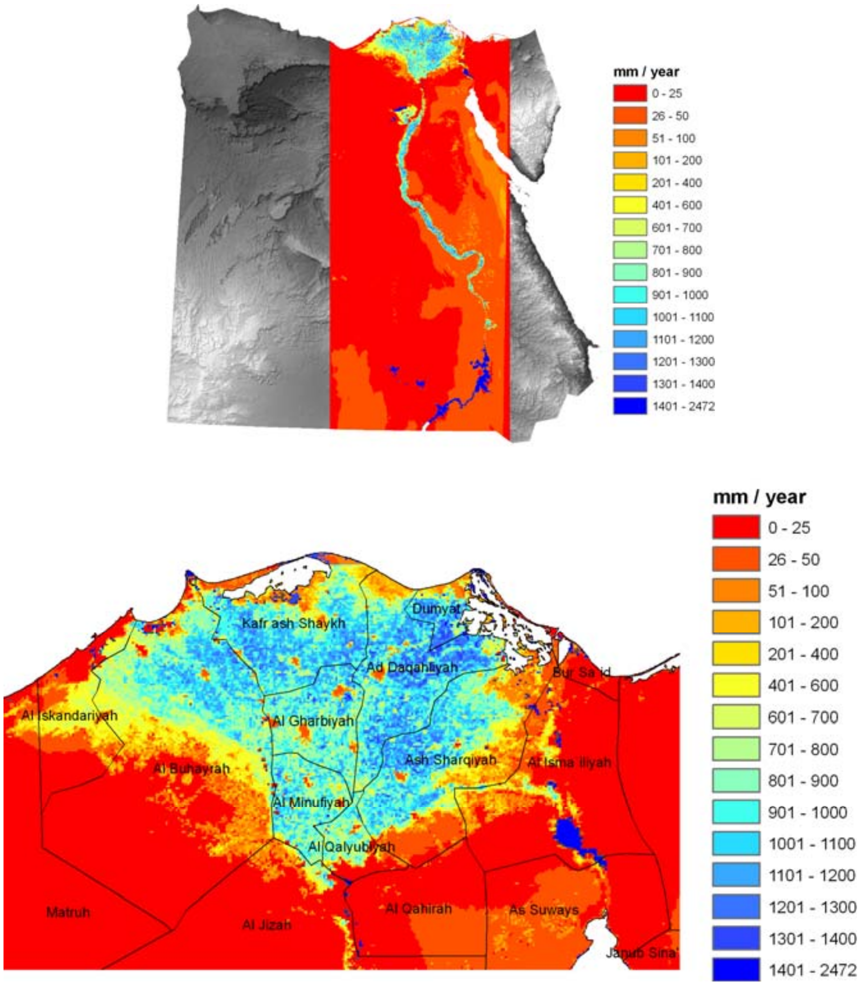

Figure 7. Actual evapotranspiration for 2007 in the Nile delta based on remote sensing.

Figure 7 shows the actual ET over the entire Nile Basin in Egypt for one particular year (2007). By using comparable information from other years, the long-term actual ET for irrigated lands is estimated at 32 $km^3\ y^{-1}$, while ET from non-irrigated areas (mainly from seepage) is about 8 $km^3\ y^{-1}$. Actual water allocations over the last decade, as recorded at Aswan, are higher than the 55.5 km^3 entitlement, and are on average 68 km^3 per year. Based on these figures, and including some other data sources, the entire Nile Basin water balance has been constructed (Table 1).

The study showed that focusing on the real water consumption, based on unbiased non-political estimates from remote sensing, provides decision makers with the necessary information to discuss the Nile water resources.

Table 1. Estimated water balances for the Nile Basin in Egypt for a representative year under current conditions.

In (km^3)		Out (km^3)	
Outflow Aswan	68.0	ET irrigation	32.0
Rainfall	0.5	ET other	8.0
		Industry/domestic	1.0
		ET seepage	2.3
		Outflow to sea (rest)	25.2
Total	*68.5*	*Total*	*68.5*

3.3 Scenario-Based Modeling

As indicated earlier in this paper, various modeling tools exist ranging from completely physically-based models to conceptual allocation models. Policy makers require models that have a focus on scenario analyses, rather than models that are too complex to use for practical applications. There are too many modeling studies where the final conclusion is that the model is able to mimic reality. Moreover, in many cases relative model accuracy (comparing model base-line with model scenario) is much higher than the actual accuracy (comparing model to observations) (e.g. Bormann, 2005; Droogers et al., 2008a).

For a hypothetical basin, derived from a real situation in Northern Africa, concepts of scenario analysis were demonstrated (Droogers and Perry, 2008). The hypothetical basin comprises four catchment areas and two irrigation systems, one upstream and one downstream in the basin (Figure 8). Groundwater tables in the basin are dropping at alarming rates and interventions are discussed to improve the efficiency of the irrigation systems. The latter are based on observations that the efficiency, defined as the amount of water allocated to a system divided by the uptake of plants, is around 50%. Based on this number, it was concluded that huge amount of water could be saved.

However, a first basin-wide analysis showed that by far the major consumers of water in the basin are forests and natural vegetation. Actual ET from irrigated crops is about 20% of overall ET in the basin. Since managing ET from forests and natural vegetation is difficult, the focus here remains on irrigated agriculture. Note that managing non-irrigated water consumption has been under debate for reforestation projects, as in many cases these new forests consume more water by ET compared to the original vegetation (Calder, 1999).

Considering only the irrigation sector, it is important to evaluate the different locations of the two irrigation systems in the basin. Irri01 is located upstream and outflow of this system might be reused downstream, while outflow of the downstream system is lost from the basin. In Figure 9 the water balance of the two systems is depicted, indicating that about 50% of the incoming water (irrigation and rainfall) is consumed by ET. In terms of water saving programs, it is important to recognize three different outflow components:

- beneficial outflow: crop transpiration
- non-beneficial outflow: soil evaporation, drainage (downstream)
- reusable outflow: percolation (upstream), drainage (upstream)

By estimating these three terms, different interventions for the upstream and the downstream irrigation systems can be assessed to obtain the real water saving.

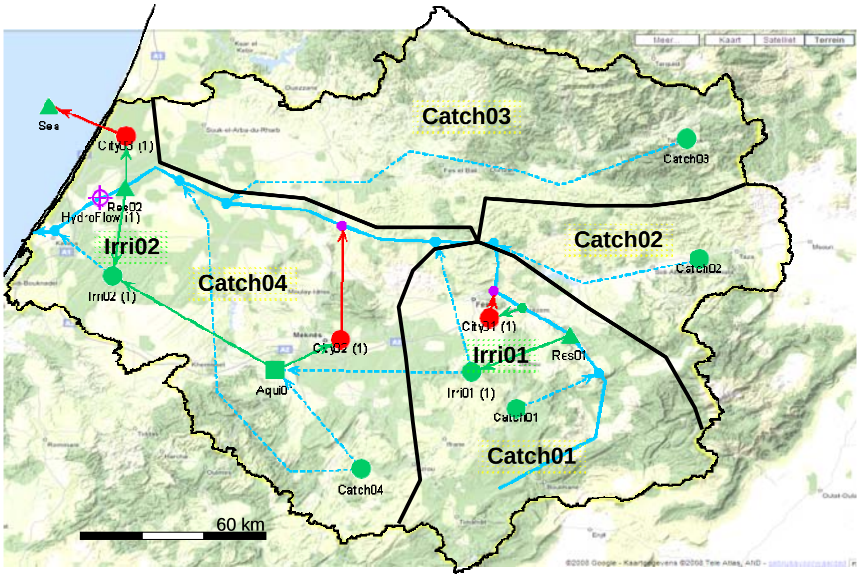

Figure 8. Hypothetical basin including the four catchment areas.

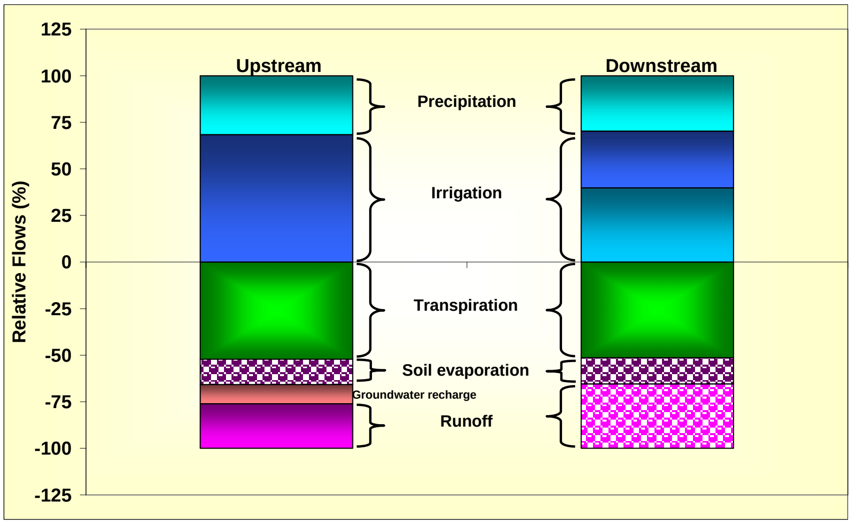

Figure 9. Water balance of the two irrigation systems.

4 The Way Forward

The main message conveyed in this paper is summarized by the following four points:

- Evapotranspiration (ET) should be considered as the main consumer of water, in the same way as rainfall is regarded as the only source of water.
- Irrigation should always be considered in a location-specific (basin) context.
- Remote sensing data can support policy making by evaluating current and past water consumption (ET).
- Simulation modeling supports policy making by evaluating different scenarios (interventions).

In practice this means that projects should include an evaluation of the full hydrological cycle considering the appropriate domain. The preferred domain in this respect is not the irrigation system but a hydrological (sub)basin. In cases where the entire basin is not considered, one should understand the upstream and downstream interactions of the domain under study.

Policy supporting tools should include a combination of remote sensing and simulation models. A somewhat unexplored subject is the role that remote sensing information can play in calibrating models (Immerzeel and Droogers, 2008). Currently, model development has progressed to the extent that further development is hardly required for pratical applications; the main challenges are in obtaining data and information necessary as inputs to these models (Immerzeel et al.,2008). Typical examples of remote sensing products that have emerged recently to the benefit of user groups include (i) actual rainfall provided by the TRMM satellite, (ii) actual ET information available on a near real-time basis, and (iii) changes in groundwater observed from space using the GRACE satellite (Figure 10 to Figure 12).

This information is essential to obtain realistic model outputs that can be used to explore the impact of interventions. A typical example of such an approach is the ongoing IFAD project in Kenya on Green Water Credits (Dent and Kauffman, 2008). By combining remotely sensed information and modeling tools, a much better understanding of the impact of certain interventions on all water related issues, including erosion, can be obtained (Figure 13 and Figure 14).

Finally, the phrase by Lord Kelvin “To measure is to know” can be expanded to “To measure ET is to know where to act”.

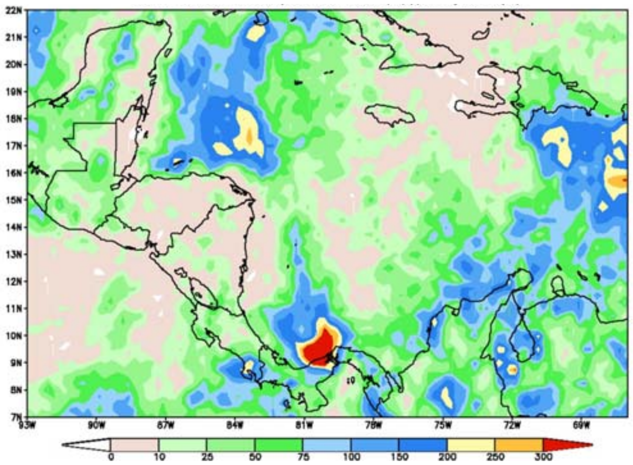

Figure 10. Satellite-estimated precipitation (TRMM) 22-28 October 2008 (source: http://trmm.gsfc.nasa.gov)

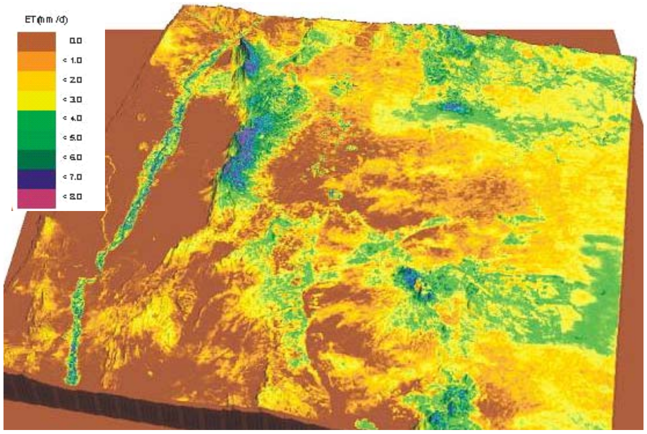

Figure 11. Remote Sensing of actual ET, Rio Grande, New Mexico, June 16, 2003 (Source Hong and Hendrickx, 2003).

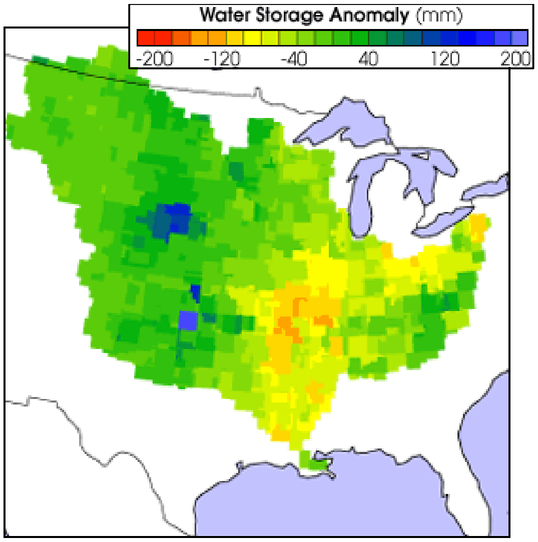

Figure 12. Typical example of GRACE results showing changes in groundwater for the Mississippi Basin, July 2005 (Rodell et al., 2006).

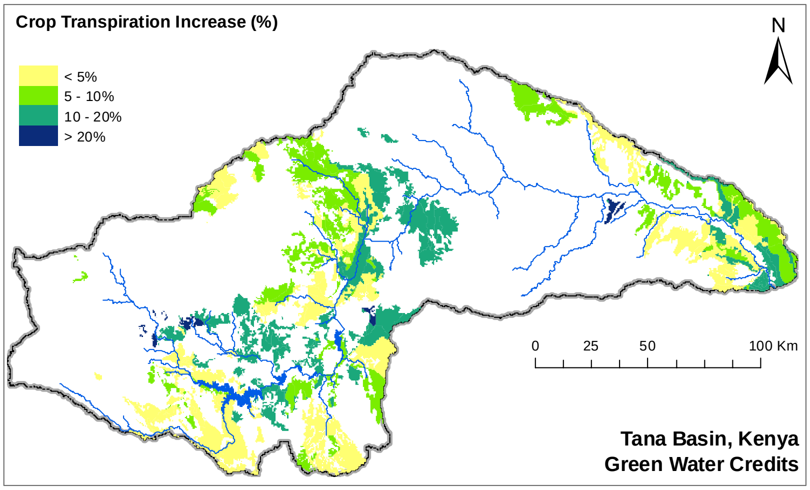

Figure 13. Scenario analyses for the Tana Basin, Kenya. Spatial variation of increases in actual crop transpiration under the Enhance Water Productivity scenario.

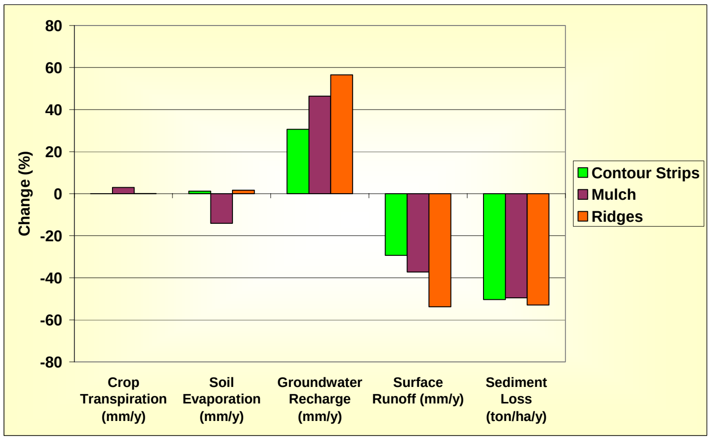

Figure 14. A comparison of three water management scenarios in the Tana Basin, Kenya.

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