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# A Developing Crisis in Irrigation Advisory Services

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## Abstract.

*Driven by increasingly severe water shortages, irrigation management advisory services will need to achieve dramatic advances in analytical capabilities in the span of a decade or two. Limited water supplies are driving the adoption of deficit irrigation strategies, requiring more precise control of soil water conditions to manage - rather than avoid - crop water stress. Increasing dependence on waste water reuse is stimulating interest in bioremediation in the rhizosphere for distributed, low cost tertiary treatment of irrigation return flows even before they leave the root zone. These paradigm changes will depend upon more precise management of soil water movement, dwell times and root system contact.*

*These and other developing challenges imply an order of magnitude increase in complexity of irrigation management, and a corresponding need for far more sophisticated advisory services. The window of time is short; 'next generation' advisory services are already needed in many areas of the world.*

**Keywords.** Irrigation, optimization, deficit irrigation,

## Introduction

As an introduction to this paper it is instructive to consider three recent events involving food and water. One event was the sharp decline in worldwide grain reserves in 2008. Seeing the volatility in food prices of 2008 as an early warning sign for what lies ahead, key policy makers have begun taking food security seriously for the first time since the beginning of the Green Revolution of the 1950's (Baulcombe, 2010). In short, the recent food shortages of 2008 are seen as the beginning of what promises to be a recurring crisis.

A second event was an address to the World Economic Forum in Davos last year by Ban Ki-Moon, Secretary General of the United Nations, who observed; *"we have enjoyed a series of regional water bubbles to support economic growth over the past 50 years or so, especially in agriculture. We are now on the verge of water bankruptcy in many places with no way of paying the debt back. In fact, a number of these regional bubbles are now bursting in parts of China, the Middle East, the southwestern US and India; more will follow."*

A third event is the development of water markets in response to the prolonged drought in the Murray-Darling Basin of Australia. For generations farmers there have regarded water as a free resource and an immutable entitlement, much the same as we do in the western US. But in response to the persistent and devastating drought that attitude has been shifting. Water markets there were sanctioned by the government beginning in 1991 as a strategy to make best use of the limited supplies of water. Initial resistance to that arrangement gave way to widespread adoption. By 2004 more than 82% of all farms had participated in water trading at some time, and the general perception was that the markets had saved much of the agricultural industry (Bjornland, 2006).

These anecdotes highlight three converging forces that are beginning to change the way irrigation is practiced; (i) we are entering a period of food shortages that will not end in the foreseeable future;(ii) those food shortages will be aggravated by water shortages in much of the world; and (iii) the natural response of irrigated agriculture will be to allocate irrigation water in the most economically efficient way.

The implication of the third of these items is that irrigated agriculture will need to adopt a new management paradigm, maximization of net economic returns to water. That paradigm shift will be a major challenge for irrigation advisory services. And the indications are that we do not have the luxury of time. We must move quickly to be ready to deal with the accelerating competition for water and the increasing demand for food production from irrigation agriculture.

## Shortages of food and water

During the last 50 years irretrievable water use has increased more than 400%. By the end of the last century we began to recognize that the world is approaching the limits of available water. Sandra Postel, in a seminal 1996 article in Science estimated that by 2025 the world demand for fresh water might be approaching the limits of readily accessible supplies (Postel et al., 1996) . Her assertion was reinforced by Harald Frederiksen (1997), then head of the Water Resources sector of the World Bank, who had concluded that: *"Given the variability of climates and the inertia of political and social institutions … a worldwide water crisis may already be unavoidable."* Today we are seeing those forecasts play out in local instances of water bankruptcy. Figure 1 indicates the startling rate of decline of per capita water availability in some representativecountries (derived from Sekler, et al, 1998).

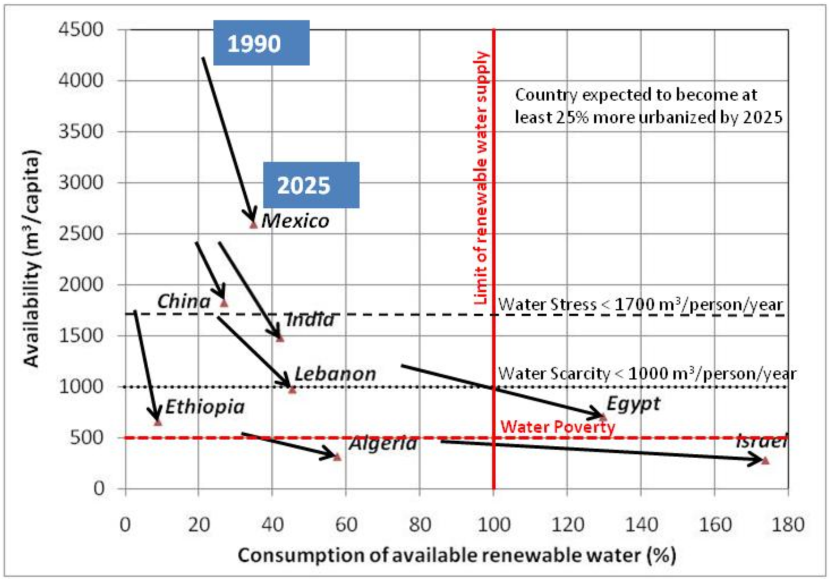

**Figure 1: Declining Water *per capita* – 1995 to 2025**

The problem of water shortages aggravates - and is aggravated by - other issues. Again citing Ban Ki-Moon's words: "water security is the gossamer that links together the web of food, energy, climate, economic growth and human security challenges that the world economy faces over the next two decades."

David Baulcombe articulated the broader problem succinctly; "Somehow the world must produce 50% to 100% more food than at present under environmental conditions that have not applied in the past." (Baulcombe, 2010). The environmental conditions he was talking about are stark: "The highest levels of food crop productivity in many regions deplete stocks of non-renewable resources, damage ecosystem services, and have a large carbon footprint (through carbon depletion of soils, fuel combustion and the energy cost of fertilizer production). Thus the challenge of water supply not only concerns the amount of food produced, it is also about equity, energy use and sustainability."

## Meeting the challenges

The various ways that individual countries might meet these challenges might be classified as follows:

- "Sustainable intensification", which is defined as crop production that is: resistant to stresses and diseases; produces consistent yields using renewable inputs; avoids depletion of minerals, biodiversity and natural capital; and protects ecosystems services. The goal is high yields with lower inputs of water or fertilizer. Sustainable intensification will largely depend upon breeding or genetic modification, rather than changes in irrigation practices. The likely price of sustainability may be some reduction in yields from the most intensive, industrial farming of today.
- "Virtual water"; At a UN sponsored convocation of water resource leaders of middle eastern countries in Egypt in 2003, most of which are nearing the limits of exploitable water, virtual water (e.g. buying Canadian wheat produced with Canadian water) was often cited as a solution for water short countries. But a principle conclusion reported by the World Economic

Forum last year was that; “with agriculture remaining a thinly-traded good, gains from trading virtual water are limited.”

- “Capping demand”; water demand management is seen as a cost effective way to deal with shortages in water supplies, particularly in developing countries where it will often make it possible to postpone large investments in water supply infrastructure. It has been estimated that demand management could defer large investments in water supply infrastructure; for example, a $2 million investment in demand management might delay a $200 million investment in new infrastructure for ten years (Joberg, 2007).

### *Capping demand*

It is the third of these options where irrigation management will be a central issue. Joberg (2007) outlined four general approaches to capping demand: (i) institutional changes in the control of water resources (such as decentralization of control or privatization); (ii) market based strategies; (iii) non-market interventions (e.g. legal restrictions); and (iv) direct interventions (maintenance, technical innovation). The first three of these strategies can change the perception of irrigation water from a free resource to an economic input, the use of which must be rationalized by net economic returns and the stewardship of which must account for externalities.

That altered perception of irrigation water as an economic input with associated costs and responsibilities will motivate adoption of a different management paradigm; rather than the current, widely accepted paradigm of maximizing crop yields per unit of land, the goal of the coming decade will become maximization of net benefits per unit of water use. Benefits may be defined narrowly as net farm profits, or more broadly to encompass food security, pollution abatement or other social objectives, but one essential fact remains: the new management paradigm implies deficit irrigation in some form and to some degree.

## The role of irrigation

Irrigation is the overwhelmingly dominant factor in global water use, accounting for about 70% of all water diversions worldwide, and on the order of 90% in the most water-short countries. It is inescapable that the developing water crisis will require maximizing economic efficiency of irrigated agriculture. Efficient use of irrigation water is determined by the intrinsic efficiency of the application system and the effectiveness of irrigation management. It is a widely held opinion of irrigation professionals that irrigation management is the weakest link (Hennesey, 1997) .  Let me point out three challenge areas which need to be addressed within the next ten or twenty years.

1. Irrigators of the future will necessarily adopt deficit irrigation management strategies to maximize net economic returns or net benefits of water use;
2. They will rely to a greater extent on reuse of wastewater, and that will involve Ecological Engineering as an integral part of irrigation system management;
3. The scope of issues to be dealt with by irrigation engineers will expand to encompass a wider range of challenges that we have given little thought to in the past.

### *Deficit irrigation*

Today the conventional management paradigm is first to apply sufficient water to prevent crop stress that would reduce crop yield or quality, and secondly to do so with the minimum required water in order to minimize the environmental costs of irrigation. But basic economics indicate that net benefits derived from a limited irrigation water supply will be maximized by deliberately applying something less than the maximum crop water requirements. And because deliberate under-irrigation further reduces return flows and the environmental costs of irrigation it is consistent with good stewardship. These precepts imply the need for a new management paradigm: deficit irrigation, the deliberate under-irrigation of crops. Water stress will be accepted and managed rather than avoided.

### *Ecological engineering*

Recapture and reuse of wastewater offers the only source of additional water for irrigation in many areas where water supplies are limited. One area of Ecological Engineering[1] deals with management of rhizosphere processes in the root zone. With precise control of rhizosphere processes we can mitigate and even reverse the water quality degradation associated with irrigation. To that end, the irrigation engineer of tomorrow may be managing irrigation to insure sufficient root zone dwell time and root system contact to take advantage of rhizosphere processes that break down organics, sequester heavy metals and capture excess nutrients. If done effectively, nutrients in applied water can be captured and utilized by crops, and the quality of return flows can be higher than the original diversions.

### *Increased scope*

Other issues will increasingly impinge on irrigation practice to promote societal objectives other than food production. Two important examples are climate change and public health. Irrigation management will inevitably be a key factor in mitigation of climate change. The large carbon footprint of intensive agriculture, through carbon depletion of soils, fuel combustion and the energy cost of fertilizer production, can be minimized by reductions in all of these inputs as part of a deficit irrigation strategy.

Regarding the issue of public health, many developing countries are moving aggressively to expand irrigation, but development of irrigation schemes often entrain a series of other public health issues. The water may provide a medium for movement of pathogens and create an environment for vector-borne diseases. Outbreaks of malaria, filaria, encephalitis and bilharzia often follow new irrigation development. When pesticides are used to control the disease vectors -- the mosquitoes in the case of malaria -- the residues of pesticides often end up mixed with domestic water supplies, creating another public health problem. (To further complicate matters, mosquitoes are becoming increasingly resistant to pesticides.)

Finding water management-based interventions to control these problems is emerging as a prominent issue. The International Water Management Institute (IWMI) has declared it a research priority to determine how irrigation management can help control malaria. Controlling disease vectors may require that the irrigation schedules include significant intervals when irrigation will be stopped altogether at strategic times.

Other examples include public health, social equity in land redistribution, full employment and population dispersal, all of which are already objectives of irrigation projects in some countries.

### *Irrigation management for the next decade*

All of these considerations imply a need for a much higher level of precision in our management of crop water use than is common today. Current irrigation management generally employs a simple decision rule: irrigation should commence when soil moisture reaches a stipulated ‘management allowed depletion’. Because soil moisture often varies dramatically throughout a

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[1] Defined by Oregon State University, which now offers undergraduate degree program by that name

field, and determinations of soil moisture based on either cumulative evapotranspiration (ET) or soil moisture measurements are actually quite uncertain, management based on soil water depletion is generally uncertain. Where water is cheap and abundant the problem of uncertainty can be avoided by relying on a margin for error; maintaining soil moisture content well above critical levels and keeping some soil moisture in reserve as a hedge against uncertainty.

But deficit irrigation, the paradigm of the future, must be managed differently. Crops will be subjected to managed levels of stress, and maintaining reserves of soil moisture to prevent unintended stress will be costly. Techniques for monitoring crop stress using such technologies as infrared thermometry, stem water potential or trunk diameter may offer a way to know more precisely when a crop has reached a management allowed stress. But optimization of irrigation water use depends upon prediction; we need to be able to predict when a stipulated level of stress will be reached in a specified fraction of a field, what water supply will be needed to implement the desired stress regime, and ultimately, what crop yield will result. To do that we must link water use and yield to the stress indices we use.

Perhaps the most important challenge will be reliable modeling of crop responses to applied water. Since general yield models usually are based on crop transpiration, accurate modeling of crop yields for entire fields will probably require modeling patterns of crop transpiration in heterogeneous fields.

In view of these considerations, a more appropriate decision rule would be to irrigate when a specified fraction of the field has reached an allowable level of depletion with a specified probability. For example, we might call for irrigation when there is a 25% probability that 50% of the field has reached 40% depletion, or 50% of the field has reached a specified level of crop stress. Such a decision rule will require that we quantify the statistical characteristics of soil moisture, the uncertainty of soil moisture determinations, and the relationship between soil moisture and whatever stress index we use.

Implementing such a decision rule will not be possible without monitoring and controlling spatially variable patterns of soil water content in heterogeneous fields, anticipating the spatial distribution of water stress in fields and estimating how field-wide crop yields will be affected by the resulting patterns of stress. Additionally, management of rhizosphere processes will depend upon carefully controlled movement of water through the root zone. Rather than simply applying water at or below the infiltration rates of soils, irrigators will need to virtually *titrate* the water at rates designed to achieve desired dwell times and root system contact.

Experience with prototype development of advanced irrigation advisory programs to support optimal use of limited water indicates that the analytical engines and client interface software will need an order of magnitude increase in computational power and sophistication than the programs of today. Development of such programs will be a continuous evolutionary process that can be expedited by building the program in the public domain. And producers using such programs will require intensive field support.

## *Challenges for irrigation advisory programs in the coming decade*

Principal analytical challenges will include:

1. *Modeling of application efficiencies*: application efficiencies are normally assumed *a priori* in conventional irrigation management, but since efficiencies vary with irrigation management strategies they must be explicitly analyzed for partial irrigation. That will require modeling the disposition of applied water; i.e. the spatial variability of applied water, surface water accumulation and redistribution, spray losses and, ultimately, the spatial distribution of soil water content.

2. *Modeling rhizosphere chemistry and biological processes*: to insure sustainability by managing root zone salinity and optimizing bioremediation in the rhizosphere to insure uptake, sequestration or decomposition of factors that threaten sustainability.
3. *Conjunctive irrigation scheduling:* simultaneous scheduling of irrigations for multiple fields that share a common source of water, rather than scheduling each field independently, to facilitate optimal allocation of limited water among multiple fields;
4. *Long range (full season) forecasting of crop water requirements:* in order to better anticipate when irrigation demands will exceed delivery system capacities, giving irrigation managers more time and flexibility to modify irrigation schedules;
5. *A user interface that facilitates expert inputs*: to identify feasible irrigation management strategies that are optimized to meet the needs of individual farm managers it is necessary to elicit information from those individuals regarding their own experience, awareness of constraints and individual preferences.
6. Explicit modeling of the uncertainties of water use and crop yield, coupled with a decision model for irrigation management to maximize the statistical expectation of benefits under conditions of uncertainty;
7. Linking analytical results to crop yield models and budget spreadsheets, tailored to the specific economic circumstances of individual farms, to facilitate economic assessment of alternative water use strategies.

### *A collaborative structure*

The capabilities outlined above would be expected to evolve continually as the underlying science and engineering advance and other research teams around the world develop improved algorithms for the various elements of the program. Furthermore, given the complexities of the problem and the urgency of the need, collaboration in the development of advanced irrigation management tools will be vitally important. These considerations imply:

8. a program structure that is flexible and adaptable so that individual components of the program can be readily upgraded or replaced;
9. controlled open source code options to permit users to adapt the system to accommodate local circumstances, science and preferred practices while still insuring the integrity of the system.

### *Field support*

And finally, significant technical support in the field will be needed to deal with more complex data input requirements; monitor outputs to detect errors and validate the model; recalibrate the farm-specific parameters used as field data become available; and train users in interpreting outputs and implementing recommended management plans. This will require more sophisticated technical support institutions than those in place today. There will be a need for focused, specialized technical assistance along the lines of mobile labs, to assist individual farms with: (i) surveying field characteristics and irrigation hardware; (ii) setting up site specific data inputs; (iii) installing requisite instrumentation; and (iv) training users on error checking and interpretation of the resulting advisory service outputs.

To put this issue in perspective, consider the comparative costs of application systems vs management programs. A center pivot for a 125 acre field can provide a high potential application efficiency. With all its dedicated infrastructure the cost can easily reach $80,000 or more. Taking maintenance, repair and equivalent annual capital cost of such a system together the total annual cost might be on the order of $8,000. By contrast, initial mobile lab support for setting up, calibrating and error checking an advanced advisory program for one field might be on the order $2,000, or about $200 annualized investment. Subsequent annual field support by an irrigation scheduling service might cost an additional $2,000, for a total annual cost of $2,200, roughly 30% as much as the application system.

## Conclusion

Irrigation management will necessarily shift to a new management paradigm based on regulated deficit irrigation in order to deal with a rapidly increasing competition for water and accelerating demand for food production. This new management paradigm will be a significant challenge for the next two decades.

Analysis of application efficiencies will be necessary to analyze the disposition of applied water under deficit irrigation. Conjunctive scheduling of multiple fields will be necessary to facilitate allocation of limited water between multiple fields sharing a water supply. User participation in the analytical process will be required because no optimization program can fully represent the local circumstances, preferences and constraints that individual farmers will need to deal with. Regulated deficit irrigation also implies elimination of margins of error in management of soil moisture conditions, which implies that we will need to deal explicitly with the uncertainties of irrigation scheduling; analysis of uncertainty and risk, and development of appropriate decision models for uncertain conditions will be needed. Our ability to more accurately estimate yields will be critical.

Development of analytical tools to achieve these ends will involve an order of magnitude increase in complexity. Increased investment in field technical support will be needed as a bridge between the technical sophistication of advisory programs and working farm managers. The process will be facilitated and accelerated by a modular, open source code design philosophy.

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