Irrigation Advisory Services and Participatory Extension in Irrigation Management

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IRRIGATION ADVISORY SERVICES FOR OPTIMUM USE OF LIMITED WATER

by
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Irrigation Advisory Services for Optimum Use of Limited Water

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Abstract

Conventional irrigation practices in most of the world are designed to avoid crop stress in order to maximize yields. During the next few decades, as the inevitable expansion of irrigated lands for increased food production comes into conflict with accelerating economic competition for water and rising environmental concerns, this fundamental precept of irrigation management will probably be abandoned. The new operational rule that replaces it will be based on maximizing total benefits rather than yields (English, et al. 2002). This alternative approach, which might be referred to simply as ‘optimization’, is recognized by economists and a growing number of irrigation professionals as the most rational basis for irrigation management.

A number of individual farmers, seeing the potential advantages of this approach, have attempted to develop optimum irrigation strategies on their own, but they have had little guidance from the scientific, economic or engineering communities. In fact, at present, there appear to be no educational or outreach programs providing advice on irrigation optimization for working farms anywhere in the world.

The present paper outlines the principles of irrigation optimization and discusses the application of these principles for profit maximization, food security and national interest. The paper then addresses the need for advisory services to assist farmers with this fundamentally different approach to irrigation management. The new challenges associated with optimum irrigation management are explored. The limited efforts to apply the principles of optimization under real-world conditions are discussed. A recently proposed project to initiate a formal, structured advisory service for irrigation optimization in an irrigated basin of the western United States is outlined in some detail. Though not funded to date, the proposed project illustrates some of the likely aspects of optimum advisory services.

Introduction

A variety of government agencies, consulting companies and other organizations assist farmers with irrigation planning, and with scientific irrigation scheduling. At the heart of these advisory services are systematic procedures for determining when to irrigate individual fields and how much water to apply. These services generally have two fundamental objectives; to maximize crop yields, and to achieve the highest attainable irrigation efficiencies consistent with maximum yields.

This paper concerns irrigation advisory services with a different objective. Rather than striving for maximum crop yields it will seek to maximize the benefits derived from irrigation. The definition of benefits may differ from one situation to the next. In some cases the benefits will be measured in terms of farm profits. Research indicates that profit-maximizing strategies may increase net farm incomes by 5 or 10 percent, and possibly much more when water supplies are limited. In other cases the benefits may be increased food security, regional or national income or employment, or mitigation of environmental damage from irrigation. The approach taken to maximize one or another of these benefits might be described in simplest terms as ‘optimization’.

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The objective of maximizing benefits is fundamentally different from maximization of yields and requires an altogether different approach to irrigation management. Maximizing yields implies full irrigation of the crop. Maximizing benefits will generally mean deficit irrigation, the deliberate under-irrigation of a crop.

A proposed project discussed in this paper will develop, test and implement an optimum irrigation advisory service in the Klamath Basin of eastern Oregon. This is an area in crisis. Competition for water and demands for improved water quality have put intense economic pressure on irrigated agriculture in the region and inflamed political tensions between farmers, environmentalists, native Americans and a coastal fishing industry.

The proposed project will draw on pre-existing research to generate guidelines for optimum irrigation management in the basin. The guidelines will be developed and tested in partnership with cooperating farms interested in exploring alternative irrigation strategies. Ultimately these guidelines will be made available to local farms in an easily accessible, user-friendly format. An outreach program will present the guidelines to the farming community and provide technical support for farms interested in implementing them.

It is anticipated that this project will benefit individual farms through increased net incomes. The community as a whole will also benefit from more effective control of the timing and distribution of water to all farms and other water users in the region, reduced total water use and improved water quality in rivers receiving irrigation return flows. Institutional changes will be necessary for this project to achieve maximum effect, including more rigorous record-keeping, creation of a water banking system and changes in rules that now restrict the transfer of water rights.

Principles of Optimum Irrigation

Current irrigation practice is generally predicated on meeting crop water demand in order to maximize crop yields. This is, fundamentally, a physiological objective, and it is the basis for conventional irrigation design and management worldwide. However, research has clearly shown that there is more to be gained when irrigation decisions are based instead on an economic objective, the maximization of specific benefits.

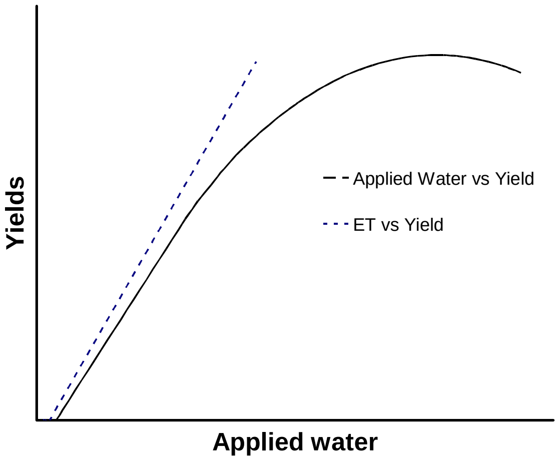
An overview

We begin by considering the general relationship between applied water and crop yield per unit of land, illustrated in Figure 1. Two functions are shown, one representing the relationship between consumptive use of water (ET) and yield, the other representing the relationship between applied water and yield. Abundant research has shown that the ET-yield relationship is linear, at least as a first order approximation (Vaux and Pruitt, 1983). The applied water-yield relationship is more complex. At low levels of applied water, up to about 50 percent of full irrigation, yields increase more or less linearly with applied water (Vaux and Pruitt, 1983). As more water is applied the relationship becomes curvilinear, a consequence of accelerating losses from surface evaporation, runoff and deep percolation. Beyond the point of maximum yield the curve turns downward, reflecting yield losses from anaerobic root zone conditions, disease and leaching of nutrients from excessive water use.

What level of applied water would constitute ‘full’ irrigation in Figure 1? The nominal irrigation requirement for a given crop is generally defined as the amount of water needed to achieve ‘full production potential’ (Doorenbos and Pruitt, 1977). For purposes of this paper, let us interpret that to mean the level of applied water that achieves the highest *field average* yield per unit of land, the peak of the curve in Figure 1.

There are three ways one might make more productive use of irrigation water. One would be to increase crop yield potential by genetic manipulation or selective breeding to produce greater yield with each unit of water consumed. That would increase the slope of the ET-yield

Figure 1
General form of the relationship between applied water and crop yield



curve. The applied water curve would move upward as a result. Greater yield would be produced with a given level of applied water.

A second way would be to build more efficient irrigation systems. Since the displacement between the ET and applied water curves is due to system losses (percolation, runoff), the increased efficiency would cause the applied water curve to track the ET curve more closely. Less applied water would be needed to achieve a given yield.

The third way to increase the productivity of water would be to simply apply less water. The applied water-yield curve is not altered if we do that. We would simply be irrigating at a lower point on the curve, something less than the yield-maximizing level. In doing so, we could attain a higher irrigation efficiency. The yield per unit of land would be less, since we would no longer be at the maximum yield point, but the yield per unit of applied water would be greater. Additionally, the costs of production and the environmental impacts of irrigation would also be reduced. At some reduced level of irrigation the benefits derived from each unit of applied water would be maximized.

Irrigation optimization, as discussed in this paper, is concerned with this third option.

Maximizing net income when water is not limited

If our objective is to maximize yield per unit of land, the conventional approach to irrigation, we can determine the amount of water to apply by setting the derivative of the yield function to zero and solving for *w*. In other words, conventional irrigation is defined by the equation:

$$\frac{\partial y(w)}{\partial w} = 0 \tag{1}$$

If we wish to maximize profits, however, we must explicitly consider production costs and revenues. The revenue derived from the crop will be determined by multiplying the yield ($y(w)$) by a crop price (P_c). Relevant production costs include: (i) variable costs of water, energy, labor and maintenance; (ii) capital and other fixed costs associated with irrigation system capacity; and (iii) the costs of chemical applications, harvest and other production costs that vary with yields (and therefore with water use). Let us represent production costs as a function of applied water, $c(w)$ (\$/m^3). The relationship between applied water and net income can then be written:

$$i(w) = p_c \cdot y(w) - c(w) \tag{2}$$

where p_c is the unit price paid for the crop ($/Mg) and *i(w)* represents net income per unit of land ($/ha). Optimum water use can be determined by setting the derivative of equation 2 to zero and solving for *w*:

$$\frac{\partial i(w)}{\partial w} = p_c \cdot \frac{\partial y(w)}{\partial w} - \frac{\partial c(w)}{\partial w} = 0 \tag{3}$$

After rearranging this equation, optimum irrigation is defined by:

$$\frac{\partial y(w)}{\partial w} = \frac{1}{p_c} \frac{\partial c(w)}{\partial w} \tag{4}$$

The right side of this equation must be positive since the inverse of crop price and the derivative of the cost function must both be positive and non-zero. Equation 4 therefore indicates that at the optimum point the derivative of the yield function will be positive and non-zero. That is, the profit maximizing point will be found in the rising part of the yield curve, to the left of the yield-maximizing point. Thus a profit-maximizing strategy will use less water per unit of land than the conventional, yield-maximizing strategy.

As an example, English and Raja (1996) analyzed optimum irrigation of winter wheat on an Oregon farm based on a crop price of $147/Mg and using the following locally derived yield and cost functions:

$$y(w) = -.5348 + .03326 \cdot w - .0000273 \cdot w^2 \tag{5}$$

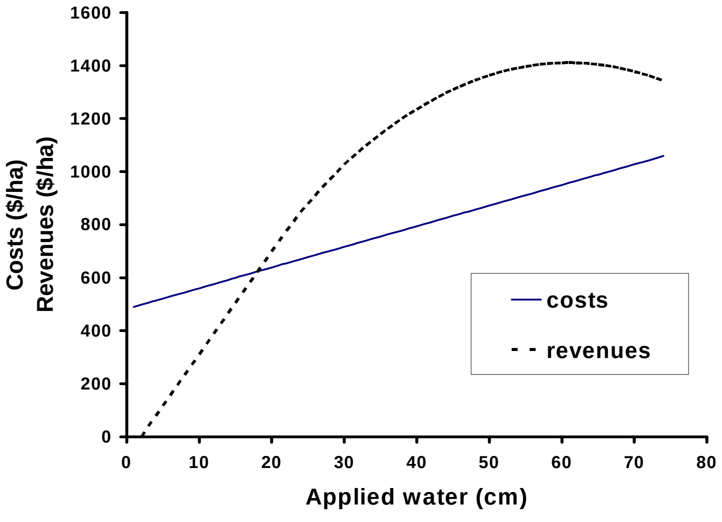
$$c(w) = 482.30 + 0.779 \cdot w \tag{6}$$

The resulting cost and revenue curves are shown in Figure 2.

Using these functions in Equation 1 and solving for *w*, the yield-maximizing level of applied water would be 610 mm, and net farm income would then be $453.70 per hectare. But the profit-maximizing level of irrigation, from Equation 4, would be 510 mm, 16% less than full irrigation. The net income would be $491.51/ha, an increase of 8.3% over the yield-maximizing option.

Figure 2

Costs and revenues as a function of applied water: (wheat in the Columbia Basin)



Maximizing net income when water is the limiting resource

When irrigation is constrained by limited water availability or limited irrigation system capacity, the water saved by reducing the depth of irrigation might be used to irrigate additional land. The problem then is to determine the optimum tradeoff between the depth of applied water and the area to be irrigated. That is, we wish to maximize the total profit (*I(w), $*)from an irrigated field of given area, where:

$$I(w) = [p_c y(w) - c(w)] \cdot A \tag{7}$$

The irrigated area, *A* (ha) is determined by dividing the total volume of available water, W_T (m^3), by the depth of applied water, *w*, as:

$$A = \frac{W_T}{w} \tag{8}$$

Combining equations 7 and 8, optimum water use is then defined by the value of *w* that satisfies the equation (English, 1990):

$$-A \cdot \frac{\partial i(w)}{\partial w} = i(w) \cdot \frac{\partial A}{\partial w} \tag{9}$$

Using the earlier yield and cost functions (Equations 5 and 6) and crop price, but assuming a constrained water supply, English and Raja (1996*)* estimated that the profit maximizing depth of irrigation for the case cited earlier would be 370 mm, about 39 percent less than the nominal irrigation requirement of 610 mm. The water thus saved could be used to increase the area irrigated by 64 percent, and the net income by 49 percent.

Optimization for multiple fields and crops

If a farm has a limited amount of land but ample water, the optimization analysis can proceed on a field-by-field basis. The problem becomes more complex when multiple fields and crops are involved and water is limited. Since limited water implies an opportunity cost for water, the decision-maker must consider all fields and any alternative uses of water simultaneously, allocating more water to more profitable crops, or perhaps marketing water to off-farm users. Such whole-farm analyses typically rely on mathematical programming techniques (e.g. Linear Programming or Dynamic Programming) to optimize for the entire farm as a single planning unit.

The added complexity of whole-farm analysis is illustrated in a paper by Martin and vanBrocklin (1989) who used dynamic programming to determine optimal planting and water use strategies for a mix of un-irrigated and irrigated crops. Areas planted in three crops were limited by whole-farm decisions and by governmental production constraints. The water, drawn primarily from a limited ground water source, was rationed under a water-bank program, with water allocations contracted in five-year blocks. The analysis also accounted for the variability of seasonal weather. Their estimates of the optimum fraction of available land to irrigate varied from about 50% to 100% over the five seasons of the analysis. The optimal depth of applied water varied from 65% to 85% of full irrigation.

Food security

Conventional irrigation management is predicated on maximizing the rate of food production per unit of land (Mg per hectare). Maximization of *total* food production, $Y_{(w)}$ (Mg) can be a more important concern. The problem of maximizing food production with a limited supply of water, can be stated as:

$$\text{Maximize:} \quad Y(w) = y(w) \cdot A \tag{10}$$

where the total irrigated area, *A*, is determined by the total water supply and depth applied, as in Equation 8. Taking a derivative with respect to *w* and rearranging terms leads to the defining equation:

$$\frac{\partial y(w)}{\partial w} = -\left[\frac{1}{A} y(w) \frac{\partial A}{\partial w} \right] \tag{11}$$

The inverse of *A* and the quantity *y(w)* are both positive and non-zero. If the total water supply is constrained, and if water saved by reducing the depth of irrigation (*w*) is used to put additional land under irrigation, *A* will increase as *w* decreases. The derivative of *A* is therefore negative and non-zero. So, when *w* is at the point that maximizes total yield the right side of the equation must be non-zero and positive. That point must therefore be to the left of W_{Max} in Figure 1. In short, maximum total food production with a limited water supply is achieved with less than full irrigation.

An analysis of maize production in southern Africa illustrates the point (from English, et al., 2002). Figure 3 shows maize yield per hectare as a function of applied water, expressed as a percentage of full water irrigation (based on Solomon, 1985), as follows:

$$y(w) = 6.0\,(-0.84 + 4.43\,W_R - 3.52\,W_R^2 + 1.11W_R^3 - 0.18W_R^4) \tag{12}$$

$$W_R = \frac{(w + rain))}{W_{MAX}} \tag{13}$$

where W_R is the relative available water, *w* represents depth of irrigation (mm), *rain* indicates effective rainfall (mm) and W_{MAX} is the amount of water needed for maximum yield per hectare (m^3/ha).

The maximum attainable yield in this case would be 6.0 Mg/ha, which would be attained with 525 m^3/ha. English, et al. (2002) divided the yield per unit land by the volume of water associated with that yield to determine the yield per unit of applied water, shown in Figure 4. At full irrigation the productivity of the water would be 11.4 kg/m^3. As irrigation depth is reduced productivity increases, reaching a maximum of 14.6 kg/m^3 at 59 % of full irrigation. Maximum total yield, in this case, would be achieved by applying 59% of the nominal full water requirement, and using the water thus saved to expand the irrigated area by almost 70%.

Efficiency, adequacy and leaching

Since the application of water is always non-uniform, some fraction of an irrigated field may be under-irrigated even when the remainder is fully irrigated or over-irrigated[2]. If commonly accepted guidelines are followed, full irrigation will result in about 90% of the field being over-irrigated in order to limit the under-irrigated fraction to an acceptable 10%. Most of the excess water applied to the over-irrigated 90% will be lost as deep drainage below the root zone.

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[2] The percentage of a field that is fully irrigated is referred to as the adequacy of irrigation. Common guidelines call for 90% adequacy (or 75% for low valued crops), meaning that 90% of the field should receive enough applied water to avoid loss of crop yield or quality.

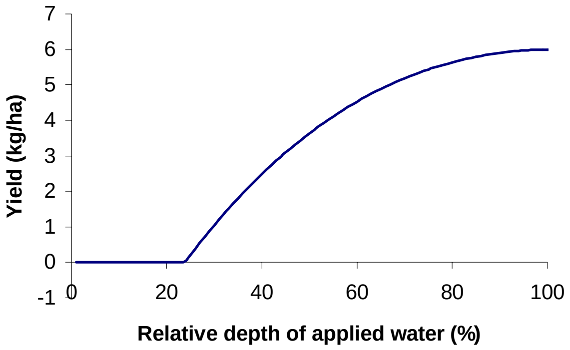


Figure 3
Maize yield per unit of land

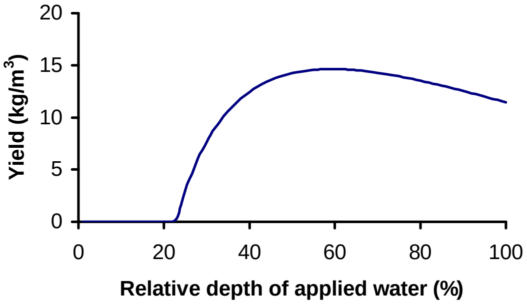


Figure 4
Maize yield per unit of water

If less water is applied a larger fraction of the field will be under-irrigated. Deep drainage (leaching) losses will be reduced as a result, as will the leaching of soluble chemicals, while application efficiency will increase (Hart and Reynolds, 1965). Yields will be reduced as well, but the profitability and productivity of the water will increase, as noted earlier.

An analysis by Stewart, et al. (1974) provides some perspective on changes in deep percolation that might be expected as irrigation depth is reduced. Using experimental data relating corn yield to applied water in Davis, CA, they estimated that a 5.8% reduction in total applied water would be accompanied by a 40% reduction in percolation. They also estimated that yields would be reduced by 1.1%, though there would be no reduction in profits.

The foregoing discussion can be summarized as follows: (i) optimization implies reduced irrigation, and results in increased application efficiency; (ii) at the optimum point, yield reductions per unit of land will be small, while reductions in water use will be relatively large; (iii) total crop production from a limited water supply will be increased; (iv) net farm income will increase up to a point; and (v) leaching and attendant non-point source pollution will be reduced. These are generalizations, of course, and in certain situations some of them may not apply.

Other issues

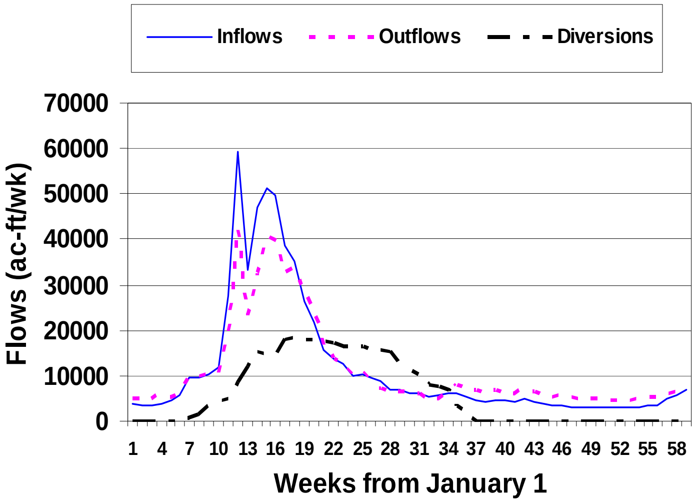
While the foregoing discussion outlined the potential benefits of economic optimization in irrigation management, there are several critical and in some cases controversial issues that should be understood. These include the question of whether reduced irrigation will actually save water, how salinity might be managed when irrigation depth is reduced and what additional risk is faced by farmers employing an optimization strategy.

Controversy about water savings

There is no question that in some circumstances optimum irrigation management will save water that would otherwise be irretrievably lost. For example, Kelly and Ayer (1982) estimated that if corn and cotton in California were optimally irrigated the water saved could supply a city of over 600,000 people. Much of that water would otherwise be lost to the saline sinks of the southern San Joaquin Valley.

Such cases notwithstanding, it is true that irrigation return flows from one farm may be the primary source of irrigation water for other farms (Sekler, 1999). Figure 5 illustrates this situation for a river basin in Colorado (from English and Amorocho, 1975). The Solid line shows basin inflows during one calendar year, the dotted line basin outflows. The broken line shows total in-basin diversions for irrigation. Between the 7th and 19th weeks, during the period of rapid snowmelt in the surrounding mountains, basin inflows exceed outflows, sometimes by a wide margin. This difference between inflows and outflows is largely due to irrigation diversions within the basin. Between the 19th and 33rd weeks, however, outflows and inflows are nearly equal, with no net water retention in the basin, even though irrigation diversions continue at a high rate. And after the 33rd week, outflows exceed inflows. It appears, then, that from the 19th week until the end of the year stream flows are being augmented by water stored within the basin. What is the source of this additional water? The answer lies in the low irrigation efficiency of the basin, an average on-farm efficiency of about 16%. Much of the water diverted for irrigation is lost through canal seepage and deep percolation. That water eventually returns to the river, but it may be many weeks before it reappears in surface flows. That ‘wasted’ irrigation water, diverted again and again as it moves through the valley, is therefore supporting the irrigation of downstream farms through the summer, and augmenting stream flows in the fall and winter. In this case, recapture and reuse improves the overall basin efficiency substantially.

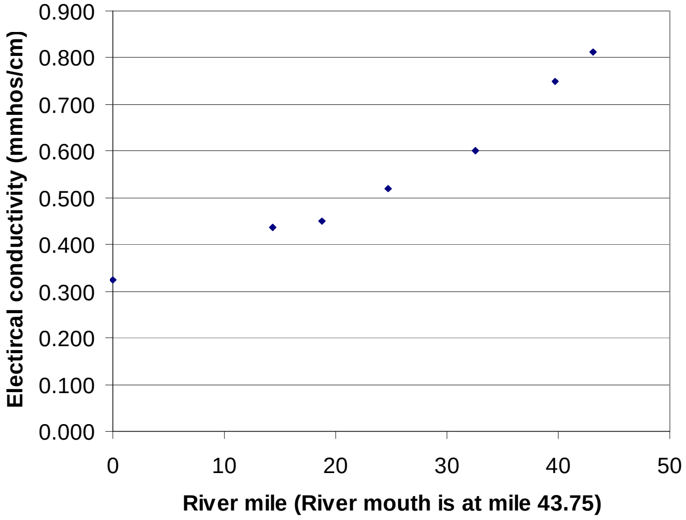
<u>Figure 5</u>
Inflows, outflows and diversions: the Roaring Fork River basin, 1966



Nevertheless, even when virtually all return flows are recaptured and reused, with basin-wide efficiencies approaching 100%, increased on-farm efficiencies may significantly increase the net economic returns to irrigation. These gains are realized by (i) reducing operational costs to individual farmers, as discussed earlier, (ii) improving control of the distribution and timing of irrigation water deliveries among farmers, and therefore enabling more effective use of the water, and (iii) reducing the negative, off-farm effects of irrigation (Wichelns, 2002).

Additionally, even though irrigation return flows may be recaptured for further use, the quality of that water is generally degraded. In that case, farm efficiencies may help to preserve the quality and productivity of water. The above example of the Roaring Fork River is a case in point. Excess water percolating below the root zone entrains dissolved salts picked up from underlying rock formations of the Roaring Fork Basin. Repeated recycling of return flows compounds the effect. Figure 6 illustrates this process, showing measured salinity of the river in the uppermost reach of the river, and successive measurements of salinity as the water moves downstream. In a 70 km reach of the river the salinity has increased from approximately 0.3 dS/m to approximately 0.8 dS/m.

<u>Figure 6</u>
Salinity of the Roaring Fork River



Salinity

That brings us to the issue of salinity. Where salinity is a hazard, water must drain through the crop root zone to prevent solutes from accumulating to levels detrimental to crop production. The loss of productivity from excess salinity may take decades to develop or just one crop season, depending on the severity of the problem. The minimum fraction of applied water that must pass through the root zone, termed the leaching requirement, has been established by Hoffman and vanGenuchten (1983). How frequently the leaching requirement must be met is a very complex issue that depends upon the salt tolerance of the crop, the variation of salt tolerance during plant growth, the salinity of the irrigation water, the amount of effective rainfall, and soil drainage (Glenn Hoffman, personal communication, 2002). For rotations that include both sensitive and tolerant crops, it may be possible to grow a salt sensitive crop followed by a tolerant crop before salinity reaches detrimental levels and leaching must occur. When both non-saline and saline irrigation waters are available it may be possible to control salinity by cycling the waters for several years before leaching is required (Rhoades, et al., 1988).

The problem of controlling salinity is exacerbated when irrigation management strives to maximize returns to water by irrigating less, since less water may then be available to satisfy the leaching requirement. If the leaching requirement is not satisfied everywhere in the field, soil salinity will increase in those parts of the field where the applied water is less than the sum of evapotranspiration plus leaching requirement. Because of the innate non-uniformity of applied water, one must decide whether to accept some yield reductions in parts of the field rather than over-irrigating most of the field.

Given the spatial variabilities of soils and applied water, the unequal sensitivities of different crops at different stages of growth and the complex aquatic chemistry involved, the problem of irrigation optimization under saline conditions is challenging indeed. Nevertheless, the economic principles still apply where salinity is a concern. Knapp and Dinar (1987) used a dynamic programming model to study alternative strategies for irrigation using a high cost primary source of water (salinity 0.67 dS/m) and low cost reused drain water (salinity 7.96 dS/m) on a soil with an initial salinity (as EC_e) of 7 dS/m. The optimal level of irrigation was found to be sensitive to production costs, but in any event would be less than the yield maximizing level of irrigation. Soil salinity would be reduced in the course of the irrigation season, suggesting that the optimal strategy would be sustainable.

Analytical models

The new irrigation management paradigm will require increased use of operations research, the branch of applied mathematics concerned with formulation and solution of optimization problems. Operations research provides the algorithms for identifying optimal strategies (Hillier and Lieberman, 1980). A wide variety of such algorithms have been proposed specifically for irrigation optimization during the past 40 years. Perhaps the most familiar of these has been linear programming. Various adaptations of this technique have overcome difficulties specifically associated with irrigation optimization; convex linear programming accommodates a non-linear relationship between applied water and crop yield; chance constrained linear programming allows for a stochastic water supply (Maji and Heady, 1978).

Dynamic programming has also been used frequently in research on irrigation optimization (Martin and van Brocklin, 1989). Though not as computationally efficient as linear programming, this more flexible technique allows greater freedom in the use of discrete and stochastic variables and non-linear functional relationships. Simulation modeling, allows the greatest flexibility in accommodating the complexities of the real world (*e.g.* English, et al., 1992), but simulation is more computationally intensive, and must be linked to a search algorithm to reduce the number of simulations needed to arrive at an optimum. A promising technique employed by Canpolat (1997) and Alvarez, et al. (2002) used genetic algorithms to substantially increase the efficiency of the search procedure for evaluating complex sets of alternative seasonal irrigation strategies.

In some circumstances, optimization analysis may be complicated by uncertainty, and uncertainty implies risk. A variety of algorithms have been proposed for choosing between alternative strategies where risk is a concern. Stochastic dominance techniques have been used to derive quasi-optimal strategies that account for risk in a general way, narrowing the range of alternatives to those most likely to conform to the manager’s attitudes about risk (Mjelde, et al., 1990). The irrigation manager may also consider defensive strategies to mitigate risk, for example buying insurance and accepting a lower guaranteed profit in exchange for guaranteed avoidance of serious loss, or using a portfolio approach with several parallel irrigation strategies as a way of reducing variance without substantially reducing expected net income (English and Orlob, 1978).

A study by Martin and VanBrocklin (1989) illustrates incorporation of risk and uncertainty into irrigation planning. They considered two alternative objectives; (i) to maximize net income over a five year planning period; or (ii) to maximize the minimum return over a five year period. The second of these is a classical risk-avoidance strategy. These alternative objectives led to substantially different irrigation strategies, both in terms of allocations of land and water within a season and intra-seasonal allocation of water.

Optimization in Practice

The principles of irrigation optimization have been the subject of extensive research for several decades, but to date those principles are have not been put to use in production agriculture. Broad guidelines that approximate optimum irrigation management strategies have been proposed, for example, Keller and Bleisner (1990) suggest under-irrigating by 20% when water supplies are limited. But such rules of thumb may sometimes miss the optimum by a wide margin. English and Raja (1996) found that optimum water use may be on the order of 30% to 50% less than full irrigation for three crops in three very different settings (wheat in the Columbia Basin, cotton in California and maize in sub-Saharan Africa) under water limiting conditions.

Many individual farmers in water-short areas have developed their own *ad hoc* strategies to maximize net income. Their efforts have generally been more intuitive than scientific, and they too may miss the optimum level of water use by a wide margin. An assessment of such intuitive strategies on water-limited farms in the Columbia Basin found farmers using *less* than the optimal amount by an average of 20% (Bonneville Power Administration, 1987). But it is significant that many farmers have shown a willingness to experiment with reducing irrigation to optimize their use of water.

The intuitive efforts of individual farmers notwithstanding, it appears that systematic, science-based optimization procedures are not presently being used in production agriculture anywhere in the United States, and perhaps not anywhere in the world. A literature search to verify this assertion found no cases where the principles of optimization are being rigorously applied under field conditions. In a further effort to confirm this important assertion an informal survey of irrigation professionals was conducted. Leading figures in irrigation were contacted, including research leaders and extension specialists at the state level, NRCS and ARS research and outreach personnel involved with irrigation management on a national level, individuals responsible for regional irrigation advisory services (CIMIS and Agrimet), members of the EWRI Irrigation and Drainage Council (of the American Society of Civil Engineers) and individuals with extensive international contacts at the Institute for Sustainable Agriculture (University of Cordoba, Spain), and the International Water Management Institute. The survey elicited a consistent response: though a few described intuitive strategies devised by individual farmers, none of these individuals were aware of any systematic use of science-based optimization strategies anywhere in the world.

Contrasting optimum and conventional practices

The optimization paradigm has clear implications for irrigation management, demanding more complex analyses, greater technical competence and investment in new technologies. The manager will need to assume more responsibility for formulating system specifications and developing case-specific strategies, rather than relying on general guidelines and rules of thumb.

Conventional irrigation practices are based on two key specifications, the crop water requirement and the nominal application efficiency. The crop water requirement has long been defined as that which will prevent crop water stress in order to avoid loss of yield or quality (Haise and Hagan, 1967). Nominal application efficiency derives from a stipulation noted earlier (footnote 2) that irrigation adequacy should be 90% for high or medium valued crops, or 75% for low valued crops. Conventional irrigation is therefore defined in terms of the amount of applied water required to prevent stress in 90% of the field. Though somewhat dated, these stipulations are still the foundation of standard irrigation practice worldwide The 1992 revision of FAO 24 defines crop water requirements in terms of full production potential (Doorenbos and Pruitt, 1992). A recent NRCS revision to the National Engineering Handbook assumes 90% adequacy in deriving nominal application efficiencies for various irrigation systems (NRCS, 1996).

Under the new paradigm, irrigation planning can no longer be based on such *a-priori* specifications. To determine an optimal irrigation strategy the analyst will need to employ crop yield models and operations research, and will need to plan for some degree of crop stress. Rather than regarding application efficiency as a pre-determined constant for a given irrigation system, the efficiency will become a decision variable, determined in large part by the management strategy chosen (English, 1999).

Irrigation scheduling will also be more challenging. As water use is reduced and the margin for error narrows, more precise field determinations of crop water uptake, soil moisture and salinity will be needed. New techniques for measuring soil moisture and salinity, and progressively more accurate models of evapotranspiration, will be critical in this effort. The inescapable spatial and temporal variability of soil moisture measurements may necessitate mathematical filtering to reduce uncertainty (English, et al., 1981; Aboitiz-Uriarte, 1983).

While an irrigation system is commonly thought of in terms of its hardware -- the distribution system, pumps, land improvements, etc.-- the technology also includes information in the form of data, theoretical relationships, analytical tools and the training to utilize them. The optimization paradigm outlined here involves much greater analytical complexity and technical sophistication than currently needed for conventional irrigation management. Accordingly, we should anticipate that the irrigation manager will need a higher level of technical competence and better sources of information and advice. The cooperative irrigation advisory services (e.g. CIMIS, Agrimet) and commercial irrigation scheduling companies that have emerged over the past three decades to assist farmers with conventional irrigation scheduling indicate a need for such specialized assistance, even without the added complexity of optimization. The greater challenges of managing irrigation for maximum benefit imply a greater demand for such advisory services. A broader and more sophisticated menu of information and advice may be demanded of these services as farmers more vigorously pursue an economic approach to irrigation management.

Proposals for Establishing Advisory Services

Two proposals have recently been put forward by the author and others to establish advisory services for optimum irrigation management. The specific objective of both proposals is maximization of farm profits. The first of these involved research and extension specialists in irrigation management at universities in Oregon, Texas, Nebraska, Montana and Washington, in cooperation with counterparts in the Department of Agriculture (Agricultural Research Service). This group of eighteen professionals organized a consortium to establish irrigation advisory services in five states. These services were to be provided in selected regions in which (i) water supplies are limited, (ii) local farmers have demonstrated a willingness to experiment with lower levels of irrigation, and (iii) irrigation scheduling services are already established. The proposal was submitted to the US Department of Agriculture in 2001, but has not been funded.

A second proposal prepared by Oregon State University in 2001 would establish an advisory service in the Klamath Basin, a large irrigated area along the Oregon-California border. The proposal was submitted to the US Bureau of Reclamation (BOR), a federal agency that supplies water to approximately 80,000 ha of irrigated land in the basin. Irrigation in the Klamath Basin has been a dominant user of water in the basin since the early 1900's. Now, native American tribes, environmental groups and a commercial fishing industry are challenging agricultural interests in court with claims for a substantial share of the limited available water. In 2001, as a consequence of this intensified competition for water, coupled with a severe drought, the BOR suspended deliveries of irrigation water early in the irrigation season. Though irrigation water is again being provided this year, negotiations and legal and political struggles have intensified. The final resolution of this confllict remains to be determined, but it now seems likely that farms in the basin may face significant water shortages in the future. Water quality issues have put additional pressure on irrigated agriculture. The BOR is now attempting to reduce agricultural demands for water, offering subsidies to farmers who agree to leave a fraction of their land idle. But there are concerns that extensive land idling would undermine the economic base of the agricultural sector. Irrigation optimization would seem to be a particularly useful strategy under these circumstances, one that would improve farm profits, enable better control of water distributions, and mitigate environmental impacts. The Klamath Basin proposal serves as an instructive example of the opportunities and challenges for optimal irrigation advisory services.

Initially, the general approach will be conservative, focusing on drought tolerant crops (e.g. alfalfa, small grains) and emphasizing low-risk strategies. With a year or two of accumulated experience the project will begin to deal more with the issues of risk and drought sensitive crops. The project will be a team effort involving cooperating farmers willing to participate as advisors, clients and critics. Three factors suggest that farmers may have an interest in such a program: (i) the water shortage in the region, which will force consideration of deficit irrigation and make optimization strategies more attractive, (ii) the fact that the farmers themselves are advocating a water market, and (iii) the financial incentives offered for reduced water use, and possibly for water quality mitigation.

Analytical tools for identifying optimum irrigation strategies will include a regional data base, simulation models and optimization algorithms. The regional data base will include soils data, representative crop rotations, weather data, ET data, farm profiles and economic factors. The simulation models will estimate crop yields and application efficiencies using a combination of ET/Yield models (Doorenbos and Kassam, 1979) in tandem with an irrigation efficiency model (English, et al., 1992). The optimization algorithm will be either a variant of mathematical programming or genetic algorithms.

Specific recommendations will be developed for the cooperating farms, tailored to the circumstances of each individual farm. Technical support will be provided to assist with interpretation and implementation of the recommended strategies. An Extension program will be developed to support the advisory service with a public information program on optimum irrigation and periodic workshops on optimization.

All participants will meet in an annual workshop to review results, problems and perceptions, and to refine analytical tools and operational procedures. This working group will also establish specifications for a set of regional extension bulletins outlining quasi-optimal strategies for hypothetical ‘model’ farms in the region. The bulletins will recommend cropping patterns and water allocations for various crops under different scenarios of water availability and economic circumstances. Guidelines for adapting suggested strategies to different irrigation systems will also be developed.

Preconditions: public perceptions and institutional issues

Public perceptions and institutional issues that could limit the effectiveness of the project will need to be addressed. The most important concern is skepticism within the irrigation community regarding the value of this approach. The potential economic gains for individual farmers are often not clearly perceived by the farmers themselves. And in fact, the financial advantages may be negligible in areas that are dominated by flood irrigated pasture. Financial incentives may therefore be needed to motivate farmers to experiment with optimization. The Klamath Basin Water Users Association, an ad hoc farm organization, has drafted a proposal for a general water market through which farmers could exchange credits for reduced water use on a limited and individual basis. In order to avoid unintended adverse effects on ground water supplies and the general agricultural economy, the water conservation actions that would qualify for market exchanges would be restricted to development of new surface water sources, improved management of existing sources, substitution of ground water for project surface water, and idling of land. It will be important to the proposed project that conservation of water by improved (optimum) management be recognized as an acceptable conservation technique.

Another problem is the widespread belief that the high overall water use efficiency in the region (about 92%) implies that reduced water use on one farm will mean less available to neighboring farms that routinely capture return flows in wells or drainage ditches. To deal with this public perception, the OSU program will seek to (i) demonstrate the economic benefits for individual farmers, and (ii) analyze and publicize the regional economic benefits derived from improved control of water deliveries.

One additional issue is infrastructure. An ideal water market will require that individual farms use less than their legal entitlement of water, and offer that water for sale to others. But the existing infrastructure and the agencies that manage irrigation are not equipped to measure water deliveries to individual farms, maintain records of deliveries or certify credits for farms that use less than their allotment of water. Installation of flow measuring devices at farm delivery points will be expensive, and is unlikely in the immediate future. Water use by individual farmers may therefore need to be quantified on the basis of the number of times head-gates are opened, the length of time they are open and the characteristic flow rate of each gate when open. Irrigation districts will need to establish these characteristic delivery rates at farm head gates and institute procedures for keeping records of the times and durations of deliveries to individual farms.

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