IRRIGATION WATER SUPPLY AS A BIOECONOMIC PROCESS

Gary D. Lynne, William G. Boggess, and Kenneth M. Portier

Abstract

Irrigation water is produced within the irrigation subprocess of a farm. Water supply is identified for effective field water, which sets the upper bound on water available for plant use. Georgescu-Roegen process analysis concepts are merged with the neoclassical theory of cost as the underlying framework. The approach is illustrated for a permanent overhead system used in a Florida citrus grove. The marginal cost for the 2.54 centimeters application depth dominates all other depths for the higher water levels. Process analysis is an important analytical tool for increasing understanding of the features of irrigation water supply.

Key words: water supply, irrigation costs, water costs, process analysis.

Increased productivity at an economically efficient level of operation is still a laudable goal for American agriculture. Remaining competitive requires that agriculturalists continue to seek more cost effective means of production. Irrigators in particular need better information to ensure the water producing component of the farm firm becomes and remains efficient. Irrigation water losses can be substantial if incorrect decisions are made, especially in the humid regions of the United States where variability of rainfall becomes a factor. In addition, irrigation is increasing rapidly in the humid region. Georgia and South Carolina, for example, experienced increases of 313 and 216 percent in irrigated acreage over the period 1974 to 1978 (U.S. Bureau of the Census, p. 10). The overall increase in the humid region of the United States was 68 percent (U.S. Bureau of the Census, p. 9).

The increased and important role of irrigation, and the continual concern about cost-price relationships, enhances the need for irrigation costs research. Articles on the demand for agricultural water have been widely published (Hexem and Heady; Gowon et al.; Stewart and Hagan). However, professional journals contain little information regarding the supply costs, or the nature of the water supply function.

"Producing" irrigation water, and the efficiency of that process, is the focus of this paper. Water cannot generally be purchased, like fertilizer or seed. Water occurring in nature is combined with labor, capital, and management at the intrafirm level to produce "irrigation water."

Lacewell and McGrann called for more integration of economics and the physical sciences. This paper answers this call, demonstrating how economic principles of cost and supply can be combined with soil and agronomic principles, within an analysis of process. In addition, process analysis (Georgescu-Roegen, 1971) concepts are fused with neoclassical concepts of cost to estimate the marginal (supply) cost of irrigation water. A secondary purpose of the paper is to address the fact that root-zone water storage capacity is critical in irrigation (Hansen et al.), and therefore must be linked to economic principles of cost.

The process analysis approach for developing a water supply function has several advantages, which include: (1) giving both the analyst and the potential user of model results a better understanding of how the irrigation process works through time; (2) a model of such processes enables the manager to test, *ex ante*, various possible impacts on irrigation costs, from a particular management decision; (3) separating the supply side issues from those in water demand clarifies the nature of the decision process for questions of irrigation strategy; and (4) using process analysis and simulation models facilitates estimation of the water supply function over any period of time desired. In this paper, the supply function is defined for a crop season.

ECONOMIC THEORY AND IRRIGATION WATER SUPPLY

Georgescu-Roegen (hereinafter referred to as GR; 1970, 1971, 1972) introduced the notion of process analysis in reaction to an expressed concern for neoclassical production theory, wherein

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"...economists have found intellectual comfort in pure symbolism, so that they have gradually stopped considering even the traditional classification of production factors" (GR, 1972, p. 279).

That is, GR highlights an apparent lack of professional interest for the reality of how processes actually operate. It is this actuality, a concern for how the water supply process works in an irrigation operation, that is the focus of this study.

The analytical boundary (GR, 1972, p. 282) of the water supply process includes the irrigation system (well, pump, pipe, sprinklers), the managerial control, and the root zone of the crop and soil of concern. In particular, the boundary is defined by an overhead system on a hectare of citrus, grown on Astatula fine sand, with a root zone of 152 cm. The focus is on the interface of the roots with the available water and on the supply of this water by the manager (irrigation) and nature (rainfall). Inputs crossing this boundary include rainfall and irrigation water; the economic output is the effective field water supply.

By defining the analytical coordinates (GR, 1972, p. 284), the functional becomes (GR, 1971, p. 236):

$$(1) Q_o^T(t) = \Phi[R_o^T(t), I_o^T(t), M_o^T(t), W_o^T(t); L_o^T(t), K_o^T(t), H_o^T(t)],$$

where T represents the duration. This is a relation from a set of functions to one function (GR, 1971, p. 236). The expression is general; for this paper, t is a day and the terms are defined as:

Q(t) = effective field water supply on any given day;

R(t) = rainfall and the flow from other natural sources;

I(t) = irrigation water pumped and distributed, and the inputs for operating these pumps;

M(t) = maintenance and repair to the irrigation equipment;

W(t) = "loss" of water, through evaporation, deep percolation, and adhesion to soil;

L(t) = the services of land (Ricardian land, GR, 1971, p. 231);

K(t) = capital services from the well, pump, and distribution system; and

H(t) = labor and management.

In the GR parlance, L(t), K(t), and H(t) are the "agents", acting to organize and control the flow of elements which are used or acted upon [in R(t), I(t), M(t), and W(t)] (1971, p. 230).

The next step is to relate the process of equation (1) to the costs of production. As GR notes (1971, p. 244),

Cost is the only element that counts in this problem. And in cost, all qualitative differences between factors vanish into one homogeneous entity, money. The only role the production function (as developed above) has in this particular case is to enable us to know what factors, and in what amounts, enter into the cost—(of the process).

GR thus eliminates the need to be concerned about the tradeoffs that went into designing and installing the system. A permanent overhead sprinkler system for Florida citrus has certain inherent features based on "standard engineering practice". Once the system is on the farm, the task is to describe the process, how it works, and how it relates to cost.

In merging process analysis with the neoclassical concept of a water supply function, there is a special problem. There are two water supply functions, the first being the one for irrigation water, which is derived from:

$$(2) C_{wi} = h(w_i) + C^*_{wi}$$

where C^*_{wi} is the fixed cost, and $h(w_i)$ is the variable cost. The marginal cost is then simply:

$$(3) MC_{wi} = h'(w_i).$$

The shortrun supply function is the MC_{wi} above the point where it intersects the AVC_{wi} curve. Of course, this is an empirical question. If the goal is only to cover the costs of irrigating, the producer will be acting as a perfectly discriminating monopsonist, claiming the entire producer surplus from the irrigation subprocess as a return to the entire farm, as assumed herein. It is also likely, but not necessary, that $h''(w_i) > 0$. An upward rising Mc_{wi} curve would, of course, reflect diminishing returns.

Equation (3) is not sufficient, in that irrigation water (w_i) affects yield only indirectly. It is the *available water* in the soil reservoir that must be the focus, an often missed point by analysts who have used a range of water "proxies" in demand and irrigation strategy analysis. These have included rainfall plus irrigation water (Hexem and Heady); field water supply (Stewart and Hagan); and soil moisture tension (Miller et al.). Using rainfall plus irrigation water is fraught with difficulties, especially in humid areas where rains can easily occur shortly after an irrigation. Similarly, soil moisture tension bears no direct relationship to the concept of cost. Field water supply, while an important variable, must be adjusted for losses before it gains substantial meaning to economic analysis.

The focus for economic analysis must be on the effective field water.

There are three classes of soil water, namely the unavailable, available, and gravitational forms (Hansen et al., p. 46). Available water is defined as the difference between the amount of water in the soil at field capacity (FC) and the permanent wilting point (PWP). The FC and PWP, in turn, are usually defined for soil moisture tensions of about 1/3 atmosphere and upwards of 15 atmospheres, respectively (Hansen et al., p. 49).

Effective field water supply is field water net of all losses to evaporation, deep percolation, adhesion, and runoff.[1] It is the upper bound on available water. Thus, the relevant cost equation for time period T becomes:

$$(4)\ C_{ws} = g(w_s) + C^{\bullet}_{ws}$$

where w_s is the effective water from rainfall, irrigation water, and resident soil water[2] during $t = 0 - T$.

Obviously, the processes at work affect this function. The irrigation strategy, defined by the depth of application for any given trigger, affects curve location. The level of plant transpiration also has a substantial influence, as the larger the transpiration, the more room there is for water. The quantity and distribution of rainfall obviously will affect this function, with rainfall coming after an irrigation increasing the cost for effective water.

The fixed costs are still $C^{\bullet}_{wi} = C^{\bullet}_{ws}$ and the water supply function is:

$$(5)\ MC_{ws} = g'(w_s)$$

which is only indirectly related to $h'(w_i)$. It is expected that $g''(w_s) > 0$, reflecting diminishing returns.

After planting, control is exercised through selection of trigger and depth levels. Trigger refers to the irrigation timing decision and depth relates to the amount of water applied. The simulation model described in the next section represents this process and the subsequent section shows how to use the process analysis results in an aggregation using neoclassical concepts of cost.

SIMULATION OF THE IRRIGATION PROCESS

Simulation was used to generate the data set for estimating the effective field water and the MC_{ws} function. A FORTRAN program monitors the soil water balance through a crop season, given estimates of rainfall on a daily basis. Historical rainfall data for each day in the period 1930-31 to 1977-78 were used.

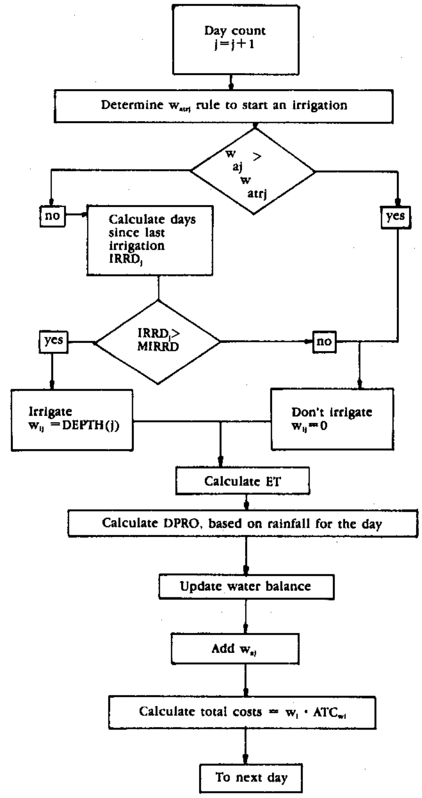

Figure 1. Flow Chart for Soil Moisture Balance Calculations and Irrigation Algorithm.

The order of calculations in the soil water model are illustrated in Figure 1. First, a water trigger (w_{atr}, in cm) for the day is determined, based on:

$$(6)\ w_{atrj} = PROP_j\ (FC - PWP)$$

where $PROP_j$ is the percentage trigger. When $PROP_j = 1.00$, the soil is returned to field capacity, to maintain the maximum amount of available water (w_{am}), or $w_{atrj} = w_{am}$. If $w_{aj} > w_{atrj}$, $w_{ij} = 0$. If the criterion is not satisfied, the number of days since the last irrigation ($IRRD_j$) is calculated. If the system is capable of being used today ($IRRD_j > MIRRD$), irrigation water is applied at the level specified by $DEPTH_j$. If not, $w_{ij} = 0$.

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[1]There would also generally be distributional losses from the source to the crop canopy. These are netted out of irrigation water applied (w_i), before calculating field water.

[2]There may also be upward movement from ground water through capillary action. However, this is not significant in the deep sandy soils of the study area.

Evapotranspiration (ET_j) is then calculated for the day based on the level of w_{aj}. David and Hiler have suggested relationships for various soil and crop characteristics. The one assumed in this simulation for "Valencia" citrus on Astatula fine sand was:

$$(7)\ ET = a\ (w_a)^b\ (PET)\ \text{for}\ w_a \leq w_{am}$$

and

$$ET = PET,\ \text{for}\ w_a = w_{am}$$

where w_{am} is the maximum available water in the soil, measured at field capacity, and PET is the potential ET. The values were a = 1.0 and b = 0.2, based on work by Koo (1953).

Deep percolation, runoff, and adhesion to soil particles ($DPRO_j$) is then calculated by difference, as the sum of all inflows to the system for the day from irrigation (w_{ij}) and rainfall (w_{rj}) less the ET_j and the maximum available storage capacity (w_{am}).

At the end of each day, the w_{aj} level is updated, by subtracting the ET_j and the $DPRO_j$ from the starting w_{aj} "that morning", and adding the w_{ij} applied and the w_{rj} received during the day. That is, the water balance equation is:

$$(8)\ w_{aj} = w_{aj-1} + w_{rj} + w_{ij} - ET_j - DPRO_j$$

for the jth day. The program then proceeds to the next day. The simulator operates for an entire calendar year plus January through harvest of the next year (485 days). This extended growing season must be considered for some varieties of citrus because tree bloom and fruit set occurs during the spring period at the same time the current crop is on the tree.

At the end of each year, the program adds the w_s values, or $w_s = \Sigma\ (w_{rj} + w_{ij} - DPRO_j)$ + change in the resident soil water, over the 485 days in each of the 48 crop seasons. In other words, the w_s is calculated from resident available soil water in the root zone at the beginning of the season, plus irrigation water and rainfall, less deep percolation, runoff, and adhesion to soil particles, less available soil water at the end of the season. This is the empirical equivalent of $Q_0^T(t)$, for T = a season.

After the water balance conditions have been simulated for all years, the costs of irrigation in each year are calculated. The most popular irrigation system for Florida citrus is the permanent overhead sprinkler, accounting for 32 percent of the hectarage (Harrison and Koo). Systems are generally designed to deliver .25 to .38 centimeters per hour, or a range of 4.57 to 6.86 centimeters per 18-hour operating day. In addition, the systems typically have the capacity to accomplish one irrigation a week (Harrison), meaning MIRRD = 7 days.

The ET for citrus ranges from .17 to .41 centimeters per day and averages about .27 centimeters per day, under conditions of no stress (Koo and Sites). Assuming 90 percent irrigation efficiency, this implies the system must be able to deliver up to .45 centimeters per day, or up to 3.18 centimeters per week, well within typical design limits. This suggests the current systems may be "overdesigned" from an economic efficiency perspective. That is, the typical systems can deliver up to 6.86 centimeters per week while the highest ET requirement does not exceed 3.18 centimeters. However, a second consideration is that these systems may also be used for frost protection, which requires more capacity (Harrison).

The point of this discussion is that these systems are not stressed, suggesting that $h'(w_i)$ can be assumed constant, signifying constant returns to scale. Thus, only a point estimate of the cost, such as provided by Muraro is required. Muraro showed the typical permanent overhead system variable costs were \$159.18 per hectare to pump 33.5 centimeters per year in 1979-80. The fixed costs were estimated at \$180.38 per hectare,[3] giving:

$$(9)\ C_{wi} = \$5.23\ w_i + \$180.38.$$

The $h'(w_i)$ function is then:

(10) MC_{wi} = 0.0, when all w_s is supplied by rainfall, and
MC_{wi} = \$5.23 per centimeter, when irrigation water is applied.

The \$5.23 estimate also reflects an assumed system efficiency of 90 percent, or a 10 percent loss from the water source to ground surface.

Such a linear cost structure has been assumed in other studies (Boggess et al.; Bras and Cordova; Stewart et al.). This is also the cost structure imbedded in the Oklahoma State Irrigation Cost Generator (Kletke et al.), which has been modified for use in several United States locations (d'Almada et al.).

C_{ws} was also calculated for each season. Then, the MC_{ws} was estimated for each year by interval estimation, using linear segments of C_{ws}. This data base was also used to estimate the $E[w_s]$, $E[C_{ws}]$, and $E[MC_{ws}]$, the expected values. The $E[MC_{ws}]$ plotted at the mean differences over these intervals are illustrated in Figure 2.

[3]These are joint costs in the production of water for frost protection and irrigation. Thus, this is appropriate as long as the demand for both water types is also considered simultaneously.

SELECTING THE WATER SUPPLY FUNCTION

The $E(MC_{ws})$ and the expected values of other cost measures are shown in Table 1. For any given depth, all the cost curves have anticipated properties. The average variable and average total costs increase in a "U-shaped" fashion, illustrating diminishing returns, Table 1. Average fixed costs, of course, decrease. The $E(MC_{ws})$ curves increase at an increasing rate, also as expected, Figure 2.

The reason these cost functions have the "textbook" properties is illustrated in Figure 3, for the average conditions over the 48 crop seasons. Losses increase at an increasing rate, especially for the higher depths, suggesting even less of the irrigation water is effective. This phenomenon is especially pronounced at the higher w_s levels, which is logical. As an attempt is made to keep the soil reservoir near capacity with a higher depth for any given irrigation, there is even more water lost. For lower w_s levels, there is little difference in such losses, suggesting nearly all the rainfall is effective; that is, more of the soil water reservoir is being maintained. Water loss is a direct loss of profit to the farmer, accounting for the rapid increase in costs.

With this backdrop, the discussion can be focused on the task of selecting the supply curve. Based on a fundamental economic principle: supply costs represent the least cost way to provide some quantity of effective water. This least cost analysis is accomplished herein with a year-by-year pairwise comparison of the marginal costs for each depth of application at given w_s levels. This provides the basis for probabilistic statements about which strategy will dominate, in the least cost sense. That is, as shown in Figure 2, the 2.54 depth appears to dominate the others, on the average, at least for the higher w_s levels. However, such average dominance may not be reassuring to either the analyst or the irrigation manager. Thus further examination is needed. Probability measures of dominance provide explanation as follows.

First, the difference between the MC_{ws} estimate for each of the depths was compared with the 2.54 cm choice in each of the 48 crop seasons. Second, the MC_{ws} for particular w_s levels were estimated by linear interpolation across the intervals. This was necessary because the level of w_s was not necessarily the same for any given trigger, across depths. Yet, it was necessary to compare the MC_{ws} estimates at some particular w_s in order to choose the supply function. As an example, the results for the year

TABLE 1. EXPECTED COSTS OF PRODUCING EFFECTIVE WATER IN CITRUS PRODUCTION, PERMANENT OVERHEAD SPRINKLERS, 1930-31 TO 1977-78 RAINFALL DATA, CENTRAL RIDGE AREA, FLORIDA

TRIG[a]	w_s	ATC	AVC	AFC	MC
			(for effective water, w_s)		
	cm	Dollars			
DEPTH = 2.54 cm					
0	105.87	1.70	0.00	1.70	
15	113.24	2.10	0.51	1.59	7.80
30	115.44	2.33	0.77	1.56	14.06
45	117.30	2.66	1.13	1.54	23.45
60	119.17	3.16	1.65	1.51	34.58
75	121.02	4.29	2.80	1.49	76.60
DEPTH = 3.81 cm					
0	105.87	1.70	0.00	1.70	
15	114.02	2.21	0.63	1.58	8.85
30	116.13	2.46	0.91	1.55	15.92
45	117.94	2.85	1.32	1.53	27.42
60	119.65	3.67	2.16	1.51	60.05
75	121.03	5.68	4.19	1.49	180.51
DEPTH = 5.08 cm					
0	105.87	1.70	0.00	1.70	
15	114.52	2.30	0.73	1.58	9.64
30	116.59	2.60	1.05	1.55	19.03
45	118.23	3.13	1.61	1.53	40.89
60	119.65	4.39	2.88	1.51	108.60
75	121.03	7.08	5.59	1.49	240.67
DEPTH = 6.35 cm					
0	105.87	1.70	0.00	1.70	
15	114.92	2.42	0.85	1.57	10.84
30	116.80	2.81	1.27	1.54	26.42
45	118.23	3.54	2.01	1.53	62.55
60	119.65	5.10	3.60	1.51	135.75
75	121.03	8.47	6.98	1.49	300.84

[a]TRIG is the "trigger level" for starting irrigation, expressed in percentage of available water at field capacity; DEPTH is application in cm; w_s is the effective water; ATC is average total cost of w_s; AVC is average variable cost; AFC is average fixed cost; and MC is marginal cost.

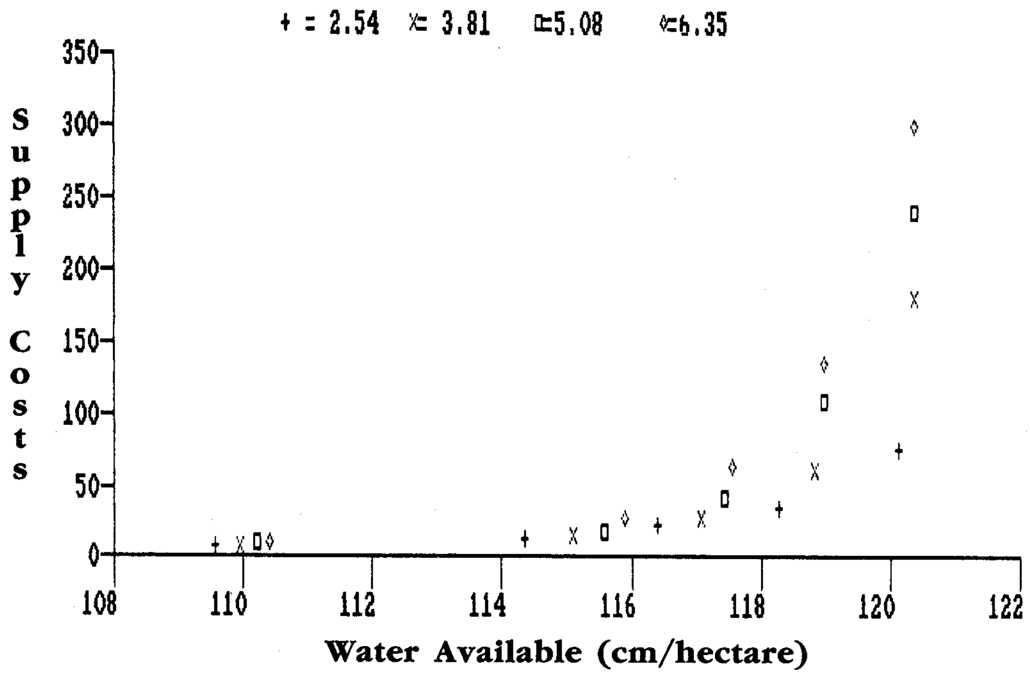

Figure 2. Expected (Average) Marginal Costs by DEPTH of Water Application, 1930/31 to 1977/78, Central Florida Citrus, Overhead Sprinklers.

1931 for depths 2.54 and 3.81 cm are illustrated in Table 2. For this case, the interpolated marginal cost (IMC_{ws}) was lower for the 2.54 cm depth than for the 3.81 cm depth at 119 centimeters, which contributes to the probability count favoring the 2.54 cm strategy. The comparisons are matched pairs, having both occurred under one set of daily rainfall events in each season. It is statistically important for the comparisons to be made in this manner: the only way to reveal the true differences among the cost curves is if comparisons are made under identical conditions in R(t) and L(t) in some (cdf) T.

The cumulative distribution function (cdf) as related to differences in marginal cost are displayed in figures 4, 5, and 6 at the 115 cm, 117 cm, and 119 cm w_s levels, respectively. The probabilities that the 2.54 cm strategy dominates the others in a lowest cost sense allows non-parametric statements about the risk. The cdf analysis provides the additional insight needed to evaluate the amount of risk in any particular decision setting.

TABLE 2. ILLUSTRATION OF PAIRWISE COMPARISON OF MARGINAL COSTS ASSOCIATED WITH PARTICULAR APPLICATIONS, CROP YEAR 1930-31, CENTRAL RIDGE AREA, FLORIDA[a]

DEPTH = 2.54 cm			DEPTH = 3.81 cm		
w_s	MC_{ws}	IMC_{ws}	w_s	MC_{ws}	IMC_{ws}
118.6705	43.0481		117.5085	19.4516	
120.2580	60.0264	46.5721	119.0095	60.3305	60.0717

[a] DEPTH is application; w_s is effective field water supply; MC_{ws} is marginal cost; IMC_{ws} is interpolated MC_{ws}, for 119 cm of w_s.

At the 115 centimeters level of w_s, there is at least a 0.60 probability the 2.54 cm MC_{ws} curve will be lower than the 3.81 cm curve, increasing to 0.69 and 0.73 for the 5.08 cm and 6.35 cm depths, respectively, Figure 4. This suggests the irrigation manager has a more than equal chance of being better off with the 2.54 cm strategy, even when lower water levels are desired. If the manager does choose the 2.54 cm strategy and "loses", the maximum loss is $19.13, which occurs if 2.54 cm is chosen rather than 6.35 cm. However, the probability is 0.96 that the loss will be less than or equal to $15.59, and 0.91 that the loss is less than or equal to $12.63. The maximum gain from the 2.54 cm strategy also occurs when compared to 6.35 cm applications, at $43.60, Figure 4.

The 2.54 cm depth looks ever better as w_s is increased, figures 5 and 6. At the 119 centimeters w_s level, the probability is near or at 1.0 that the 2.54 cm application will always give a lower cost at the margin, Figure 4.

While the probabilities favor selecting the 2.54 cm strategy when w_s = 117 cm, the amount at risk increases, as compared to the 115 cm level. The loss may be as high as $27.70, Figure 5, but only at a probability of 0.02, for selection of 2.54 cm rather than 6.35 cm. The amount at risk declines for the 119 cm level. The maximum loss is $6.46, which could occur with a probability of 0.02, Figure 6.

It is also the case that 3.81 cm dominates both the 5.08 cm and 6.35 cm depths, in a

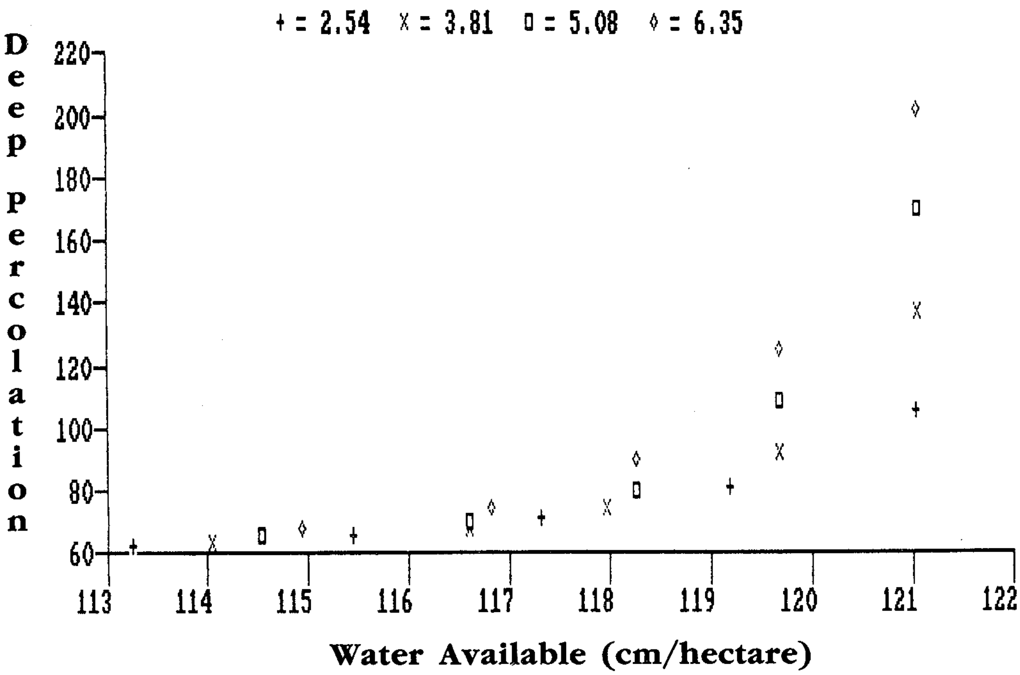

Figure 3. Expected (Average) Water Losses to Deep Percolation, Runoff, and Adhesion, 1930/31 to 1977/78, Central Florida Citrus, Overhead Sprinklers.

stochastic sense, over nearly the entire range of values. This is especially clear for the 119 cm level, Figure 6, where the 3.81 cdf function is always below the others, displaying first degree stochastic dominance. For the other two w_s levels, the 3.81 cm strategy clearly displays second degree stochastic dominance (Anderson et al., pp. 282-285).

MODEL VALIDATION AND VERIFICATION

The logic of the model was checked in cooperation with colleagues familiar with modeling such systems. Continual checks and balances of model results against experimental results as regards the water balances were made. This was done by checking predictions against theoretical expectations and common sense. This is the same procedure used by Miller and Halter (p. 425).

Each component part of the model is defensible in its own right. The overall ET predictions, which are extremely crucial in determining what the effective water will be, are based in the general work by David and Hiler, and the Florida trials by Koo (1953). The cost estimates of irrigation water are based on many years of such estimates by Muraro. The information on soil water holding properties of soils is from Florida experimental results (Choate and Harrison). An extensive literature review (including Anderson and Maass; Lembke and Jones; also, see Boggess et al., for a listing) including study of the irrigation strategy literature was accomplished during the modeling process.

Verification becomes the focus. As noted by Miller and Halter, the ultimate test of the validity of a computer simulation model is in the results from decisions made with the use of the model (p. 424). The results appear reasonable to extension personnel familiar with the irrigation processes in the Central Florida ridge area. Prior to the availability of this model, the recommendation has been to irrigate citrus heavily in the spring, and irrigate very little in the summer. This has been based primarily on the costs of irrigation, because yield response has been shown very stable over all triggers from 35 to 65 percent (Koo, 1969). Thus, the goal becomes to lower costs by reducing water losses, which is consistent with simulations of this paper.

CONCLUSIONS

The water supply curve can be generated, based on the underlying climatic, soil, water, plant, and economic processes. The approach shows how to integrate over the underlying

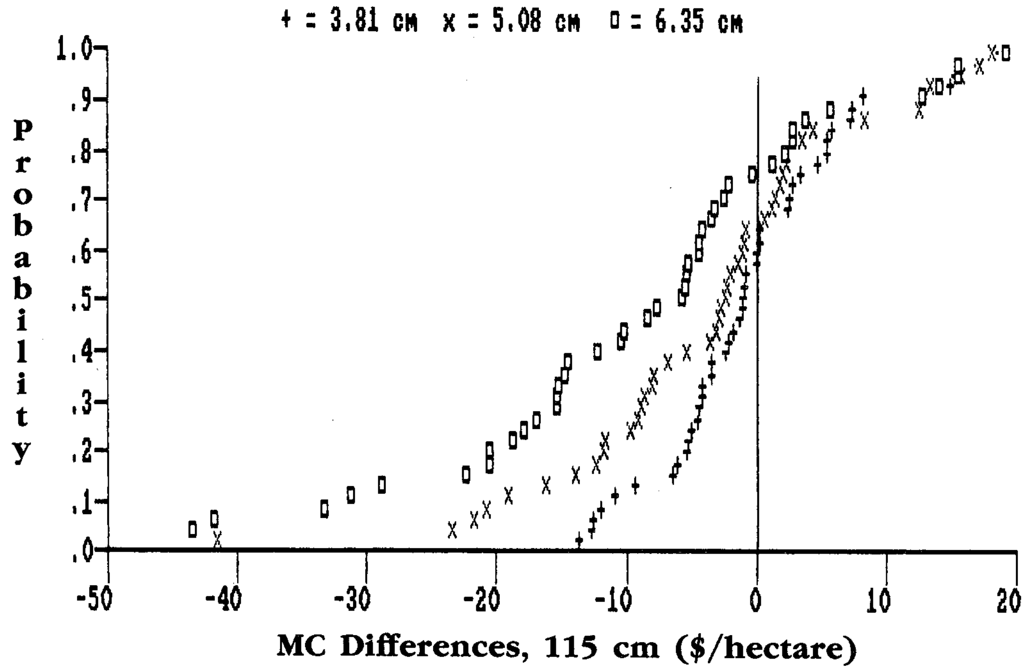

Figure 4. Cumulative Probability Distribution of Differences Between Marginal Cost Estimates for the 2.54 centimeters DEPTH Versus Other Depths at 115 centimeters of Effective Field Water Supply.

processes in an irrigation setting, and to give insights about "actuality", as the economics profession has been challenged by Georgescu-Roegen (1972, p. 279).

A significant result is the finding of a positive sloped supply curve for effective field water supply even when the MC_{wi} is constant. This has important implications for strategy analysis since it suggests that even if the derived demand curve for available water is horizontal, the op-

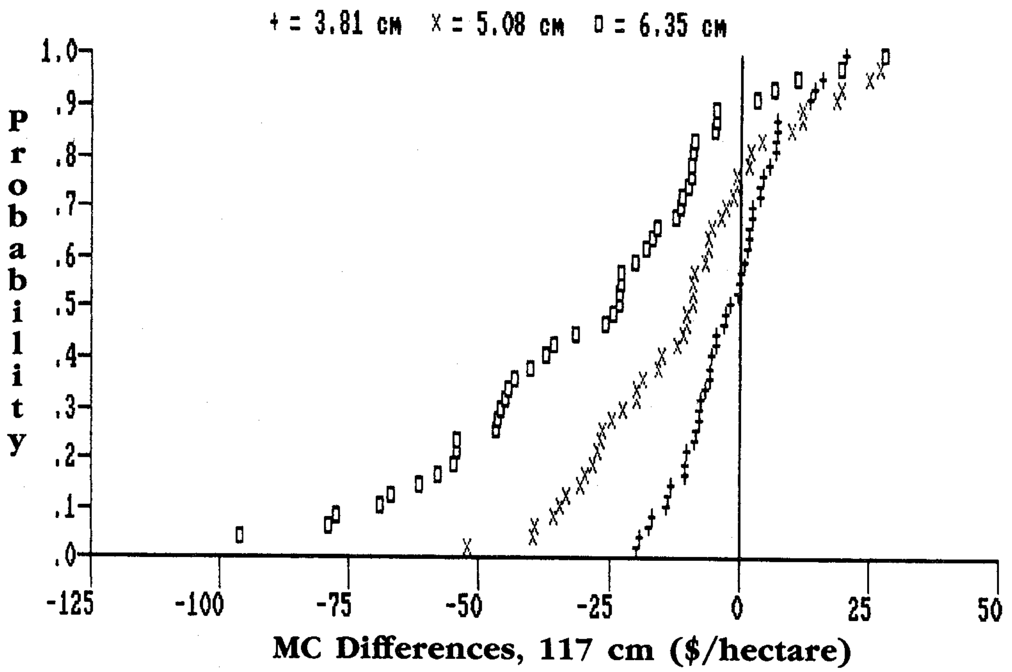

Figure 5. Cumulative Probability Distribution of Differences Between Marginal Cost Estimates for the 2.54 centimeters DEPTH Versus Other Depths at 117 centimeters of Effective Field Water Supply.

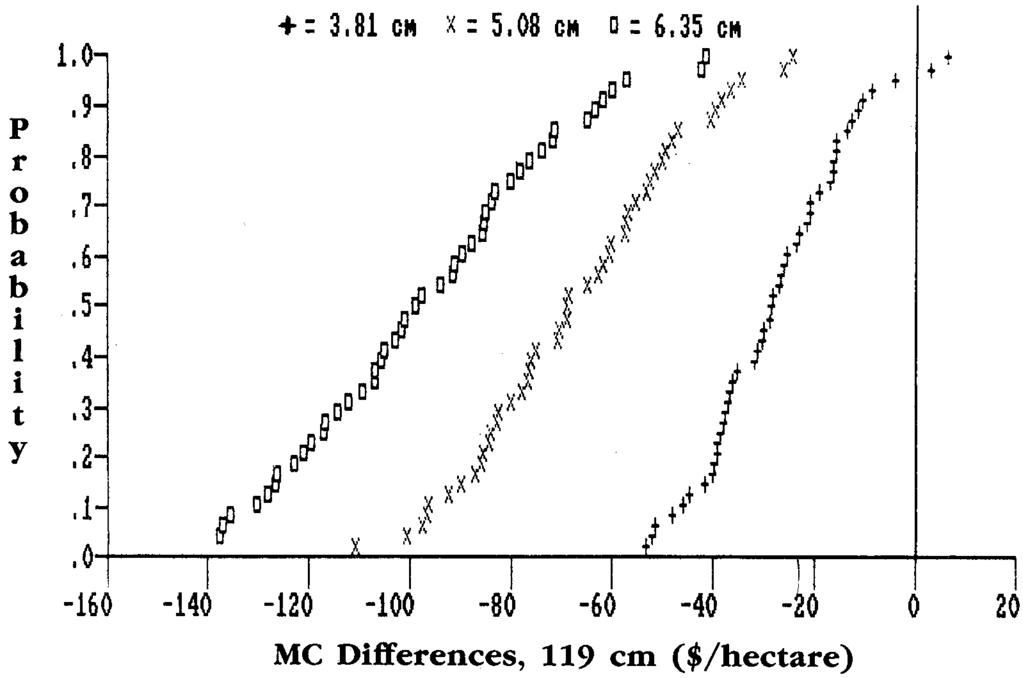

Figure 6. Cumulative Probability Distribution of Differences Between Marginal Cost Estimates for the 2.54 centimeters DEPTH Versus Other Depths at 119 centimeters of Effective Field Water Supply.

timum water level will always be at some level less than that providing maximum yield. Marginal costs tend to increase in the production of most products, including effective water.

It is apparent the irrigation manager plays an active role in defining the slope and location of the water supply curve in cost space. Yet, there are limits placed on that role by the nature of the crop, soil, and atmospheric conditions. The amount and pattern of rainfall dominates, making the approach herein of special significance to irrigation economics in humid and sub-humid areas.

The results also suggest the task of the manager is to control the amount of water in the soil "reservoir". If irrigation strategies are incorrectly selected, the resultant supply curve may be higher in cost space, giving economic waste. This point seems to have been missed by most economic analysts, as the emphasis in the literature has been on field water supply (usually the sum of gross irrigation and rainfall), which is only remotely related to effective field water, except under desert conditions. Using field water supply in analysis may be adequate in the more arid regions of the United States, but could lead to substantial distortion in the humid eastern areas. The effective strategy is the one that reduces deep percolation. The supply curve is described by the situation where water losses are minimized, giving the largest amount of water supply for any given expenditure.

The important water variable for water supply analysis is effective water. Plants respond to available water in the root zone, which is bounded by the effective water that can be supplied. In addition, it is straightforward to explain the character of this variable to those not schooled in the technical aspects of soil-water-plant relationships. Yet, the variable does have meaning to crop and soil scientists as well. Communication among individuals from all the various disciplines could be served by standardizing irrigation cost work around this common water quantity measurement.

The methodology and approach can be generalized to other soil types, atmospheric conditions, crops, and management strategies. There is a unique supply curve for every such set.

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