ON THE NECESSARY AND SUFFICIENT CONDITIONS FOR A LONG-TERM IRRIGATED AGRICULTURE*

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The objectives of this paper are: (1) to describe the physical factors involved in the plant-soil-water relationship, including the constituents of water quality and drainage in an irrigated agriculture, and (2) to discuss the economic interrelations of private and community investment in irrigation and drainage over time, for a sustained hydraulic agriculture.

Societies based on an irrigated agriculture have appeared and disappeared through several millenia of man's history. Analogous counterparts of the process continue in modern times. If manifestations of such failures are not to continue to repeat themselves, resource economists must evaluate the necessary and sufficient conditions for survival of an irrigated agriculture.

Water Quality and Irrigation

For years, water resource economists have been infected with the "water is water" syndrome, ignoring until recently the quality dimensions of this resource. The water that falls on the surface of the earth as rain is, for all practical purposes, pure H_2O. As it travels over and through the earth's crust, water picks up and carries in solution a portion of the minerals with which it comes in contact.

Pure rain water may degenerate in quality, while retaining nearly its same volume, as it passes through several nonconsumptive uses, or as it passes toward the sea or underground basin. Characterization of water quality may differ considerably, depending on the particular use intended. This paper is concerned primarily with irrigation; therefore, the quality of water as related to municipal and industrial uses will be excluded from the discussion.

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Demise of the early culture which, by all accounts, flourished for several centuries along the Tigris and Euphrates Rivers before the birth of Christ, has been attributed to a combination of three factors [Marr, 1967]. Salinization of the soil over time was certainly important. Another factor apparently was the gradual buildup of silt on the fields themselves. This raised the lands to a higher elevation than that of the canals, eliminating the head of water available to the irrigator. Finally, due to recurrent invasions and wars, there appears to have been a breakdown of the administrative structure required to organize the thousands of workers needed annually to repair and clean the silt and vegetative growth from the main canals and laterals.

Salinization of the soils in this area was not something that occurred over night, or even in one century. Although the records are not precise, it took an estimated 3,000 years from the time of the initial small stream diversions until the entire area was returned to its present state of salt flats and desert. The first recorded indication of the buildup of soil salts is inferred from the increased proportion of the land planted to highly salt-tolerant barley rather than to the less tolerant wheat crop. Gradual decline of yields of these crops over time supports this view. As more and more acreage went out of production and yields declined, so did the population and political power of the area [Marr, 1967].

This was not an isolated occurrence in world history. There is some evidence that similar, pre-Columbian disasters occurred in what is now the southwestern United States, as well as in the Middle East. In fact, an economy or culture based on irrigated agriculture which has survived over a few hundred years is really an exception, rather than the rule. Have contemporary project planners heeded these warnings as well as they might, so that modern technology can be brought to bear in solving the problems? Or, is our civilization to have the same unhappy destiny?

Salinization or salts in soils is without question the most prevalent problem in irrigated arid regions of the world. Under more humid conditions, soluble salts are generally carried through the soil and transported by streams to the ocean. Sometimes they accumulate naturally in inland areas. When this happens, the land may become unfit for commercial agriculture, such as the salt flats and playas of the Intermountain area in North America.

Productive soils may be salinized at different rates, depending on the amount of dissolved salts imported with the irrigation water. When water is applied to a crop, most of the moisture leaves the soil through evapotranspiration; but, the salts remain in the soil. If a portion of the irrigation water percolates past the plant's root zone toward the water table, soluble salts will be carried out of the zone. But if the water leaching beyond the root zone does not contain as much of the dissolved salts as entered with the irrigation water, the net result is salt accumulation within the soil, creating what is often referred to as an unfavorable salt balance.

The deleterious impact of salinization upon quality of a soil or an irrigation water depends on variables other than salt per se. Bernstein [1967], in his paper, "Quantitative Assessment of Irrigation Water Quality," considers three factors or conditions affecting water quality determinations--salt tolerance of crops, soil permeability, and drainage. Salt tolerance of crop plant species, i.e., their response to varying degrees of soil salinity, has been studied extensively at the U. S. Salinity Laboratory at Riverside, California. This work, using the electroconductivity (EC) of the soil saturation extract[1] as a measure of salinization, has been summarized by Bernstein [1967]. Figure 1 indicates that salt tolerance of selected crops to soil salinity values between EC[2] of 0 to 21. Barley and Bermuda grass are highly salt tolerant. Little or no yield reduction will occur until EC values of about 10 prevail; then a rapid yield reduction can be expected.[3] Bernstein [1967] states, "Since there is approximately a tenfold range in salt tolerance, one might expect, roughly, a comparable range in permissible salt contents of irrigation waters." However, the degree of soil water salinity is dependent on the proportion of the irrigation water evapotranspired relative to the fraction of the water which is leached past the root zone.

Soil permeability and water infiltration rates are factors in soil salinity in that they influence the irrigator's ability to manage the amounts of water needed to meet both the evapotranspirational losses and the water required to carry the excess salts past the root zone. The permeability of some soils may be so low that water stands in the field for several days after irrigation. In this event, damage to the crop will often occur from poor aeration and scalding.

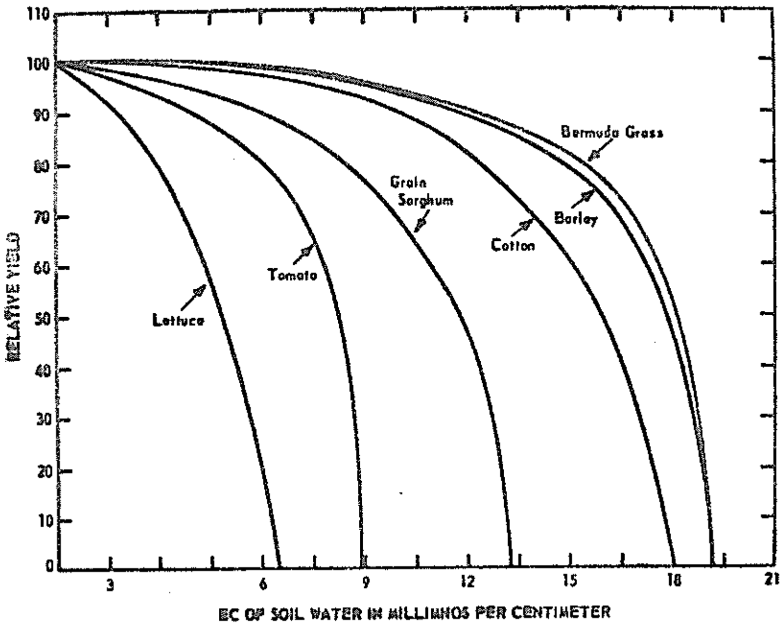

Figure 1. Salt tolerance of selected crops from Bernstein [1964].

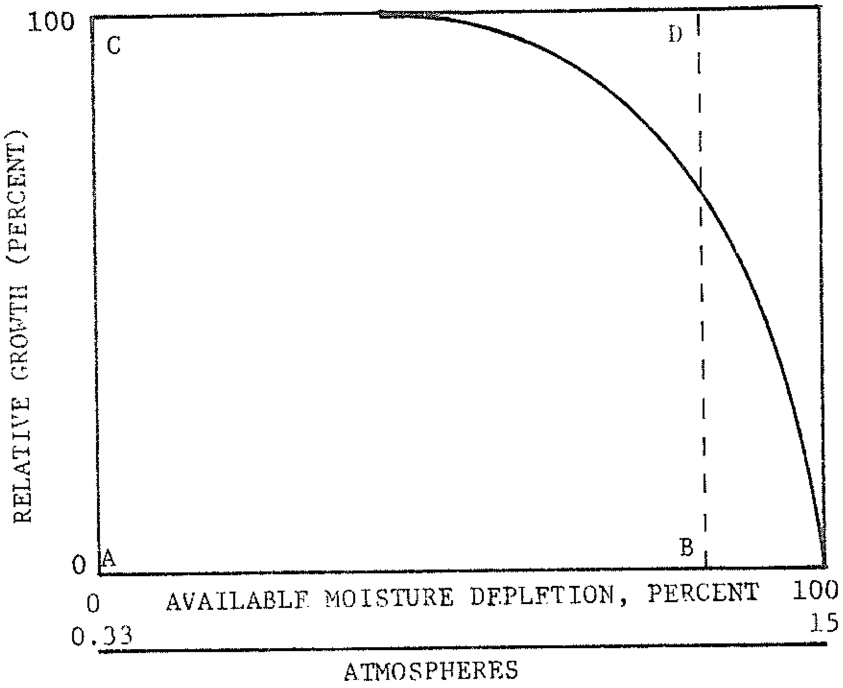

Figure 2. Plant growth in relation to available soil moisture.

For an irrigation system to be successful, provision must be made for percolation of some water below the root zone to leach away the yield-depressing salts. Adequate drainage must also be available to prevent a rise in the water table, and thus forestall an upward movement of salts by capillary action. If subsurface drainage is not available naturally, it must be supplied by artificial means, such as buried drain tiles.

Using Bernstein's [1967] definition of the leaching fraction as:

$$LF = \frac{D_d}{D_i}, \tag{1}$$

or the ratio of the depth of drainage water D_d to the total amount of irrigation water percolated into the soil D_i, then $D_d = D_i - D_e$, where D_e equals the amount evapotranspired. In other terms, if $D_i = I_t$ and $D_e = E_t$, where I and E are the average infiltration rates and evapotranspiration rates, respectively, over time t, then

$$LF = 1 - \frac{Et_c}{It_i} \tag{2}$$

where drainage is not limiting and t_c and t_i are duration of the irrigation cycle and irrigation application, respectively.

If the drainage rate is limiting, then the difference in value between infiltration and evapotranspiration cannot exceed drainage without causing waterlogging. If O is the average drainage rate per day without a rising water table, the $LF = O/E + O$. Therefore, there is an upper limit to the leaching fraction which limits the salt content of usable irrigation water. This is best shown by an example:

if $E = 0.3$ inch per day

and $O = 0.1$ inch per day,

$$\text{then } LF = \frac{0.1}{0.3 + 0.1} = 0.25 \tag{3}$$

Once the upper limit of LF is calculated, the suitability of an irrigation water can be determined by the ratio of its conductivity to that of the drainage water:

$$LF = \frac{EC_i}{EC_d} \text{ or } EC_i = LF \times EC_d \tag{4}$$

where EC_d is the maximum permissible electroconductivity of drainage water. If the maximum permissible electroconductivity of the soil water is 3 millimhos (this level reduces lettuce production by 25 percent, see

Figure 1), the EC of the irrigation water cannot exceed EC = 0.25 x 3.0 = 0.75.

However, if field tile drainage increases the average rate to $O = 0.15$ inch per day, then an irrigation water of EC = 1.0 can be used successfully without loss of yield.

Effect of Soil Moisture Stress on Plant Growth

Although very little direct quantitative information is available on plant growth as influenced by soil salinity and soil moisture in combination, some tentative suppositions must be made if a wide range of irrigation water qualities are to be analyzed.

Most plant scientists agree, in general, that plant growth within an irrigation cycle is a function of total soil moisture stress in the active root zone. Moore [1961], drawing on the work of Hagan [1955] and others, used the inverted soil-moisture-release curve to describe the relative rate of growth between field capacity and the permanent wilting point (see Figure 2). If it can be assumed that each irrigation cycle is independent of all others (no hysteresis), the production response may be described as a series of irrigation regimes. Weights may be attached to individual irrigation cycles to take into a ccount the effect of soil moisture stress during critical periods of plant growth (tillering, boot state, and flowering).

If the crop is reirrigated at a moisture depletion percent of 80, then the area under the curve between 0 and 80, as a fraction of the rectangle ABCD in Figure 2, will give the index of relative growth for one irrigation cycle. This can be represented mathematically as:

$$I\theta_i = \frac{\int_0^{\theta_i} g(x)\,dx}{\theta_i \times 100} \qquad (5)$$

where I is the fraction of potential growth for one irrigation cycle, and θ_i, is the moisture depletion percent at which the irrigation cycle is terminated with a new irrigation application.

A Model Combining Quality and Quantity of Water

Growth retardation from the part of moisture stress due to salinity alone is related primarily and directly to the osmotic pressure of the soil solution. Because the electrical conductivities of soil solutions are highly correlated with their osmotic pressures, the simple conductivity measurements can be used. The relationship between osmotic pressure in atmospheres and electrical conductivity is given approximately by:

$$OP = 0.36(EC_e \times 10^3) \text{ [Reeves and Fireman, 1967]} \qquad (6)$$

Assuming that moisture stress (whether it results from a physical reduction in soil moisture or from the osmotic pressure of dissolved salts) is additive with respect to reducing growth rates and yields, then it is possible to construct a theoretical response surface for quality and quantity of water.[6]

Figure 3 is an idealized representation of the production response surface, depicting for three salt tolerance groups the effect of different irrigation regimes and water qualities for one soil type. At the left-hand edge of the surface (zero EC) is a curve similar to the moisture-release curve shown in Figure 2. Relative growth curves for varying soil conductivities appear as traces for the medium tolerance group, beginning on the horizontal axis and extending upward and over the response surface. For detailed research purposes, the specific response curve for any crop in question should be used. This grouping for a medium tolerance group is used to illustrate a first approximation. The traces parallel to the base in Figure 3 represent isoquants, i.e., lines of equal production. The slope of these isoquants indicates the marginal rate of substitution between water quality and water quantity.

Assuming that the effects of moisture stress and of electroconductivity of the saturated soil after irrigation are additive, combining:

$$G_j = f(x) \qquad (7)$$

where G_j is the crop response to soil moisture depletion, with

$$G_k = g(s) \qquad (8)$$

where G_k is the crop response to the salt content of the soil, to obtain

$$G_{jk} = F(xs) \qquad (9)$$

the net response for one irrigation cycle can be represented as the double integral

$$G_{ri} = \zeta_0^{\theta_i}\zeta_0^{e_s}\theta_{jk}dx\ ds \qquad (10)$$

where θ_i is the soil moisture at the time the crop is reirrigated, and e_s is the conductivity of the soil water in the root zone at the end of the irrigation cycle.

The index of growth within an irrigation cycle would be the definite integral of equation (1) over the volume of the cubic defined as (θ_i) (e_s) (100) or

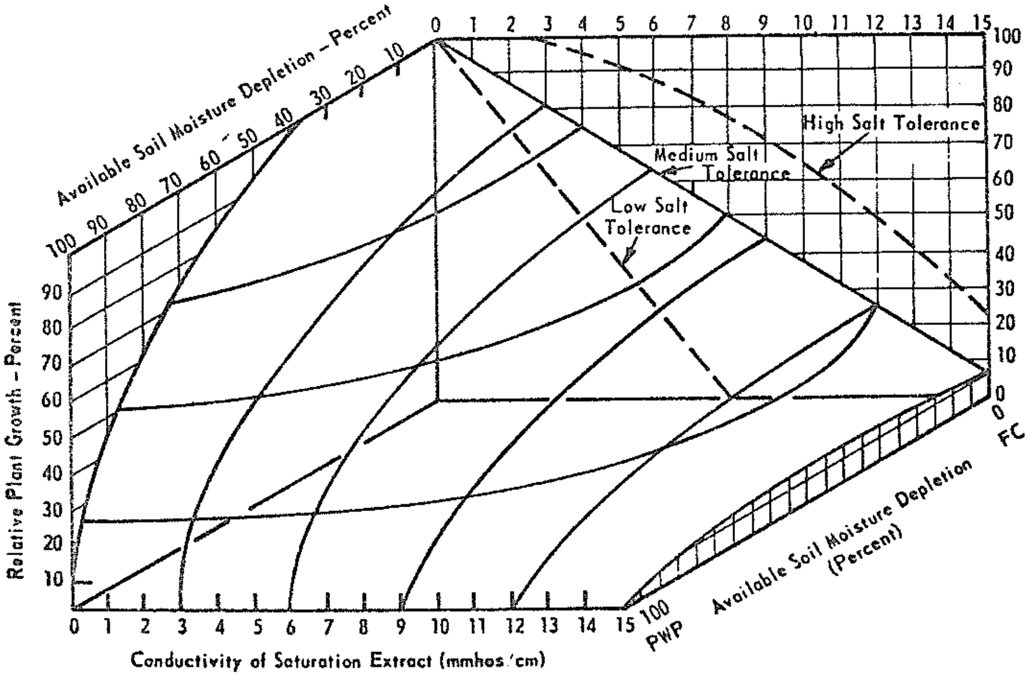

Figure 3. Hypothetical crop response surface.

$$I_{\theta_i e_s} = \frac{\zeta_{\vartheta}^{\theta_i} \zeta_{0}^{e_s} \theta_{jk}\, dx\, ds}{(\theta)(e_s)(100)} \tag{11}$$

To obtain the total growth for the entire season, G_{ri} is summed for each irrigation cycle, i. For a particular crop, G_{ri} can be weighted to reflect the effects of critical periods in the development of the plant, such as germination, flowering, seed development.

A major problem in this synthesized approach is that the variables are not stated in terms of quantities of water applies, but rather in terms of soil-moisture tension, electroconductivities, and relative yields. The situation is further complicated by the fact that the leaching efficiency of a small water application may be greater in terms of units of salts removed from the root zone per unit of water applied, than that of a deep water application. However, for purposes of simplifying the presentation, we will assume there is a related surface, stated in terms of actual quantities of water applied, associated with the surface shown in Figure 3.

This second surface would necessarily take into account the water lost due to surface evaporation, the water required to achieve uniform wetting throughout a field, and the leaching efficiency of different depths of water application with respect to salt removal.

Summary of the Physical Factors Affecting Water Quality Considerations

Thus far only the physical factors associated with crop response to the qualitative and quantitative dimensions of irrigation water have been considered. An attempt has been made to show that there are physical limitations to the use of certain irrigation waters in certain locations. That is, due to the physical conditions of climate, soil permeability, drainage (natural or artificial), the salt tolerance of the crops adaptable to a specific location, irrigation water of a given quality may or may not be usable. These limitations are not absolute, and there is a degree of substitutability among them. For example, artificial tile drainage can be substituted for natural drainage, or the quantity of water can be substituted for quality of water using a higher leaching fraction. Also, crops with a higher salt tolerance can be used to replace sensitive crops as the quality of water deteriorates. In the concept of a long-run, steady state, these physical factors can be used to describe the limitations to the possibility of a long-term, irrigated agriculture. In the parlance of logic, the physical factors can be termed the necessary but not sufficient conditions for a long-term agriculture.

Other Constituents of Water Quality

Major attention has been given to salt concentration as a measure of irrigation water usability. However, other constituents are also important and, in certain localities, may be of overriding importance. An example is sodium, which can cause an alkali buildup under certain situations. Crops, especially those of woody plants, can accumulate harmful levels of sodium in the leaves when the exchangeable sodium percentage (ESP) of the soil is as low as 5 percent [Bernstein, 1967]. Sodium also affects soil properties by causing dispersion of the soil particles, with a resultant drastic reduction in the infiltration rate. Sodic soils are usually treated by adding gypsum or other acid-forming amendments. Little is known about the effect of boron and other trace elements which may be present in local irrigation waters in sufficient quantity to create toxic conditions for plants. As little as one ppm boron can be toxic to some plants.

Economic Considerations of Irrigation Water Quality

Assume a production function based on the above description of physical variables as follows:

$$y = f(W_1 \; W_2, \; R, D, L, K) \qquad (12)$$

where output y is some function of f, of W_1, defined here as the quantity of "pure" water, W_2 is the electroconductivity of W_1, R is average rainfall, D is the drainage variable, and L and K are labor and capital, respectively.

A'priori, a high inverse intercorrelation between W_2 (water quality) and drainage could be expected. As the EC of the irrigation water increases, drainage would necessarily also increase, although in the short run, D could approach zero. Perhaps this last statement should be elaborated. If an individual farm or field on a farm is being considered, irrigated crops could be grown for a short period of time with no drainage. However, with low-quality water, this time could be surprisingly short. For example, the depth of irrigation water applied, (D_i), of known EC_i that will contain sufficient salt to increase the EC of the soil in one foot of the root zone (D_s) by an amount (ΔEC_i), is calculated by the equation:

$$D_i/D_s = \frac{d_s}{d_w} \; (SP/100) \; (\Delta EC_e/EC_i) \quad [\text{USDA, 1954}] \qquad (13)$$

where d_s/d_w is the ratio of the densities of the soil and water, and SP is the saturation percentage. Letting $EC_i \times 10^6 = 1{,}000$, $d_s = 1.2$ gm cm^{-3}, $d_w = 1$ gm cm^{-3}, SP = 40, and $\Delta EC_e \times 10^6 = 4{,}000$, then $D_i/D_s = 1.9$. This means that less than two feet per acre of reasonably good quality water contain sufficient salt to change a one-foot depth of salt-free soil to a saline condition in one year, if there is no leaching.

If the production function is developed for an irrigation project or district service area, investment in a district-wide drainage system must be included in the drainage variable. Subsurface drainage water from higher elevations may accumulate in low-lying areas on farms at lower elevations, or as perched water tables down slope. It may be impossible to remove the drainage water from a farm without a district-wide system of interceptor drains or collecting drains. Corrective measures require community action. The interdependency with respect to drainage in the Imperial Valley of California for example, involves two levels of hierarchy--the private farmer and the community of farmers represented by the irrigation district. Just as in the of joint action being required to obtain a supply of water, the economic feasibility of on-farm drainage requires collective action to remove the effluent from the district.

Drainage of a large geographic area, such as the Central Valley of California, the Indus Plains of Pakistan, or the Gangetic Plan in India, may require group action of an aggregate of communities. A good example of communal participation is the Master Drain for the San Joaquin Valley. This points to a problem of sequential decisions at different levels of hierarchy, both private and public, before a necessary physical condition can be met. A study of the optimal timing for these decisions would be an interesting investigation, because of the interdependency and the external diseconomies involved, but such is not a part of this paper. Where an aggregate of communities must act jointly to solve a drainage problem due to irrigation return flows re-entering the source of supply and reducing its quality dimension, account must be taken of the external diseconomies inflicted on the downstream users. A system of trade-offs based on welfare criteria must be established in order to minimize the total cost for the entire river basin [Kneese, 1964, Chap.3].

Rainfall is included as a variable because it may be sufficient to supply the leaching requirement. If rainfall is sufficient during the winter months to reduce the salt content of the root zone to zero each year, irrigation water of a much lower quality could be used during the summer than would otherwise be possible. However, in an area such as the Imperial Valley of California, where the rainfall averages less than two inches a year, leaching must be accomplished using low-quality Colorado River water.

Rainfall during the crop growing season can contribute to the leaching requirement, and to evapotranspiration as well. Such rainfall, although it complicates the analysis, does not preclude a solution to the analytical problem. Also, when water from two or more sources, with differing water qualities are used, account must be taken of the timing and quality of each source. A simple average conductivity for the entire season may give erroneous results.

Water Quality and Conservation

In the terminology of resource conservation, irrigated agriculture becomes a flow resource with a critical zone [Wantrup, 1952]. This is not a simple flow resource situation which provides a good or service in many time periods, but a bundle of highly interrelated, complementary flow resources. Irrigation water is a flow resource, a certain amount of which becomes available each year. The soil root zone also can be considered as giving off a flow of services, in that each year the soil can be used as a reservoir for holding moisture and nutrients, and as an adhesive force which keeps a plant in place.

To conserve this bundle of resources above its critical zone, the use rate of the resource must not be so high that in any one time period the salt content of soil moisture in the root zone passes the critical level, causing the productivity of the resource bundle to be irretrievably lost. This point would occur when reclamation of the salinized soil was no longer economical. In the ancient civilizations of Mesopotamia, the critical zone was passed; and the land reverted back to desert when the salt content of the soil extract became too great, although for several centuries this had been a highly productive area.

In the United States there was a case where an irrigation project came to the brink of the critical zone. The sole source of water for the Imperial Irrigation District of California is the flow of the Colorado River. Here, irrigated acreage increased rapidly in the first two decades of this century. Symptoms of waterlogging and salting-up began to appear in the 1920's. By the 1930's the problem was serious, and some 50,000 acres with poor natural drainage temporarily went out of production. Soil Conservation Service engineers recommended extensive field tiling and a broad network of collection ditches to remove the excess saline water from individual farms and the district service area. However, farm product prices at this time were quite low due to the economic depression, and farmers were unwilling to make the large capital investments that appeared necessary. Lands in the district continued to revert to desert. During the 1940's, agricultural income improved, and along with it willingness to invest in drainage, both privately and collectively. By 1966, almost 13,000 miles of tile drains had been installed, covering over 300,000 acres in the district. The district has also dug over 1,400 miles of open ditch to carry the effluent from the tile drains to the New and Alamo Rivers, through which it flows into the Salton Sea [Smith, 1966].

The Imperial Valley case indicates the importance of factor and product prices, as well as the necessary physical conditions. It can be asserted that if the physical factors specify the necessary conditions, then economic factors can be used to describe the sufficient conditions for a long-term irrigated agriculture. Attaching product prices and factor prices to the production function, a present-value profit equation can be written:

$$\pi_{pv} = B_i \sum_{n=1}^{n} \sum_{j=1}^{m} P_i Y_i f(X_{11}, X_{12}, \ldots, X_{nm}) - c_{ij} X_{ij} \qquad (14)$$

where π_{pv} is the present value of a future stream of income summed over inputs (X_{ij}) and time, P_i and C_i are product and factor prices, respectively, and B_i is the appropriate discount factor.

Theoretically, it would be possible to calculate a maximum π which optimized the use rates of each resource in each time period. However, the problem is not to determine an optimum, but rather to specify conditions for Survival implies establishing a critical minimum conservation use rate of the resources. Survival also would mean that the present value of the future stream will always be greater than unity. Stated in this form, survival also implies that π for each subplanning period must be positive. The length of the subplanning period can exceed one year, but cannot be so long that the critical zone resources involved can, at any one time, become "trapped" in the critical zone.[5]

The previously described "salt" problem of the Imperial Valley was not anticipated when the project was initiated. If the additional drainage investment required had been included in the original project feasibility analysis, the benefit-cost ratio would not have been so favorable. As the quality of the Colorado River continues to deteriorate, there is some question as to how long an irrigated agriculture can be maintained in the Valley. With the present technology and fixed water supply, there is an upper limit to the substitution between water quality and quantity. As this limit is approached, more salt-tolerant (lower-valued) crops must be included in the crop mix. Lower-valued crops, along with greater investment in drainage, reduce the value of the profit equation. This is, the Valley is faced with an increasing cost function and a decreasing revenue function over time.

Ignoring for a moment the impact on the profit equation created by substituting more-tolerant for less-tolerant crops in the cropping pattern, the Imperial Valley experience points out the risk involved in using long-term average prices to determine project feasibility. Long-term average prices, without consideration of the variance about the mean, ignore the possibility that product prices can assume values below those expected, for a number of years in succession. For resources without a critical zone, this does not present the hazard that could be encountered with a critical zone resource. The irreversibility of critical zone resources necessitates greater care to insure against the probability of premature project failure. For example, if the depression of the 1930's had continued for an additional 10 years, El Centro might now be called Mesopotamia West.

Thus far, the precise definition of the expression "long-term irrigated agriculture" has not been made. In fact, using an exact number of years such as 200 or 1,000, would have little meaning. A workable definition would be a planning horizon where all structures and facilities had become worn out or obsolete, in other words, when all costs with respect to planning have become variable costs. If the maximum design life of the structure included in a project is 100 years, then the planning period should be at least 101 years. The additional year beyond the design life forces consideration of, in the original project, the design of replacement structures. For example, this approach would have forced the designers of Shasta Dam to consider in their original design the "new" Shasta Dam that will be required when Shasta Reservoir has been silted-in due to the turbulence constituent of water quality. In another case, what additional facilities should be constructed in the Central Arizona Project to replace presently planned structures to minimize the impact of Colorado River water containing 1,500 ppm of dissolved salts sometime in the next century?

If the present value of a dollar 100 years in the future at a 3 percent discount rate is only $0.052 and at a 6 percent discount rate only $0.029, concern for the economic viability of future generations dwindles rapidly beyond the century planning period. Possibly the present value of future incomes and costs, 100 years from now is so small, or predicting technological change is so uncertain, they can be ignored. However, concern for the survival of a productive use of a rapidly growing world population requires a longer-run outlook.

Summary

An attempt has been made to show that the necessary conditions for a long-term irrigated agriculture can be described in terms of specified physical factors: salt tolerance of crops, soil permeability, climate, and drainage. For a given location, there is a range of substitutability among these factors. The sufficient condition, however, must be defined in terms of the economic considerations involved in long-term survival. A resource with a critical zone implies that conservation must not drop below the critical minimum level any time during the planning period if the critical zone is a true "trapping state." For the sum of the stream of benefits from a project to be at a survival level for the entire planning period, the resource must be maintained above the critical zone for each subperiod.

Footnotes

[1] The salt content of a soil or water can be estimated by passing an electrical current through a sample of water or through a water extract of soil sample [USDA, 1954]. This electrical conductance is expressed in millimha/ca or EC x 10^3.

[2] Unless otherwise indicated, electroconductivity in this paper will be expressed in millimhos/cm or EC x 10^3.

[3] Pincock has used these data to estimate the possible effects of a deteriorating water quality in the Welton-Mohawk Irrigation Project in Arizona [Stewart and Pincock, 1967].

[4] An early attempt to measure this relation was made by Wadleigh [Wadleigh, Gauch and Magstad, 1964], using guayule plants and water with various salt concentrations under three different irrigation regimes.

[5] It would be possible to visualize a very large π for the first time period and zero for the remaining time periods where $\pi_{pv}/N > 0$.

References

1. Bernstein, Leon. 1967. Quantitative assessment of irrigation water quality. Water quality criteria, American Society for Testing and Materials, Special Technical Publication No. 416.

2. Bernstein, Leon. 1964. Salt tolerance of plants. USDA Information Bulletin No. 283.

3. Hagan, Robert M. 1955. Factors affecting soil moisture-plant growth relations. Report of the XIV International Horticultural Congress, Scheveningen, Netherlands, pp. 86.

4. Kneese, A. V. 1964. The economics of regional water quality mangement. Resources for the Future. Johns Hopkins Press. pp. 41.

5. Marr, Paul D. 1967. The social context of irrigation. Irrigation of Agricultural Lands. Agronomy Monograph Series No. 11, American Society of Agronomy. pp. 12-24.

6. Moore, C. V. 1961. A general analytical framework for estimating the production function for crops using irrigation water. Journal of Farm Economics, Vol. 42, No. 4, pp. 876-888.

7. Reaves, Ronald C. and Milton Fireman. 1967. Salt problems in relation to irrigation. Irrigation of Agricultural Lands. American Society of Agronomy Monograph No. 14. pp. 988-1008.

8. Smith, Jack F. 1966. Imperial Valley salt balance. USDA, SCS. Imperial Irrigation District. (Unnumbered publication.)

9. Stewart, C. E. and Glade Pincock. 1967. Impacts of water quality on the agricultural industry in the Colorado River basin. Water Resources and Economic Development of the West. Report No. 19. pp. 116-136.

10. U. S. Department of Agriculture. 1954. Diagnosis and improvement of saline and alkali soils. USDA Handbook No. 60.

11. Wadleigh, C. H., H. G. Gauch and O. C. Magstad. 1946. Growth and rubber accumulation in guayule as conditioned by soil salinity and irrigation regime. USDA Technical Bulletin No. 925.

12. Wantrup, S. V. 1952. Resource conservation. University of California Press.

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