Advances in Irrigation

Volume 1

Edited by
Daniel Hillel

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PREFACE

Water constitutes one of the principal constraints to increasing food production in our hungry world. So tenuous and delicate is the balance between the demand for water by crops and its supply by precipitation that even short-term dry spells often reduce production significantly, and prolonged droughts can cause total crop failure and mass starvation. Irrigation is the artificial application of water to agricultural crops, designed to permit farming in arid regions and to offset drought in semiarid or semihumid regions. As such, it plays a key role in feeding an expanding population and seems destined to play an even greater role in the foreseeable future. Even in areas where total rainfall is ample, it is often unevenly distributed during the year so that only with irrigation is multiple cropping possible. In fact, the potential productivity of irrigated land can exceed that of unirrigated land severalfold, particularly in dry regions, due both to increased yields per crop and to the possibility of multiple cropping.

The process of irrigation generally consists of introducing water into the part of the soil profile that serves as the root zone, for the subsequent use of the crop. A well-managed irrigation system is one that optimizes the spatial and temporal distribution of water, not necessarily to obtain the highest yields or to use the lowest amount of water possible, nor always to attain the highest yield per unit amount of water, but to maximize the benefit-to-cost ratio. Although the problem and its solution are site specific in each case, the principles involved are indeed universal. From its early and primitive antecedents in the great river valleys of the Middle East some seven millennia ago, irrigation has envolved into a highly sophisticated operation, involving the simultaneous monitoring and at least partial control of weather, soil, and crop variables. Yet progress continues. What with the steepening costs of energy and water, the search for means to increase the efficiency of irrigation and of water utilization is becoming all the more urgent.

This volume is the first of a new serial publication entitled *Advances in Irrigation*. Designed to follow the format of such existing serials as *Advances in Agronomy* and *Advances in Hydroscience*, also published by Academic Press, the new serial is aimed at fulfilling a perceived global need for periodically updated comprehensive elucidations of the various topics of contemporary interest and importance related to the rapidly advancing science and engineering practice of irrigation. Scientific and professional journals report highly specific developments and are necessarily limited to short, entirely technical, communications. At the opposite end of the spectrum of publications are the textbooks on irrigation, which tend to be very general and avoid in-depth analyses of specific topics. Between the journals and the textbooks, there is room, and need, for a regular ongoing forum wherein to present the developments arising out of irrigation research in the form of critical reviews of selected topics that from time to time appear to be ripe for such presentation. Such reviews do not merely summarize and encapsulate what is precisely known at present, but assess its significance in relation to alternative approaches, analyze the trends, and point to future prospects. The aim is thus both to inform of progress to date, and to spur continued progress. The contributions envisaged will include, but not be limited to, state-of-the-art reports, critiques of current practices, economic analyses, case studies of irrigation in different locations, changing concepts of irrigation, and water-use efficiency. Considerations will be given to such topics as energy and irrigation, controlled-environment crop production, conjuctive use of rainfall and irrigation, and the precise role of irrigation in regional and global food production.

Toward the aim described, we have invited the participation of several of the leading researchers to help launch this new serial. As is well known, excellent scientists are, by definition, very busy people, notoriously (and understandably) reluctant to be harnessed to any fixed schedule. Some of the people invited to contribute to this volume will therefore appear only in a subsequent volume. However, we are fortunate to have been granted the timely participation of a sufficient number of outstanding contributors to make this an even better volume than we had dared hope for initially. As Editor, I wish to express my gratitude for their exemplary cooperation.

DANIEL HILLEL

And the Lord God planted a garden in the east, in Eden.
. . . And out of the ground the Lord God raised
Every tree that is pleasing to the sight and good for food;
And the tree of life was also within the garden,
And the tree of the knowledge of good and evil.
And a river emerged from Eden to water the garden,
And from thence it parted and became four heads.
. . . And the Lord God placed man in the garden of Eden
To work it and to preserve it.

GENESIS 2 : 8–10, 15

INTRODUCTION

The Book of Genesis tells the story most succinctly: the first tree plantation[1] was irrigated by a river, which was divided into four channels. And man, so lacking—then as now—in the knowledge of good and evil, was appointed custodian and entrusted with the protection of God's garden. Alas, greedy man soon abused the trust, succumbing to momentary temptation and becoming more a consumer (beyond his needs) than a preserver. He, and his descendants, must thenceforth and forever suffer the consequences of this folly. Man's entire relationship to the environment is illustrated therein.

In the specific context of irrigation, the lesson is even more startlingly clear. Injudicious management of soil and water—out of ignorance or shortsighted greed—can destroy the bountiful garden on which we all depend for our sustenance. Since its inception seven or more millennia ago in the river valleys of eastern, southern, and southwestern Asia, and northeastern Africa, irrigation development has in some places become ultimately self-destructive. All too often, the short-term gain in production, leading to intensive settlement, was followed inexorably by long-term loss, in the form of water resource depletion and pollution, as well as of soil erosion and degradation. The problem is not inherent in the principle of irrigation per se, but in its frequently careless practice. What is at fault is the unmeasured application of water to land with little control over

[1]The word "paradise," incidentally, is derived from the Old Persian word *pairi-daēza*, meaning an enclosed park, or orchard.

quantity or quality, without knowledge or regard for the potentially insidious processes thereby set in motion.

It is the universal fallacy of man to assume that if a little of something is good, then the more the better. In irrigation (and indeed in so many other walks of life, as we tend to discover only too late), just enough is best, and by that we mean a measured quantity of water applied at a rate calibrated to meet the continuous requirements of the crop, no less and certainly no more. The application of too little water is an obvious waste, as it might fail to produce the sought-after benefit. Excessive flooding of the land, is, however, even more destructive, as it saturates the soil, impedes aeration, leaches nutrients, induces greater evaporation and salinization, and ultimately raises the water table to a level that can only be drained at an enormous (and at times prohibitive) expense. Even where groundwater drainage of irrigated land is feasible, there remains the problem of its disposal. Dumping it back into the stream merely serves to salinize the water supply—diminished in any case—upon which depend other irrigators further downstream.[2]

Advances in the science and art of irrigation necessarily imply the gradual acquisition and utilization of knowledge leading to more precise control over the quantity and quality of water applied. The aim of such control must be to optimize the practice of irrigation in conjunction with all the other interacting variables which together govern crop production.

Control of irrigation should properly begin at the source—the river, reservoir, or aquifer. Withdrawal of water from a source in excess of the rate of replenishment eventually depletes the source[3] and might deprive the crops of their water supply at the very time of greatest need. The measured withdrawal of water should be calibrated to answer seasonal crop needs on a continuous, time-variable basis in accordance with crop growth stages, changing evaporative demand, and space-and-time-variable soil conditions. Too many irrigation projects have been (and indeed still are being) designed by hydraulic engineers alone, without sufficient regard for the utilization of water in the field. Irrigation systems

[2]The word "rival," now taken to mean "adversary" was originally used in Roman law as a term for those who shared the water of a *rivus*, or irrigation channel.

[3]Especially serious is the depletion of groundwater from an aquifer. It might cost the user little to drill a well and begin pumping water out of the ground. If pumping exceeds recharge, however, the water table is gradually lowered to where it can no longer be pumped profitably. Having already realized his profit, the groundwater exploiter might then abandon the land or sell it to others. The cost of restoring the water table afterward is likely to be enormously greater than the cost of lowering it in the first place, but that problem is generally left for future generations.

which deliver water to the field on a fixed, imposed schedule, leave the irrigator with little choice or discretion, and no incentive, to economize his water use. Ideally, water should be available *on demand,* and be priced in proportion, or even in progressive disproportion, to the quantity used per unit area of land.

Proper control of irrigation continues beyond the source of the water, and extends through its conveyance and delivery to the field. The prevalent use of open and unlined canals too often entails large losses of water by seepage, which causes waterlogging of adjacent lands and exacerbates the drainage problem. Unlined canals are also subject to frequent breaching of their banks, because of scouring by flowing water or uncontrolled crossings by animals.[4] Still another problem in unlined canals is the flow-hindering effect of riparian vegetation. Ideally, the conveyance of water should be carried out in closed conduits, and under sufficient pressure to permit delivery to fields of various elevations. However, the capital costs of closed conveyance systems, and the energy costs of pressurizing water, are considered prohibitive in many situations.

Ultimately, the major control of irrigation rests in the hands of the irrigator in the field. Unfortunately, it is here that we can still witness the greatest inefficiency. Even the terms used to characterize efficiency are obscure and confusing. In principle, any measure of utilization or application efficiency should refer to the quantity of a resource actually utilized beneficially as a fraction of the total quantity applied. "Irrigation efficiency" has variously been defined as the quantity of water added to the root zone, or the quantity of evapotranspiration, or just the quantity of transpiration, each as a fraction of the total quantity of water delivered to the field.

One of the problems here is that the root zone of a growing crop is practically impossible to define with any degree of precision (as it varies in time, with the crop, and indeed with the method of irrigation). Two processes which strongly affect the profile moisture storage and the disposition of applied water are in effect invisible to the onlooker, and measurable only with much difficulty and imprecision by the scientist: evaporation and deep percolation. In the absence of universal, simple and reliable ways for the practical irrigator to measure these time-variable and space-variable processes, and given the uncertainty in the very definition of irrigation efficiency, it is not surprising that in so many (perhaps most)

[4]Water buffaloes are a particular problem in South Asia, where they habitually wade into the canals to wallow in the water, incidentally churning up the bottom and damaging the banks.

cases, irrigation water is applied very inefficiently indeed. The problem is compounded by the difficulty of achieving uniform distribution and supply to the root zone in surface-irrigation systems (still the most prevalent of irrigation systems) where the irrigator depends on the hydraulic properties of the soil itself, which tends to be spatially heterogeneous, to distribute, absorb, and retain the applied water.

Even more baffling than "irrigation efficiency" is the term "water use efficiency," commonly defined as the ratio of crop yield (total aboveground dry matter in some cases, or grain yield in other cases) to the total quantity of water "consumed" by evapotranspiration. An alternative definition proposed lately is to relate the yield increment resulting from irrigation (i.e., the yield of the irrigated crop minus the yield without irrigation) to the amount of irrigation, or to the increment of evapotranspiration resulting from irrigation. By either of these definitions, the qualities related to each other (weight of crop per volume of water, in effect "apples divided by oranges") do not provide us with any universal criterion of efficiency ranging, say, between 0 and 100%.

The ultimate test of efficiency, in realistic terms, is that of economic profitability. And that, evidently, is the least objective and universal of all measures of efficiency. The economics of each country or region differs from that of all others, and much depends on local policies and priorities; indeed on the whole complex system of incentives and rewards. The cost of water relative to the costs of other inputs—energy, labor, capital—is an extremely important factor. Water is kept artificially cheap in too many places, through policy manipulation or maintenance of anachronistic vested "water rights". Individual farmers may find it profitable, and hence "smart," to waste water even knowingly, as the means to save water may be more expensive than the water to be saved. All too often, society as a whole bears the costs or, worse yet, the deleterious consequences of today's "smart" practices (e.g., depletion of water resources) as they are passed on to future generations.

The widespread habit of lumping evaporation from the soil with transpiration by the crop in the single term "evapotranspiration," however convenient, actually adds to confusion. Transpiration is a necessary, one might even say a productive, expenditure of water in crop production. Evaporation, on the other hand, is often a partially avoidable loss. The two processes interact, of course, and may be mutually compensatory, but only to a limited degree. An irrigation system which minimizes evaporation from the soil (e.g., drip irrigation) can in fact produce a significant savings of water.

Various names are being developed and improved in the continuing effort to achieve a higher level of control in irrigation. Among these are the use of laser guidance systems for precision shaping of the land surface; precision tillage and mulching to promote infiltration and reduce evaporation while minimizing the expenditure of energy; metering valves and pressure control devices to regulate water delivery; flumes and weirs to measure the amount of water used (it is amazing, and disconcerting, to discover in how many cases water is still being applied without any measure!). The conjunctive use of precipitation (rainfall) and irrigation can result in a large savings of water and an increase of the land area which can be effectively irrigated. Above all, there is steady progress in developing methods to monitor and control the various components of the dynamic balance of water in the field. As we develop the ability to measure the pertinent variables more reliably, the degree of uncertainty associated with water management diminishes and greater control becomes possible.

A crucial problem in irrigation management is to determine just when, where, and in what amount to apply the water for greatest beneficial effect. To determine the optimal timing and quantity of irrigation, there are at least three alternative or mutually complementary approaches. The answer can be sought in the soil, in the plant, and in the microclimate. The soil "reservoir" can be monitored for its moisture content or potential with a view to determining the root zone's deficit to, say "field capacity." Additionally, measurements of the salt concentraton of the soil solution and of the groundwater (if present not far below the root zone) can indicate the adequacy, or inadequacy, of irrigation. Or, the plant can be observed in an attempt to detect early signs of incipient stress, so as to be able to irrigate in time to forestall any substantial yield reduction due to stress. Finally, the weather can be monitored to determine the evaporative demand. As shown in the chapters of this book, all these approaches are being pursued concurrently.

For many years, the predominant approach to irrigation has been (and still is in many places) to apply water as infrequently as practicable, and only when the soil moisture reservoir in the root zone is almost completely depleted of so-called "available" (or, to use a more recently coined term, "extractable") water. Soil moisture is then replenished by a massive application of water sufficient to saturate the soil to some depth. Such periodic and abrupt saturation of the soil's surface zone tends to impeded aeration, and the subsequent gradual desiccation of that zone could be further impediment to root growth and function there. In the last decade, however, evidence has been mounting that a better approach might be to attempt to establish and continuously maintain a wet (but unsaturated) soil moisture regime in order to prevent the plants from experiencing stress and thus promote their maximal, uninterrupted growth. There are indications that in many (though not all) cases the increased yield may be more than proportionate to the increased water use. In optimal combination with improved fertilization, soil amendments, tillage, and pest control, high frequency irrigation, if calibrated precisely to answer the transpirational needs of the crop while preventing any possible accumulation of salts in the root zone, may hold the best promise at present to help us achieve a higher level of beneficial control over irrigation. However, no technical system, however sophisticated, is a panacea. The efficacy of a system depends on how it is used. Improperly used, even the most advanced system can fail. Progress demands that we continue to work painstakingly to achieve better, more comprehensive, and more precise knowledge of the complex processes we are attempting to control, and then to determine how to achieve such control economically under various circumstances.

In irrigation, as in all science, the so-called "last word" is only the "latest word," and must never be allowed to become the "final word."

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