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IRRIGATION: AN HISTORICAL PERSPECTIVE

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INTRODUCTION

Irrigation can be broadly defined as the practice of applying additional water (beyond what is available from rainfall) to soil to enable or enhance plant growth and yield, and, in some cases, the quality of foliage or harvested plant parts. The water source could be groundwater pumped to the surface, or surface water diverted from one position on the landscape to another. Development of irrigation water often entails development of large-scale, geographically significant dams and water impoundments and/or diversions that can provide additional functions apart from crop growth enhancement, e.g., flood control, recreation, or generation of electricity. In many cases sustainable irrigation development requires concomitant development of surface and/or subsurface drainage.

ANCIENT ORIGINS AND IMPORTANCE

Irrigation may be the single most strategically important intentional environmental modification humans have learned to perform. While irrigation's impact has not always been as critical to the global agricultural economy and food supply as it is today, it has always had major local impacts and profound historical and social consequences. In the Bible's book of Genesis, we are told that God's creation of humans was accompanied shortly thereafter by His assignation to Adam of the stewardship of the irrigated orchard that was Paradise. The four life-giving water heads of Judeo-Christian Paradise are also mentioned in the 47th Sura of the Koran (1). Some anthropologists and historians point to the development of irrigation as the catalyst for the interaction of engineering, organizational, political and related creative or entrepreneurial skills and activities which produced the outcome referred to as "civilization" (2–5). In the ancient Persian language, the word *abadan*, civilized, is derived from the root word *ab*, water (1). Fundamental differences in social, cultural, religious, political, esthetic, economic, technological, and environmental outlook have been attributed to modern groupings of humankind related to their use of irrigation (5).

The earliest archeological evidence of irrigation in farming dates to about 6000 B.C. in the Middle East's Jordan Valley (1). It is widely believed that irrigation was being practiced in Egypt at about the same time (6), and the earliest pictorial representation of irrigation is from Egypt around 3100 B.C. (1). In the following millennia, irrigation spread throughout Persia, the Middle East and westward along the Mediterranean. In the same broad time frame, irrigation technology sprang up more or less independently across the Asian continent in India, Pakistan, China, and elsewhere. In the New World the Inca, Maya, and Aztec made wide use of irrigation. The technology migrated as far North as the current southwestern U.S., where the Hohokam built some 700 miles of irrigation canals in what is today central Arizona to feed their emerging civilization, only to mysteriously abandon it in the 14th century A.D. (3).

In the ancient world, the level of irrigation sophistication varied from one setting to the next. The differences, however, stemmed mostly from variations in understanding of both large- and small-scale hydraulic principles, as well as the capabilities to construct feats of hydraulic engineering. The Assyrians, for example, built an inverted siphon into the Nineveh Aqueduct 700 years before the birth of Christ, an engineering feat unrivaled until the 1860 construction of the pressurized siphons of the New York Aqueduct (3).

Some ancient irrigation schemes have survived to the present day where geologic, soil, and climatic conditions were favorable and where then-known management principles were adequate for the prevailing conditions. However, some ancient schemes failed. In the Mesopotamian Valley, Syria, Egypt, and other areas throughout the Middle East, there were many cases where the principles of salt management and drainage were insufficiently understood, resulting in eventual permanent impairment of the land (1).

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Siltation of ancient dams and reservoirs is a testament to inadequate soil conservation measures that eventually reduced the productivity of the land as well as destroyed the capacity of reservoirs to provide an adequate supply of water (3). Erosion of irrigation channels, in geologically unstable areas like the Chilean deserts, and catastrophic failure of irrigation channels after earthquakes often defeated the best efforts of ancient engineers to maintain water supplies (3).

Modern irrigation technology probably began with the Mormon settlement of the Utah Great Salt Lake Basin in 1847, and their eventual cultivation of nearly 2.5 million ha irrigated across the inter-mountain western U.S. by the turn of the century. Whereas relationships of mass, energy, and turbulence of flow were mastered at remarkably high levels of proficiency in ancient cultures, understanding of chemistry and physico-chemical interactions of soil and salt-bearing water was relatively meager even into the 19th century.

MODERNIZATION OF IRRIGATION

The mid-19th century marked a conjunction of several ascending areas of scientific learning, including chemistry, physical chemistry, physics, mineralogy, and biology. These were adapted, blended, and applied in important emerging new sub-disciplines of soil chemistry, soil physics, plant physiology, and agronomy, whose fundamental principles were to prove essential for sustainable irrigation system design and operation.

In ancient irrigation developments, soils, climate, and water quality came together in more forgiving combinations at some locations than at others. Where seasonal rains provided leaching, where soils were permeable and well drained, and/or where irrigation water had favorable combinations of electrolyte concentrations and specific cations, irrigation has continued to the present day, even without sophisticated management. In other areas, salinization, increased soil sodicity, and elevated water tables have limited the life spans of irrigation schemes or impaired their productivity. As irrigation moved into more marginal settings, with less productive soils, poorer drainage, and greater salinity and sodicity problems, the success or failure and ultimate longevity of the schemes became more dependent on knowledgeable application and adaptation of scientific principles. America's Mormon pioneers, choosing to settle in a remote salt-impaired desert habitat, were forced of necessity to use trial and error and the enlightened application of all available new knowledge to reclaim their lands from the desert and to practice a sustainable irrigated crop husbandry. They were so successful in their efforts that their approaches to irrigation and salt-threatened arid land reclamation and management provided the guiding principles for development of irrigation throughout the western U.S. from 1902 (with passage of the Reclamation Act) to the close of the 20th century (3). The science of irrigated agriculture and arid zone soil science in general relied heavily on the foundation and contributions stemming from these mid-19th century origins (7). Development of irrigation in the western U.S. was further spurred by passage of the Desert Land Act of 1877 and the Carey Act of 1894, which provided land for settlement and governmental infrastructure for development. The first university level irrigation course is believed to have been taught by Elwood Mead (Lake Mead's namesake) at the Agricultural College of Colorado in Fort Collins, Colorado (8). Mead later took positions with the United State Department of Agriculture and eventually was a commissioner for the Bureau of Reclamation. Worldwide, many of the practical modern principles of irrigation system design and irrigated soil management can be traced to the lessons learned in the settling of the American West from 1847 to the close of World War II, when the total U.S. irrigated area had grown to 7.5 million ha (6).

Following World War II, irrigation development worldwide entered a heady period of rapid expansion. World populations were growing, in part because of increased life expectancies resulting from new medicines and use of DDT to control malaria and other disease carrying insects. The advances in technology spurred by the first and second world wars were being applied to all avenues of life including agriculture. Electrical, steam and internal combustion power sources became available to pump and pressurize water. New pump designs, the patenting of the center pivot and other sprinkler delivery systems came together in a few short decades between and immediately following the wars to revolutionize the ability to deliver water (7).

CURRENT STATUS

In the U.S., Soviet Union, Australia, and Africa huge government-sponsored programs were initiated in the 1930s, 40s and 50s to build dams for hydropower, flood control, irrigation, and to encourage settlement and stabilization of sparsely populated frontiers. The worldwide total irrigated area was about 94 million ha in 1950 and grew to 198 million ha by 1970 (9). In contrast, the world total irrigated area grew to only about 220 million ha by 1990

)) and to 263 million ha by 1996 (10). Not surprisingly, ıe easiest, least technically challenging, least expensive rigation developments occurred first, and more difficult, ıore technically challenging, more expensive projects ominate the remaining potential for water development. n some instances, dams and large-scale water development projects have been hampered by poor economies and he instability of the countries in the potential development ıreas, rather than by the cost or technical challenges per se.

Today 60% of the earth's grain production and half he value of all crops harvested result from irrigation (10). Perhaps most remarkable is the agricultural production efficiency that irrigation provides worldwide. Some 50 million ha of the earth's most productive irrigated cropland (4% of the earth's total cropland) produces a third of the entire planet's food crop (11). Hectare for hectare, irrigated land produces two to two and a half times the yield and three times the crop value per hectare compared with non-irrigated land (10, 12, 13). Yet, the irrigated portion amounts to only about one sixth of the world's total cropped area (14) and about 5% of the world's total production area, which includes cropland, range and pasture (15). In America, most fresh fruits and vegetables in grocery stores come from irrigated agriculture. Beyond survival and economic impact, even our entertainment and esthetics rely heavily on irrigation. Nearly all garden nursery stock in America is propagated and maintained under irrigation and today's parks, play fields, golf courses, and commercial landscaping are seldom established and maintained without irrigation.

To put the global production impact of irrigated agriculture in perspective, it would require over a quarter billion hectares of new rainfed agricultural land (an area the size of Argentina) to supply the average additional production that irrigation's high yield and efficiency provides. Actually, this estimate is conservative. If the land currently irrigated was no longer irrigated but left in production, its output would be well below the mean of existing rainfed land; this is because the lion's share of irrigation occurs in arid or semiarid environments. Furthermore, additional rainfed land brought into production to replace irrigated agriculture, would be well below the current rainfed average productivity; this is because the rainfed land with greatest yield potential has already been brought into production. A more realistic estimate might be double or triple the quarter billion hectare nominal replacement estimate.

In a world of six billion people, irrigation has become essential by providing yet another benefit that cannot be immediately quantified, but which is as important as or more important than production efficiency or economic gain, or even the often uncredited benefits in many irrigation development schemes of hydropower, flood control, transportation, and rural development. The overriding benefit is security—security derived from food production stability. Substantial portions of the world food supply are subject to precipitous and often unpredictable yield reductions due to drought. Irrigation was a key component of the "Green Revolution" of the 1960s and 70s, which stabilized food production in the developing world, providing a new tier of nations the opportunity to turn some of their monetary and human resources to nonagricultural avenues of economic and social development. Much of the drop in the rate of increase of worldwide food production in the last two decades relates to the decrease in the rate of irrigation development since 1980.

ISSUES AFFECTING THE FUTURE

Although there are large projects currently underway or planned for the near future, notably in China, Pakistan, Brazil, Canada, Spain, and Portugal, the equal of the great dam building era from 1930 to 1970 will likely never be seen again. Much of the development of irrigation in the last decade has been achieved through exploitation of groundwater or by smaller scale entrepreneurial surface water developments. In Australia, for example, with the disastrous deflation of the world wool market in the 1990s, substantial numbers of individual sheep stations ceased raising animals and developed their surface water supplies to grow vast hectares of irrigated cotton and rice.

Worldwide, further expansions in irrigated area are unlikely to be large because of the limited remaining surface water sources to exploit and because of the growing environmental concerns, especially related to soil waterlogging, salinization, and sodication problems. Future increases in irrigated area will likely come mainly from the development of the so-called "supplemental" irrigation in humid rainfed areas, from improvements in water use efficiencies associated with utilization of existing irrigation resources, and from improvements in the reuse of municipal, industrial and agricultural wastewaters. Howell (10) noted that improved efficiencies have resulted in a reduction in the mean applied depth of water in the U.S. from about 650 mm annually in 1965 to 500 mm currently. These increased efficiencies have come in great part from the improved understanding of the energy physics of water which led to modern evapotranspiration (ET) theory and ET-based crop irrigation scheduling (9, 10). Many other water conservation practices were developed in the last half of the 20th century, including drip and microirrigation, which has spread from the hyper-xeric conditions of Israel in the early 1950s (1) to nearly every climate and rainfall environment where there is a need, for one reason or another, to conserve water.

Loss of productive capacity caused by soil salinization, sodication, and waterlogging, as well as runoff contamination, riparian habitat impairment, and species losses, are often cited by critics of irrigation as evidence of fundamental drawbacks to irrigated agriculture. Surveys have indicated that of the existing irrigated lands, some 40–50 million ha show measurable degradation from waterlogging, salinization, and sodication (16, 17). Erosion and sedimentation of reservoirs and channels caused the failures of ancient irrigation schemes and have limited the life expectancy of some modern dams to only a few decades as well (3, 18). These problems should not be trivialized. They demonstrate the need for intensified research and conservation, as well as improved dissemination and use of known prophylactic and remedial technologies. However, neither should they be overstated nor presented without due consideration of mitigating factors.

If rates of production loss from these problems are weighted by relative yield or economic value of irrigation compared to rainfed agriculture, and if other positive effects of irrigation are considered, the relative magnitude of negative impacts of irrigation is greatly diminished. For example, runoff contamination from irrigated land would have to be three times the mean for rainfed land, on a crop value basis, or two to two and a half times the mean, on a yield basis, to be "comparable" to problems from nonirrigated agriculture because of the respective relative efficiencies of irrigated agriculture. Both the absolute and relative area of impaired production, plus the degree of impairment, need to be compared on a global basis to rainfed losses, as well as the potential for remediation and production expansion under either circumstance. Positive impacts of irrigation water development include many social and economic benefits such as hydropower, flood control, transportation, recreation, and rural development. Positive environmental effects result from crops, field borders, canals, ditches, and reservoirs that provide significant expansions of habitat for a variety of wildlife compared to undeveloped arid land.

As with all agriculture in recent years, irrigated agriculture has greatly improved its ability to provide humanity's essential needs in closer harmony with environmental needs. This remains a key priority in modern irrigated agricultural research along with continued improvement of production potential to meet the needs of a growing population. Population growth is occurring mostly in underdeveloped nations, where there is an added expectation of improved diet and standard of living. This expectation raises the need for improved production per capita above a simple linear extrapolation based on population. Only high yield intensive production from irrigated agriculture has shown the potential to meet these projected needs.

The knowledge and technology exist to design and operate irrigated agricultural systems sustainably, and without environmental damage or irreversible soil impairment (9, 16, 19). The problem lies in implementing known scientific principles and technologies in a timely fashion as part and parcel of irrigation project and system design and management. This is true both on a regional or project basis and at the farm or field level. Politics and economics play pivotal roles in how well known science and technology are applied. In this respect irrigated agriculture is no different than the myriad manifestations of rainfed agriculture, or any other environmentally impacting activity. Because of modern political and economic considerations, there is usually great pressure, when designing and developing a large-scale irrigation project, to allocate resources for development of as many irrigated hectares as possible at the outset. This often occurs without provision of an adequate technical or social support network to the farming community making the transition to irrigated agriculture. Many schemes fail to provide sufficient financial or technical resources to install drainage systems, to educate farmers or to include them in policy formulation. The resouces are needed to help guarantee prudent water application and salinity or drainage management compatible with the social, technical and financial capabilities of the water users. These are not failures of irrigation. They are failures of human institutions. In this respect, human political, economic, and institutional considerations rather than technical advances or water availability may represent the real challenges for irrigation in the 21st century. These obstacles must be overcome if irrigated agriculture is to provide the production advantage required to satisfy future human needs and meet improved dietary and living standard expectations.

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