Land Transformation in Agriculture
Edited by M. G. Wolman and F. G. A. Fournier

CHAPTER 5.I
The Impact of Irrigation

L. SHANAN

5.I.1 INTRODUCTION

Irrigation is generally defined as the application of water to the land for the purpose of supplying moisture essential to plant growth. In the process, irrigation projects transform the land in two ways:

(1) by direct modifications of the land surface that occur when canal networks are constructed and land is cleared, shaped and levelled for irrigation;
(2) by indirect in-depth transformations that take place when the water and salt balances in the region are changed following the import of additional quantities of water and salt into the area.

Most of these transformations are permanent and irreversible. This chapter describes the dynamics of these transformations, and by using specific case studies examines the concomitant hazards that develop which may even threaten the existence of the society that created the irrigation project.

Seasonal rainfall fluctuations make rain-fed farming a risky venture. Irrigation reduces some of the uncertainties and so promotes increased production. In desert and arid zones, irrigation enables the economic development of areas which otherwise would be unproductive and uninhabitable. Irrigation development is as old as recorded history. In about 2000 BC, an inscription on the tomb of the Assyrian Queen Semiramis proclaimed that 'I constrained the mighty river to flow according to my will and led its waters to fertilize lands that before had been barren and without inhabitants'. The Bible reports that the prophet Elisha in about 865 BC stated 'thus sayeth the Lord, Make this valley full of ditches . . . Ye shall not seė wind, neither shall ye seen rain; yet that valley shall be filled with water, that Ye may drink, both ye and your cattle and your beasts' (Kings II, 3:16–17).

There is evidence of continuous irrigation for thousands of years in the Nile Valley and for comparatively long periods in Syria, Persia, India, Java and

Italy. Egypt claims to have the world's oldest dam built about 5000 years ago to supply drinking water and for irrigation, and basin irrigation introduced at that time still plays a significant role in Egyptian agriculture. Records show that irrigation in China was begun about 4000 years ago, and there are reservoirs in Sri Lanka more than 2000 years old. It is also interesting to note that the potential damages from irrigation have been known since early times. As far back as 2300 BC, the Babylonian Code of Khammurabi provided that 'If anyone opens his irrigation canals to let in water, but is careless and the water floods the fields of his neighbour, he shall measure out grain to the latter in proportion to the yield of the neighbouring field.'

An excellent historic example of extensive land transformations resulting from irrigation development is found in the stoney-gravel limestone desert of the Negev area in Israel. Remnants of these ancient irrigation systems date back from the Israelite period (about 1000 BC) and from the Nabatean–Roman–Byzantine era (300 BC to 600 AD). In the absence of permanent water sources, the ancient farmers developed 'runoff' farm systems that used sporadic flash floods for irrigating. Each farm unit comprised a watershed to collect runoff from the hillsides and a group of terraced fields in the valley bottoms for cultivation. The hillsides were subdivided into small catchments by channels leading the hillside runoff water to the terraced fields. The stone and gravel cover was cleared from the ground surface of the catchments to increase the rates of runoff and placed in geometric patterned heaps of mounds and strips. Gravel mounds and strips, hillside collecting channels and stone-walled terraced fields transformed about 300 000 ha of the barren desert into a productive water-collecting system, and enabled the ancient settlers to cultivate about 15 000 ha and establish a permanent agricultural civilization in a 100 mm annual rainfall region.

5.1.2 THE PRESENT AND FUTURE EXTENT OF IRRIGATION

The area of land irrigated in the world today is close to 250 million hectares, of which about two-thirds is situated in five countries—China, India, Pakistan, the Soviet Union and the USA. With world populations growing concurrently with expectations of higher standards of living, world food and fibre demands will increase. Since arid lands become highly productive with the introduction of irrigation water, and the productivity of rain-fed areas increases considerably with supplementary irrigation, the improvement of existing irrigation projects and the opening up of new irrigated areas will continue to make significant contributions to solving the world's expanding food and fibre needs. In order to ensure the stability and permanency of these projects we cannot afford to overlook the potential hazards intrinsic to irrigation development, and we must be aware of the land transformations that may take place.

5.I.3 LAND TRANSFORMATIONS

Land transformations resulting from irrigation development are in all cases spectacular—especially when seen from the air or recorded in satellite imagery. Aerial photographs showing the boundaries between the desert and the sown in, for example, the Nile Valley in Egypt, the Central Valley in California, or the Rajasthan Canal in India, exhibit dramatic pictures of the contrasting land surfaces and highlight the transformations that have taken place as a result of irrigation making the deserts blossom. These land transformations can be classified into two categories:

(1) surface modifications resulting from implementing various irrigation methods;
(2) in-depth changes caused by disturbing the local or regional salt and water balance.

Most of these transformations are irreversible and permanent. All irrigation projects involve transferring water from one area to another—from a water-surplus region to a water-deficient one. Some major irrigation schemes call for inter-regional water transfers from one basin to another using major dams for inter-annual or inter-seasonal storage. They often require main canals hundreds of kilometres in length to transport the water. Inherent in this irrigation development are the land transformations caused by the construction of these large multi-purpose dams—such as those that have followed the building of the Aswan, Kariba, Tarbella and Boulder Dams. Reservoir sedimentation, steam bed aggradation, flooding of upstream forests and villages are only some of the many problems concomitant to major schemes. This chapter, however, is confined to land transformations that are directly related to the irrigation development.

5.I.3.1 Surface Transformations

Irrigation water is applied to land using one of the four main methods:

(1) surface flooding;
(2) partial wetting of the surface in furrows;
(3) surface sprinkling;
(4) by drip (or 'trickle').

All methods, particularly surface ones, involve considerable land preparation.

The first land transformation follows clearing the land of trees, brush or other vegetation. In the semi-arid zones (for example in the western part of the United States) relatively dense cover of sagebrush, grease-wood, chaparral, scrub oak, pine or mesquite have to be eradicated from proposed irrigated lands, and in the monsoon areas such as Thailand, India, Indonesia etc. tropical and sub-tropical jungle forests must be cut down and eliminated before development can begin. Small brush up to 0.5 m in height can be removed by ploughing, while vigorous vegetative growth usually requires the clearing operations to be carried out with large and powerful tractors. In some cases deep-rooted tree stumps must be blasted away—leaving the land with a bomb-pitted look of a war zone. In other cases stones, boulders and rock outcrops have to be hauled away from the project lands.

The land having been cleared, it next becomes necessary to smooth (or grade the surface) to facilitate uniform water distribution. These works bring about another land transformation. Surface smoothing is usually accomplished by the use of harrows, graders, scrapers, bulldozers and landplanes—but in under-developed countries hand labour and bullock-drawn wooden planing boards are often used for this work. On accurately levelled land, water will be distributed uniformly over the fields; but when the levelling is done poorly and the ground surface remains rough and irregular, some parts of the fields will receive more water than others. The final shape of the land surface will depend on the method of irrigation to be used. In many of the older irrigation systems, where the wild-flooding method is common, water flows from the supply ditches over the fields and is guided only by the slope of the land. This method requires minimum amounts of land levelling (say, up to about 200 cubic metres of earth moving per hectare), but irrigation by this method is generally the least efficient of all methods. More efficient methods of surface flooding call for accurate land shaping and grading and 1500 cubic metres of earth may neen to be moved per hectare. In the border method of irrigation the land is divided into long, narrow strips 5–15 m wide, extending for 100–400 m down the prevailing land slope, and the border strips are separated by levees, 0.1–0.3 m high. Border strips are levelled transversely, so that water will flow at an even depth over the whole width. The longitudinal slope is graded to a design gradient to enable an even percolation of the irrigation water over the entire border. In the level basin method the land is shaped into accurately levelled plots ranging in size from 0.2 to 1.0 ha and surrounded by low bunds. The basin method is suited both to permeable soils which must be covered quickly with water in order to prevent excessive losses near the supply ditches, and to heavy soils with slow percolation rates. It is the method most commonly used for rice ('paddy') irrigation all over the world. Small, level basins are also used for irrigating orchards. Levelling works for constructing either borders or basins transform the original natural land surface into clearly discernable rectangular or square patterned fields.

In the irrigation methods described above, almost the entire land surface is wetted at the time of irrigation. When furrow irrigation is used, the fields are only partially wetted. Furrows (20–30 cm in depth) or corrugations (10–15 cm) are spaced according to the plant rows—one furrow or corrugation being provided for each row. For efficient furrow irrigation the land must be graded accurately and the flow of water into the furrows controlled. The pattern created by this method is neither square or rectangular, but the fields are formed into long, thin, parallel linear strips leading away from the delivery ditches.

In sprinkler irrigation projects, water is applied to the crop in the form of a spray. Unlike the surface methods, sprinkler irrigation requires less land levelling and can be used economically on undulating lands, on soils too shallow to prevent proper levelling, and on soils too porous for good water distribution by surface methods. The land transformation process is partly dependent on whether the sprinkler system is semi-permanent or portable. A particularly dramatic land metamorphosis takes place when central pivot installations are introduced on a large scale. In these schemes, combinations of rotating and fixed sprinklers deliver water from central pivots through continually rotating booms to circular-shaped fields. The fields can have diameters of up to 1 km. These systems when seen from the air or on satellite photographs show up as green circles in a patterned design on a beige desert background.

Drip irrigation systems consist of extensive networks of small-diameter plastic pipes delivering low flows of a few litres per hour to the plants through special emitters. From each emitter, water spreads laterally and vertically in the soil profile. Drip systems require little land levelling. Dissolved salts are left in the soil near the edge of the wetted zone and these salts must be periodically leached out of the root zone by rainfall or by irrigation. The system is adaptable to a wide variety of shallow, sandy or stoney soils as well as undulating and steep topographic conditions. With the world's expanding population pressures, planners will be forced to bring the more difficult areas into production, and we can expect that extensive areas will come under drip irrigation in the future to enable otherwise unirrigable areas to be developed.

5.I.3.2 In-depth Transformations

Since man first began to question the nature of the four basic elements (water, fire, earth and air) he has pondered on the behaviour of water. The early philosophers were puzzled by the continual flow of rivers to the sea and wondered why the level of seas did not continually rise. The early Greek philosophers of the fourth and sixth centuries BC imagined immense underground reservoirs from which the rivers extruded, and it was not until the advent of the early Roman philosophers in the first century AD that the 'evaporation–condensation' phase of the hydrological cycle came to be understood. This lack of appreciation of the hydrological processes contributed to the disintegration of some of the ancient irrigation systems. It was not until the Middle Ages, however, that da Vinci gave the first realistic representation of the water balance equation, when he wrote that in the course of a year, the amount of water that rises from a particular region will be as great as the flows in the rivers and the rainfall that descends in that region.

In the nineteenth century the hydrological cycle was first analysed as a system of storage with a given input producing a specific output. The quantity of water moving through the hydrological cycle in a unit of time could then be evaluated from the water balance equation:

$$I - O = S$$

where 'I' is the inflow during a given period (surface water, groundwater and precipitation); 'O' is the outflow during the period (evaporation, transpiration, surface runoff and groundwater discharge from the area); and 'S' is the change in storage in retention, depression, interception, soil moisture and groundwater levels. Implicit in this approach is the understanding that feedback mechanisms in the system constantly tend to bring about some state of equilibrium.

In a non-irrigated area a stable but changing water balance is developed between the annual rainfall input, ranging from 100 to 1000 mm, the vegetation and the groundwater. With the introduction of irrigation the balance is disturbed. Since irrigation may add the equivalent of, say, 500–1500 mm of water to the annual rainfall, this three- to ten-fold increase in water input will significantly upset the previous prevailing water balance. From its original steady state of equilibrium with system variables oscillating around long-term averages, the additional input forces the entire system over some threshold value into new levels of equilibrium or into meta-stable equilibrium states. The rate of change to the new levels will depend on the pedology, geology, climate and crops grown in the region.

It is important to recognize all the changes that can result from human intervention into the input–output response-process and how the modified hydrological system transforms the land of a particular region. The transformations will depend on both the spatial and the time scales over which the intervention is applied. A few in-depth micro-scale transformations may be observed in relatively short time periods measured perhaps in years, but most macro-scale changes require decades or even centuries to become hazardous threats to the permanency of the system. Some effects may be local and cover only a few hectares, while others may be regional and affect thousands of hectares. In projects where irrigation is supplemental rather than continuous, these effects are generally limited and easier to control. This chapter focuses on the large-scale transformations that develop as dynamic meta-stable processes passing through a number of thresholds before they become problematic and approach a state of irreversibility. Four deleterious land transformations follow irrigation development:

(1) waterlogging;
(2) saline and alkaline soil development;

(3) sea-water intrusion;
(4) land subsidence.

These transformations are now described and illustrated with some typical case studies.

5.I.3.2.1 Waterlogging

Waterlogging is the result of a rise in the groundwater level. An area is generally classed as waterlogged if the water table lies less than 2 m from the ground surface. When waterlogging reaches the root zone of the plants, yields diminish significantly because the roots need a soil–air–water environment to grow and cannot survive in free water. There are four principal causes of waterlogging—leakage from canals, wastage from distribution networks, over-irrigation and lack of suitable drainage facilities. Following the waterlogging process, saline conditions generally develop on the surface.

Many examples of waterlogged areas can be found in the irrigated areas of the world—in India, Pakistan, the USA, Australia, North Africa and China. The case history of Pakistan has been selected because it is a good example of an extensive occurrence of the phenomena and demonstrates the engineering and management measures governments must introduce in order to control regional waterlogging.

There is evidence that irrigation has been practised along the Indus River system in Pakistan from 3000 BC onwards. In the beginning, only narrow strips of land adjoining the river banks were irrigated. With time, irrigation has been extended. Pakistan contains probably the largest irrigation system in the world, and today about 15 million hectares are irrigated, of which more than 75% is served by government canals. The irrigation system comprises the Indus river and its major tributaries, 3 storage reservoirs, 19 barrage/headworks, 43 canal commands and about 90 000 watercourse systems. The total length of the canals is about 56 000 km and there are more than 1.6 million kilometres of watercourses and farm channels.

The physical layout of the canal systems and the methods of delivering water were evolved to fit the pattern of available supplies in the unregulated rivers, and to conform to the legal conditions and water allocations of the Pakistan–India Indus Water Treaty of 1960. The system was planned to bring to maturity the largest possible cropped area with the minimum consumption of water. Consequently, irrigation intensities are generally low (25% in the kharif season and 50% in the rabi season) so that the water can be spread over as large an area as possible. A basic canal design concept underlying the planning has been to achieve equitable water distribution with the minimum of human interference in the management of the system. Overall irrigation efficiencies, however, are relatively low—possibly about 30%—and studies show that 35–45% of the water delivered by the canals never reaches the farmers' fields. Since the natural drainage is inadequate and artificial drainage was not provided in the early project years, extensive over-irrigation combined with excessive leakage from the canals have led to a rise in the water table.

Rates of rise of the water table have been relatively rapid—about 30–40 cm a year. Depending on the initial depth of the water table, areas along the main canals were the first to become waterlogged, but subsequently waterlogging spread to the contiguous areas. The potential need for drainage to prevent this land transformation was realized when large-scale development was initiated, and a network of observation points was established to monitor the changing groundwater conditions. Waterlogging conditions measured in 1978 showed that in the 14.6 million hectares surveyed, the water table was less than 1.8 m below the surface on 13% of the area and between 1.8 m and 3.0 m on 41% of the area. In some areas, the water table is still rising; but in those projects where the government has initiated drainage schemes (see SCARP programs described below), the water table is slowly being controlled and some cases even lowered. Unless these drainage measures continue to be implemented, 50% of the irrigated fields will have to be abandoned in the future and the land will be transformed into unproductive saline waterlogged swamps, which will be useless to Pakistan.

5.I.3.2.2 Salinity—the Second of the 'Twin Menaces'

All irrigation water contain salts and the salt concentrations in soils tend to increase as water evaporates from the surface or is transpired by plants. In order to maintain a favourable root-zone salt balance, more water (called the 'leaching requirement') must be applied to the soil than is used by the evapo-transpiration process. The excess water drains to the groundwater table, and in the absence of drainage it contributes to the development of waterlogging conditions described in the foregoing. Salts accumulate in the upper soil profile as evaporation and transpiration remove water, and highly saline or alkaline conditions develop as more and more water moves upward from the water table by capillary action. This salinization of the upper soil profile increases continuously and when it reaches intolerable levels the land goes out of production.

The rate of salt accumulation depends on the soil surface temperatures, the chemical composition of the ground and surface waters and on the physical and chemical properties of the soil. As the balance between the sodium, magnesium and calcium ions changes in the soil, sodium becomes absorbed on the fine clay particles and the soil properties are modified. Soil swelling, colloidal dispersion and void clogging create impermeable soil profiles and unsatisfactory root aeration conditions, with subsequent significant reductions in production.

In order to prevent the development of these salinity conditions in irrigated areas, two courses of action are possible:

(1) installing surface or subsoil drainage to remove water from the upper 2 or 3 metres;
(2) developing vertical drains (wells) to lower the water table with the use of pumps.

The first method is feasible where suitable outlets for the drains are available. However, this solution may only transfer the problem downstream because when saline drainage water is discharged into local rivers, irrigation projects situated further downstream may be adversely affected. For example, the Colorado River's salinity has been rising during the last few decades as it flows downstream through the States of Nevada, Arizona and California. The current level of salinity at the Imperial Dam is about 900 ppm (parts per million), and is predicted to continue to rise and to reach about 1200 ppm in the year 2000. The cost of the damages due to this high saline content is expected to amount to about $80 million a year and indicates the stake that the irrigators and urban water users in the Colorado Basin have in the measures needed to control the salinity.

The second method of controlling water levels in the ground, pumping from wells, requires a relatively costly energy input to operate, but it has the advantage that a portion of the groundwater pumped can be used for irrigation in conjunction with the surface water. The management of a conjunctive operation, however, can only be done on a large scale and often requires government control of the regional water balance.

Pakistan also provides an example of the salinity problem. As mentioned previously, large-scale irrigation development in Pakistan led to rapid rises in the groundwater table. Groundwater has been a traditional source of irrigation water in the region, and the predominant method of using groundwater was, until the 1970s, the 'Persian-wheel' driven by draft animals. Over 200 000 units are still reported to be in operation. During the last 20 years, modern diesel- and electric-powered tube wells have been introduced in both the public and private sectors.

The water–salt balance in the Indus Basin represents a complex and difficult problem because the average slope of the area is about 1:5000 and there is no natural drainage for disposing of saline effluents. The irrigated plain is underlain by an extensive groundwater aquifer covering about 16 million hectares. One-third of this area has 'fresh' groundwater (1000 ppm TDS—total dissolved salts), one-tenth a moderate salinity content (1000–3000 ppm TDS) and the remainder is highly saline (>3000 ppm TDS). Total recharge of the aquifer is about 50–75 × 10^9 cubic metres per year. At present about 180 000 private tube wells and 12 500 public tube wells jointly pump about 45 × 10^9 cubic metres per year from the groundwater. Without this pumping, the Indus Basin would be a large lake. The Indus

Basin has also been acting as a large salt sink. Average annual river water diverted for irrigation is about 100–120 × 10^9 cubic metres per year, with an initial average salinity of 130 ppm. This means an annual addition of 16 million tonnes of salt to the 16 million hectares of irrigated land, i.e. about 1 tonne of additional salt is added annually to every hectare.

With the recognition of the expanding salinity hazard in the late 1950s, the first large-scale groundwater development and salinity control programme was initiated with the Government Salinity Control and Regulation Project (SCARP I). The plan proposed to control salinity by pumping large quantities of water from the aquifer, spreading if over the land and so leaching down the salts. Parallel with the SCARP I programme, private tube well development took place at an accelerated rate and total private groundwater development today far exceeds the public tube well programme. Because of its success, SCARP I has been followed by a series of five-year SCARP plans and SCARP V is currently in operation. The design of the SCARP projects is based on sophisticated criteria for handling the difficult groundwater and aquifer conditions, such as delineating mixing zones for conjunctive use of different levels of groundwater and surface water, and the programme includes mining certain groundwater areas, combining private and public tube well development, and remodelling canals to increase surface water supplies.

The SCARP programmes are at present under review and an overall strategy is being developed to create a permanent water–salt balance in the Indus Basin by adopting strategies for both prevention and cure. Plans are now being evaluated to dispose of the salts by:

(1) constructing large outfall drains to discharge highly saline effluents to the lower reaches of the Indus River and to the sea during the flood season;
(2) transporting some of the saline water to large evaporating areas in the desert.

During the past 20 years, 30–50% of the water sector's budgetary allocations have been spent on implementing salinity control measures. In the future similar large expenditures will have to continue to be invested in eliminating the long-term salinity hazard of the Indus Basin.

5.I.3.2.3 Seawater Intrusion

Two types of seawater intrusion will be discussed:

(a) subsurface intrusion into coastal aquifers; and
(b) surface flow intrusion into rivers.

(a) Subsurface coastal sea intrusion

Seawater intrusion into coastal aquifers is a problem of worldwide significance. It results when excessive groundwater pumping causes lateral and upward movement of seawater into the coastal wells. Unless controlled, the phenomenon causes significant rises in the salinity levels of the coastal groundwaters and concomitant detrimental effects on the lands being irrigated by these sources. Coastal aquifers discharge their unexploited groundwater to the sea. In many countries these aquifers serve as major water supply sources for the intensively developed agricultural areas and densely settled municipal areas in the coastal plains—such as in California, Florida and Israel. Exploitation of a coastal aquifer can be maintained indefinitely without causing hazardous consequences provided the maximum 'safe yield' of the aquifer is not exceeded. Simulation models for the behaviour of coastal aquifers have been developed in many countries to evaluate potential yields and are useful tools in predicting the behaviour of the groundwater system under alternative abstraction options. These models, although using idealized conditions and approximate assumptions, give results sufficiently accurate to enable the planner to establish the rate of groundwater development most suited to the local or regional conditions. Since lateral and vertical flow rates of groundwater are extremely slow, a critical lowering of the water table near the coast does not bring on immediate seawater intrusion because of the relatively long period required for the salt water to move inland. Thus in interpreting groundwater model results, it is extremely important to give full attention to the time scale which will generally be measured in decades rather than in years.

An excellent sample case history of successful management to date of a coastal aquifer and the prevention of the damaging effects of seawater intrusion on a regional scale is found in Israel. Israel's main water system is a nationwide grid of interconnected waterworks in which surface, ground and reclaimed water are integrated. Israel's water supply is based mainly on two elements:

(1) the waters of the Jordan river and of Lake Kinnereth in the North;
(2) the groundwaters of two principal aquifers—the coastal sandstones and the Yarkon–Turonian limestones.

Other than Lake Kinnereth, there are no favourable surface storage facilities in Israel and the need to provide regulation falls on the two main aquifers. These aquifers make up about 60% of all the nation's freshwater resources, and the coastal aquifer which supplies about 30% of the water consumption of Israel is used as a major long-term regulating reservoir. This aquifer flows towards the Mediterranean, is phreatic with water level depths ranging from a few metres to about 90 m below the ground surface. The aquifer is replenished by percolating rainfall and return flows from irrigation and waste water. The coastal plain overlying the aquifer has a total area of about 2 million hectares and includes the major urban communities of Israel, accounting for about 50% of Israel's population (in 1983 about 3.3 million). The projected population of the coastal plain is expected to double by the year 2010.

The coastal aquifer has an estimated yield of about 160×10^6 cubic metres a year and the limestone aquifer about 200×10^6 cubic metres a year. In order to enable large-scale immigration into Israel and a rapid development of agriculture during the years 1955–64, the coastal aquifer was exploited at an average rate of 330×10^6 cubic metres a year and the limestone aquifer at a rate of 260×10^6 cubic metres a year, causing an annual overdraft amounting to about 230×10^6 cubic metres. Over-pumping of the groundwater led to serious intrusion of seawater into the heavily over-exploited coastal aquifer. By the year 1964, however, the National Jordan conduit had been completed and water could be brought from Lake Kinnereth in the north, to supply the needs of the south. Some of this imported water was injected into wells in the coastal plain in order to repair the saline intrusion damage as rapidly as possible. Since then, using the results of simulation models, groundwater abstraction has been controlled and reduced to rates that ensure a sustained long-term programme of conjunctive use of Jordan water and groundwater.

The combination of a shallow phreatic water table, sandy soils, dense populations, intensive agriculture, and excessive pumping could have led to a potential disaster in Israel. Sound long-term planning using simulation and hybrid computer models, backed up by suitable water laws and competent government management, enabled the full use of the water resources to be achieved without creating critical irreversible and disastrous conditions. Problems still remain. Water quality records show that considerable parts of the aquifer are polluted by nitrates, and unless this is controlled the quality of a major portion of the urban water supply wells in the coastal aquifer will exceed the maximum allowable drinking water standards by the year 2000. On-going studies are evaluating the appropriate engineering techniques needed in the coming decades to ensure that the quality of the aquifer water conforms to these standards.

(b) Seawater intrusion into rivers

As more and more fresh water supplies are diverted or pumped from rivers, the flows reaching the sea decrease; eventually a point is reached when tidal flows begin to move upstream and cause deleterious increases in river salinity. This problem is worldwide, and many downstream riparian areas suffering from serious salt damage will go out of production unless a timely solution is found. The case history of the Chao Phya river in Thailand illustrates the problem.

The Chao Phya provides the major water source for the irrigation in the Central Plain and Delta of Thailand. The average annual supply is about 23×10^9 cubic metres a year, although variations of flow from year to year may be large. Flows reaching the Central Plain are being gradually reduced owing to intensification of rice production in the Northern Regions and expanding irrigation development along some of the upstream tributaries of the Chao Phya. The total crop land in the Central Plain is about 1.4 million hectares in the wet season, and the Royal Irrigation Department (RID) plans to increase production by expanding dry season cultivation from about the present 0.2 million hectares to more than 0.6 million hectares. The additional water for this development must come from storage in upstream reservoirs on the Chao Phya and its tributaries. This will aggravate the present hazardous condition when, during periods of low flow in the dry season (January to May), seawater flows upstream for about 30–40 km from the Chao Phya estuary. The irrigated areas affected today by the saline water intrusion cover about 1500 km^2, and the seawater intrusions also have deleterious effects on the domestic water supplies. The problem is a difficult one to solve because of the conflicting interests between the development targets of the Northern Regions and of the Central Plain. It has been estimated that a minimum flow of about 150 cubic metres a second must be maintained in the Chao Phya river at Bankok to ensure a salinity level of about 1000 ppm (TDS). However, 30 m^3/s of this flow will eventually be required to supply water to the Bankok area, and only 120 m^3/s will remain to flow south of Bankok. Under these conditions the salinity level will rise to 2000 ppm (TDS).

A study made by the RID in 1968 concluded that the value of water released from the upstream dams was greater for salinity control than for power. It is essential to assess accurately the amount of water to be allocated to control seawater in the Chao Phya river and to supply water to all the available irrigable land. Hence priorities for development must be established on a basin-wide plan to take into account irrigation, power, municipal supplies and salinity control requirements.

5.I.3.2.4 Land Subsidence

In recent years it has become apparent that extensive exploitation of groundwater has brought about land subsidence in many localities of the world. A casebook being prepared by UNESCO reports on the occurrence of more than 40 major land subsidence areas in the world and also describes methods for measuring, predicting and controlling the phenomenon.

Subsidence due to excessive groundwater pumping develops under two geological conditions. First, in carbonate rocks overlain by unconsolidated deposits that receive buoyant support from the groundwater, when the water table is lowered that support is lost; unconsolidated material may move downwards into openings in the carbonate rocks, often causing catastrophic collapses. Second, in semi-consolidated sediments of high porosity underlain by sand–gravel aquifers of low compressibility and inter-bedded with clayey aquitards of low permeability and low compressibility, pumpage from the aquifers is accompanied by vertical leakage from the aquitards. Since the compressibility of the clay is one or two orders of magnitude greater than the compressibility of the sand, the total compaction of the clay aquitard is much greater than that of the sand–gravel aquifer; the sediments undergo irreversible compaction as water is squeezed out of the interstices and result in land subsidences. Since the hydraulic conductivity of the clay is several orders of magnitude less than that of sand, the subsidence process is a slow one.

Land subsidence ranges from as little as 20–30 cm to up to 900 cm (in some parts of California), and the areal extent from small areas 10 km^2 in size to extensive zones covering up to 13 500 km^2 (also in California). The principal problems arising from land subsidence are:

(1) differential changes in the gradients of streams, drains and canals;
(2) failure of wells due to rupturing of the well casing;
(3) tidal encroachment in lowland coastal areas;
(4) damage to buildings, roads, railways, power lines and water supply systems.

Land subsidence in Arizona is used here as a typical case history. Arizona's current consumption of water from all sources is about 5.9×10^9 cubic metres a year, of which only about 3.4×10^9 cubic metres are renewable—hence Arizona is mining its groundwater at almost twice the natural replenishment rate, and during the last 30 years Arizona has already overdrawn about 75×10^9 cubic metres. The main culprit for this rate of depletion is agriculture, which uses about 90% of all water consumed in the state. The only way to solve this problem without radically reducing the irrigated areas is to bring in additional water supplies. This is the purpose of the Central Valley Project which, when completed, will include a 480 km canal transporting annually about 1.5×10^9 cubic metres of water from the Colorado River into Arizona. This, however, will eliminate only part of the overdraft. Consequently, the State Legislature has passed the Groundwater Act of 1980 to maintain a long-term balance between groundwater withdrawals and recharge (by natural or artificial means). Arizona has become the first state in the USA to limit the pumping of groundwater. In order to achieve an eventual balance, it is already recognized that agriculture's share of the state's water resources will have to be reduced from 90% to about 70%. This will be accomplished by changing present cropping patterns, improving irrigation efficiencies, reducing waste, introducing more efficient water consumption crops, and initiating a recycling programme for use of sewage effluents.

5.I.4 MODERN PLANNING METHODOLOGIES

Concern with the relationship between land transformation and irrigation is not new. In Mesopotamia, for example, where irrigation was developed on a regional scale in about 2300 BC, the country faced serious salinization difficulties—the earliest and probably most serious land transformation occurring at about 2000 BC when many settlements had to be abandoned. Since that time, irrigation planning has made tremendous strides. Engineers have learned the lessons of earlier civilizations, and today modern technology gives the engineer techniques to analyse the problems and predict the behaviour of the water system on both macro and micro scales. The tools are available to avoid a number of mistakes of the past.

Man's use of the soil has advanced through three stages. In the first stage, an ecological balance was maintained because shifting cultivation, or low irrigation intensities, did not deplete the soil fertility permanently. In the second stage, soil exhaustion occurred because the fertility of the soil was mined without replacing nutrients removed by cultivation, leaching or erosion. In the third stage, man has learned to conserve the productivity of the soil by returning as much or more than he removed, so that permanent cultivation or irrigation has become possible. The objective in irrigation management must be to maintain a dynamic balance in the salt–water input–output relationship and to replace fertility losses with fertilizers and with good farm management. There is no need to assume that technology will remain constant, nor need we prophesy doom for modern irrigation projects.

Historical evidence favours the view that 'necessity is the mother of invention', and new technologies will be developed to meet any potential hazard that may arise—particularly since these problems do not appear suddenly but develop over a decade or two. A good example of present-day regional irrigation planning can be found in the Rio Colorado Basin Project, the plan for which was prepared in the 1970s and included more than 20 irrigation sub-projects covering a total of about 0.8 million hectares. This basin-wide study used multiple social, economic and regional objectives to evaluate various development options in an overall water resource plan, and developed mathematical simulation and optimization models to predict potential problems, future benefits and investment costs. A more recent major study is being carried out in India on a scheme funded by the World Bank—the Sadar Sarovar Project in the State of Gujarat. This multiple-purpose hydro-power and irrigation project will use the waters of the Narmada river to irrigate 2.2 million hectares of land from the year 1990. The Narmada Planning Board established by the State of Gujarat has developed optimization models to examine the benefits from alternative cropping programmes and, because groundwater and salinity problems are expected to develop, surface and groundwater simulation models have been set up to predict the rates of groundwater rise in various zones of the project. The results of these simulation models are already being incorporated into the design, and extensive public and private tube well schemes for conjunctive use of ground and surface waters are being anticipated so as to ensure the permanency of the project by maintaining a satisfactory salt–water balance in the region.

5.I.5 STABILITY AND PERMANENCE

Surface and in-depth land transformation always follow in the wake of irrigation development. The surface modifications take place during the construction period, while the in-depth changes appear only after the introduction of water into an area. While surface modifications can be regarded as beneficial to man, the in-depth changes carry inherent potentially harmful features—waterlogging, salinity, seawater intrusion and land subsidence. These hazards must be controlled in time lest their deleterious effects become malignant and reach dangerous and irreversible levels. Good management is therefore a key ingredient of irrigation development. Management must continually monitor the water and salt balances so as to predict the rates of build-up of the hazards. Finances must be made available in time to introduce the measures needed to control the changes so that they do not reach injurious states, placing the project in jeopardy.

The main lessons to be learned from the history of irrigation are that governments must recognize these potential hazards, in the early project planning stages, and establish competent operational management structures to detect and heed early-warning signals that precede problematic situations. There are no perfect solutions, and choices will always have to be made between various policy options, trading off losses in production and farmer's income in order to achieve long-term stability and permanence. Good planning, the quintessence of engineering, is essential to ensure lasting survival of an irrigation project and the society dependent on it. In the past, emphasis in planning has been placed on the need to meet plant water demands to attain maximum yields (per unit of land). Greater weight should now be given to the management of supplies, with the aim of maximizing economic returns on water (rather than land) and minimizing long-term hazards. In carrying out the economic analysis of a project, the investments required to prevent long-term project failure must be included in the stream of costs, or a concomitant reduction in the stream of benefits must be made to take into account a probable reduction in yields as the hazards advance.

5.I.6 FURTHER READING

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