14 Influences of Irrigation on Drainage

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14.1 Introduction

Irrigated agriculture is by far the greatest user of water on earth. Estimates of global annual water use amount to 3000 – 3500 10^9 m^3, with 2500 10^9 m^3 being used for irrigation, 500 10^9 m^3 for industry, and 200 10^9 m^3 for other purposes, including domestic water supplies (Schulze and Van Staveren 1980). The limits to the availability of land, and especially of water, necessitate the careful use of these resources, particularly the efficient use of water in irrigation.

Irrigation, a human intervention, has a twofold effect on the natural environment:
- It changes the land surface of the area and its vegetation;
- It affects the area's regime of soil moisture, solutes, and groundwater: water and solutes that would not be present naturally are brought to the area by the irrigation canals.

Two important risks involved in irrigation are those of waterlogging and salinization. Waterlogging occurs when more water is entering the area than is being discharged from it; the watertable will then rise, and can eventually approach the soil surface, thereby rendering the rootzone unsuitable for crop growth. Salinization occurs when more salts are entering the area than are leaving it.

This chapter will discuss the influences that irrigation has on drainage in general, giving attention to both waterlogging and salinity. We shall begin by exploring the origin of excess water (Section 14.2). Following that, we discuss salinity on both a regional and a local scale (Section 14.3). Because irrigation efficiencies are related to the water balance of irrigation systems, they are one of the means used to demonstrate the relationship between irrigation and drainage. After a discussion of efficiencies in general, we shall present several examples that show this relationship (Section 14.4). Finally, we discuss the use of a drainage system for irrigation (Section 14.5).

14.2 Where Water Leaves an Irrigation System

Introduction

Irrigation today is practised on some 260 million hectares in the world. About half of this area is in arid or semi-arid regions. There, the irrigation water supplied usually exceeds 10 000 m^3/ha or 1000 mm a year, significantly more than the annual precipitation. As a consequence, irrigation in such regions has a great impact on the environment.

As the major user of water, irrigation affects the water balance of an irrigation

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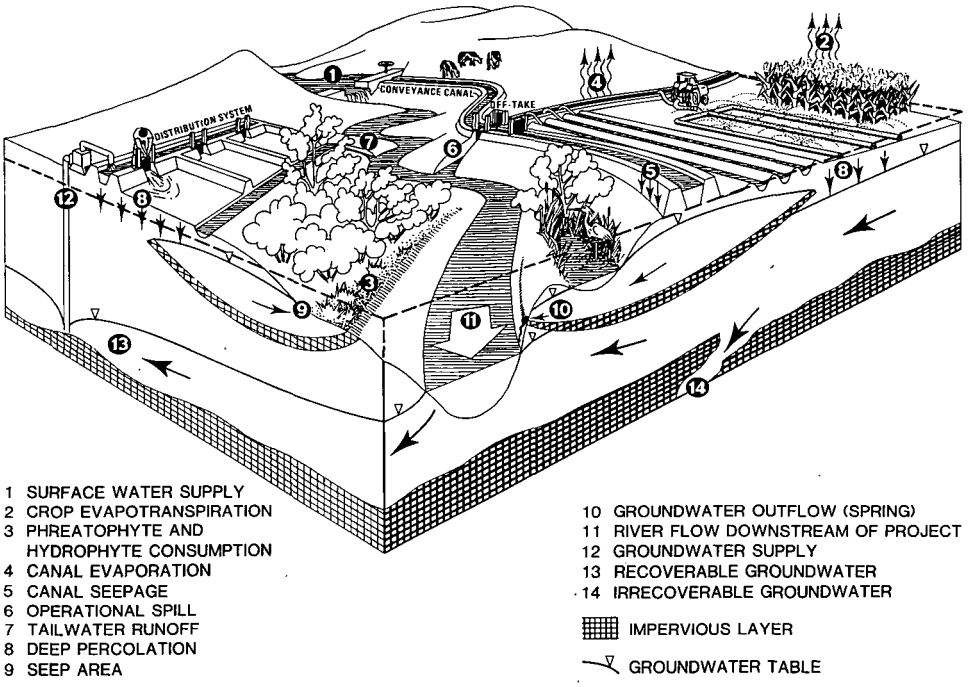

Figure 14.1 A river basin and an irrigated area

scheme. This is illustrated in Figure 14.1, which is based on the report of the Interagency Task Force on Irrigation Efficiencies (Boone 1979). In the following explanation of this figure, the numbers cited in the text refer to the numbers in the figure.

To apply a given quantity of irrigation water to a crop, water has to be diverted from a supply source (1). The quantity diverted has to be greater than the quantity required by the crop because the diverted water will leave the irrigated area not only as evapotranspiration by the irrigated crop (2), but also as consumption by non-irrigated vegetation (3), as evaporation (4), as seepage (5) from the conveyance and distribution systems, and as operational spills (6), tailwater runoff (7), and deep percolation (8).

Phreatophyte and hydrophyte consumption (3) is evapotranspiration by non-irrigated vegetation growing adjacent to irrigation canals and drains, or in areas with shallow watertables. The existence of such vegetation often provides or enhances wildlife habitats.

Water Leaving the Conveyance and Distribution Systems

The amount of seepage (5) from the conveyance and distribution systems depends on the type and condition of these systems; lined canals and pipe lines will have less seepage than unlined canals. Most of the water lost through seepage returns to the river, either directly through drains in the seep area (9) or indirectly via groundwater outflow (10). Upon reaching the river, this water is once again available for instream

use (fisheries, recreation, shipping) and for downstream diversion (11). The quality of such return-flow water, however, has usually deteriorated, which may cause problems to downstream water users.

Operational spills (6) result from a reduction in the demand for water after it has been withdrawn from the supply source. Such spills also result if the flow diverted from the river is significantly more than the water required by the farmers. These spills usually return to the river within a few days. Because spills seldom become polluted, they can provide good-quality water for instream or downstream uses. The main disadvantage of spills is that they require the irrigation system to be over-dimensioned; but this, in turn, makes it easier for the system management to meet the water demands of the farmers.

Percolation

A small percentage of the water applied to the crops should move downward below the rootzone. This deep percolation (8) is needed to remove salts that would otherwise accumulate in the rootzone. Poor irrigation management or the non-uniform application of water inherent in many irrigation systems often causes excessive quantities of deep percolation.

Irrigation water that percolates deeply and recharges an aquifer adds to the water supply available to the users of groundwater (12). Some farms and small irrigation systems depend entirely on supplies of 'recoverable' groundwater (13). Aquifers are sometimes used to store excess surface water or to meet the water requirements in dry seasons or dry years.

'Irrecoverable' groundwater (14) is groundwater that cannot be pumped economically or that needs to flow out of the area to prevent the groundwater from becoming saline.

Surface Runoff

Applying irrigation water on graded fields often results in tailwater runoff (7) at the lower ends of the fields. The quantity depends on the field-application method, the field design, soil conditions, and operational practices. Some tailwater runoff may be unavoidable when fields are graded to achieve adequate uniformity and efficiency of water application. Tailwater can destroy the lower parts of a field, or it can be consumed by phreatophytes, or reach stream channels as return flow. It may be collected on-farm and pumped back into the distribution system for re-use, or it may be intercepted by other users as a supplemental or even a primary water source.

Return Flows

Return flows to rivers resulting from operational spills (6), tailwater runoff (7), drainage flows (9), or groundwater discharge (10) may provide all or part of a downstream user's water supply. In arid and semi-arid regions, such return flows often support fish and wildlife, which would otherwise not exist.

The entire process of diversion, conveyance, field application, and return flow may take from a few hours, with tailwater runoff, to several years when water returns via the groundwater system. These return flows, especially those from a groundwater system, may supplement the dry-season low flows downstream of the irrigated area.

In Figure 14.2, the quantity of water diverted from the river for irrigation is

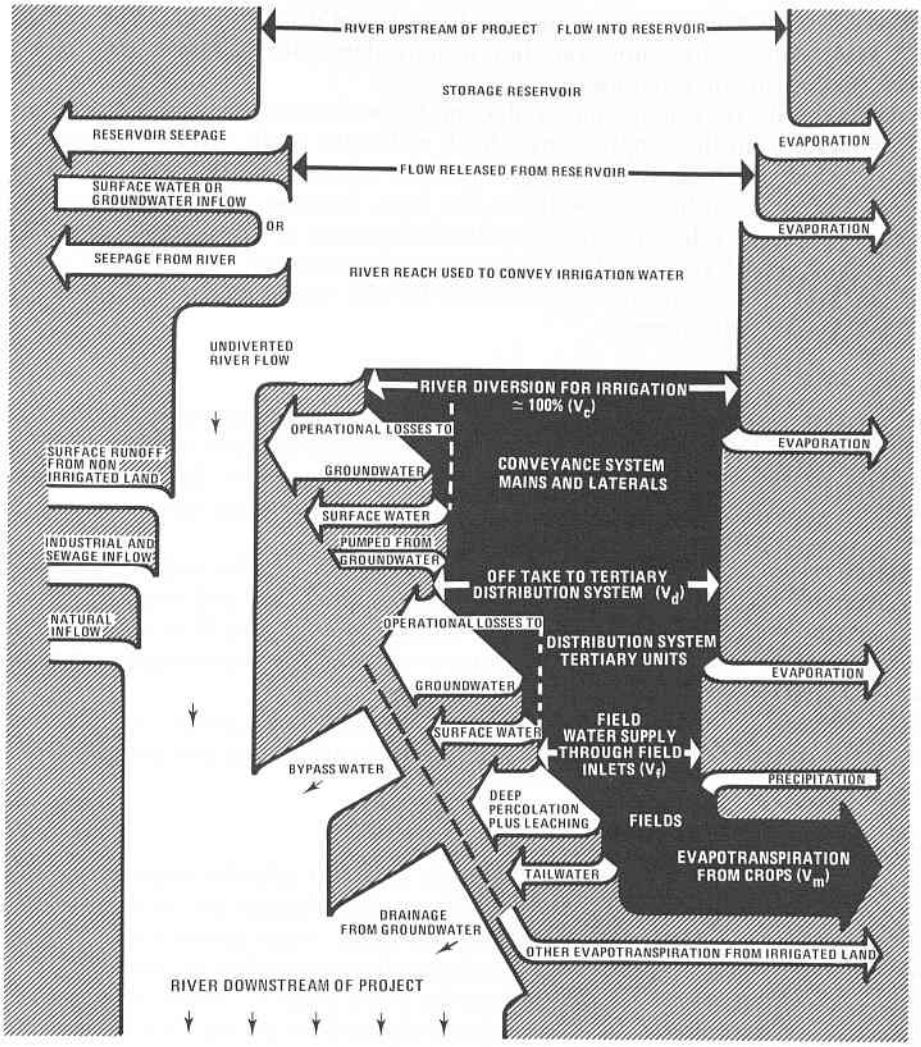

Figure 14.2 The relative magnitude of quantities of water flowing through an 'average' irrigation system (Bos 1979)

expressed as 100%. The width of the arrows in the figure illustrates the relative magnitude of water quantities in an 'average' irrigation system in arid or semi-arid regions.

Example of Changed Hydrology

One of the most natural types of irrigation was practised for millennia in the Nile Valley of Egypt, and was, in present-day terminology, highly sustainable. Agriculture was only possible through the residual soil moisture after controlled flooding, the so-called flood irrigation. Historically, the land was inundated during the six-week

period of river flood, around September to November, when the natural discharge of the Nile is at its maximum. The depth of the flooding varied from 1 to 3 m. The surplus water was drained back to the Nile. Crops were planted in the wet soil, ripened under the winter sun, and were harvested in spring.

The need for a better use of the land, especially after the introduction of cotton as a cash crop, led to a gradual change from flood irrigation to perennial irrigation. This started in the nineteenth century, and continued until 1967, the year that marked the completion of the Aswan High Dam.

The influence of the High Dam on the natural hydrology of the area is illustrated in Figure 14.3A, which depicts the seasonal fluctuations of the piezometric head in the aquifer under the clay-cap of the Nile Delta for the years 1958, 1968, and 1978 (Farid 1980). In 1958, before the Dam, the piezometric head was subject to considerable annual variation, and there was still a relationship with the natural regime of the Nile. In 1978, well after the completion of the Aswan High Dam, the head is constant, and is relatively high. This phenomenon is also shown in Figure 14.3B, where the piezometric head in the aquifer is at ground level, whereas the watertable is almost 1 m below ground level. This means that there is no natural

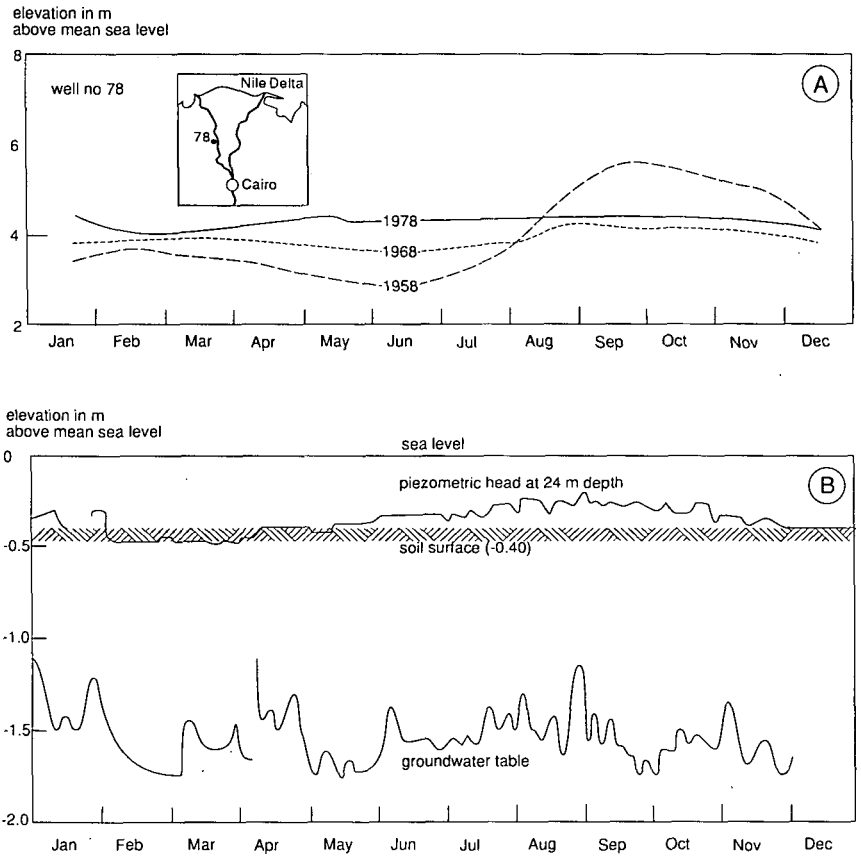

Figure 14.3 Fluctuations of the piezometric head in the Nile Delta aquifer

drainage, but continuous seepage inflow. Before 1958, the piezometric head varied throughout the year, thereby creating the possibility of natural drainage.

Example of Groundwater Recharge

Generally, the groundwater under an irrigation system in arid conditions is recharged by various sources:

- Water flowing in rivers;
- Water flowing in the canals of the irrigation system;
- Water applied to the fields;
- Groundwater flow from higher to lower elevations.

The effect of such recharge is shown in Figure 14.4 for the Pakistani Punjab. There, the introduction of irrigation was followed by a distinct rise of the groundwater. Calculations point out that about one-third of the rise of the groundwater must be attributed to percolation from irrigated fields; the remaining two-thirds is due to seepage from link canals, main canals, and field canals (Ahmad and Chaudhry 1988).

For Egyptian desert reclamation, Attia (1989) reports that about 30% of the groundwater recharge originates from the distribution system, and 70% from the field application of water. In the Grand Valley, U.S.A., the deep percolation from the fields is only 20% of the total water loss from the fields and the canal system together.

The volume (or depth) of water with which the groundwater is recharged in an irrigated area is variable. When there is hardly any rainfall and there is a water shortage in the irrigation system, it can be as little as, say, 50 mm annually. Under conditions of heavy rainfall (monsoon) and soils with a high permeability, it can be as much as 400 mm per rainy season. If half of the recharge is disposed of as (natural) drainage and the soil has a drainable porosity of 5%, this can mean a rise of 4 m in the groundwater level between the start and the end of the rainy season.

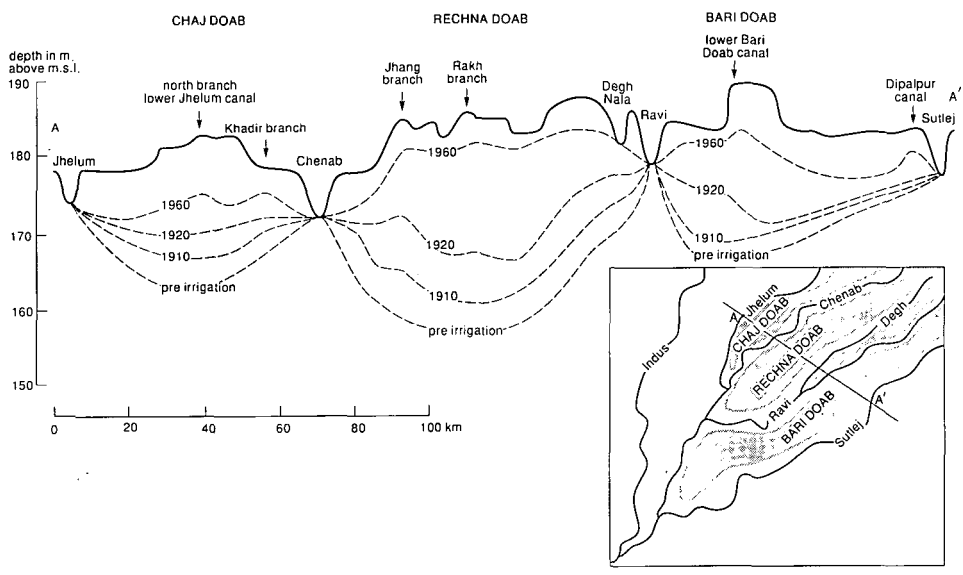

Figure 14.4 Groundwater profiles in north-eastern Pakistan (Bhatti 1987)

14.3 Salinity

In every drop of water, there are salts and, in irrigation water, even when of undisputed quality, there are considerable quantities of salts. In the vicinity of Cairo, for example, Nile water has an electrical conductivity of 0.6 dS/m, which equals about 360 mg/l. If 1 ha of land (10 000 m^2) receives 600 mm of such water per growing season, the amount of salts supplied is about 2000 kg. These salts must be evacuated via percolation, the downward flux of the soil water. This flux can be due to irrigation, or rainfall, or both. The related drainage water has to be discharged either by the natural drainage system or by a man-made one.

Salinity on a Regional Scale

An area's salt balance is affected not only by the introduction of irrigation, but also by changes in land use, which can affect the area's natural salinity. Since it is often impossible to consider irrigation systems separately from other human interventions in an area, we shall give some attention here to 'natural' salinity under conditions where rain-fed agriculture is possible.

In dry continental conditions, the natural vegetation is usually grassland with trees (savanna) or grassland without trees (prairie, steppe). The water balance of such an area is disturbed when the land use is changed. When grassland is turned into farm land, when trees are cut, or when there is overgrazing, the actual evapotranspiration will decrease, thereby creating 'excess' water. When this excess water is evacuated from the area by natural drainage, salinity problems will not develop. When there is no natural drainage, or not enough, however, the excess water will collect at locations with a low surface elevation and will evaporate there, leaving the salts behind. This effect is sometimes referred to as 'saline seep' (AADEO 1979).

Saline seeps are characterised by high watertables, the accumulation of salts, and salt-tolerant vegetation. Saline seeps will occur under natural conditions, but, at many locations, their extent has increased rapidly through man's interference with nature. Saline seeps can be controlled by growing useful salt-tolerant crops in salt-affected areas or by subsurface drainage of specific seep areas. Nevertheless, it is much better to prevent the formation and percolation of excess moisture in the area. Subsurface flow into saline seeps can be prevented by continuous cropping, by planting deep-rooting perennials (forages), and by eliminating seepage from irrigation canals. Deep-rooting perennial crops use more water than cereals do, for instance, and they use water for a longer period. This applies even more so for trees. Some areas have been 'drained' by afforestation.

Generally, ecosystems are very sensitive to changes in the water balance. Consider an area with an annual rainfall of 500 mm, and an actual evapotranspiration of 480 mm. The long-term average excess of water is 20 mm a year. A simple water-and-salt-balance calculation shows that if this quantity of excess water is not discharged by (natural) drainage, and if the evaporation from wet and salty spots is 1000 mm a year, approximately 2% of the area will salinize (Van der Molen 1984).

The effect that changes in land use have on salinity should not be underestimated. In many countries in the world (e.g. Northern America and Australia), they have led to salinity problems. Also, the present salinity problems of the Indo-Gangetic Plain

in India might be related to changes in land use. Around 1950, 22% of India's geographical area was covered with dense forest, but recent satellite surveys have shown that nowadays only half of this area is still forest (Mathur and Garg 1991). Large tracts of *usar* (Hindi for barren) lands typically occur in low-lying basins between productive land. Similar to the 'saline seeps' of Alberta in Canada, there has always been *usar* land in India, but its extent is steadily increasing.

Introducing irrigation has a far greater effect on the natural environment than changes in land use. One of the most common consequences is that a drainage system is needed for sustainable, irrigated, agricultural production.

Salinity on a Local Scale

The control of salinity on a local scale can normally be achieved by draining off the percolation water and keeping the watertable at a sufficient depth. If natural drainage and seepage can be neglected, the required design drain discharge for salinity control will be in the range of 1 – 2 mm/d (see Chapter 15). The percolation will not be equally distributed over a field; its pattern will vary from year to year and from season to season, depending on the irrigation method and the amount of water applied. Nevertheless, for surface irrigation and sprinkling, and for a large range of soils provided with sufficient drainage, we can estimate the long-term minimum percolation losses to be around one quarter of the diverted irrigation water. The percolation losses will be higher for coarse soils and lower for fine soils.

Groundwater may support crop growth by capillary rise through the unsaturated zone. If this continues long enough, the watertable will fall, and this supply will diminish to zero. If the groundwater is replenished, however, (e.g. by seepage), the capillary rise will continue and the profile will salinize because of the upward flux of water and salts. To avoid this problem, watertables should be kept at a certain minimum depth. The required depth mainly depends on the soil type (see Chapter 15).

One should not expect salinity problems to disappear merely by installing a drainage system. High salinities will remain if the soils are not leached, and the key to leaching is the availability of water.

Mobilization of Salts in the Subsoil

Up to now, we have dealt with salinity as if it were supplied from the surface only. In many areas, however, which historically had low groundwater levels, irrigation is now causing these levels to rise. There, 'fossil' salts that have accumulated in deep soil layers are being mobilized and transported upward with the groundwater in the direction of the rootzone.

The salinity of such groundwater will create problems for farmers who install tubewells to supplement the often-low canal supply of irrigation water. In this respect, deep tubewells are more damaging than shallow tubewells. Shallow tubewells also have the advantage that, with the smaller groups of users that they supply, the responsibilities for maintenance and operation are better shared than with deep tubewells, which have a larger yield.

'Fossil' salts are mobilized not only by deep tubewells. Any drainage system will cause the flow of water through deeper layers. The salt balance of a drainage pilot area in Egypt could only be 'closed' when a much higher than expected salt content

of the groundwater was assumed (Abdel-Dayem and Ritzema 1990). The topsoil of the pilot area had been leached in about two years after the implementation of the drainage system, but the subsoil was still desalinizing after several years.

Other solutes may also be mobilized by drainage. In the San Joaquin River Valley in California, U.S.A., selenium was discovered to be the cause of deaths and deformities in aquatic wildlife in the Kesterson Reservoir (Summers and Anderson 1989). Much of the drainage water in parts of the San Joaquin Valley is high in concentrations of dissolved solids, and contains selenium, molybdenum, boron, and other elements. The origin of selenium as a toxic element in the San Joaquin Valley is natural, which means that treating the source is impossible. With subsurface drainage, because the flow through the subsoil will extend to a depth of about one-fourth of the drain spacing, a ban on more subsurface drainage could prevent the mobilization of the selenium.

14.4 Water Balances and Irrigation Efficiencies

14.4.1 Irrigation Efficiencies

The process of supplying irrigation water is usually split into three parts (Bos and Nugteren 1990):

- Conveyance (i.e. the transport of water between the source and the tertiary unit offtake);
- Distribution (i.e. the transport of water between the tertiary offtake and the field inlet);
- Field application (i.e. the application of water downstream of the field inlet).

Figure 14.5 presents a diagram of the flow of water in irrigation as a water balance for an irrigated area. In this figure, the scheme is divided into the three separate parts of the water-supply process. Irrigation efficiencies are basically ratios of volumes: for example, the ratio of 'evapotranspiration minus effective precipitation (V_m)' over 'flow diverted or pumped from the river or reservoir (V_c)' is the project or overall irrigation efficiency. If more data on a system are available, other efficiencies can be calculated. The irrigation efficiencies used here are those of ICID (1978; Bos 1980):

Conveyance efficiency $$e_c = \frac{V_d + V_2}{V_c + V_1}$$

Distribution efficiency $$e_d = \frac{V_f + V_3}{V_d}$$

Field-application efficiency $$e_a = \frac{V_m}{V_f}$$

Overall or project efficiency $$e_p = \frac{V_m + V_2 + V_3}{V_c + V_1}$$

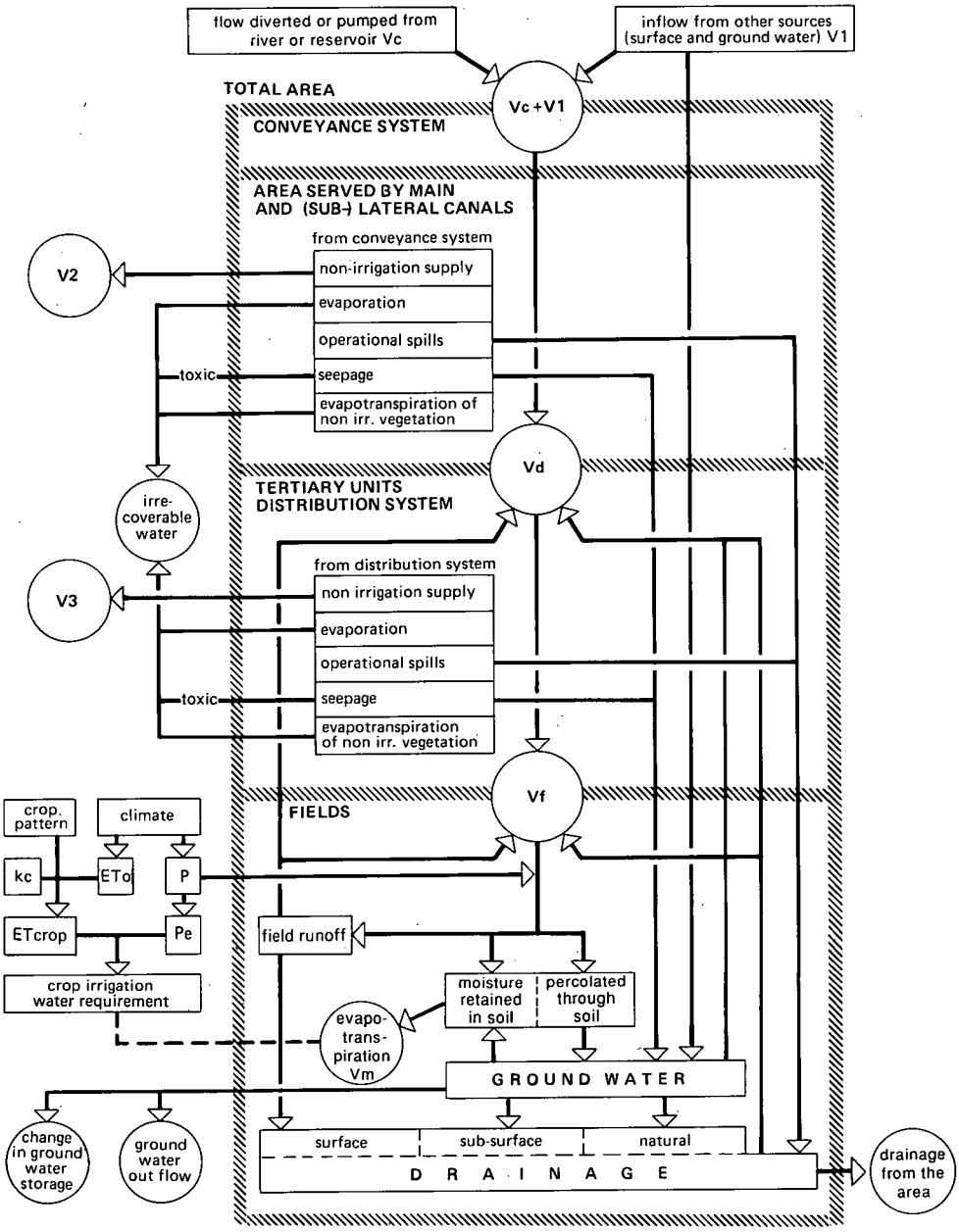

Figure 14.5 A diagram of the flow of water in an irrigation process (Wolters 1992)

where

V_c = volume diverted or pumped from the river (m^3)
V_d = volume delivered to the distribution system (m^3)
V_f = volume of water furnished to the fields (m^3)

V_m = volume of water needed, and made available, for evapotranspiration by the crop to avoid undesirable water stress in the plants throughout the growing cycle (m^3)
V_1 = inflow from other sources (m^3)
V_2 = non-irrigation deliveries from the conveyance system (m^3)
V_3 = non-irrigation deliveries from the distribution system (m^3)

Since the purpose of irrigation is generally to grow crops, the part of the water that turns into 'evapotranspiration' is the most important in the water balance. Figure 14.2 showed that, of the volume of water at the start of the process, only a portion will become evapotranspiration. In the evaluation of the water balance of irrigation schemes, the 'crop irrigation water requirement' plays an important role. Under what is generally described as well-watered conditions, crops will reach their potential evapotranspiration. Under conditions of water shortage, however, the actual evapotranspiration will be lower than the potential (see Chapter 5). The deviation of the actual evapotranspiration from the potential depends on the degree of water shortage, which, in turn, depends on the total volume of water supplied to the area, and the division of that water over the area.

Rainfall can lead to excess water in irrigation schemes. The occurrence of rain with time is random and can be variable over a large area. If the travel time of water in the system is long, water already released for irrigation becomes excess water if rain suddenly starts. Rain can fall just before or after an irrigation, and then either the rain will not be effective or most of the irrigation water will percolate. If the rain intensity is high, the water cannot infiltrate and will become surface runoff.

Water not turned into evapotranspiration can be divided into a 'recoverable' volume of water (e.g. seepage from the conveyance and distribution systems, operational spills, surface runoff from fields, percolation) and an 'irrecoverable' volume of water (e.g. evaporation from fallow land, evaporation from the conveyance and distribution systems, evapotranspiration by non-irrigated crops). Whether water is recoverable depends, among other things, on its quality: its salinity may have become too high, or it may have picked up toxic substances.

Whenever there is a water shortage, drainage water tends to be re-used for agriculture. Drainage water that has left the area can be re-used somewhere else. If re-used inside the area, it will affect the performance of the system: evapotranspiration will increase without more water being diverted to the system.

There is a difference between re-used drainage water supplied to the distribution system, or to the conveyance system (Wolters and Bos 1990). Usually, the total volume of re-use can be divided into two parts: official and unofficial. The official part is the volume of water re-used with facilities installed by the system management (by gravity or pumping); the unofficial part is the generally unknown volume of water re-used by the farmers.

Re-use usually leads to a poorer water quality downstream of the irrigation system because drainage water from an irrigation scheme can be quite saline; as well, it usually transports chemicals in the form of pesticides, herbicides, and fertilizer. This is a world-wide problem, and one that is becoming increasingly serious (see Chapter 25).

Whether or Not to Increase Irrigation Efficiencies

The limits to the availability of water and land for irrigated agriculture necessitate the careful use of these resources. This is the reason why many irrigation system managers strive to increase the efficiency of their irrigation water use. An increased efficiency can have many positive effects, but negative effects as well. The positive effects are (Wolters 1992):

- A larger area can be irrigated with the same volume of water, and the effect of a water shortage will be less severe;
- The competition between water users can be reduced;
- Water can be kept in storage for the current (or another) season;
- Groundwater levels will be lower, which can lead to lower investment costs for the control of waterlogging and salinity;
- There will be less flooding;
- Better use will be made of fertilizers and pesticides, and there will be less contamination of groundwater, and less leaching of minerals;
- Health hazards can be reduced;
- Energy can be saved;
- There will be fewer irrecoverable losses;
- Instream flows, after withdrawals, can be larger, thereby benefitting aquatic life, recreation, and water quality.

The negative effects of increasing the efficiency of irrigation water use are:

- Soil salinity may increase because of reduced leaching;
- Wetlands and other wildlife habitats may cease to exist;
- Groundwater levels will fall and aquifers will receive less recharge;
- Water retention in upstream river-basin areas will be reduced;
- There will be a need for a more expensive infrastructure, and for a more accurate operation and monitoring.

These lists show that when one is considering increasing efficiencies, many effects have to be considered. The relationship between irrigation efficiencies and drainage will be illustrated in the next two sections.

14.4.2 Conveyance and Distribution Efficiency

Water losses in the conveyance and distribution systems of an 'average' irrigation scheme can be considerable (see Figure 14.2). They occur mainly through seepage and incorrect management practices. The importance of these factors is illustrated in Figure 14.6, which compares the conveyance efficiencies (e_c) of two similarly-managed systems in Australia: the Goulbourn and the Campaspe systems. When the Goulbourn system first operated, its conveyance efficiency, e_c, was about 0.50, while that of the leaking Campaspe system was as low as $e_c = 0.39$. In the Goulbourn system, after proper structures had been installed to measure and regulate flows and the related improvement in its operational practices, its e_c-value rose to about 0.80. Later, the leaking Campaspe was lined and fitted with structures similar to those in the Goulbourn system, and its operational practices, too, were improved. As a result,

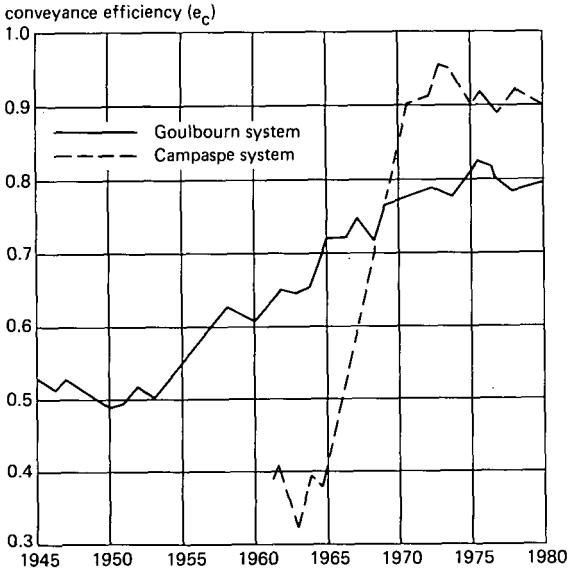

Figure 14.6 Conveyance efficiencies as a function of time in two irrigation systems in Australia (Tregear 1981)

its e_c-value rose to about 0.90, some 10% higher than that of the unlined Goulbourn system (Tregear 1981).

The importance of increasing the conveyance efficiency of an irrigation system has also been proven in the Beni Amino Scheme in the Moroccan Tadla region. There, waterlogging completely disappeared after the canals had been lined. The existing natural drainage capacity was capable of discharging the prevalent excess water (Tadla 1964).

Rate of Change of Groundwater Depth

The efficiency with which irrigation water is used influences the rate of change in groundwater depth. Hence, a change in the water management of an irrigation system could alter the need for a drainage system. We shall illustrate this by comparing some performance indicators of the Rio Tunuyan Scheme (Bos et al. 1991). The e_p (here the overall irrigation efficiency of canal water use) is the ratio of the crop water use over the volume of water diverted into the canal system. Figure 14.7 shows the monthly average value of this efficiency. This figure also shows monthly average values of rainfall and of the groundwater depth below the soil surface. Contrasting the average monthly rainfall data with the depth to groundwater shows that the watertable drops during most of the high rainfall months. This is probably because the rainfall is low in comparison with the evapotranspiration.

Figure 14.8 shows the monthly ratio of crop irrigation water use over the diverted volume of canal water, versus average monthly changes in groundwater level. There is a trend that, in months with an e_p-value below 60%, the groundwater level rises, and in months when this ratio exceeds 60%, the groundwater level falls. The e_p can thus be used as a management indicator to control the groundwater depth below the soil surface.

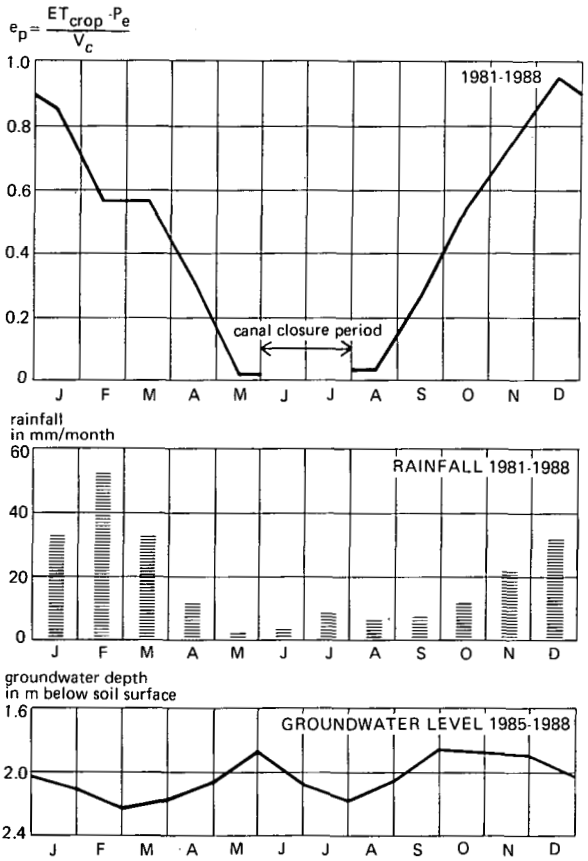

Figure 14.7 Ratio of crop water use over the water diverted into the canal system

The Rio Tunuyan Valley is a typical example of an irrigated area where a high groundwater level has to be prevented to limit the capillary rise of water. An increase in capillary rise would result in a net flow of water, with salts, towards the soil surface, which would reduce crop production. Figure 14.7 shows that the watertable rises about 0.2 m/month immediately before and after the canal closure period, which are months with a very low overall efficiency of irrigation water use. A change in water management aimed at increasing the overall irrigation efficiency to about 40% during this period would contribute to solving the waterlogging and salinity problems in this valley.

14.4.3 Field Application Efficiency

The components of a water and salt balance at field level are illustrated in Figure 14.9. Frequently, water that originates from irrigation recharges the groundwater at a rate that exceeds the natural discharge. As a result, the watertable rises at a rate that depends greatly on the volume of water applied to the field. The excessively-

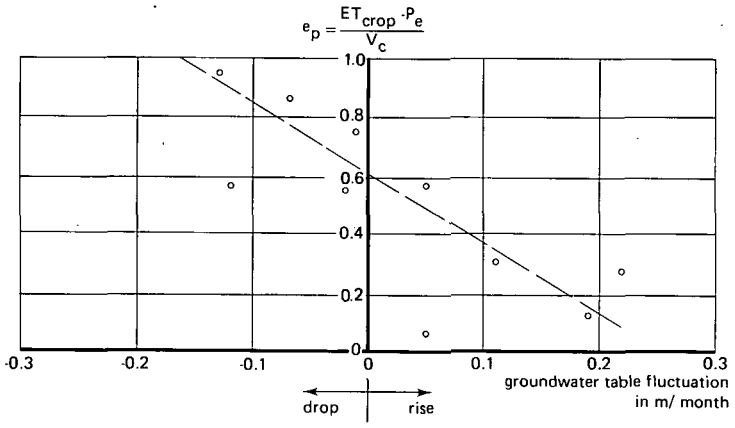

Figure 14.8 Relation of the overall irrigation efficiency of canal water use and the groundwater fluctuation, monthly averages

applied water will percolate to the groundwater and thus leach the rootzone to a salt level that is acceptable for crop growth. Often, however, the farmer will apply additional water to his fields because he thinks they need more leaching. As a result, the watertable below the irrigated and leached fields will continue to rise. The ensuing problems of waterlogging and salinity are often more severe than the original problems that triggered off the initial leaching.

In literature (Chapter 15; Bos and Nugteren 1990; FAO 1980; Wolters 1992), tables and graphs can be found with values for field application efficiency per field application method, soil type, etc. Seasonal average e_a-values of 60% are common

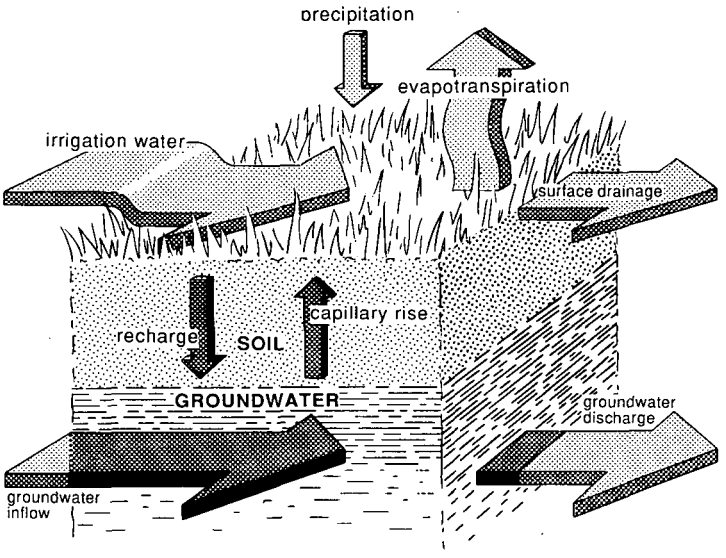

Figure 14.9 Principle of a water and salt balance in an irrigated area

for non-rice schemes with field application methods such as furrow and border, and on medium to heavy soils. For sprinkler-irrigated schemes, a typical e_a-value would be 70%. Nevertheless, it is possible to find seasonal averages that deviate considerably from these values. The highest seasonal e_a-values of 80% and over, for a wide range of soil types and field application methods, are always associated with water shortages in the peak season (Wolters 1991).

Very often, field application efficiency values presented in the tables in literature are averages over a year or a season, although the need for water and the availability of water vary considerably within a growing season. Because of these variations, field application efficiency values also vary. Seasonal average values are good indications of the overall water balance, but do not have a direct relationship with what actually happens in the fields. The volumes involved are also different within the season. A relatively low efficiency at the start of the growing season is much less of a problem, from a water conservation point of view, than a relatively low efficiency in the peak season, when the volumes of water are much greater. Field application efficiencies (and other efficiencies as well) should be considered per month instead of per season. A very high monthly value of e_a implies that hardly any water, and consequently hardly any salts, are evacuated from the fields. Such an efficiency is only acceptable when rainfall, or some other source of water, will evacuate the excess salts in another period of the year.

Generally, the long-term minimum percolation losses with surface irrigation and sprinkling can be estimated around 20 – 25% for a wide range of soils provided with sufficient drainage. The percolation losses will be higher for very coarse soils (e.g. sand), and lower for very fine soils (e.g. silty clay and clay).

In an Egyptian desert reclamation strip, consisting of medium-grained fluvial sands and predominantly irrigated with level basins at a frequency of about five times a month, an overall efficiency of about 30% was found (Attia 1989). The main problem in such areas is the low water retention of the soils. The only way to counteract this would be to choose an application system that can apply water at very brief intervals, and in a small quantity per application.

Increasing field application efficiencies, by reducing the irrigation supply and improving the uniformity of field application, is generally expected to be beneficial. One effect could be that the occurrence of harmful or toxic elements in drainage water (as in the San Joaquin Valley) is counteracted, because of the reduced drainage water outflow. But, a question that arises is: 'How much improvement can be made in irrigation efficiencies when lands are already supplied with less water than required?' Supposing that the salt balance of the rootzone has always been in equilibrium, reducing the water supply could lead to salinization. Periodic leaching to maintain a favourable rootzone salt balance is then no solution, because it would nullify the positive effect of reduced percolation through the reduced irrigation supply.

Another expectedly-beneficial effect of increasing irrigation efficiency is the availability of more water. But, if the 'extra' water were then to be used to expand the cultivated land in an area like the San Joaquin Valley, the effect might even be counter-productive, because sources of toxic solubles that are at present immobile might be mobilized and enter the environment.

14.5 Combined Irrigation and Drainage Systems

It is possible to use a drainage system for irrigation as well. This is known as 'infiltration irrigation', 'sub-irrigation', or 'inverse drainage'. The method is applied in The Netherlands for the cultivation of flower bulbs. In the open ditches between the bulb fields, the water level is carefully maintained by the supply or withdrawal of water. This method was developed in an area close to the North Sea dunes. The soils have been levelled to exactly 0.55 m above polder water level, which is very accurately kept constant. The soils in this area are deep and highly permeable. In the most advanced version of sub-irrigation, the water flows through a fairly dense network of parallel sub-surface pipe drains that have been laid horizontally for this purpose.

Successful sub-irrigation is only possible under the following conditions:
- A flat soil surface;
- Small water losses to the underground and adjacent areas;
- Permeable soils (also when always saturated or at field capacity).

Sub-irrigation is known to be used in a steady and a non-steady manner: steady for a situation where the water level in the ditches is maintained at a fixed level (e.g. for the flower bulbs on sandy soils in The Netherlands), and non-steady when the water level in the ditches is increased to field level for short periods (e.g. in coastal plains in the humid tropics).

The relationship between irrigation and drainage is illustrated in Figure 14.10, which shows the schematic watertable elevation with steady-state infiltration, for which an 'inverse drainage' formula can be derived (Hooghoudt 1940)

$$q = \frac{8K_b d(n - h) + 4K_t(n^2 - h^2)}{L^2}$$

where

q = water supply rate by infiltration (m/d)
K_t = saturated hydraulic conductivity above drain level (m/d)
K_b = saturated hydraulic conductivity below drain level (m/d)
d = equivalent depth (m)

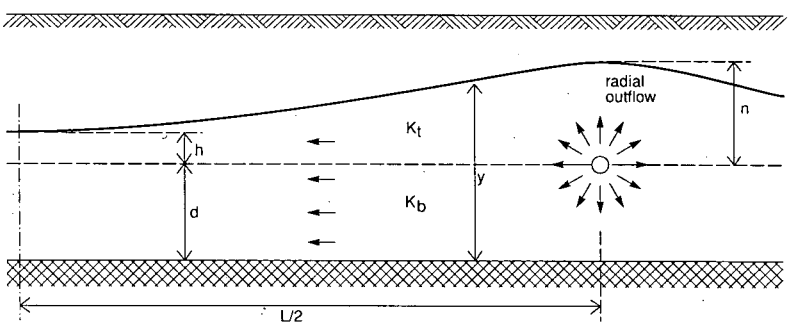

Figure 14.10 Schematic watertable for 'inverse' drainage

n = infiltration head (m)
h = elevation of water above drain level, midway between the drains (m)
L = drain spacing (m)

One of the assumptions for the infiltration-spacing equation is the absence of entrance resistance near the drain. This appears to be correct for infiltration via drain pipes, but not for infiltration via open ditches. With open ditches, the entrance resistance, combined with radial resistance, appears to be the determining factor. The total resistance to flow can then be assumed to be concentrated near the infiltration surface of the open ditches, and the flow resistance in the aquifer can be neglected.

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