Irrigation-Induced River Salinization: Five Major Irrigated Basins in the Arid Zone

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IWMI thanks the European Union for the financial support given for this study. IWMI also gratefully acknowledges the unrestricted and program support provided by the following Governments, Development Banks, Agencies, and Foundations: Australia, Belgium, Brazil, Canada, China, Denmark, Germany, India, Iran, Japan, Mexico, Netherlands, Norway, Pakistan, Peru, South Africa, Sweden, Switzerland, United Kingdom, United States of America and European Union (EU); African Development Bank (AfDB), Asian Development Bank (ADB), Ford Foundation, and World Bank. The Governments of Nepal, Pakistan, and Sri Lanka provided logistical support for IWMI-related activities in these countries.

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Smedema, L. 2000. *Irrigation-induced river salinization: Five major irrigated basins in the arid zone.* Colombo, Sri Lanka: International Water Management Institute.

/ water resources development / irrigation management / river basin development / drainage / arid lands / water quality /

ISBN 92-9090-391-0

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The International Irrigation Management Institute, one of sixteen centers supported by the Consultative Group on International Agricultural Research (CGIAR), was incorporated by an Act of Parliament in Sri Lanka. The Act is currently under amendment to read International Water Management Institute (IWMI).

Contents

Acknowledgements

This publication was prepared as a joint activity by the International Water Management Institute (IWMI) and the International Program for Technology and Research in Irrigation and Drainage (IPTRID). Both institutions are extensively involved in research in the sustainable management of land and water resources for irrigated agriculture of which the control of river salinity is obviously a key element. Both are repositories of extensive knowledge on the subject and, moreover, could be relied on for well-established contacts in the selected basins. The study could also draw on a number of related studies undertaken by IWMI, the World Bank, and by some of the national basin management institutions. The author gratefully acknowledges the ready cooperation of all the institutions and resource persons contacted.

CHAPTER 1

INTRODUCTION

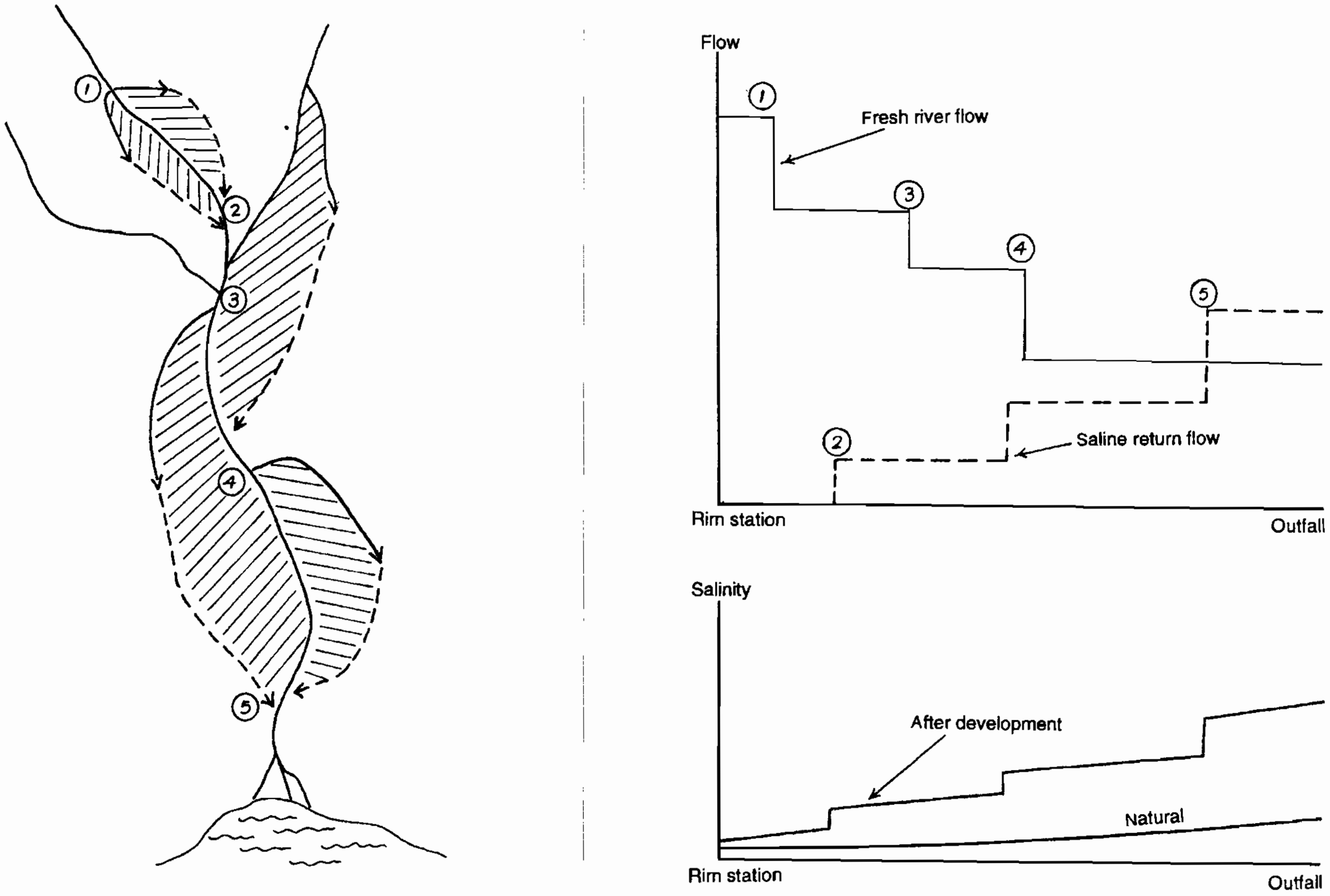
Rivers in irrigated basins typically serve both as the sources of the irrigation water and as the sinks for the drainage water. While most of the irrigation water is diverted from the upper reaches of the rivers, most drainage water returns to the lower reaches. These functional and spatial linkages basically explain the increase in downstream river salinity observed in almost all irrigated basins in the arid zone (figure 1). This irrigation-induced increase in river salinity generally reinforces already existing natural trends. In the humid zone where the natural salinity and the impacts of the irrigation diversion and drainage return on the river regime are proportionally much less, this phenomenon is generally not noticeable.

The increase in downstream river salinity typically becomes more pronounced when the irrigated land use expands and intensifies and when municipal and industrial developments add to the salt-loading of the river water. Control of the river salinity is usually possible but generally requires the adoption of costly and painful changes in current water use practices and/or poses equally painful restrictions on further developments in the basin. However, without such control measures, the underlying processes may be expected to continue until the river salinity reaches its final equilibrium level, which may be so high that many important water-related human activities in the lower basin would become seriously impaired and many environmental values irreparably damaged. The irrigated agriculture in the basin, generally being the largest water user, would be one of the main victims.

This publication reports on a study of the increase in river salinity and the implemented control programs in five major irrigated basins in the arid zone. The study is limited to salinity. Although salinity is no longer the only water quality concern in irrigated basins, in most basins it is still by far the dominant concern. The basins studied are: the Aral Sea Basin in Central Asia, the Colorado Basin in the western USA, the Indus Basin in Pakistan, the Murray-Darling Basin in southeastern Australia and the Nile Basin in Egypt. These basins cover a range of physiographical and geological conditions but are all located in the (semi) arid zone and are relatively large in size (mostly in the 0.5–1.0 million km^2 range).

Irrigation was the main initial water development and all five basins still support important irrigated agriculture sectors. However, other sectors with a stake in the use of the river water are rapidly gaining importance. The role of legal and institutional factors is recognized although in this publication these factors have not been dealt with as extensively as the technical factors. Together, the five basins constitute a fairly representative set from which important lessons on the control of river salinity in irrigated basins in the arid zone can be drawn.

Figure 1. Schematic outline of the problem.



CHAPTER 2

SALINITY

For the benefit of the general reader, this chapter presents some essential background information on the nature and dynamics of salts in the soils and in water, their sources and global patterns, and their potential harmful impacts. For a more detailed discussion, reference is made to the standard works on soil and water salinity by Ghassemi, Jakeman, and Nix (1995); Szablocs (1989); and Tanji (1990).

2.1 Terminology

Salts commonly occurr in almost all natural substances and environments. Most salts found in soils and waters are generally naturally formed mineral salts. In solution, the salt compounds dissociate, completely or partly, into the constituent anions and cations. The major cations found in soil and water are sodium (Na^+), calcium (Ca^{++}), magnesium (Mg^{++}), and potassium (K^+) while the major anions are chloride (Cl^-), sulphate (SO_4^-), hydrocarbonate (HCO_3^-), carbonate (CO_3^-), and nitrate (NO_3^-). In the solid phase, the ions are bonded and form mineral salts such as $CaCO_3$, $MgCO_3$, Ca_2SO_4, NaCl, MgC_{12}, Na_2SO_4, and others.

Salinity is a general term indicating the presence of rather high levels of salts. The level of salinity is generally assessed by measuring the concentration of the salts in a water solution. This concentration expressed as the weight of the salts per unit volume of water, is called the "total dissolved solids" (TDS), which is usually given in mg/l or in its numerical equivalent, "parts per million" (the ppm unit). These units are typically used when the TDS is determined by desiccating the solution.

The salt concentration may however also be determined indirectly by measuring the electrical conductivity (EC) of the solution, as there is a fairly consistent linear relationship between the salt concentration of a solution and its EC value. According to the International System of Units (IS), the unit for electrical conductivity is deci-Siemens per meter (dS/m), which is numerically equivalent to the formerly used mmho/cm unit. For the common range of river salinity, the TDS and the EC units may be mutually converted by applying the rule that 1.0 dS/m = 640 mg/l. Soil salinity is standardly measured in the "saturation extract," which is the solution extracted from a fully saturated soil-paste. The electrical conductivity of this extract is known as the ECe value and most of the documented crop responses to soil salinity are based on this indicator.

As salts differ in their solubility in water, the salt composition of a water body may change when the solution is diluted (e.g., by the inflow of freshwater) or become more concentrated (e.g., by evaporation). Most chloride salts are highly soluble as are most nitrate and sulphate salts whilst alkali earth carbonates ($CaCO_3$ and $MgCO_3$) and gypsum ($CaSO_4$) are less soluble. The latter salts gradually precipitate when solutions become more concentrated. These low-soluble salts are again mobilized when the solutions become diluted. These precipitation and dissolution processes commonly occurr in the soil. The river salinity, however, almost never exceeds the solubility limits of even the least-soluble salts.

2.2 Salt Sources

The salts found in the soils and in the waters in a river basin generally originate from, or are classified as, one or more of the following types:

2.2.1 *Primary Salts*

These are the salts continuously released from rocks and soils by mineral weathering and dissolution. Due to limited rainfall and leaching, most arid-zone landscapes are rich in primary salinity. The releases are, however, counteracted by salt precipitation and other forms of salt immobilization and indications are that in most irrigated basins in the arid zone, except for those basins with relatively young soils and with only moderate salinity, rates of immobilization are about the same as those of release.

2.2.2 *Fossil Salts*

Almost all basins in the arid zone harbor large quantities of "fossil salts," trapped in the sedimentary rock strata and aquifers, formed during previous geological periods when (part of) the basin was occupied by the sea, salt lake, salt playa, salt desert, or some other salt sink. By geological uplifting and/or erosion, some of these deeper buried saline strata may later have moved to the surface and become exposed. Release and mobilization of these fossil salts by natural or by anthropogenic processes constitute a virtually inexhaustible source of salts in many irrigated basins.

2.2.3 *Atmospheric Salts*

Salts carried by rainfall or wind may constitute a significant source of salt in coastal areas. The atmospheric fallout of salts in coastal zones may well amount to 100–200 kg/ha/yr. while even in areas far inland it may still be about 10–20 kg/ha/yr. (Tanji 1990). Some parts of Australia are reported to be exposed to an annual atmospheric salt fallout of 10–100 kg/ha, presumably mostly originating from nearby desert areas.

2.2.4 Salts in Irrigation Water

All irrigated land has to cope with the salt-load carried by the applied irrigation water. Without adequate leaching and drainage, these salts risk remaining in the soil/land when the water (evapo) transpires. The annual salt-loading by this source depends on the volume and salinity of the applied irrigation water but in the arid zone it may easily be about 2–3 tons/ha (refers to an annual application of 1,000 mm with a salinity of 200–300 mg/l). As most of these added salts are not main plant nutrients, the crops take up only a very small percentage.

2.2.5 Salts in Fertilizers

The average salt content of a package of commonly used fertilizers may well be about 65–70 percent and even though it may generally be assumed that at least half of these salts will be taken up by the crops, the net salt-loading by the applied fertilizers may not be insignificant in basins where modern high-input farming is practiced (may well be about 200–300 kg/ha/yr., which is however still quite small compared to the salt-loading by the irrigation water).

2.2.6 Other Anthropogenic Salts

Residential and industrial developments also import or mobilize salts in the basin, some of which may add to the salt-loading of the basin through fallout of polluted air and disposal of waste into the basin waters. However, even at high levels of settlement and industrial development, this usually remains a minor source. The harm generally derives less from the salt quantity than from the types of salts, some of which may be highly toxic to public health and the environment.

2.3 Salt Regimes

The global occurrence of soil and water salinity has distinct zonal characteristics (Kovda 1973). While salinity commonly occurrs in the arid zone, it is generally not found in the humid zones where rainfall exceeds the evaporation and salts are readily leached from the land and diluted in the water bodies. As shown in table 1, there is a close relationship between the rainfall/evaporation ratio and the distribution of salinity within the arid zone.

The salts in arid landscapes tend to migrate, moving with the water or with the eroded material, to the geomorphological bottom areas, typically occupied by the plains that, because of their easy command, flat topography, and soil suitability, are precisely the areas favored for irrigation development (Smedema 1990). The salinity conditions in these bottom plains, however, are seldom uniform, as geological and leaching/drainage conditions vary in space and may also have varied over time. Moreover, various geochemical processes may also have influenced the salt concentration, distribution, and composition.

Table 1. Climate-salinity relationships in Eurasia.

Climatic landscape	Mean annual temperature (°C)	Annual rainfall (mm)	Annual potential evapotrans-piration (mm)	Residential salinity of sedimentary rocks	Maximum river water salinity (g/l)	Maximum lake water salinity (g/l)	Maximum ground-water salinity (g/l)	Salinity in top horizons of solonchak soils (%)
Desert	15–18	80–100	2,000–2,500	Common	20–90	350–400	200–350	25–75
Semidesert	10–12	200–300	1,000–1,500	Frequent	10–30	300–250	100–150	5–8
Steppe	5–10	300–450	800–1,000	Rare	3–7	100–250	50–100	2–3
Forest steppe	3–5	350–500	500–800	None	<1	<100	<3	<1

Source: Kovda 1973.

The resident salt storage in the plains of the arid zone may be enormous. A profile of 50–100 m depth in the Indus Plains may be calculated to easily store salt in the region of 1,000–2,000 tons/ha. This value compares to 250 tons deposited by 100 years of irrigation with water of 250 mg/l and an annual applied water depth of 1,000 mm. Under natural conditions, these buried fossil salts do little harm. However, these resident salts do become a major burden when they are mobilized and become part of the salt dynamics of the basins. As will be discussed in more detail later, rising water tables, induced seepage flows, tube-well pumping and other features of large-scale irrigation development have, in many instances, led to such mobilization.

2.4 Safe Limits

The damage caused by high levels of river salinity has been studied in considerable detail for the Colorado River (USBR 1988). The main findings are summarized below:

2.4.1 Agricultural Use

Reductions of crop yields due to the use of saline irrigation water were identified as the main form of agricultural damage. It was recognized that the use of such water also incurs other damage and costs (restrictions on crop choice, need for using more costly irrigation practices, need for improved drainage, etc.). However, many of these adjustments appeared to be at least partly motivated by external considerations and the costs directly attributable to salinity could not be generally quantified. Damage to other agricultural water use (drinking water for animals and other incidental on-farm usages) was found to be negligibly small.

The yield reductions for most common crops due to salinity have been extensively researched and documented. Most crops have fairly distinct threshold levels below which the damage is minimal while above that level yields fall almost linearly with increasing levels of salinity. For sensitive crops, yields may become affected when the salinity of the applied water exceeds 500 mg/l while for tolerant crops this may not occur until it reaches levels of 3,000–4,000 mg/l. According to FAO (1985), the following general criteria apply: no yield reduction for EC < 0.7 dS/m (450 mg/l), slight yield reduction for EC = 0.7–3.0 dS/m (450–2,000 mg/l), and severe yield reduction for EC > 3.0 dS/m (2,000 mg/l). Crop growth may also be affected by high concentrations of specific salts or ions, notably by excess sodium, chloride, bicarbonate, boron, and various trace elements and heavy metals but river water seldom reaches these toxic levels (for details see FAO 1985).

2.4.2 Municipal and Industrial (M&I) Use

The World Meteorological Organisation's (WMO's) safe limit for human drinking water is around 1,500 mg/l but this limit is of little relevance, as water becomes unpalatable to most users at much lower salinity (usually taken at 500 mg/l). Users typically respond to taste deterioration by purchasing more bottled water. Switching to alternative supplies (shifting the intake farther upstream, changing from surface water to groundwater, etc.) is usually a more feasible option than treatment. Salinity and the related hardness of the water also affect various other household usages, even at very low concentrations. Lifetimes of some sensitive household appliances and systems may be affected when salinity rises above 100 mg/l.

A number of industrial systems and processes are highly vulnerable to salinity. Corrosion substantially shortens the lifetimes of metal pipe systems, especially of cooling systems, when salinity levels of the water rise above 100 mg/l. This also applies to various treatments and distribution facilities operated by water supply and wastewater utilities. Most food processing industries can tolerate salinity levels of up to 500 mg/l but some other industrial processes, e.g., the paper industry, require much higher standards (< 100 mg/l).

2.4.3 Environmental Use

Damage to the environment, other than that already implicitly covered by the previous categories, was not identified in the Colorado study. Some specific environmental damage such as loss in aquatic and riverine habitat and scenery, loss of biodiversity, loss of assimilative capacity, etc., did occur but this damage was judged to be more due to the discharge reduction than to the increased salinity of the river.

CHAPTER 3

IRRIGATION DEVELOPMENT

This chapter briefly describes how irrigation development impacts on the natural hydrological and salinity regimes of the basin. The land salinization processes involved and the related water management issues are also discussed.

3.1 Water Resources Development

Early irrigation development in river basins was generally based on the run-of-river diversion but now the river flow in most basins is partly or fully regulated through the construction of reservoir dams and other storage facilities. These regulation works have generally drastically changed the natural flow regimes of the rivers. Depending on the installed storage capacity, previous short-duration variations in flow may hardly be noticeable, although the impacts of annual variations in weather conditions and rainfall may still be quite pronounced. The buffering impact of the reservoirs is even greater on the salinity. The general experience is that salts mix rapidly and completely in the reservoirs and depending on the size of the reservoir relative to the river flow, smooth out most of the seasonal salinity variations. Large reservoirs generally moderate the high salinity levels during the low-flow seasons as well as the lower salinity levels during high-flow seasons (figures 2a and 2b). The general experience is also that the salt precipitation in the reservoirs or elsewhere in the river system is so small that it may almost always be neglected in basin-level salt balance calculations.

Water abstractions have greatly reduced the downstream river flows in many irrigated basins in the arid zone. In some of these basins, the low-flow discharges to the sea have been reduced to a trickle while in the more heavily regulated basins, this has almost become a year-round feature (Williams 1987). The Yellow River in China reportedly had no outflow to the sea during a period of 136 days in 1996. The Colorado River has had no significant flow reaching the sea for the last 10–20 years and in most years the flow in this river ceases well upstream of its mouth. The lower reach of the Jordan River has deteriorated into a minor drain. These dramatic changes in the downstream flow regime have greatly affected the ecological functioning of the river and the ecology of the channel beds and floodplains.

The institutional, organizational, legal, and financial arrangements for the development and the management of the water resources in the basins and irrigation schemes are usually very country-specific. In most federally organized countries, the water rights rest with the States and water resources development and management are primarily a State responsibility. The federal governments, however, have often used their contribution in the costs to acquire some regulatory influence while the States may also have delegated some activities to specialized

Figure 2a. Impact of flow regulation on river salinity: Regime before regulation (1941) (Colorado River, Lee's Ferry, USBR 1977).

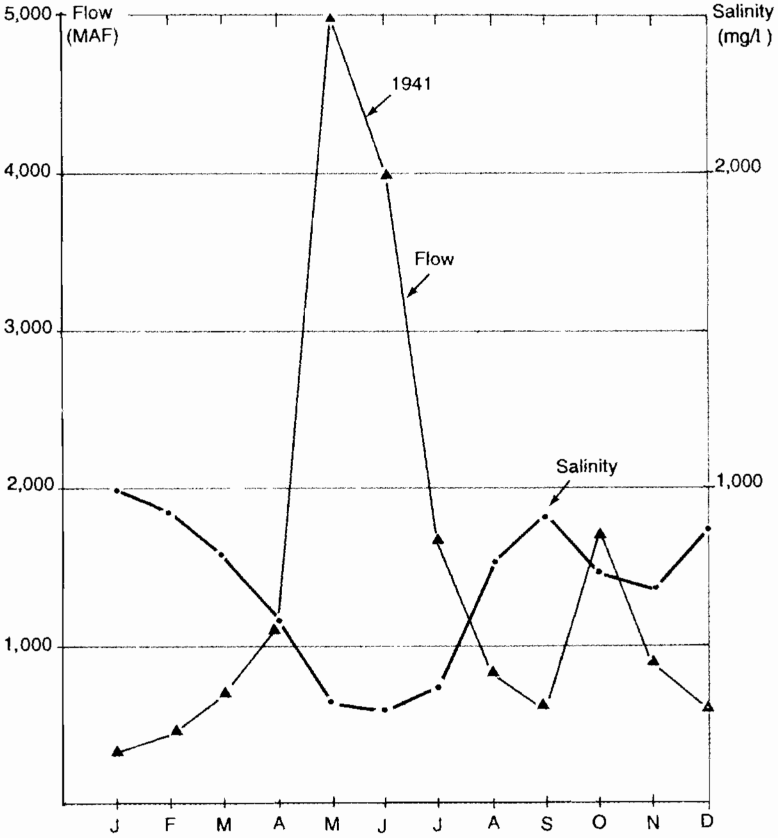
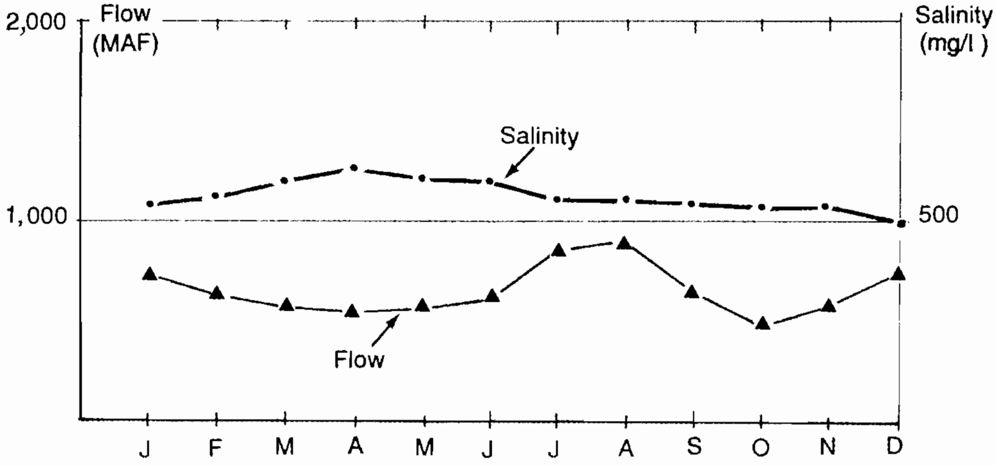


Figure 2b. Impact of flow regulation on river salinity: Regime after regulation (1993) (Colorado River, Lee's Ferry, USBR 1977).



federal institutions. This applies specially to basins spreading over more than one State. In almost all countries, central governments have also assumed a leading role in environmental matters related to water resources development and management.

3.2 Irrigation-Induced Salinity

Irrigation development in river basins in the arid zone may activate one or more of the following processes, which, as will be described later, are likely to lead to increased levels of downstream river salinity.

3.2.1 Land Salinization

Irrigation development in the arid zone almost inevitably leads to increased recharge to the groundwater (not only due to deep percolation of irrigation water losses but also due to less retention/more recharge by rainfall). Where the increased groundwater recharge exceeds the natural drainage capacity of the aquifer system, water tables will rise until a new equilibrium between recharge and discharge is established. In natural imperfectly drained land, this new equilibrium may not be reached until the water table has risen into the root zone and the land has become waterlogged. When the groundwater is saline (as is typically the case in the arid zone), this waterlogging will also lead to salinization of the land.

This twin problem of waterlogging and land salinization is of widespread occurrence in the arid zone, seriously affecting the productivity of the irrigated land in this zone (Ghassemi, Jakeman, and Nix 1995). The problem can be combated effectively, and already affected land can be reclaimed by the development of improved drainage (deepening and densification of the existing open drainage systems, installation of subsurface drainage systems, assuring adequate maintenance, etc.). However, since the drainage effluent will generally be quite saline, drainage development may be constrained by the lack of acceptable disposal sites (see discussion in section 3.3). The disposal problem may be reduced by judiciously matching the reclamation program with the flow regime of the receiving river.

3.2.2 Drainage Water Salinity

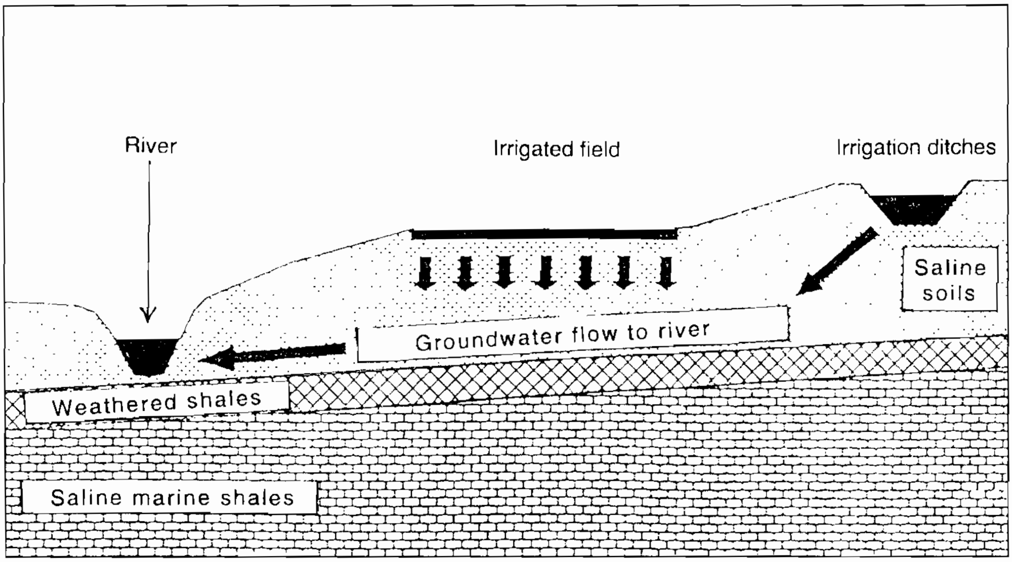
When river water is applied to the land for irrigation, crops will take up only a very small fraction of the applied salts. As a result, the salts will accumulate in the root zone unless there is a net downward leaching/drainage flow to remove the salts from the soil and the land. In the long-term, the root zone salinity of irrigated land in the arid zone will stabilize at a level where there is an equilibrium between the salt influx (by the irrigation water) and the salt outflux (by the leaching/drainage water). This equilibrium level is largely determined by the salt concentration of the applied irrigation water and by the leaching fraction, which is the leaching/drainage flow expressed as a fraction of the applied irrigation water.

Under equilibrium salt balance conditions, there is a pronounced inverse relationship between the salinity of leaching/drainage water and the irrigation efficiency (which is related to the leaching fraction), i.e., the leaching/drainage water becomes more concentrated with increasing irrigation efficiency and less concentrated with decreasing irrigation efficiency. Model calculations predict that under highly efficient irrigation with a leaching fraction of 10 percent, the leaching/drainage water may be expected to be about 10 times as concentrated as the applied irrigation water while for a leaching fraction of 20 percent, this concentration would be about 5 times (FAO 1985). In practice, the relationships between the salinity of the leaching/ drainage water and the irrigation efficiency may not be always as predicted. Equilibrium conditions may not exist or the relationships may be disturbed by the leaching/drainage water having picked up resident or other salts, being (partly) generated by rainfall or containing significant other flow components (surface irrigation waste, drainage flows from nonirrigated land, etc.).

3.2.3 Salt Mobilization

Irrigation development in the arid zone introduces a new source of water, which may dramatically change the prevailing geohydrological flow regimes. Additional groundwater recharge, fed by the deep percolating irrigation losses, may build up groundwater bodies and induce previously nonexisting groundwater flows. As explained earlier, areas chosen for irrigation development in the arid zone are likely to have a rather high resident salinity. As illustrated in figure 3, these new groundwater flows may load the rivers with large quantities of previously harmless, deeply stored resident salts.

Figure 3. Mobilization of primary and fossil salts by irrigation-induced groundwater flows.



Source: USBR 1977

In some cases, drainage improvements may inadvertently enhance this salt mobilization. This, for example, is often the case when vertical (tube well) type of subsurface drainage is installed. As groundwater salinity typically increases with depth, skimming types of drainage technologies (like horizontal pipe drainage), which draw most of its water from the upper groundwater zones, generally mobilize less-resident salts. In areas naturally subject to upward saline seepage (such as the northern part of the Nile Delta), improved drainage, which lowers the phreatic drainage base, will increase this seepage and the salinity of the drainage water.

3.3 Disposal of Saline Drainage Water

As discussed above, drainage water from irrigated land in the arid zone is likely to have a fairly high salinity that may pose problems for its disposal, especially when there is no ready access to natural or otherwise acceptable salt sinks (seas, salt lakes, etc.). For such schemes, one of the following modes of disposal or disposal management options may be considered.

3.3.1 Down the River

This is the natural mode of disposal, which was traditionally used in almost all basins until the limits of the downstream salinity were reached. In some cases, reaching these limits can be prevented by enhancing the river flow during critical low flow periods, e.g., by changing reservoir operation rules, by limiting the upstream water diversions, by reducing the saline water disposal during low-flow periods or by otherwise adjusting the salinity disposal to the dilution capacity of the receiving river.

3.3.2 Evaporation Ponds

Evaporation ponds are widely applied throughout the arid zone. Typically, these are natural depressions in the landscape towards which the drainage water can be easily directed. They are usually located in desert areas outside the irrigated perimeters, either sideways or at the lower end of the irrigation systems. However, small constructed evaporation ponds, e.g., serving individual farms, may also be found within irrigated schemes.

3.3.3 Limiting the Saline Effluent Generation

Although salt balances need to be maintained, some options for limiting the disposal flow are generally available. Reuse of drainage water is such an option, although it is clearly not a long-term solution as salts are being stored somewhere in the basin and limits will eventually be reached. The same applies to not meeting the leaching/drainage needs. Improving irrigation efficiencies helps by leaving more water in the river and also by reducing the drainage volumes but as the latter will have a higher salinity (see discussion in section 3.2), this will generally offer only limited relief to the downstream salinity.

3.3.4 Limiting the Salt Mobilization

This is a highly effective and desirable measure with no negative side effects. Ideally, the fossil and other resident salts stored in the basin should not be mobilized, but as irrigation development almost inevitably leads to rises in the water table and generation of new piezometric gradients and groundwater flows, this mobilization cannot be always avoided. Judicious irrigation development planning can help. In some cases, the mobilized salts may also be prevented from reaching the river by the installation of interception drains.

3.3.5 Land Use Planning

Land use planning in the basin can help in various ways to limit river water abstraction, generation of saline drainage flows, and salt mobilization or otherwise help control downstream river salinity. Less-water-demanding crops may be grown, irrigated land with uncontrollably high saline drainage rates may be retired or converted to rain-fed cropping, land with a high salinity may be left unreclaimed, and unproductive depressions may be designated as salt sinks (the "dry drainage" solution).

3.3.6 Outfall Drains

The construction of special drains for the collection and transport of saline effluent to a natural salt sink (usually the sea) may ultimately be required for basins that have no ready access to such sinks. Temporary solutions may be appropriate as intermediate steps but, as indicated above, most of these solutions have a limited capacity and do not fully maintain or restore the salt balance and, therefore, do not assure the long-term sustainability of irrigated agriculture in the basin.

3.3.7 Other Options

Disposal by means of bores to shallow saline aquifers is reportedly practiced in the southern part of the Murray Basin (Ghassemi, Jakeman, and Nix 1995). The salinity of the effluent is typically 1,000–2,000 mg/l and that of the receiving aquifer 25,000 mg/l and higher. Injection into deep aquifers is under investigation but is generally judged to have limited opportunities (FAO 1997). Desalinization is applied in a special case in the Colorado Basin (see annex B) but wider application will probably become only a serious option when the costs of disposal approach the costs of desalinization. In most basins this point has not yet been reached.

CHAPTER 4

THE SELECTED BASINS

The global and climatic setting of the selected basins is shown in figure 4. All main continents are represented. Some pertinent general characteristics and special features of the selected basin are given in this chapter. More complete and detailed information on each basin is provided in the attached annexes.

4.1 Brief Characterizations

These short descriptions are presented to familiarize the reader, without reading the annexes, with the prevailing salinity conditions, problems, and some other related features of the selected five basins.

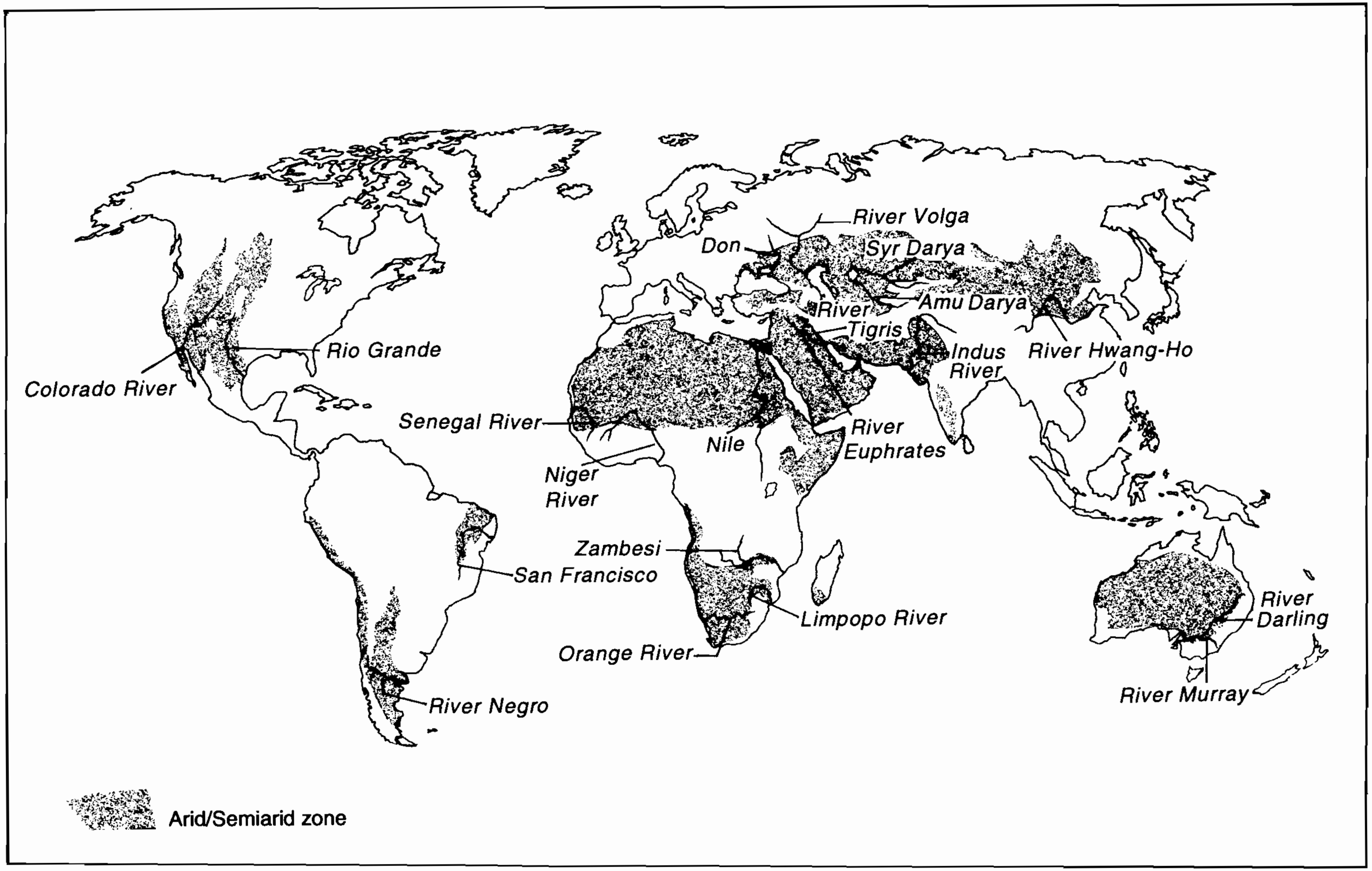
4.1.1 Aral Sea Basin

The rapid expansion of irrigated area and the related increased abstraction of the river water after the Second World War have greatly disturbed the natural hydrological and salinity regimes and have placed the socioeconomic future of the basin in considerable jeopardy. The greatly reduced river discharges to the Aral Sea have cut its size by half, increased its salinity threefold and have resulted in large-scale environmental degradation of the sea and its surrounding areas. The downstream flow and salinity conditions in the rivers have deteriorated to the extent that basic community and environmental functions are under severe stress and no further non-compensated abstraction and disposal of saline drainage can be allowed. The challenge is to halt further degradation of the Aral Sea and of the river functions, and, if possible, achieve some limited restoration of the past damage, without jeopardizing further socioeconomic development of the basin.

4.1.2 Colorado Basin

The experiences with salinity control in this basin offer, in many respects, a "window to the future" for many other basins. The basin features a highly intensive, diversified, and competitive use of the river water, sophisticated institutional and legal arrangements, highly developed stakeholder participation as well as an international dimension as, although most of the basin is in the USA, the river runs to the sea through Mexico. Some of the river salinity control measures instituted are, in fact, motivated by the Colorado water sharing agreement

Figure 4. Major river basins of the arid/semiarid zone (adapted from UNEP 1992).



that stipulates the delivery of a specified volume of water of a specified salinity to Mexico. A unique feature of this basin is also the considerable export of water, for irrigation and M&I use, from the basin to adjoining water-scarce areas. The current export already amounts to some 30 percent of the river flow and is bound to increase through trading with financially strong users outside the basin.

4.1.3 Indus Basin

The Indus Basin is such a dominant feature of Pakistan that the basin and the country are almost synonymous. The basin harbors almost all of the country's important irrigated agriculture sector and most of its major urban and industrial centers. The river water is currently almost exclusively used for irrigation as other water demands are still limited and are mostly met from the groundwater resources. The basin is subject to a massive problem of irrigation-induced waterlogging and land salinization, seriously affecting some 35 percent of the irrigated lands. The import of salt with the irrigation water far exceeds the disposal while the mobilization of fossil salts from deeper strata further adds to land salinization problems. Increased salt disposal from the basin is of strategic importance to the survival of irrigated agriculture in the basin. Steps are being taken to achieve this by investing in improved land drainage, by constructing outfall drains to the sea, and by instituting reforms meant both to promote more efficient water use and to assure better maintenance of the drainage systems.

4.1.4 Murray-Darling Basin

Current salinity conditions and driving forces in this basin are broadly comparable to those in the Colorado Basin. One similarity is that both basins spread over several States and are located in countries with strongly developed federated governmental structures under which water affairs are primarily handled by the States. Although the current river salinity is still mostly at an acceptable level, the noticeably increasing trends have raised acute concerns amongst the water users as well as in the civil society at large. Another striking similarity with the Colorado Basin is in the technical measures taken to control downstream river salinity (land use planning, interception of saline seepage flows, restrictions on the down-the-river disposal of saline drainage water, etc.) but there are also significant differences in the political approaches, in the implementation arrangements, and in the sharing of the costs.

4.1.5 Nile Basin

Egypt has long since embarked on improved drainage of its irrigated land, which has, by and large, brought land salinization in the basin under control. River salinity would not be a problem if the drainage water could be allowed, as done in the past, to discharge to the sea. Available fresh river flows are becoming increasingly insufficient to meet the water requirements of the ever-expanding area of irrigated land in the adjoining deserts and of the growing urban and industrial sectors; and the new challenge is to reuse drainage water to the maximum extent possible without harmfully salinizing the land and water resources. Although salinity problems in this basin are essentially confined to the Egyptian part of the basin, since salinity cannot be separated from water availability, the water requirements of the upstream countries from where the river flow originates should also be considered.

4.2 Land and Water Resources

In all five basins, only the bottom parts of the basin (the "plains" in which most of the irrigated areas are sited) are properly located in the arid/semiarid zone while the main catchments are mostly outside this zone, typically in areas with higher rainfall and many mountains. The annual rainfall in the plains varies from <100 mm to 500 mm in most basins and is somewhat higher in the upper basin than in the lower basin. Most basins, at least in the upper catchments, also have defined rainy and dry seasons. The five basins studied share these features with almost all other major irrigated basins in the arid zone.

Some other items of information on the land and water resources of the studied basins are presented in table 2. The "size" data in this table refer to the total watershed of the basin while the river flow data refer to long-term average flows passing through the "rim stations" and the final outfall points to the sea. The rim stations are the points where the main river/tributaries leave the catchment and enter the plains; most basins have such stations, typically coinciding with existing or potential dam sites.

Table 2. Land and water resources of the selected basins.

Basin	Size	Annual Flow		Reservoir capacity	Irrigated area	Water use for irrigation
		At the rim stations	At the outlet to the sea			
	(M ha)	(km^3)	(km^3)	(km^3)	(M ha)	(%)
Aral Sea (Amu Darya and Syr Darya)	180	116.0	11.5	55	7.5	90
Colorado	63	18.5	Nil	76	2.0*	80
Indus	94	181.0	39.0	19	16.2	95
Murray-Darling	106	24.3	5.5	30	1.5	95
Nile**	296	55.5	13.3	130	3.1	85

*Including 0.6 million hectares (M ha) outside the basin and 0.2 M ha in Mexico.

**Value for the size is for the entire basin but all other values are for Egypt only.

The reservoir capacity in the table refers to the total storage. The Colorado River is clearly a highly regulated river with a constructed storage capacity of more than four times the annual river flow. The Nile and Murray-Darling basins also already have considerable storage capacities while the Aral Sea Basin and, most notably the Indus Basin, are relatively less-developed. As mentioned earlier, in the Lower Colorado River, the seasonal variations in salinity (lower during the high-flow season and higher during the low-flow season) have largely disappeared. However, this is far less the case in the Indus and Aral Sea basins, which have considerably less reservoir storage. However, the storage in all the basins is sufficient both to enhance river flows during periods with extreme low inflows and to dilute associated high-salinity levels.

The differences in the use of the river flow for irrigation (last column of table 2) reflect the relative importance of the irrigation versus the municipal and industrial (M&I) and other uses of the river water. The M&I sector is of considerable importance in the Colorado and of growing significance in the Nile Basin while in the other three basins, the irrigation sector is still using almost all the water. However, even in the Colorado, some 80 percent of the water goes to irrigation indicating that even in highly developed basins, the quantitative demands of these other users remain limited.

The "flow to the sea" figures confirm the previously mentioned high rates of river flow depletion. Abstraction varies from 100 percent for the Colorado to about 90 percent for the Aral Sea, about 80 percent for the Indus, and some 75 percent for the Nile and the Murray-Darling. The absolute outflows to the sea are quite small in all the basins (nil for the Colorado and quite minimal in most years for the Syr Darya), except for the Indus River where, due to limited storage, there is still a large discharge to the sea during the rainy season. For navigation purposes and prevention of salt intrusion, a fairly high outflow to the sea is also maintained in the Nile River. The discharges of the Amu Darya and Syr Darya rivers to the Aral Sea have fallen well below the minimal requirements for the physical survival of the Aral Sea, as well as for the ecological well-being of the lower reaches of the rivers. The latter applies even more to the lower reach of the Colorado River.

4.3 Institutional Arrangements

The institutional arrangements for the development and management of the water resources in the five basins are all quite different. In four of the basins (Aral Sea, Colorado, Indus, and Nile), the arrangements are complicated because these rivers and the sea cross international boundaries while three basins (Colorado, Indus, and Murray-Darling) face comparable problems within the country as they serve the interests of more than one province/State.

In three of the international basins (Aral Sea, Indus, and Nile), most of the headwaters are outside the countries in which most of the water is used. Although some agreements have already been made, conflicts of interests remain. As the water in the headwaters is, in all cases, of good quality, cross boundary salt fluxes are generally not a major issue. The existing flow-sharing agreements, however, have an important bearing on the downstream salinity as these agreements determine the availability of upstream dilution of water for downstream river salinity control. In the fourth international basin (Colorado), the headwaters and most of the uses are in one country (USA) but the tail end is in another country (Mexico). Here the current updated agreement covers both the quantity and the salinity of Mexico's entitlement.

Most of the involved countries have a pronounced federated structure as far as water resources development and management are concerned. In the USA (Colorado), Pakistan (Indus), and Australia (Murray-Darling), the authority over the water resources rests with the provinces/States and the federal governments have, principally, only a regulatory role. For pursuing common interests, solving entitlement conflicts, and implementing cross-boundary projects, various types of consultative, cooperative, and executive structures have emerged, often facilitated by the federal government.

In most basins, the cross boundary planning and implementation tasks have also been delegated to inter-provincial/inter-State or federal bodies and programs. Some of these bodies and programs cover both water quantity and quality issues but with others these are treated separately. Stakeholders' participation may have been treated as an integrated part of the water resources development and management processes or function as parallel processes. The arrangements are generally quite specific for each basin and further details are given in the annexes.

CHAPTER 5

SALT BALANCES

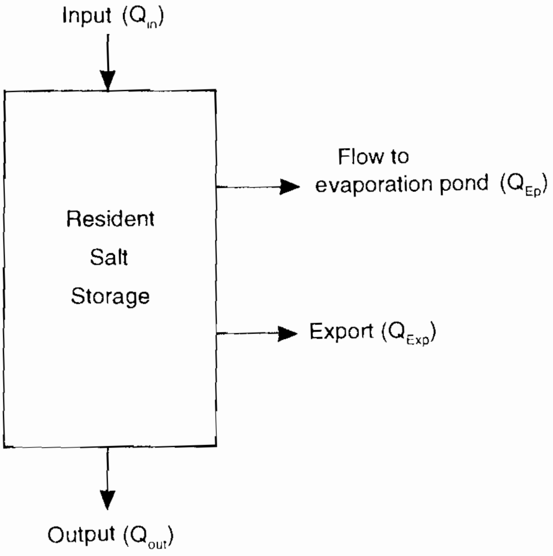
For the five basins, reasonably reliable data are available for discharge and salinity of inflows at the rim stations and also for outflows to the sea or other disposal sites. Using these data and calculating the annual salt fluxes as "annual discharge volume x weighted average salinity," annual salt balances for the basins have been calculated following the methodology presented schematically in figure 5. As shown, four modes of salt disposal have been recognized: a) down the river to the lower basin (applies to upper basins only); b) to the terminal sea or other natural disposal site; c) to evaporation ponds (E-ponds); and d) export of salt outside the basin. Where the required data were available, the basin balances have also been broken down into separate balances for the upper and lower basins.

5.1 Methodology

In the applied calculation methodology, the resident salt storage covers, in principle, the storage in both the river system and the land system (soil and underlying groundwater). However, it has generally been assumed that the salt storage of the river system is negligible compared to that of the land and that all of the calculated storage changes are changes in the land storage. This assumption needs further checking as it may not be valid for all basins (more detailed salt balance calculations for the Amu Darya and the Syr Darya basins show considerable differences between the summation of the salt balances of the separate irrigation schemes and the salt balance of the entire basin, and these differences are thought to be due to salt generation/removal processes in the river system).

In interpreting the calculated salinity balances, it should be clearly understood that the basin is treated as a "black box" and that the balances give the net change in resident salt storage in the (sub) basin. A gain in storage only means that, over the considered area and time period, on balance salt is being accumulated. However, there may be salt losses in part of the area or for part of the time. The balance calculations also do not allow differentiating between the various internal salt mobilization and immobilization processes. Very little is known about the quantitative dimensions of these internal processes. As discussed in section 2.2, the balance between mineral weathering and precipitation is likely to be negative while that between fertilizer application and crop uptake is likely to be neutral or slightly positive. Following common practice in salt balance calculations, it is assumed that these negative and positive balances cancel one another (Rhoades 1974). Even when this assumption is not entirely correct, the error on the basin salt balance would be quite small (best estimates suggest the annual net balance of these four processes, positive or negative, to be about some hundreds

Figure 5. Salt balance components.



$$Q_{in} - \{Q_{out} + Q_{Ep} + Q_{Exp}\} = \Delta \text{ Storage}$$

of kilograms of salt per hectare, which is, as will be shown in the next section, at least ten times less than the recognized salt fluxes).

Accepting the above cancel-out assumption and ignoring the other minor salt sources identified in section 2.2, a positive basin salt balance may be interpreted as indicating that salts imported with the irrigation water are accumulating in the basin. Similarly, a negative balance may be interpreted as indicating that resident salts are being mobilized and disposed of to the river system. The calculation method does not allow for differentiating between the origin of the latter salts, which may be any combination of originally imported salts and fossil, and primary or other types of resident salts. A negative balance indicates only that more salts are being disposed of to the river than are being diverted from the river, meaning that some mobilization and removal of resident salt are taking place.

5.2 Patterns and Features

The calculated salt balances (table 3) are obviously all quite different, which is not surprising in view of the different geological and physical characteristics and irrigation development histories of the involved basins. In four of the basins, the salt balance is negative meaning that these basins are desalinizing. In the Aral Sea, Colorado, and Murray-Darling, the salts being removed are mostly fossil and primary salts mobilized by irrigation developments in the middle parts of the basins. The geological age and origin of the salts and the prevailing mobilization mechanisms are however quite different for each of these three basins (see the detailed descriptions given in the annexes). In the case of the Nile, the mobilized salts are almost all marine salts of quartenary age from the deltaic lower part of the basin while the mobilization is due to improved land drainage rather than to irrigation development.

Table 3. Salt balances in million tons per year (Mt/yr.).

		Disposal				Resident storage (below rim stations)	
Basin	Input	Lower	Sea	E-pond	Exported	+ (Increase)	- (Decrease)
Aral Sea							
- Amu Darya	36.4		8.4	25.3	9.1		6.4
- Syr Darya	17.4		4.6	18.7			5.9
- Total	53.8		13.0	44.0	9.1		12.3
Colorado							
- USA	3.7	1.8			7.4*		5.5*
- Mexico	1.8					1.8	
- Total	3.7				7.4*	1.8	5.5*
Indus							
- Upper basin (Punjab)	33.0	19.0		2.2		11.8	
- Lower basin (Sindh)	19.0		16.4			2.6	
- Total	33.0		16.4	2.2		14.4	
Murray-Darling							
- Upper basin (Riverine Plain)	1.1	3.2		0.2			2.3
- Lower basin (Mallee)	3.9**		5.5	0.1			1.7
- Total	1.8**		5.5	0.3			4.0
Nile							
- Upper basin (Valley)	10.9	12.6		0.7			2.4
- Lower basin (Delta)	12.6		34.1				21.5
- Total	10.9		34.1	0.7			23.9

*Calculated on the basis of the given total river-loading of 9.2 Mt/yr. (see annex B).

**Including 0.7 Mt/yr. brought in by the Darling River (see annex D).

The Indus is the most distinctly different case in that a large part of the salts carried by the irrigation water remains in the land, especially in the upper part of the basin. Both the Nile and the Indus basins are extensive alluvial plains; however, the drainage conditions in terms of both natural and constructed drainage are much more favorable in the Nile Basin and this would seem to explain most of the contrastingly different salt regimes.

Some specific patterns and features of the salt balance of each of the five basins are highlighted below:

5.2.1 Aral Sea

In both the Amu Darya and the Syr Darya basins, there is considerable irrigation-induced mobilization of resident salts. A more detailed analysis, breaking down the basin in the upper, middle, and lower parts, shows that this mobilization occurs particularly in the middle part of the basin where, in the seventies, several pumped irrigation schemes were developed on an elevated plateau and these schemes generate highly saline seepage flows. The salt mobilization of some of these schemes is as high as 10 tons of salt/ha/yr.

The high salt influxes at the rim stations indicate that considerable salt-loading of the rivers already occurs in the catchments above the rim stations. As explained in annex A, most of the headwaters originating in the high mountain ranges are of low salinity, so considerable salt pickup must occur between the headwaters and the rim stations. This may be due to the tributaries passing through areas with saline geology.

Another remarkable feature of this basin is the high proportion of drainage water disposal to evaporation ponds (E-ponds). As many of the irrigation schemes are distant from the river, disposal to E-ponds rather than to the river makes sense as it is generally less costly and does not burden the river with salts. Suitable nearby depression sites were found in the desert adjoining the irrigation schemes. Although in the planning and management of these ponds little consideration has been given to environmental factors, to date no significant adverse environmental impacts in and around these ponds have been reported. A concern is, however, that many of the E-ponds used have reached their maximum capacity (see annex A). As few new sites are available, studies are now undertaken on how the drainage discharges to these ponds can be reduced, e.g., by using the drainage water to irrigate salt-tolerant forestry schemes that concentrate the drainage water and reduce the volumes to be disposed of.

5.2.2 Colorado

The current total salt-loading of the river is reported to be about 9.2 Mt/yr. of which, as shown in table 3, some 3.7 Mt/yr. occur above and 5.5 Mt/yr. below the rim stations. Of this total loading, about 5.2 Mt/yr. are due to natural mechanisms and 3.4 Mt/yr. are irrigation-induced (see annex B). A more detailed balance indicates that all the net mobilization of resident salts occurs in the upper basin. Most of the salt mobilization is by seepage flow passing though saline-shale strata, which underlie much of the land in the upper basin. Some of these flows are of natural origin but many are irrigation-induced. These saline seepage flows are the main cause of the salt-loading of the Colorado River and various control measures are being taken to reduce this loading (canal lining, improvement of on-farm water management, land use planning, interception drainage, etc.).

According to the detailed balance, more salt enters the lower basin than is disposed of by the four modes of disposal identified. Salt is being exported to Southern California but this disposal is more or less proportional to the water exported. All of the water entering Mexico is evaporated or otherwise consumed (there is no outflow to the sea). Some salt accumulation seems to occur in this part of the basin but the available information does not allow further pinpointing.

5.2.3 Indus

For the Indus, the balance is strongly positive with 16.6 Mt of more salt entering the rim stations annually than the amount being disposed of to the sea. Of this surplus, some 2.2 Mt/yr. are disposed of into E-ponds while the remaining 14.4 Mt/yr. are being added to the salt stored in the land (partly in the soil and partly in the underlying groundwater). This amounts to an annual increase of salt storage of about 900 kilograms of salt per irrigated hectare. This does not include the mobilization of salt by tube-well irrigation as this is an internal shift in the salt storage of the land, which is not registered in the applied balance calculations (shift of salts from deeper down to the surface layers). However, this internal mobilization, which is estimated to be about the same as the calculated external salt-loading of the land, contributes considerably to the salinization of the land as, in both cases, the salts mostly accumulate in the upper soil and shallow groundwater layers.

As mentioned earlier, most of this salt accumulation is thought to be due to underdevelopment of the drainage system in the Indus Plain. This is a vast plain in the arid zone, which did not need and did not have a well-developed arterial drainage system in the natural conditions. When irrigation was introduced, only a few additional drains were constructed and the present drainage density in most of the plain does not exceed 5–10 m/ha (compared to a drainage density of at least 50 m/ha in the Nile Plain in Egypt). Moreover, injudiciously constructed roads block many of the natural drainage ways and other infrastructure while whatever little drainage exists is seldom properly maintained. Such a system does provide for sufficient drainage to balance the incoming salts.

5.2.4 Murray

Here both the upper and the lower basins are disposing of more salt than are entering and in both parts of the basin the salt loss seems to be a mixture of salt generated by improved drainage and the reclamation of salinized irrigated land and fossil salts from the deeper strata mobilized by natural or irrigation-induced seepage flows. The quantities involved are much lower than in most of the other basins but still cause serious salinization of the downstream river flows. If the rising trends are allowed to continue, the water supply of some high-value irrigated agriculture and eventually even the water supply of the city of Adelaide may become affected. The parties involved have recently adopted an elaborate program for the control of the river salinity at its current levels (see annex D).

5.2.5 Nile

The salt balance and underlying salt regime for the Nile Basin is diametrically opposite to that in the Indus Basin. In the Nile Basin, each year some 23.9 Mt of more salt are removed from the basin than are entering and as shown in table 3, very little of this salt originates from the upper basin (the Nile Valley). The alluvial deposits of the valley have been thoroughly desalinized down to a great depth by the long history of flooding and leaching and the salt removal that still occurs is thought to be mostly made up of leached remnants of high fertilizer application and by the salts brought in by the saline seepage from the newly developed irrigation schemes on the elevated desert land along the edges of the Valley.

The desalinization of the marine deposits in the lower basin (the Delta) is far less advanced. Most of these deposits are of much younger origin and may well have been deposited in a much more marine environment than the valley deposits. While in the south, near Cairo, a fairly deep desalinized upper layer seems to have been already formed, most land in the northern zone along the Mediterranean Sea remains heavily saline up to just below the root zone (see annex E). These marine salts are being mobilized continuously by the subsurface drainage flows created by the recently installed land drainage systems and by the natural upward seepage flows generated by the prevailing piezometric head differences with the sea level. Ironically, this upward saline flow is enhanced by the improved land drainage. As most of these salts end up in the drainage systems, most of the drainage water in the northern delta zone is highly saline, with salinity values often about 2,000–3,000 mg/l.

CHAPTER 6

RIVER SALINITY

As is to be expected, in view of the inherent relationships between the land and the river systems in a basin, the salt regimes of the rivers reflect, in many respects, those of the land. This is especially true under natural conditions where the river systems are the principal recipients of drainage flows generated from the land in the basin. Irrigation and other developments have severed some of these natural relationships but in most basins they are still sufficiently strong for the rivers to remain a key indicator of the prevailing salinity conditions of the land. These relationships are further explored in this chapter and measures, which can be taken to control the rise of the river salinity, are discussed.

6.1 Natural Salinity

Natural river flows are generated by the natural drainage flows in the basin. These flows would normally pass over various land surfaces and through various subsurface formations and, in the process, would pick up salts. The degree of mineralization of the water depends on the pattern of the flow paths and on the geological properties of the formations traversed (Drewer 1988). Although, under normal conditions, the salinity of the headwater streams would generally not exceed 30 mg/l, considerably higher levels may occur in some streams arising from geologically more saline sub-catchments. Most of this variation averages out as the streams combine and the main headwater tributaries may normally be expected to have a weighted average salinity about 40–50 mg/l.

The salinity of the diverted irrigation water may be considerably higher than that of the headwaters, depending on the climate and geology of the areas and the distance traversed between the headwaters and the intake points. This distance may be relatively short (< 100–200 km for the upper catchment irrigation in the Murray and the Colorado Basin) or extremely long (4,000–5,000 km for Nile irrigation in Egypt). Over this reach, the river salinity may increase due to natural pickup, in-stream evaporation, and salt-loading by return flows from upstream-irrigated areas.

In the five basins studied, the salinity of water in reservoirs at the rim stations varies about 50–150 mg/l for the Murray Basin (upper catchment reservoirs), 140–150 mg/l for the Indus Basin (Tarbela Reservoir), 150–200 mg/l for the Colorado Basin (upper catchment reservoirs), about 200 mg/l for the Egyptian Nile Basin (Aswan Reservoir) and about 300 mg/l for the Aral Sea Basin (upper catchment reservoirs). These are the values that typically apply to the irrigation water diverted at the most upstream intakes. For the more downstream intakes, it would generally be higher.

6.2 Irrigation-Induced Salinity

In all five basins, the development of irrigation has led to an increase in the downstream river salinity. The causes and mechanisms for this increase, which have been discussed earlier, are summarized below:

- Reduction of the dilution capacity of the river system due to abstraction and consumptive use of the river water for irrigation.

- Use of the river system as a means of disposal for saline drainage water generated by regular leaching and drainage of the irrigated lands; this salt-loading by the drainage return flow is extra high when the drainage water is generated by vertical drainage or when salinized land is being reclaimed.

- Loading of the river system by primary, fossil, and other types of resident salts mobilized by irrigation-induced seepage flows, tube-well irrigation, or by some other irrigation-induced mechanisms.

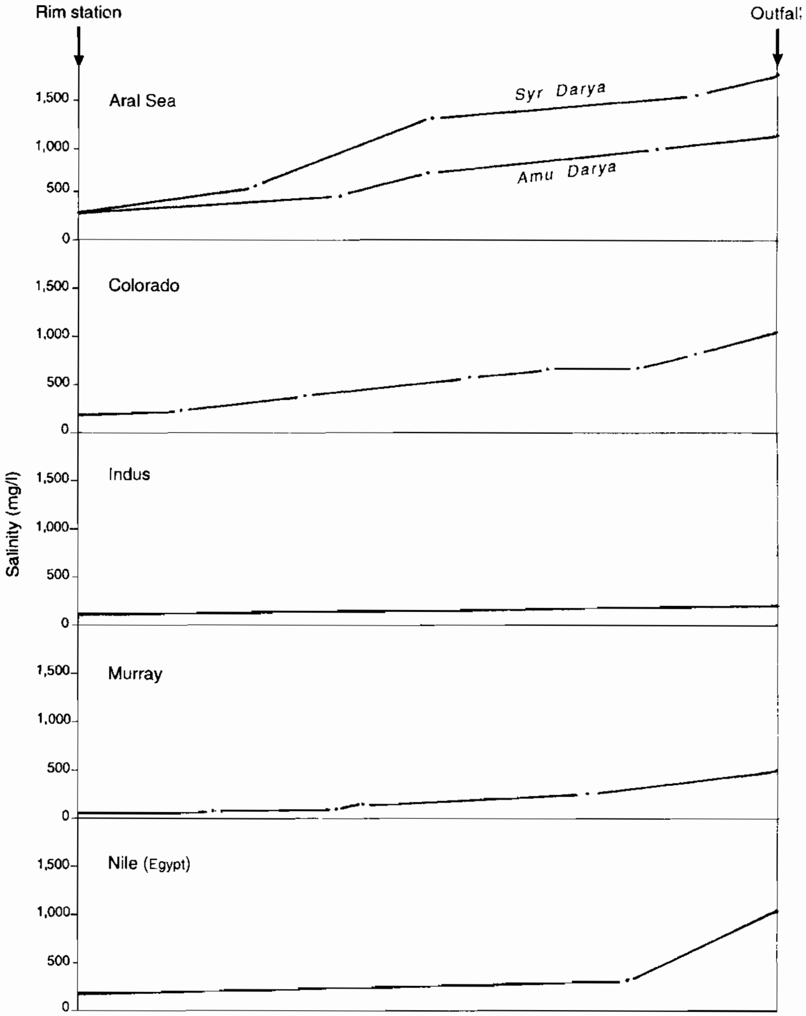
In most basins, the observed increases in downstream river salinity are not due to irrigation development alone. Flows are also reduced by abstractions for other water uses although in the five basins these abstractions are much less than the amount used for irrigation. As shown in the relevant annexes, changes in land development, other than for irrigation, have also added to the salt-loading of some rivers. A considerable part of the river salinity in the Murray-Darling River system originates from “dryland salinity” while in the Colorado Basin this applies to runoff and erosion of saline grazing land. In the latter basin, waste disposal from industry and mining also adds to the river salinity. However, although these other contributions should not be ignored, irrigation development is clearly the main factor causing the increased downstream river salinity in all the five basins studied.

6.2.1 Observed River Salinity Profiles

On the basis of the most recent data available, normalized longitudinal salinity profiles for the main stems of the river systems in the five basins have been established as shown in figure 6. The upstream ends of these profiles are the rim stations while the downstream ends are the final outfall points (in case of outfalls to a sea, the end point is taken upstream of the salt intrusion reach). All river lengths were set at unit length and stations were located according to their proportional distance from the rim stations.

The profiles depict annual average conditions. For highly regulated rivers like the Colorado and the Nile, these average profiles are quite representative but for other basins the salinity values may be considerably lower during the wet season and higher during the dry season (see the seasonal profiles for the Murray River presented in figure D2, annex D). In analyzing these salinity profiles, it should also be realized that these arid zone rivers naturally had quite pronounced salinity profiles (see figure B2, annex B).

Figure 6. Normalized salinity profiles of the five selected rivers.



The salinity profiles presented are largely in conformity with the basin-level salt balances discussed earlier and summarized in table 3. These balances show the change in the resident salt storage in the basin, much of which directly relates to the salt-loading of the river. A decrease in resident storage will generally imply more salt-loading while an increase in the resident salt storage indicates the opposite trend. However, the relationship between change in resident salt storage and river-loading is not necessarily fully reciprocal as some of the lost resident salts may be stored in an E-pond, exported, or otherwise never reach the river.

The relationship between the river salinity profile and the resident salt balance is most apparent for the Indus Basin where the minimal increase in the downstream river salinity (from 150 mg/l at the rim stations to 200 mg/l at the Kotri barrage, an increase of only some 50 mg/l) is clearly due to diverted salts being stored in the land rather than being returned to the river. In the other four basins, increasing downstream salinity reasonably agrees with the calculated salt balances. The high rates of salt mobilization in the middle parts of the Amu Darya and Syr Darya rivers and in the Nile Delta reasonably well match the relatively steep profiles in these parts of the rivers.

Differences in salt-loading, however, can only partly explain the observed river salinity profiles as these profiles reflect the combination of salt-loading and flow reduction. In the case of the Colorado River, the pronounced downstream increase in river salinity is probably more due to the high rates of water abstraction than to salt-loading, which is in fact rather moderate (even nil in the lower reach). The differences in the degree of abstraction (100% for the Colorado and 75% for the Murray, see table 2) constitute a plausible explanation for the much more moderate increase in downstream salinity in the latter river. Differences in the degree of abstraction may also largely explain the higher salinity of the Syr Darya River as compared to the Amu Darya River.

6.2.2 Generic Profiles

As river salinity profiles reflect the combined impacts of water abstraction and salt-loading and both these influencing factors may vary considerably, it is clear that a wide range of profiles may occur. The profiles given in figure 6 are just a small sample of the expected range. However, it is suggested that the observed variation can be captured, to a large extent, by distinguishing three generic type of profiles, with each type being related to a particular status of the salt balance. These three types are shown in figure 7. Other generic profile types may be conceived (e.g., based on the degrees of water abstraction, on the irrigation efficiencies, and on the percentage of drainage water reuse). However, the distinguished types are considered to be of the greatest conceptual and diagnostic value.

Equilibrium Profile. This type of profile is expected to form when the salt balance of the basin is in equilibrium (Input = Output, see figure 5). This would be the case when the following two conditions are fulfilled:

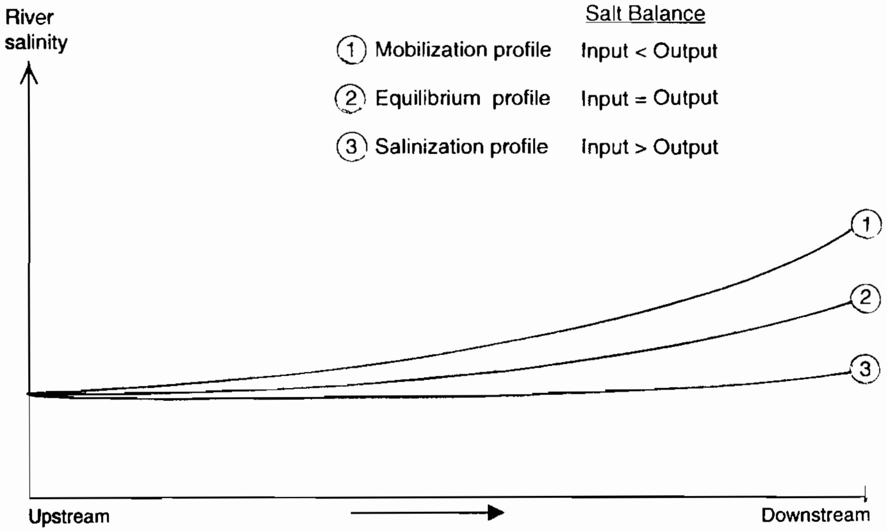
- all the salts diverted from the river with the irrigation water return to the river with the drainage flows

- there is no salt-loading of the river by primary, fossil, or other resident salts already present in the basin

Actually, these two conditions do not need to be strictly fulfilled. Since the basin is treated as a 'black box,' there could be some influx of primary or fossil salts into the river as long as this is compensated for by an equal amount of diverted salts, which are not returned.

Since in the equilibrium case the salt-load of the river system remains constant along the length of the river, the slope of the river salinity profile is determined primarily by the remaining river flow. When the rates of both abstraction and drainage return flow are constant along the length of the river and the return flow is a fixed percentage of the abstraction, the profile would theoretically be of an exponential form (see figure 8). As, in most basins, most of

Figure 7. Generic river salinity profiles.



the abstraction occurs in the upper reaches of the river while drainage return flows occur in the lower reaches, the coefficient of exponentiality may be generally expected not to be constant along the length of the river but expected to increase in the downstream direction.

Salinization Profile. This type of profile applies to cases where not all of the diverted salts return to the river but partly remain in the irrigated lands. The salt balance in this case is positive (Input > Output) and the salt-load carried by the river decreases in the downstream direction. As shown in figure 7, this profile has not only a smaller slope than the equilibrium profile but also lower river salinity values all along the length of the river.

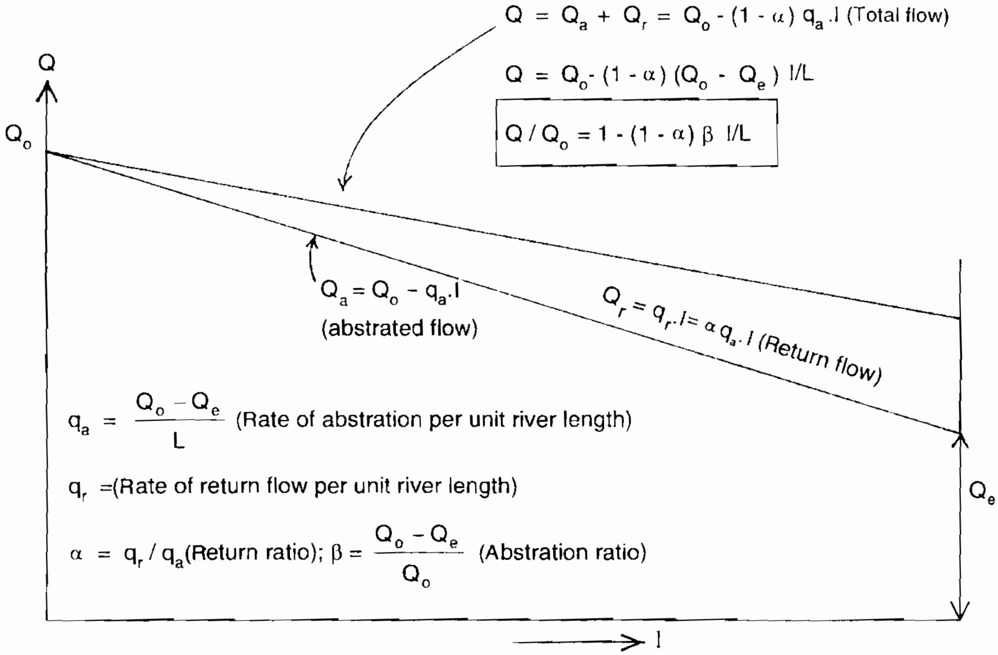
When there is no return of the diverted salts and no influx of any other type of salts, the profile would be a horizontal line with a salinity equal to the river salinity at the rim station. The full (100%) return of salts is the equilibrium profile. There can be various in-between profiles depending on the ratio of abstraction to drainage return flow and on the salinity ratio of the abstracted and drainage returns.

Mobilization Profile. This type of profile represents the negative salt balance (Input < Output), which occurs when fossil, primary, or other resident salts in the basin are being mobilized and are entering the river system. As the current study confirms, this is a very common case for irrigated basins in the arid zone, making the mobilization profile the most common of the three generic profiles.

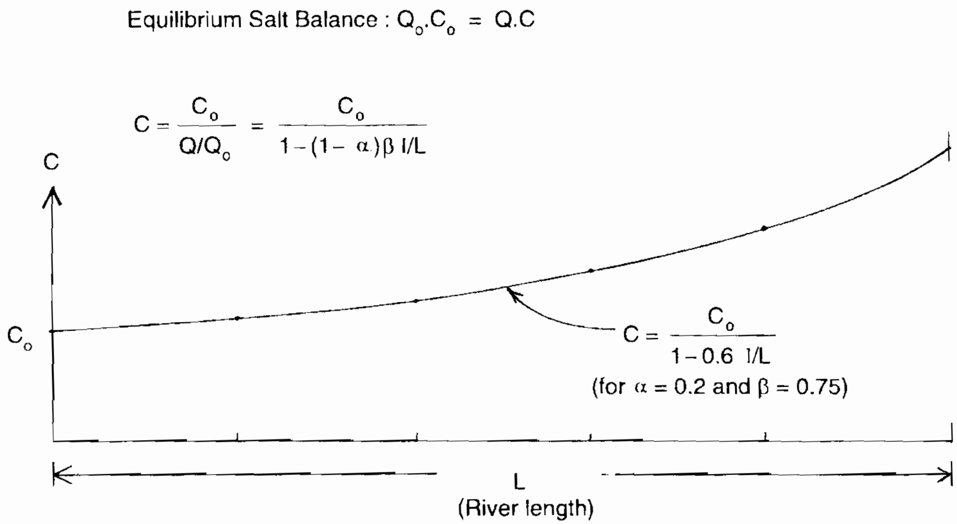
The factors that determine the shape of the mobilization profile are partly the same as for the other two profiles, i.e., the abstraction/return flow ratio and the irrigation/drainage water salinity ratio. The specific factor, in this case, is the degree of surplus loading of the river system. This surplus causes the river salinity of the mobilization profile to be higher than that of the equilibrium profile and the total salt-load of the river to increase in the downstream direction. Reaches with large influx of mobilized salts as the middle reaches of the Amu Darya

Figure 8. Computed river salinity profiles.

River Flow (Q)



River Salinity (C)



and Syr Darya rivers and the Delta reach of the Nile, show up as steeply rising sections of the profile (see figure 6).

6.2.3 Computed Profiles

River salinity profiles may also be computed when the involved systems and mechanisms are somewhat schematized. An example is presented in figure 8 where both the rate of abstraction and drainage return flow have been assumed to be constant along the length of the river. Under these conditions, an analytical formula for the equilibrium profile can be worked out, which indeed confirms, as suggested earlier, this type of profile to be of the exponential form. The shape of the profile is defined by the two parameters: α = the return ratio (drainage return as a ratio of the abstraction) and β = the abstraction ratio (abstraction as a ratio of the flow at the head of the river).

The computed increase of the river salinity (concentration/concentration at river [C/Co]) over the length of the river (l=l thus l/l=1) for a range of abstraction and return ratios is given in table 4. As is to be expected, the downstream salinity rises sharply with increasing abstraction and decreasing return ratios. For a typical flow abstraction of 60–70 percent (β = 0.6–0.7) and 20–30 percent drainage return (α = 0.2–03), the salinity at the tail end of a river is predicted to be about twice as high as it was at the head. So, for salinity at the rim stations of about 150–200 mg/l, the tail-end salinity may be expected to be about 300–400 mg/l. The profiles in figure 6 are either mobilization or salinization profiles, thus not representing the equilibrium case for which the computations apply. However, since the increase in salinity over the length of the river in the former profiles is generally more while in the latter it is less than twofold, these calculations would seem to be of the right order of magnitude.

Table 4. Calculated river salinity increase for equilibrium profiles (C/Co).

	α=0.5	α=0.4	α=0.3	α=0.2	α=0.
β=0.5	1.3	1.4	1.5	1.7	1.8
β=0.6	1.4	1.6	1.7	1.9	2.2
β=0.7	1.5	1.7	2.0	2.3	2.7
β=0.8	1.7	1.9	2.3	2.8	3.6
β=0.9	1.8	2.2	2.7	3.6	5.3

β = abstraction ratio; α = return ratio.

The analytical formula developed, being based on the maintenance of the salt balance, takes into account that the salinity of the drainage return flow increases when the return ratio decreases. This explains why the values in table 4 increase horizontally, i.e., when the abstraction ratio is kept constant and the return ratio decreases. As the irrigation efficiency is broadly inversely related to the return ratio (return ratios generally decrease as irrigation efficiencies increase), the formula implicitly also expresses the impact of irrigation efficiency on the river salinity. However, efficient irrigation generally not only reduces drainage return ratios but also lowers the abstraction ratios (more water is left in the river, as less water is needed to irrigate the same area). This water-saving impact of efficient irrigation is not accounted for in the formula but may be recognized by reading table 4 for decreasing return ratios (= increasing efficiencies), not horizontally but diagonally upwards at some arbitrary angle (reading the table this way, abstraction ratios decrease with decreasing return ratios/increasing irrigation efficiencies and the increase in river salinity becomes less than when reading horizontally).

CHAPTER 7

CONTROL MEASURES

In all five basins, increasing levels of downstream river salinity are of considerable concern and various measures are being taken to halt or reverse these trends. The adopted programs cover a wide range but are mostly a combination of the measures described in section 3.3. The institutional frameworks under which these measures are planned, implemented, and financed are generally unique to each of the basins. For a full discussion of the adopted control programs and their organizational arrangement, reference is made to the case material in the annexes; the discussion here will be limited to pointing out general features, highlighting some innovative approaches.

7.1 Management of the Drainage Return Flows

Ideally, drainage return flows from irrigated land should only return the salts originally diverted from the river. Since, under salt balance conditions, the salinity of the drainage water is inversely proportional to the flow rate (see discussion in section 3.2), a high drainage rate would generally be expected to lower the increase in river salinity. In practice, however, this may not always be true as high return flows may load the river unnecessarily with mobilized resident salts. High return flows also require extra investments in drainage systems: outfall drains, E-ponds, and the other drainage facilities used to collect and dispose of the drainage water.

Improved irrigation water management helps control drainage returns flows as it saves on the required river abstraction and reduces the disposal volumes. Specific measures to be considered include lining of canals and improving on-farm water management. These measures are, however, generally only attractive to farmers when there are adequate premiums on saving water and reducing drainage rates (see Colorado and Murray-Darling experiences in annexes B and D, respectively).

Low-salinity drainage water may be reused provided that the salt balance of the land is maintained. In most irrigation schemes, reuse is, in fact, the rule rather than the exception as many tail-end farmers depend heavily on the drainage water coming from headlands and downstream river diversions almost always include a proportion of drainage water. Even drainage water with a fairly high salinity may be reused for the irrigation of salt-tolerant tree plantations. This latter reuse is particularly advantageous when the drainage water is eventually being disposed of through an outfall drain or to E-ponds as it reduces the disposal volume.

7.2 Combating Salt Mobilization

An analysis of salt balances (chapter 5) indicated that irrigation-induced mobilization of resident salts is a major cause of salt-loading of the rivers in four out of the five studied basins (even in the fifth basin, the Indus, there is considerable internal mobilization of resident salts by the tube-well pumping that, as explained earlier, does not show up in the salt balance).

Much of the salt mobilization and the resulting river-loading seems to be an inherent feature of irrigation development in arid-zone basins. These basins, by the nature of their geomorphology and climatic setting, tend to be rich in resident salts. The introduction of irrigation, almost inevitably leads to a buildup of groundwater and a rise of the water table under the irrigated land as maintenance of the salt balance in the upper soil layers and the economics of water distribution/application both justify the allowance of some deep percolation, which will often exceed the natural drainage capacity of the land. In the process, resident salts in the deeper layers may be mobilized and become part of the (geo) hydrological and geochemical regimes of the basin. Efficient irrigation may be generally expected to reduce such mobilization as equilibrium may be established with less groundwater buildup and lower seepage flows but in the long run it should not be expected to fully prevent mobilization.

If the resident salt layers and the drainage flow paths can be mapped, measures that reduce the irrigation losses, which feed saline seepage flows, can be very effective. This also applies to the judicious construction of interceptor drains/wells that prevent saline seepage flows from reaching the drainage and river systems. Another effective measure is the replacement of tube wells pumping saline water with shallower drainage systems. The best opportunity for reducing the mobilization of resident salts (the time for which, unfortunately in most cases, has already passed), generally lies in the project planning stage. Planning of irrigated areas and the system layouts, on the basis of careful mapping and modeling of the geohydrological conditions of the area, could have prevented much of the salt mobilization and salt-loading of the rivers currently taking place in many irrigated basins in the arid zone.

7.3 Basin Management

In some basins, there is still considerable scope for river disposal, especially when extra dilution of water can be made available during certain critical periods. The downstream salinity of the Indus River is still exceptionally low during most of the year, rising to critical levels only during a short pre-monsoonal period (see annex C). In the future, when more storage may be available, it may well be possible to mitigate this critical period and allow more year-round river disposal (particularly combined with judicious management of drainage return flows, including temporary storage, and full use of alternative disposal options). In some of the other basins, there also seem to be opportunities for creating more storage or enhancing flow during critical periods by adapting reservoir operations.

Improved irrigation water management resulting in reduced abstraction of river water also helps, especially when realized by schemes in the upper reaches of the rivers. Alternative land use and/or cropping patterns (possibly including retirement of irrigated land) may be considered for schemes in the upper part of the basin having high water requirements, generating much salt-loading while yielding only low economic returns. For schemes in the threatened downstream zone, the feasibility of shifting intakes upstream may be investigated.

Extension services may also promote a general adjustment of the salt tolerance of the cropping pattern to the salinity of the irrigation water. Land use planning should also be extended to all nonirrigated land that, one way or another, contributes to the salt-loading of the river.

7.4 Non-River Disposal

In almost all the five basins, some forms of non-river disposal are already practiced. Disposal to E-ponds is the main mode of salt disposal in the Aral Sea Basin but it is also used in most of the other basins on a smaller scale. In one basin (Indus, see annex C)), there is already an operational outfall drain while this option is under consideration for the Amu Darya Basin. Deep-well injection is not yet practiced at an operational scale in any of the basins; nor is desalinization. The Yuma desalinization plant in the lower Colorado Basin was constructed as a safeguard to assure that the salinity of the river water allocated to Mexico would not exceed the agreed limit but so far the use of the plant has not been necessary (see annex B).

Many of the E-ponds currently used are located in desert areas adjoining the irrigated areas. The drainage catchments served by these ponds generally do not have a ready outlet to the main river system and the choice of this disposal option seems to be motivated as much by hydrological and cost considerations as by the desire to reduce the salt-loading of the river. Generally, the ponds seem to perform their function quite well. The lessons from the Aral Sea confirm, as predicted by evaporation fundamentals, that there is a limit to the receiving capacity of these ponds. To optimize the available E-pond capacity, drainage water that is still of usable quality should, as much as possible, be reused and further concentrated before being disposed of. Most of the constructed ponds seem to have caused no significant environmental damage. These risks have been widely publicized after the selenium poisoning observed in some E-ponds in western USA. However, in view of the experiences in other countries it would seem that these risks are rather limited and that E-ponds when well-designed and -managed, constitute a feasible and often effective alternative to river disposal.

Worldwide, there are only a few large outfall drains in operation and the available experiences, almost exclusively based on the Left Bank Outfall Drain (LBOD) in the lower Indus Basin, are still far from complete and conclusive. Many of the problems encountered during the LBOD construction are tainted by the prevailing political unrest in the area. Experiences now being gained with this drain on the nature of flow regime, on the maintenance requirements, and on the environmental impacts may well be decisive for the future prospects of this disposal option.

7.5 Institutional, Financial, and Implementation Arrangements

In two of the basins (Colorado and Murray-Darling) special institutional arrangements and programs have been set up for the control of river salinity. Such a dedicated approach is also under consideration for the Aral Sea but for the Indus and the Nile rivers, salinity remains in the control of the existing water management institutions and programs. These arrangements and programs have very little in common and the specifics may best be understood from the case-by-case descriptions given in the annexes. Here only a few key aspects will be discussed.

7.5.1 Stakeholders

The control of the river salinity can generally only be achieved by placing severe restrictions on the present or future disposal of saline water into the river and on the present or future abstraction of river water. Under these conditions, one can only expect to succeed in having the required control measures accepted and implemented when all the stakeholders have formally agreed, for example in the form of a compact with the executive agency on which measures need be taken and how the costs and benefits would be shared.

7.5.2 Baseline Conditions

The control programs need to be based on well-defined baseline conditions against which the planned salinity control can be monitored and the impacts of the implemented measures can be evaluated. Current conditions may serve as baseline conditions. It is important that the baseline conditions be established as accurately and unambiguously as possible. Normally, there will also be agreed targets indicating to which level and within which period the current salinity needs to be reduced or the future salinity will not be allowed to exceed. The baseline conditions and targets may relate to average conditions but may also cover some critical periods in the annual cycle.

7.5.3 Modeling

Simulation models that can predict and help visualize the river salinity conditions to be expected under various control scenarios have proven very useful in presenting the planned program to various audiences and in reaching agreement on the need for control and on the nature of the required measures. These and other more-refined models may also be used for the design of control programs. In the Colorado Basin, the simulation model has been even given a limited legal status as a tool for assessing benefits and contributions and for arbitrating conflicts (see annex B).

7.5.4 Cost Sharing

Since the causes of the current high river-salinity conditions generally have a complex and long history and usually cannot be precisely identified and quantified, experience shows that it is generally not productive to try to assign responsibilities for past river salinization. The best approach is to accept the costs of combating past salt-loading as common costs and to apply the "polluter pays" principle for measures required to keep the salinity within the agreed targets.

7.6 Economics

For the Colorado and the Murray basins, some indicative data on the economics of the river salinity control measures instituted are available (for more details, see annexes B and D). The given costs generally refer to the conditions obtained in the early/mid-nineties. For the Colorado, it is estimated that the total costs of salt-loading reduction average about US$70/ton of salt while the corresponding benefits are calculated to be about US$340. Costs vary considerably for the different control measures (from US$5 to US$138/ton of salt reduction). Best benefit/cost ratios are generally obtained for measures that reduce irrigation losses (improved on-farm water management and canal lining) and that control erosion of saline land. Plugging of flowing brine wells was also found to be highly cost-effective. The benefits derive mostly from the agriculture sector but damage reduction to industrial and household installations also contributes to the benefits.

For the Murray Basin, it is estimated that the annual damage of a further 1.0 mg/l increase of the river salinity (measured at Morgan in the central part of the lower basin) is about A$130,000 (US$100,000). It is also estimated that the investment costs of the initial salt interception program that is designed to reduce the river salinity at Morgan by some 80 EC units (50 mg/l) will come to some A$27 million (US$21 million) and have annual O&M costs of some A$1.7 million (US$1.3 million). Taking the total annual costs (capital and O&M) to be about US$2.5–3.5 million, this amounts to some US$50,000–70,000/mg/l river salinity reduction, which is equivalent to US$8–12/ton of river salt reduction, taking the average annual flow at Morgan at 6.1 km^3. Most of the benefits are said to derive from the M&I use of the water.

CHAPTER 8

SUMMARY AND CONCLUSIONS

In irrigated river basins, river flows are systematically depleted by the diversion of irrigation water while, on the other hand, the remaining flow is increasingly loaded with saline drainage water. As a result, rivers in these basins typically develop longitudinal salinity profiles with increasing downstream salinity levels. This phenomenon, which is generally restricted to irrigated river basins in the arid zone, was studied in five major basins (Aral Sea, Colorado, Indus, Murray-Darling, and Nile basins).

It was found that the downstream increasing salinity profiles occur in all of the studied five basins but that considerable differences exist amongst the basins. The differences can broadly be related to differences in the salt balances of the respective basins. Three generic types of profiles can be distinguished: equilibrium, salinization, and mobilization profiles.

8.1 Equilibrium Profile

This type of profile is expected to form when the salt regime of the basin is in balance, i.e., when the drainage flow returns as much salt to the river as is diverted with the irrigation water. This means that the resident salt storage in the irrigated areas and the salt-load of the river both remain at the same level. The shape of the profile depends on the degree of depletion of the river flow, on the proportion of drainage return flow, and on the spatial distribution of the abstraction and drainage return points but it may generally expected to be of an exponential form. The downstream salinity may be expected to increase with an increasing degree of flow depletion and a decreasing proportion of drainage return flow. For normal depletion and drainage return percentages, the salinity at the tail end of the river may be generally expected to be about twice as high as at the head of the river.

8.2 Salinization Profile

This type represents the case where the rate of salt diversion from the river exceeds the rate of salt disposal into the river. The salt balance of the land is positive as salts are accumulating in the irrigated areas. This profile typically occurs in basins and irrigated areas, which do not have adequate drainage systems. Since much of the salt will be accumulating in the upper soil layers, the land will gradually become more and more salinized. Although less than for the equilibrium case, the salt-loading of the river is generally still sufficient for the river salinity profile to show an increase in downstream salinity and also have a slight exponential shape.

The profile will, however, generally be flatter and have a lower salinity level all along the river than the equilibrium profile.

8.3 Mobilization Profile

In this case, the salt balance of the land is negative, meaning that more salts are being disposed of into the river than are being diverted. It means that resident salts in or near the irrigated area are being mobilized and carried to the river, usually by irrigation-induced saline drainage and seepage flows. This profile typically occurs in basins and irrigated areas, which are underlain by fossil salts or otherwise have a high resident salinity and geohydrological conditions conducive to the generation of deep seepage flows. These profiles are at a higher salinity level than the equilibrium profiles and have steep gradients, especially in the mobilization reaches of the river.

The study confirms that mobilization of resident salts is a widely occurring phenomenon in irrigated basins in the arid zone. By their climatic and geomorphologic setting, the irrigated areas in these basins typically abound with fossil and primary salts, which risk is being mobilized by changes in geohydrological regimes, induced by the irrigation water losses. Irrigation-induced mobilization of these resident salts was found to be the main source and cause of the increased downstream river salinity in four out of the five studied basins.

A number of measures can be taken to control or even reduce the increase in downstream river salinity but none of these measures are easy to adopt in a developed basin where the water resources have been almost fully allocated and used. The principal choices are between reversing the flow depletion or otherwise increasing the fresh river flows and reducing the salt-loading of the river while both maintaining the salt balance of the land and especially preventing the salinization of the land disposal of salts by means other than via the river. Within each of these broad categories there is usually a further choice as to which specific measures are to be taken.

Generally, there are no win-win solutions and the measures to be taken either place restrictions on water use or on the disposal of saline water, or add to the water use/disposal costs. Control programs have been adopted and are currently being implemented for the Colorado and the Murray basins and both programs offer useful guidance on the technical and institutional design of such programs. The control programs and measures must be generally basin-specific, taking into account the specific physical, institutional, and socioeconomic conditions of the basin. In these two basins, it was found to be of critical importance to assure that the stakeholders have a full understanding of the need for action and also that they are in full agreement with the proposed measures. It was also found that models, which can visualize and quantify the impacts of various actions (including no action), are of great help in projecting the need for action and reaching agreement on the sharing of the costs.

ANNEX A

ARAL BASIN

General

The Aral Sea Basin covers major parts of five former Soviet Union countries in Central Asia (Kazakhstan, Kyrghyzstan, Tajikistan, Turkmenistan, and Uzbekistan) but extends also slightly in some other surrounding countries (see figure A1). The basin is drained by two major river systems, the Amu Darya and the Syr Darya both of which rise in mountain ranges on the Afghanistan and China border in the southeastern part of the basin. Some of the mountain peaks are in the 6,000–7,000 m range and have permanent snow and ice covers. Both rivers discharge into the Aral Sea, a huge shallow terminal lake located in the northwestern part of the basin.

The Aral Sea is part of a large geomorphologic bottom area, which encompasses a number of similar undrained terminal lakes as well as numerous *playas* (salt-encrusted dry lake beds). Between the lower plains and the mountains, there are some intermediate plateaus and piedmont landscapes. The geology of these landscapes includes saliferous claystones and marls and highly saline aquifers. Locally, the soil material in the basin has a rather high natural salinity, made up partly by primary salinity and partly by remnant salinity from past salinization periods.

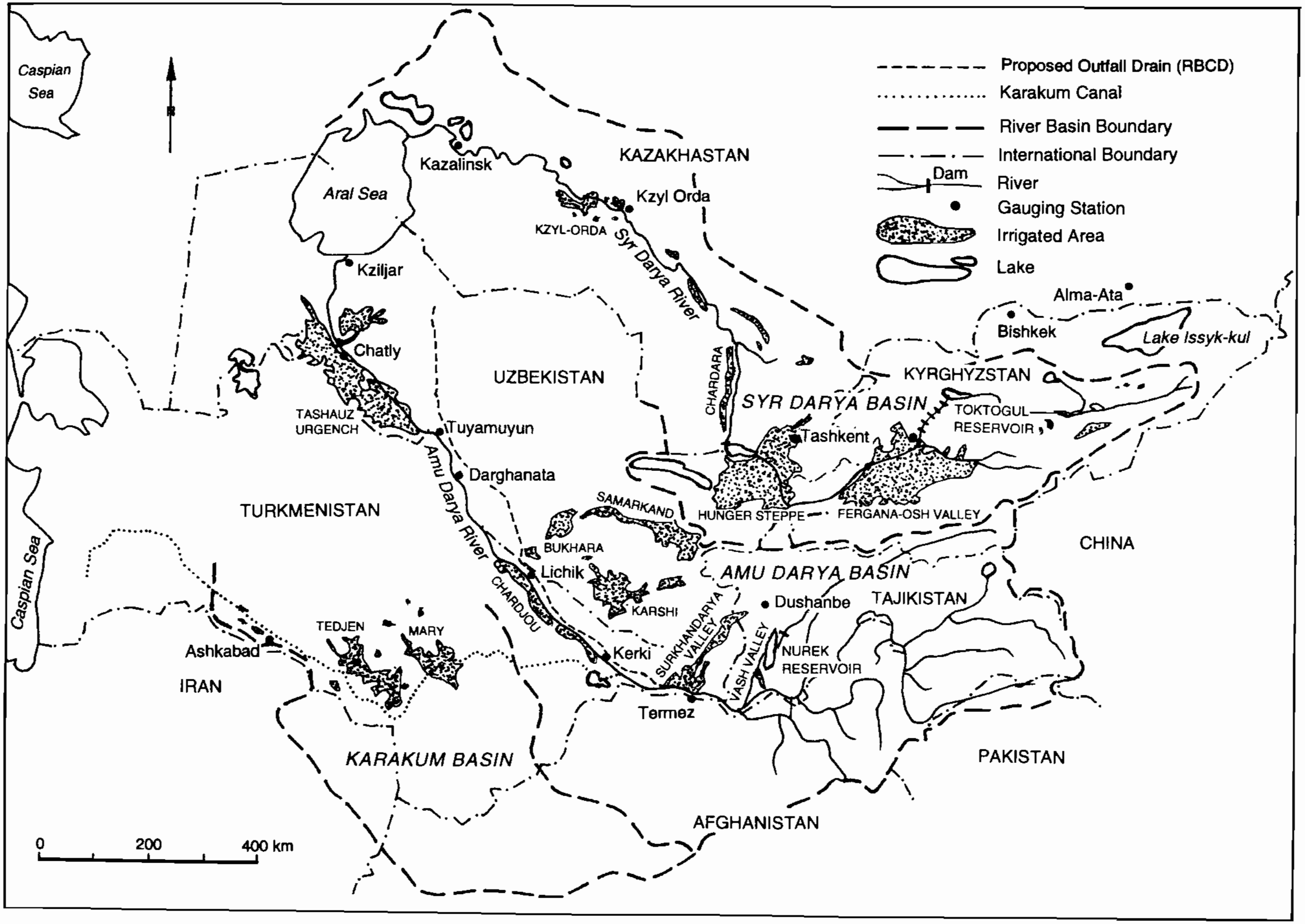
The climate is of the continental type with hot summers and cold winters. There is ample precipitation in the mountain ranges (2,000 mm and more) but the rainfall reduces sharply in the middle and lower basins and amounts to only a meager 100 mm/yr. in the lower plains bordering the Aral Sea. Due to the low temperatures and severe frost during the winter, the agricultural season is essentially limited to the summer. There are some opportunities for rain-fed cropping in the upper basins but in the low-rainfall middle and lower basins little cropping can be done without irrigation.

The entire Aral Sea Basin encompasses an area of 1.80 million km^2 of which about 20 percent is mountainous and 80 percent is plain land. The current population of the basin is estimated to be about 40 million, up from 14 million in the 1950s. The population growth in the eighties was about 2.5 percent per year but declined to about 1.5 percent in the nineties. The municipal and industrial water use is still very limited.

Water Resources Development

The total precipitation on the basin is calculated to average about 500 km^3/yr. out of which about 116 km^3/yr. are discharged as river flow (about 81 km^3/yr. for the Amu Darya and 35 km^3/yr. for the Syr Darya). The Amu Darya Basin at 1 million km^2, is the largest river basin in Central Asia and the total length of the main stem to its outfall into the Aral Sea is about 2,575 km. The Syr Darya is 2,400 km long.

Figure A1. Map of the Aral Sea Basin.



There are two major reservoirs on the main stem of the Amu Darya River, the Nurek Reservoir in the upper catchment in Tajikistan and the Tuyamuyun Reservoir Complex located at the apex of the Amu Darya Delta in Uzbekistan. There are also some small dams on the tributaries. The total capacity of these reservoirs is about 20 km^3. On the Syr Darya there are at present two major reservoirs, the large Toktogul Reservoir in the upper reaches of the river in Kyrghyzstan and the Chardarya Reservoir in the mid-reach of the river in Uzbekistan. The total capacity, including the smaller reservoirs on the tributaries, amounts to some 35 km^3. Plans exist for the construction of more reservoirs, which would make the annual regulation more effective.

Irrigation Development

Central Asia has a long tradition in irrigation, dating back to the pre-Christian era. In the early part of the current century, a reported 2 million hectares were irrigated and some major canals serving considerable areas were already constructed. The irrigated area grew to some 3.3 million hectares in the 1950s, which used about half of the surface water resources of the basin. The remainder, an estimated 56 km^3 per annum, flowed to the Aral Sea. This river discharge, together with some groundwater inflow (1 km^3) and the rainfall (8 km^3), balanced the annual evaporation losses (65 km^3) and maintained the Aral Sea at an average size of 67,000 km^2.

This changed after the Second World War when the Government of the former Soviet Union designated this part of Central Asia as a growth area for irrigated agriculture, especially for production of cotton, and started to invest heavily in the development of the main hydraulic infrastructure and irrigated State Farms in the area. The schemes developed vary in size from 50,000 hectares to 500,000 hectares while the State Farms vary from 2,000 hectares to 5,000 hectares. Most of the earliest developed land was in the plains and could be commanded by gravity diversion systems but considerable lifting became necessary when developments expanded to the elevated plateau. Some of the later schemes are also far from the river and required long conveyance canals (the Karakum Canal takes Amu Darya water over a distance of 1,450 km to the remote Karakum Desert in South Turkmenistan).

The irrigated area expanded by some 1.0–2.5%/yr. during the period of the most rapid expansion in the sixties and seventies. By the time the expansion came to a halt in the mid-eighties, the total irrigated area had grown to some 7.5 million hectares and the Aral Sea Basin had become one of the main cotton production areas of the world. More than half of the irrigated land is in Uzbekistan (which, in 1983, equalled the entire cotton production of the USA) while most of the remainder is in Kazakhstan and Turkmenistan.

Aral Sea

This large expansion of the irrigated area in the basin has exacted a severe toll on the Aral Sea. As almost all the water needed for irrigation was diverted from the Amu Darya and the Syr Darya rivers, the discharge of these rivers into the Aral Sea fell drastically. Of the estimated average annual discharge of 116 km^3, some 105 km^3 are diverted for irrigation, up from about 60 km^3 in the 1950s before the large-scale irrigation development. The river supply to the Aral Sea fell to a meager 9 km^3 in the late eighties, almost all of it coming from the Amu Darya as the Syr Darya discharge nowadays seldom reaches the sea.

As a result of this greatly reduced supply, the area of the Aral Sea shrank by about 50 percent, its volume decreased by about 65 percent, and its depth dropped by 17 m to a current average depth of less than 10 m. As the current evaporation losses (some 20–25 km^3) still far exceed the inflow, it is to be foreseen that the dimensions of the Aral Sea will reduce further unless extra supply can be found to restore the balance. The rate of fall of the Aral Sea water level has decreased but still amounted to an alarming 1.0 m/yr. in 1996.

The drastic reduction in the inflow of freshwater has also led to a sharp increase of the salinity of the remaining Aral Sea, which now ranges from 35 to 40 g/l, up from some 9–10 g/l in the early fifties. The discharges and the water quality in the lower reaches of the Amu Darya and the Syr Darya, below the main diversion points, have also been dramatically affected. Discharges during the low-flow season have fallen below the minimal ecological requirements and the water quality has fallen below the acceptable public health standards. Municipal and industrial use of the water resources in the basin have also contributed to the flow reduction and water quality degradation of the Amu Darya and Syr Darya rivers but this is a minor cause compared to irrigation.

River Salinity and Salt Balances

The salinity of the headwaters of the Amu Darya and the Syr Darya is mostly about 100 to 200 mg/l while the river salinity at the rim stations (main reservoirs) generally ranges from 450 to 500 mg/l. In the plains, the salinity of the river water increases in the downstream direction as more and more water is diverted, mostly for irrigation, and saline drainage water returns to the river (table A1). In dry years, during the low season (October–April) the river salinity at the apex of the delta reaches peaks of 2,000 mg/l in the Amu Darya and 2,500 mg/l in the Syr Darya.

Table A1. Average annual flow and salinity of the Amu Darya and Syr Darya (1985–90).

	Amu Darya		Syr Darya	
	Flow (km^3/yr.)	Salinity (mg/l)	Flow (km^3/yr.)	Salinity (mg/l)
Rim stations	80.9	450	34.5	505
- Mid-basin	43.0	670	8.0	1,320
- Apex of the Delta	29.0	850	3.0	1,360
- Outfall into Aral Sea	8.7	975	2.8	1,650

The downstream increase in the river salinity is, to a large part, due to the mobilization of fossil salts by the deep drainage and seepage return flows generated by the water losses from the irrigation schemes, many of which, as mentioned earlier, had a high degree of natural salinity when they were developed. As shown by the salt balance below (table A2), this salt-loading of the river by mobilized salts occurs especially in the mid-reach of the river and especially affects the Amu Darya.

Table A2. Average annual salt balance for the Amu Darya and Syr Darya (1985–90).

	Influx	Outflux (Mt/yr.)	Balance
Amu Darya			
Upper basin	36.4	30.5 (0.4)*	5.9
Mid- and lower basin	30.1	42.4 (34.0)*	-11.3
Syr Darya			
Upper basin	17.4	10.4	7.0
Mid- and lower basin	10.4	23. 3 (18.7)*	-12.9

*Non-river disposal, mostly to evaporation ponds.

As indicated, at present most of the salt is not disposed of into the rivers but diverted to E-ponds in the desert. These ponds, however, are running out of capacity and in the future more drainage water may need to be returned to the river, which would further increase the salinity in the lower basin, unless a viable alternative method of disposal can be found.

Remedial Programs

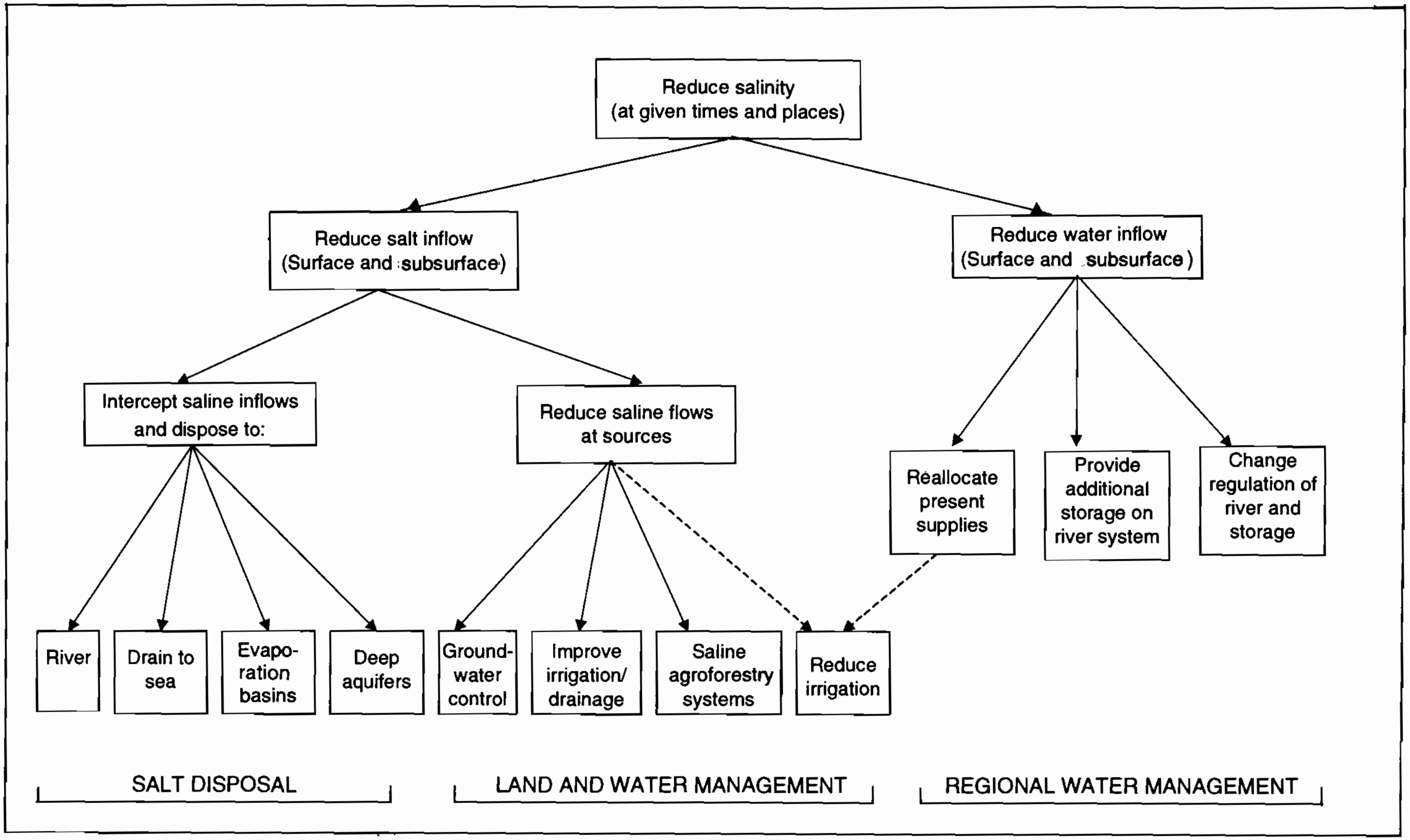
The institutional vacuum created by the breakup of the Soviet Union has complicated the solution of problems of the water resources degradation described earlier. New arrangements are now in place under which the highest political decision making and coordination in the basin rest with the Interstate Council of the Aral Sea Basin (ICAS). The Executive Committee, which became operational in 1994, implements the policies decided upon by the ICAS. Two special commissions were also established: the Interstate Commission for Water Coordination (ICWC), which coordinates the activities of the regional water organizations, and the Interstate Commission on Socioeconomic Development and Scientific, Technical and Ecological Cooperation (ICSDSTEC), which coordinates the restoration and development in the basin. Since 1994, the international donor support is coordinated under the Aral Sea Basin Program.

At an early stage, the States agreed to the two principles of "sharing of the water resources in the basin" and "common responsibility for its sustained use." It was also agreed that the water allocation should be based on well-established international and local customary laws. On the basis of these principles, plans are being prepared to combat the degradation of the water resources and the related problems in the Aral Basin. The available options, presented schematically in figure A2, may be grouped as follows:

Regional Water Management

Measures that would contribute to the improvement of the water quality in the lower reaches of the river by making more water available for dilution and flushing (reallocation of water resources, development of additional water resources, change in operating rules, etc.).

Figure A2. Salinity control options for the Amu Darya and Syr Darya rivers: Derivation of possible contributory actions.



Source: World Bank 1997.

Land and Water Management

Measures that could be taken in the irrigation schemes to reduce the volumes and/or the salt concentration of drainage and seepage flows, generated by these schemes (improved irrigation efficiencies, improved drainage technologies, reuse of drainage water, retirement of excessively salty lands, etc.).

Salt Disposal

Measures that could be taken to collect and dispose of saline drainage and seepage flows in a manner that would reduce the water quality degradation of the downstream river water (interception of highly saline flows, separate outfall drains, disposal to safe natural salt sinks, disposal during high flows, desalination, etc.).

Although there may be some partly "win-win" solutions, in most cases improvements can only be achieved by readjustment of established practices and past water allocations. It is planned that these readjustments be agreed upon through a consultative process involving all the relevant stakeholders. The extent to which these measures need to be applied depends, to a large extent, on the adopted water quality targets. It is foreseen that computer simulation and cost/benefit studies will play an important role in assisting the consultative processes and in deciding on alternative measures.

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ANNEX B

COLORADO BASIN

General

The drainage basin of the Colorado River system not only covers parts of seven States in southwestern USA but also extends into northern Mexico, where the river discharges into the Gulf of California. The size of the basin is 244,000 square miles (630,000 km^2) and the length of the main river is 1,400 miles (2,250 km). The main headwaters are in the Rocky Mountains and on the high plains of Wyoming and Colorado. The basin is usefully divided at Lee's Ferry station into the upper basin and the lower basin (see figure B1). While most of the water sources are in the upper basin, most of the water use is in the lower basin.

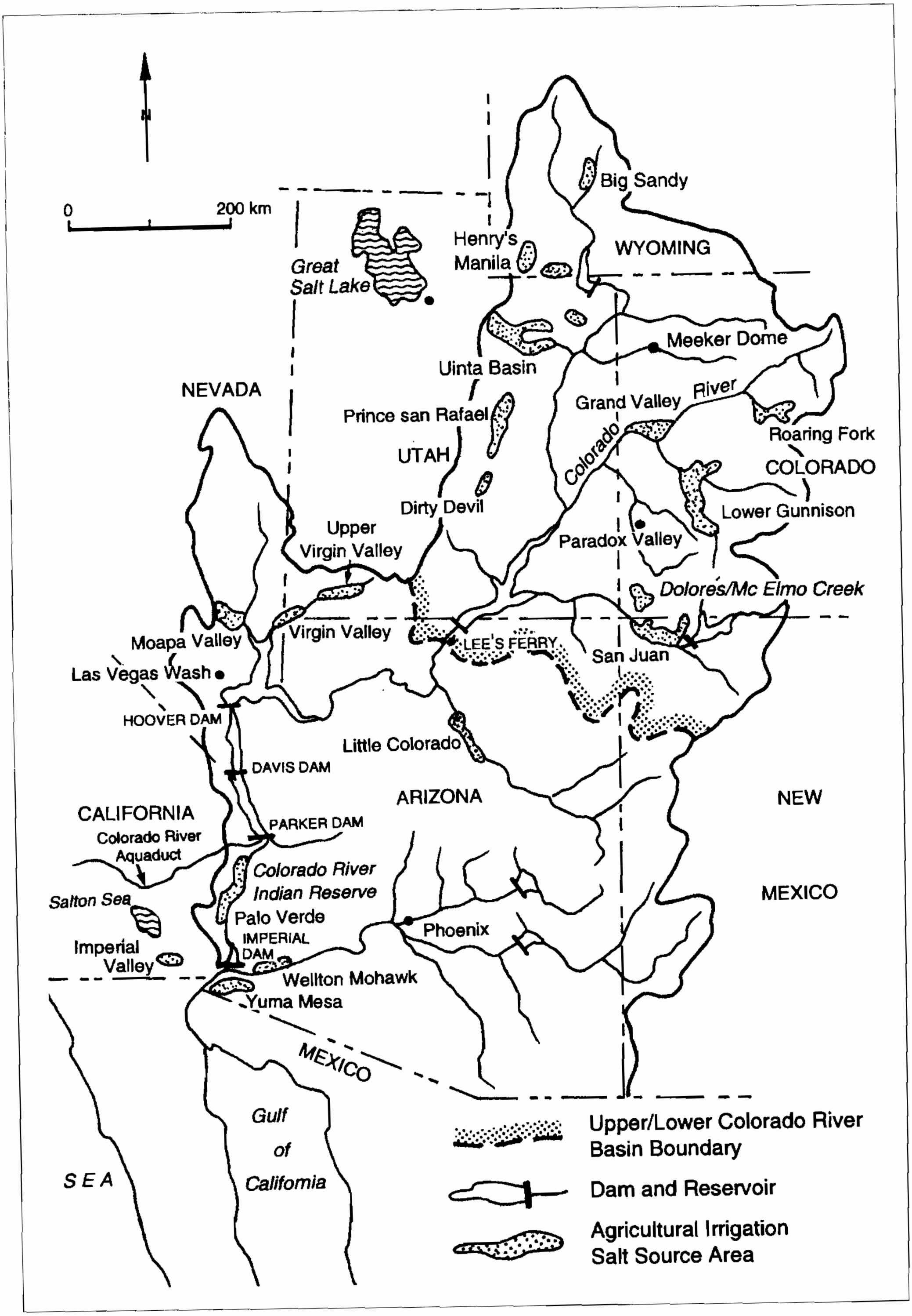
The Colorado River system is by far the most important water resource in this arid and water-scarce part of the western US. Traditionally, the main use was for irrigation but other uses (municipal, industry, and hydropower generation) also established early claims, more recently followed by demands for recreational and environmental protection purposes. Water resources development began in the early twentieth century. Many small and some large reservoirs have been constructed, to the point that the remaining opportunities for storage and low flow augmentation have become very limited. The emphasis has shifted from water resources development to improved management of the already available facilities. One of the current main management challenges is the maintenance of acceptable salinity levels at the downstream intake points.

Water Resources Development

The original unregulated river flows varied considerable during the year as well as from year to year. The highest flows typically occurred during the late spring/early summer (with monthly volumes averaging about of 3 to 4 million acre-feet) while the lowest flows occurred in winter (0.3–0.4 million acre-feet). During drought years, the volume of the total annual flow would easily drop to half the average volume. The average annual natural flow (measured at Lee's Ferry) is generally accepted to be about some 15 million acre-feet (18.5 km^3). Almost all of this water is diverted and used and hardly any discharge reaches the sea.

The first major storage reservoir, Lake Mead, controlled by the Hoover Dam, was completed in 1935 while the latest, Lake Powell, controlled by the Glenn Canyon Dam, became operational in the mid-sixties (filling was completed in the late seventies). Lake Mead alone can store some 30 million acre-feet (37 km^3) while the total constructed storage capacity on the Colorado system is now more than four times the total average annual inflow to the river system. These storages have completely altered the flow regime of the river. Discharges now vary over a narrow range and are dictated more by the water demands at the various diversion

Figure B1. Map of the Colorado River (USBR).



points than by the inflows from the catchments. Extreme variation in inflow within a year and between the years, however, still has a noticeable influence on the river flows.

In the US, the Colorado water irrigates about 1.2 million hectares (2.9 million acres) of land in the basin (about equally divided over the lower and upper basins) as well as several hundreds of thousand of acres outside the basin (including some 500,000 ha in the Imperial Valley in southern California). The irrigation development started in the late nineteenth century but most of it occurred in the first half of the twentieth century. Development has since leveled off and in some parts of the basin the irrigated area has recently even declined. There is also an extensive municipal use of the Colorado River water outside the basin (to an estimated 15 million people as compared to some 3 million inside the basin). In Mexico, the Colorado supplies water to about 0.2 million hectares (0.5 million acres) of irrigated land and close to 2.5 million people. The strongest growth in water demand currently comes from the metropolitan areas but there is also a large potential demand for more water for the manufacturing, mining, and energy industries.

Natural River Salinity

The geology of the Colorado Basin is highly complex and varied. There is a wide range of formations of different composition, age, and structural features. Several of the sedimentary shale-type formations were deposited in marine or brackish water environments and still contain much halite (sodium chloride), gypsum (calcium sulfate), and other salts in various forms of bedded or more dispersed occurrence. Salt domes also occur in some areas. Much of the groundwater in the aquifers of these formations is saline. Many of the finer sediments have high percentages of exchangeable sodium and magnesium. As is to be expected, in view of the salty nature of some of the parent material and the prevailing arid climate, there is also considerable primary salinity in the soils in some parts of the basin while other soils have become salinized after the development of the land for irrigation.

The natural salinity of the Colorado system in the mountain headwaters is typically about some 50–100 mg/l. Using historical records available since 1906, the natural (predevelopment) river salinity at Lee's Ferry, at the outlet of the upper basin, is estimated to have been about 250 mg/l while the comparable value of 334 mg/l was estimated at the Hoover Dam. Salinity measurements made during the 1926–34 period at the Yuma station (at the US-Mexican border) show an average of 539 mg/l. At that time, none of the large reservoirs yet existed but considerable water use for irrigation was already taking place and the natural salinity for Yuma would probably be somewhere in the 400–500 mg/l range.

Water Allocation and Water Use

The apportioning of the Colorado water amongst the basin Sates and between the USA and Mexico, has been laid down in a number of legal agreements and rulings. Two major "compacts," negotiated in 1922 and 1948, respectively, and a Supreme Court Decree in 1964, regulate the allocation of the Colorado River water amongst the States. By a treaty concluded in 1944, the USA was obligated to an annual delivery of 1.9 km^3 (1.5 million-acre feet) of

Colorado River water to Mexico. These compacts and the decree also provided the legal basis for a major role of the Federal Government in the water resources development in the basin.

The apportioning agreements were later complemented by agreements on the river salinity standards to be maintained at key intake points of the system. The foundation for most of these water quality agreements were laid by the investigations carried out in 1971 by the United States Bureau of Reclamation (USBR) under the "Colorado River Water Quality Improvement Program" (further described below). In 1973, the water-sharing treaty with Mexico was also amended to include the requirement that the average annual salinity of the delivered water would not exceed that at the Imperial Dam, the last diversion point in the US, just upstream of the border, by more than 115 mg/l +/- 30 mg/l (in this new agreement, there is also a slight reduction in the annual delivery: 1.36 million acre-feet as compared to 1.50 million acre-feet laid down in the 1944 treaty).

The distribution of the net/consumptive use (diversion minus return flow) of Colorado River water over the various uses is shown in table B1.

Table B1. Average Colorado River water use (1981–85).

	Upper basin	Lower basin (Million acre-feet)	Total
Reservoir losses	0.81	1.26	2.07
Agricultural use within the basin	2.31	5.10	7.41
Municipal and industrial use	0.21	0.84	1.05
Fishery, wildlife, and recreational use	Nil	0.03	0.03
Export outside the basin	0.67	4.06	4.73
Total	4.00	11.29	15.29

These data show that about 30 percent of the water is used outside the basin, especially for irrigation and urban use in Southern California. Although relatively small, the export from the upper basin has a considerable negative impact on the river salinity as most of this water is of low salinity and badly needed for dilution in the lower part of the system. After completion of the Central Arizona Project, diverting Colorado water from the lower basin, the scope for further export will be become extremely limited.

Current River Salinity

Developments in the basin, especially the introduction of large-scale irrigation, have drastically altered the natural salt regime of the Colorado River system. The large-scale irrigation development has also led to considerable mobilization of fossil salts and related saline seepage into the river system. Runoff from all kinds of nonirrigated land, however, also carries much salt to the river, both in dissolved form or attached to erosion material. Mining and drilling activities also contribute to the salt-loading of the Colorado water (drainage water from coal and other mining spoil sites may have salinity levels up to some 3,000–4,000 mg/l). Water is further lost by evaporation from the reservoirs while the large-scale M&I (municipal and industrial) use is consuming water as well as loading the system with pollutants.

The comparison in figure B2 of the current river salinity values with the natural (predevelopment) values shows that developments in the basin have led to considerable increases of the river salinity, especially in the lower basin. But even before development, the river water was already quite mineralized due to the natural influx of fossil salts (mostly carried by deep subsurface seepage flows) and primary salts (mostly carried by the surface runoff flows). Some of these salt sources are very localized but others are quite diffuse and the contribution of the various tributaries to the natural salt-loading of the system varies considerably. The total annual salt-load of the Colorado River at Lee's Ferry is estimated at some 9.2 Mt of which 5.2 Mt are natural, and 3.4 Mt are from irrigated land. It is further estimated that 47 percent of the current salinity of the Colorado River is due to natural salt-loading, 37 percent due to irrigation development, 12 percent due to reservoir evaporation, and 4 percent due to water use and disposal by the M&I sector.

Some of the salt-loading, e.g., the diffuse-loading by subsurface seepage flows cannot be easily stopped. In some cases, however, the flows can be diminished by source control or by interception while in some cases, after a leach-out period, the salt-loading reduces in time. Chemical precipitation is thought to be of negligible influence. Although concentrations in reservoirs may reach saturation levels for some lowly soluble salts like calcium carbonate, calculations show that even under the most conducive conditions, the impact of precipitation on the salt-load of the Colorado River would never be more than 1 percent.

Although the large buffering capacity provided by the reservoirs has considerably reduced the natural variation in river salinity, it is still far from uniform. It is considered that for long-term control purposes, the salinity status at the intake point is best expressed by the "normalized flow-weighted average annual salinity" value. These values are calculated by the CRSS (Colorado River Simulation System) computer program, which simulates the flow and salinity regime of the river system.

The Salinity Control Program

Efforts to control further increase of salinity in the Colorado River started in earnest during the early seventies. On the basis of investigations carried out by the USBR in 1971 and other subsequent investigations, a series of public laws were adopted and related control programs were initiated.

Federal Water Pollution Control Act and Its Amendments, 1972

The Environmental Protection Agency (EPA) interpreted this act as requiring the adoption of salinity standards for the Colorado River. In response, the involved States established the "Colorado River Basin Salinity Control Forum," to serve as a mechanism for cooperation between the various stakeholders in the use of the Colorado water. The States also agreed that a "Colorado River Basin Salinity Control Program" be prepared and that the primary responsibility for the planning and implementation of this program would rest with the USBR. In 1975, after extensive public consultations, the Forum recommended that the 1972 flow-weighted averages be taken as salinity standards for the Colorado River water, setting the standard as 723 mg/l at the Hoover Dam, 747 mg/l at the Parker Dam, and 879 mg/l at the Imperial Dam (see figure

B2). These standards and the underlying control plans were subsequently accepted by the States and approved by the EPA.

The Colorado River Basin Salinity Control Act, 1974

This act provides the legislative basis for the "Colorado River Basin Salinity Control Program." Title I deals with the maintenance of the agreed salinity standards of the Colorado water allocated to Mexico (overall, it authorized the construction of the Yuma Desalinization Plant) while title II defines and provides the authorization and the means for active river salinity control in various parts of the basin. The implementation of this act was primarily assigned to the USBR but the Department of Agriculture (USDA) and the Bureau of Land Reclamation also have a role. Although the program is led by the Federal Agencies, primarily by the USBR, there are also significant roles for the various State Agencies, especially in the implementation of the various salinity control projects. The act also created the "Colorado River Basin Advisory Council," made up of representatives of the seven basin States, to provide overall guidance to the Federal Agencies implementing the program. In 1984 and again in 1994, the Salinity Control Act was amended to extend the program. These amendments provide the authorization for further salinity control activities by the USBR and the other Federal Agencies involved.

Salinity Control Projects

Under the Colorado River Basin Salinity Control Program measures of a wide range are undertaken that are expected to improve or stop the further increase of the salinity of the Colorado River either by saving on the use of river water or by reducing the salt-loading of the river. These measures may be broadly grouped as follows:

Canal Seepage Control

Canal seepage losses are a source for saline subsurface drainage effluent and may also generate specific saline seepage fluxes. Depending on the salt-loading and the costs of control, canal systems may be lined or be converted into closed pipe systems. The canal seepage losses may vary considerably from location to location and it may be sufficient to treat critical sections only.

On-Farm Water Savings and Salinity Control

This typically includes the promotion of more precise water application methods, land leveling, improved scheduling, changes in cropping practices and patterns, and other physical interventions. It may also include extension, education, demonstration, and research programs. Most of the programs in this field are managed by the various USDA agencies in cooperation with State Agricultural Agencies.

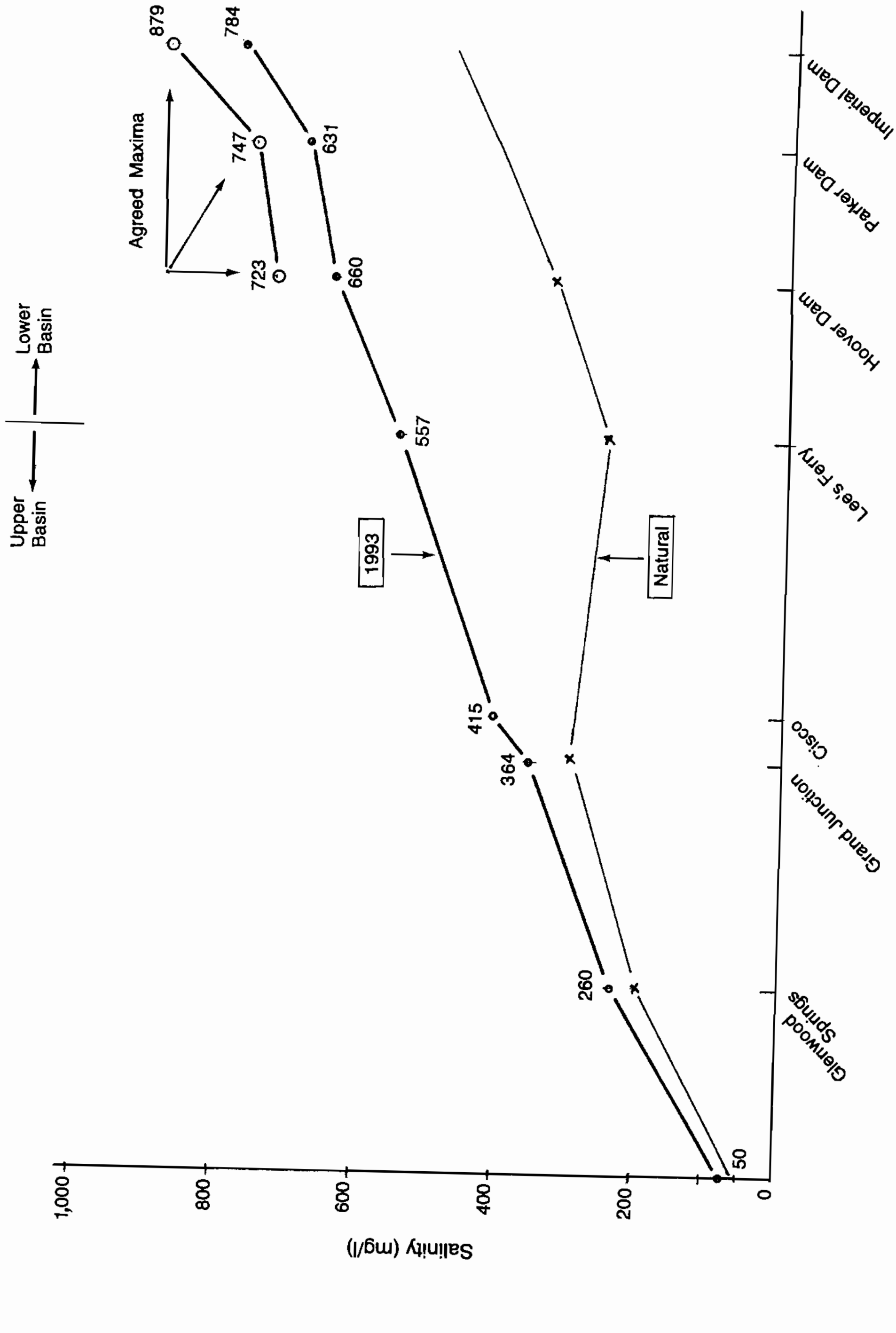


Figure B2. Salinity profiles of the Colorado River (USBR 1966 and 1977).

Retirement of Irrigated Land

On a limited scale, land with excessive water needs or with excessively large or saline return flows have been purchased from the farmers and retired from irrigated use.

Change in Land Use and Agricultural Practices

Various types of financial or regulatory incentives are used to induce farmers to promote water-saving and/or salt-load-reducing land use, soil and water management, and cropping practices.

Watershed and Rangeland Management

The Bureau of Land Reclamation, which administers some 48 million acres in the basin (about 36% of the basin) has greatly contributed to salt-load reduction by introducing improved watershed and rangeland management and improved erosion control on saline land. Although appropriate vegetation management can already achieve much improvement, badly degraded land will often also require some additional mechanical and structural measures (contour tillage, ripping, pitting, liming and other special soil management, and retention and detention works, etc.).

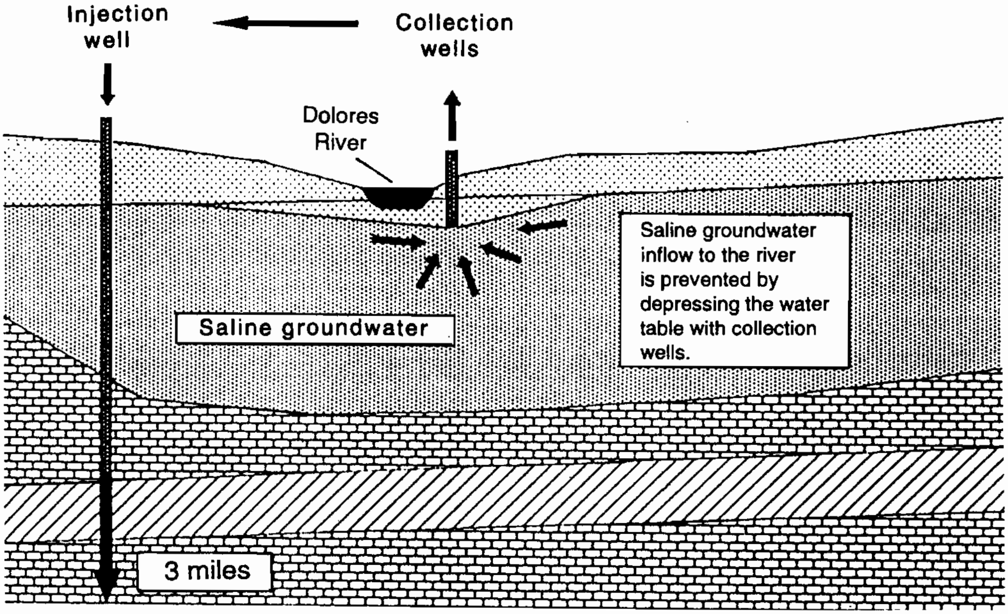
Control of Point Sources

This refers to the control of localized natural and/or man-made salt sources including natural saline seeps, springs, and local salt sources created by the many past and ongoing mining and drilling operations in the basin. Many of these point sources are located on land under control of the Bureau of Land Management, which has undertaken extensive plugging and other clean-up works. A range of techniques may be applied to stop the inflow of saline seepage and spring water into the river system. In cases where the flow is fed by irrigation water losses, this may involve canal lining or on-farm irrigation improvement but in other cases it may be more feasible to apply some form of interception technique (figure B3). The disposal problem must, of course, also be dealt with.

Reduction of M&I Salt-Loading

For the total basin, this is a rather small source but it may be significant locally. In principle, it should be controlled by regulatory obligated treatment but the mining and drilling operators may be exempted by old rights, in which case, interception, containment, diversion, and other technical measures can provide solutions.

Figure B3. Schematic of the Paradox Valley Unit.



Desalinization Works

This rather exceptional measure, taking the form of the construction of the Yuma Desalinization Plant, was applied to guarantee that the water flowing to Mexico would not exceeds its agreed maximum salinity level. The plant has a capacity to desalinate some 100 million gallons (378,500 m^3) of drainage water per day. So far the enforcement of the agreement has not required its use, and the plant is currently in a "ready reserve mode."

Impacts and Costs

The increase of the downstream river salinity has started to level off since the seventies due both to a leveling off of the rate of increase in the water use and to the launching of the salinity control programs. It is estimated that the currently implemented control program reduces the present total salt-loading of the Colorado system of 9.2 Mt/yr., by about 0.5 Mt/yr. It is estimated that a reduction of 1.0 Mt/yr. is needed to offset future predicted increases in water use.

The costs of reducing the salt-loading of the Colorado system vary considerably but average about US$70/ton of salt (the variation is reported to be from $5 to $138). These costs include the capital costs of the facilities to be constructed and other measures to be taken and the annualized O&M and similar costs. The comparable current benefits are estimated at US$340/ton. These benefits primarily derive from the agricultural use of the water, although there are also some benefits in the M&I sector as some household and other installations may be damaged by salinity. In the damage assessment, it was accepted that the Colorado water was naturally far from fresh and only the damage caused by higher-than-natural baseline salinity was counted as damage. The accepted baseline value was 334 mg/l, which is the 1942–61 flow-weighted average at the Hoover Dam (for drinking water assessment, a value of 500 mg/l was accepted as the baseline).

As benefits cannot generally be related directly to specific control measures, the priority ranking of the control measures identified is mostly based on costs. Some control measures are still very much in the testing stage and the technical experience with, and the current cost estimates of, the various measures are not all equally robust and reliable. Good results have generally been obtained with improved on-farm irrigation, canal lining, plugging of flowing brine wells, and erosion control of saline lands. Measures, which benefit specific landowners, are cost-shared while the funding of the entire program is partly paid from a surcharge on the electricity generated in the basin.

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ANNEX C

INDUS BASIN

General

The Indus is the main river system of Pakistan. The headwaters of the main stream and the four major tributaries are in the Kashmiri Mountains but there are also important tributaries originating from the mountain ranges in the North-West Frontier Province and in the adjoining part of Afghanistan. Several tributary streams join the system in the middle and lower reaches but these are all minor seasonal streams originating from the arid western part of the country (Baluchistan). The total basin measures about 365,000 square miles (0.94 million km^2) of which 200,000 square miles are in Pakistan and the length of the main stream is some 2,800 km. All the main tributaries and the main stem join each other in the southern part of the province of Punjab and only the Indus main stream continues South, through the province of Sindh, to its final outfall in the Arabian Sea, east of the city of Karachi (figure C1).

Although the Indus Plain has a large number of large and medium-sized cities and villages with an estimated total population of 70 million and also a large number of industries, which depend for their water supply on the Indus water, the total use of these sectors is still quite insignificant. An estimated 95 percent of the Indus water use is currently for irrigation and although urban and industrial uses are increasing, these uses are predicted not to exceed 10 percent for the foreseeable future.

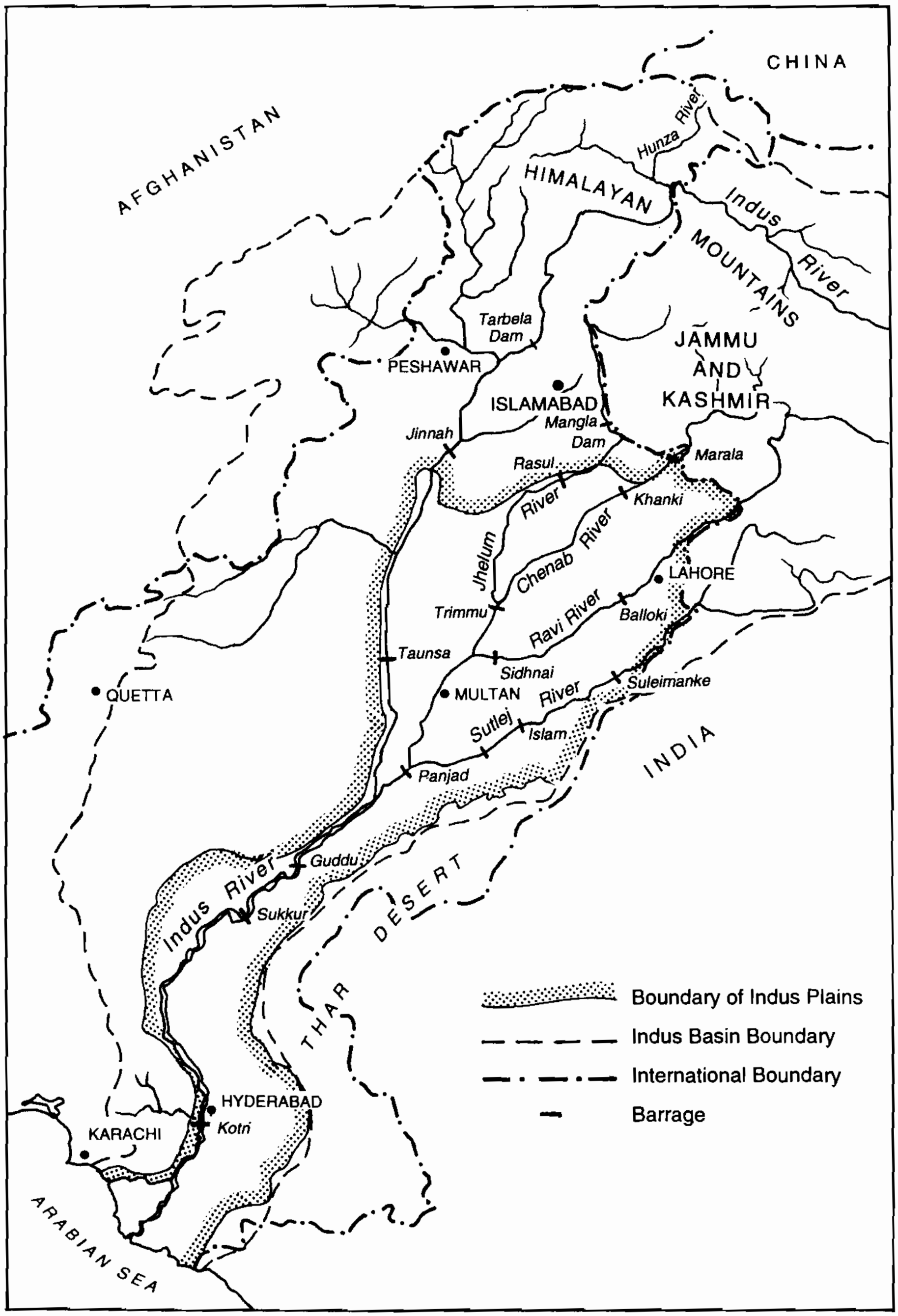
Water Resources Development

The development of the Indus water resources for irrigation started in the late nineteenth century. Initiated under the colonial rule and continued by the national government after independence, much of the Indus Plain was brought under irrigation by the construction of barrages and canal systems. These systems raised the food security to a level that could not be assured under the earlier flood irrigation systems and also otherwise greatly contributed to the economic development of the country.

Under the 1960 Indus Waters Treaty, negotiated between India and Pakistan following the partition of the subcontinent, Pakistan obtained the water rights for all the western rivers (Indus, Jhelum, and Chenab) and also the surplus flow of the three eastern rivers (Ravi, Beas, and Sutlej), which were allocated to India. Including the later surplus flow (about 20 km^3), the annual Indus water available to Pakistan averages some 181 km^3. Of this available water, some 131 km^3 are diverted to the irrigation canal systems while of the remainder an estimated 11 km^3 are lost in the river system and 39 km^3 flow to the sea. Three reservoir dams constructed on the western rivers (Chasma, Mangla, and Tarbela with a total storage capacity of 18.7 km^3)

help regulate the river flows while a fourth dam (at Kallabagh on the main Indus) is under study.

Figure C1. Map of the Indus Basin.



The canal systems in the Indus Plain serve an estimated gross irrigated area of 16.2 million hectares. The water use efficiencies are generally quite low and much of the diverted irrigation water ends up as groundwater recharge. This recharge, jointly with the recharge from the rainfall, feeds the large tube-well irrigation activity in the country (there are some 13,500 public tube wells but most of the pumping is done by the smaller farmer-owned tube wells, some 400,000 according to the latest figures). Most of the drinking water is also abstracted from the groundwater. The total groundwater pumpage, much of which is "lost" Indus water, is estimated to be about of 58 km^3.

The development and the management of these irrigation systems were initially fully entrusted to the Provincial Irrigation Departments while the role of the Federal Government remained limited to providing the necessary national policy, legal, and regulatory frameworks. This arrangement changed somewhat in 1958 when the Water and Power Development Authority (WAPDA) was established as the central body for the comprehensive development and use of the water and power resources in the country. WAPDA prepares plans, undertakes studies, and constructs works on behalf of the provinces, which retain the ultimate rights over the resources.

Water Allocation

The first legislation on the Indus water rights dates back to the late nineteenth century when large-scale irrigation development started that needed to be provided with a legal framework. In this legislation, existing users and customary riparian rights were respected and provinces were given the right to the use of the river water for the public interest. Disputes, however, emerged as the successive diversions started to take an increasingly large share of the river flow and became a concern to the most downstream Sindh Province.

While, initially, these disputes could be settled by negotiation and arbitration, later, as the stakes rose and the disputes attained political overtones, these mechanisms became less and less adequate. Several high-level efforts were undertaken during the 1960–90 period to reach agreement on the water allocation and operation rules for the Tarbela Reservoir Dam but it was not until 1991, some 15 years after completion of the dam construction, that an accord between the four provinces was signed (Water Apportionment Accord). A special body, the Indus River System Authority, was established to implement the Accord. The agreement reached is still quite limited in scope and further disputes are expected to arise whenever new projects affecting the present distribution of the Indus water are proposed (e.g., the Kallabagh Dam).

Waterlogging and Salinity

The problem of rising water tables, eventually resulting in waterlogging and salinization of the land, has been a plague detrimentally affecting irrigated agriculture in the Indus Plain during the last 30–40 years. The problem emerged slowly as original water tables were deep (typically 20–30 m below the land surface) and the irrigation-induced recharges could, in most areas, be accommodated safely for some time. The first symptoms of the problem appeared in the first half of the century but the problem only reached alarming dimensions in the fifties/sixties.

To combat the ongoing waterlogging and salinization of its irrigated land, in the early sixties the government launched the Salinity Control and Reclamation Program (SCARP). The main component of this program was the provision of improved drainage, i.e., upgrading of surface drains and the installation of tube-well drainage and later also the installation of pipe drainage. Including the ongoing SCARPS projects, the program's current coverage is about 8 million hectares. An estimated Rs 50 billion (about US$2 billion) has been expended on the program so far.

The impact of the SCARP has been limited. Some 15–20 percent of the irrigated land still suffers from severe salinity and some 20–30 percent still suffers from high water tables. Including the land with moderate salinity and/or waterlogging problems, the problem extends to about 35–40 percent of the land. Soil salinity problems are particularly serious in the Sindh where some 80–90 percent of the land is classified as moderately or severely saline.

River Salinity

The salinity of the Indus River water has been recorded regularly since the early sixties at a large number of well-distributed stations. The headwater salinity of the rivers arising from the Kashmir Mountains (Indus, Jhelum, Chenab) are mostly about 100–200 mg/l while those arising from northern Pakistan (Swat) tend to have somewhat lower values (50–150 mg/l) and those arising from northern Afghanistan somewhat higher values (150–300 mg/l). Much higher salinity, often in the range of 500–1,000 mg/l, generally prevails in the seasonal rivers originating from more arid zones of southern Afghanistan and Baluchistan. The proportional contribution of these latter tributaries to the Indus flow is however insignificant and the flow-weighted average salinity at the rim stations is generally taken as being around 150 mg/l.

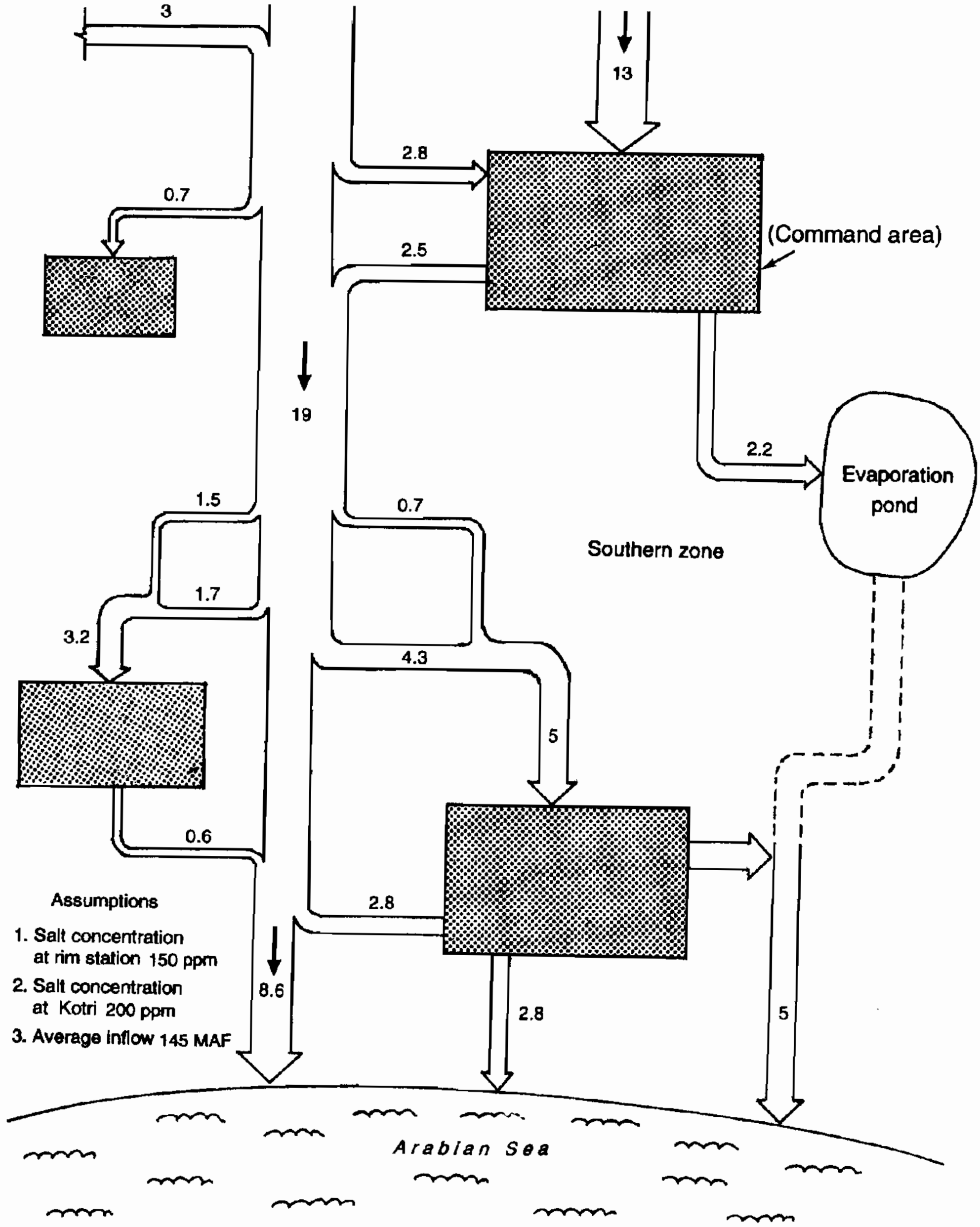
All the main rivers now have some reservoir storage, mostly sited at the rim stations where the rivers enter the plain from the surrounding uplands and foothills. Due to these storages, the previously high river salinity levels at the end of the dry season have been moderated (the salinity at the Sukkur Barrage in the mid-reach of the river, currently ranges mostly between 150 and 200 mg/l during the mid rainy months of July–August as compared to the 200–300 mg/l range during the late dry season months of February–April).

The Indus salinity in the plain, downstream of the rim stations, generally increases only slightly. At the Kotri Barrage, which is the most downstream diversion site, the flow-weighted average salinity is about 200 mg/l, which is an increase of only some 50 mg/l compared to the average of the rim stations. During the pre-monsoonal months of March, April, and May, the salinity at Kotri quite regularly exceeds the 300 mg/l level but values higher than 400 mg/l occur only during exceptionally low-flow periods.

Salt Balance

The Indus Plain is faced with a considerable salt balance problem. The average annual salt influx by the Indus River water, taken at the rim stations, is estimated to be 33.0 Mt while the outflux to the sea in only 16.4 Mt (see figure C2). This means an average annual addition of some 16.6 Mt to the salt storage in the plain. As shown below, most of this salt accumulation takes place in the Punjab plains.

Figure C2. Incoming salt distribution and disposal in the Indus irrigation system (WAPDA 1993).



Note: Values denote annual salt-load in M tons.

Table C1. Average annual salt balance for the Indus Basin.

	Influx	Outflux (Mt of salt/yr.)	Balance
Punjab (above Panjnad Barrage)	33.0	19.0	14.0
Sindh (below Panjnad Barrage)	19.0	16.4	2.6
Entire Indus Plain	33.0	16.4	16.6

Of this annual 16.6 Mt of salt accumulation, about 2.2 Mt are deposited in a series of E-ponds located in the desert area outside the irrigated plain in southeast Punjab. These E-ponds were created in the sixties for the disposal of saline drainage water and more such ponds are under development. The remainder of the salts accumulates in the soil profiles in the irrigated land and underlying strata and aquifers. It is this salt accumulation that has been the main cause of the salinization of the land noted earlier.

Salt Mobilization

An estimated 28.2 Mt of salt are annually brought to the surface by the extensive tube-well pumping taking place in the Indus Plain, mostly in the Punjab (24.7 Mt) but only 3.5 Mt in Sindh. Although this pumped salt probably includes some of the accumulated imported salt (part of the annually accumulating 16.6 Mt), most of the pumped salts are fossil salts deposited in the deeper strata and aquifers in the course of the formation of the Indus Plain. Before the large irrigation development took place, these deep fossil salts were quite harmless; however, they were mobilized and brought to the surface by the rising water tables and tube-well pumping. The salt-load added to the upper soil layers by the mobilized fossil salts is probably at least of the same magnitude as that of the imported salts.

Disposal

The country is undertaking considerable efforts to remedy the unfavorable salt balance and combat the related soil salinization. Drainage of the irrigated land is being improved to stop the ongoing salt accumulation and remove some of the past accumulation. However, in some parts of the basin, the possibilities for maintaining/restoring the salt balance through improved drainage are seriously constrained by the limitations imposed on the disposal of the saline drainage effluent. The available solutions and options have been reviewed in an environmental study by WAPDA, in 1993, from which study the following preliminary outline of a basin disposal plan has emerged.

Sindh

Although the ongoing salt accumulation is much less than in the Punjab, Sindh has a large desalinization and disposal need as much of the land is salinized and needs to be reclaimed. Being close to the sea, several feasible disposal options exist. For areas close to the Indus River, drainage water can be disposed of to the river below the Kotri Barrage, while for the more distant areas, the disposal may be done directly to the sea through existing natural or constructed outfall drains. All of these options are already being partially used and with the completion of two outfall drains (the partly completed Left Bank Outfall Drain and the Right Bank Outfall Drain currently being studied), there should be sufficient opportunity for unconstrained disposal of Sindh's saline drainage water.

Punjab

Here the disposal is much more problematic. Much of the drainage water is being reused with leached salts being returned to the land rather than being disposed of. The downstream salinity levels are still relatively low and more disposals down the river would still be acceptable during most of the year. However, special solutions would have to be found to overcome critical low-flow periods (temporary stoppage of the disposal and/or holding of the drainage water or release of extra water from the reservoir for dilution/flushing). For areas farther away from the river, the current practice of disposal into evaporation ponds may continue but this is unlikely to be a suitable permanent, large-scale solution and it may eventually be necessary to switch to an environmentally more acceptable solution. One such solution would be to provide an outfall for these ponds by extending the Left Bank Outfall Drain into the Punjab.

Further studies on the basin disposal plan will be undertaken under the recently approved "National Drainage Project." These studies will focus, in particular, on the restoration of the salt balance of the basin and providing environmentally acceptable outfalls for saline drainage. The solution of the disposal problems faced by Punjab will probably require the cooperation of Sindh, as there seem to be no feasible internal solutions. Considering the protracted disputes on the Indus water allocation, forging such a cooperation is likely to be a challenging and long process.

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ANNEX D

MURRAY-DARLING BASIN

General

The Murray-Darling Basin covers major parts of three States in Southeast Australia (New South Wales, South Australia, and Victoria) while the Canberra national capital territory is also located within its perimeter. The total basin encompasses 1,060,000 km^2, which is about 1/7th of the total area of the country. The Murray and the Darling rivers both rise from the western slopes of the Great Dividing Range on the east side of the basin (see figure D1). Almost all the river flow is generated by rainfall runoff in the mountainous upper catchment, and the contribution from the rainfall in the arid and semiarid plain areas is quite minimal. The length of the Murray River, from its headwaters to the sea, is about 2,500 km while the length of the Darling River is nearly the same.

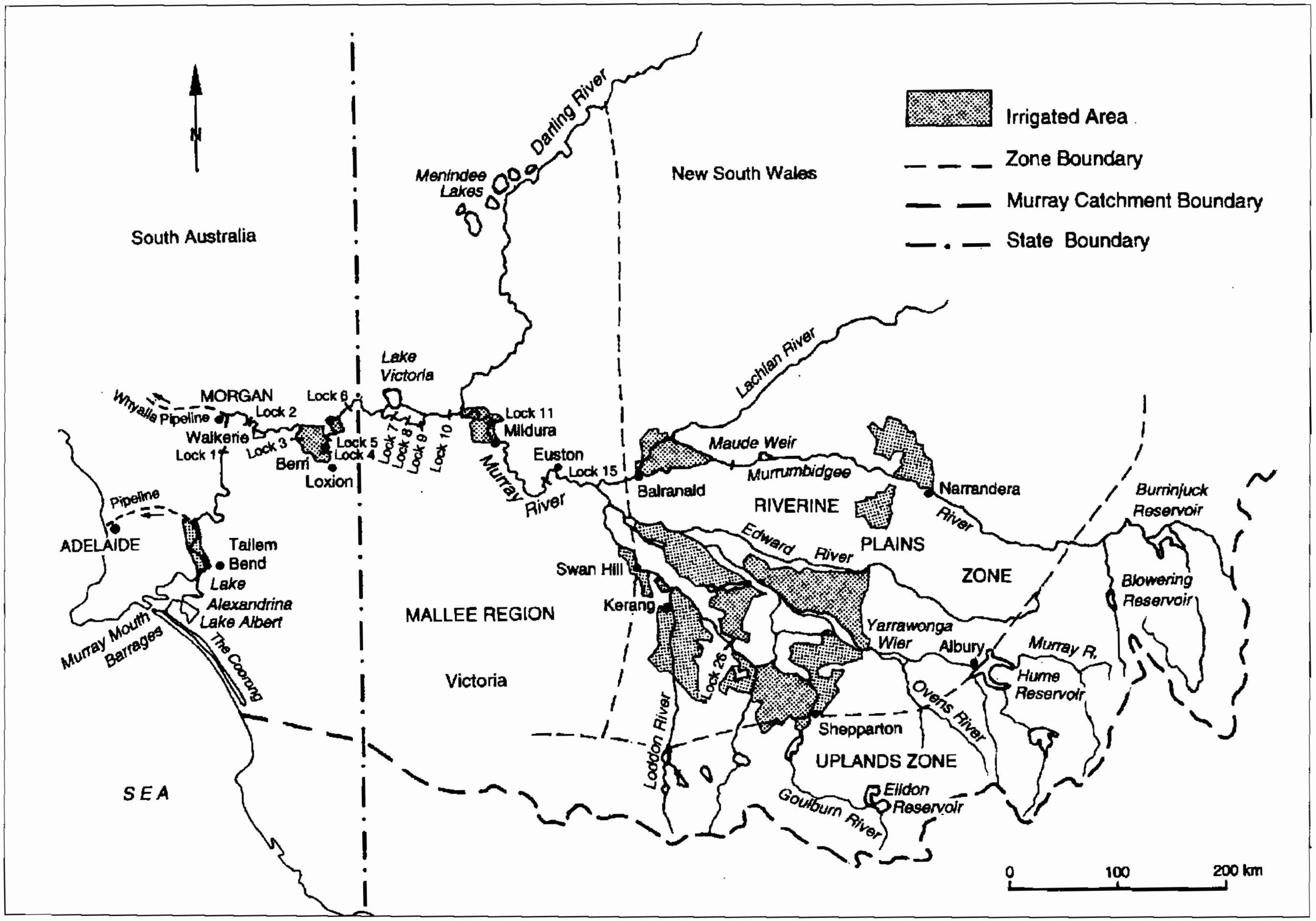
The geological history and past climatic conditions of the basin have left strata and aquifers in some parts of the basin with considerable quantities of fossil and other residual salts. Much of the land in the upper Murray Basin is underlain by quartenary fluvio-lacustrine sediments whereas much of the lower basin is of aeolian origin. Even today, further salt-loading of the lands and groundwater takes place by the influx of salts by rain and dust from the surrounding desert areas, by the continuous weathering of rock minerals, and by the import of salts to the land with applied irrigation water.

The development of the basin is of quite recent origin, starting in the latter part of the nineteenth century and remaining quite modest until the first half of the twentieth century when the State governments began actively promoting the settlement of these empty lands. Large upland areas were cleared for grazing while irrigated agriculture was established in the lower plains. The economy of the basin is still predominantly agricultural and rural although urban and industrial activities gain importance in some of the regional towns and especially in Adelaide, the region's main city located just outside the basin near the mouth of the Murray River. Irrigation developed in the Murray valley and has grown into a major economic activity. About half of the country's total gross agricultural production originates from the basin.

Water Resources and Irrigation Development

The development of the water resources in the basins, mostly for irrigation purposes, also started in the first half of the twentieth century. Several major reservoir dams have been constructed in the upper Murray catchment (Hume, Dartmouth, and others) and on tributaries of the Darling River that together with other smaller reservoirs have greatly helped regulate the river flows, particularly minimum flows that have increased significantly. Some natural lakes and constructed flood plain storage in the lower reaches of the rivers have further added to

Figure D1. River Murray system, regulation works and irrigation regions (MDBMC 1988).



the storage capacity of the basin, which currently stands at about 30 km^3. The lower reach of the Murray River has also been made navigable by the construction of a large number of locks.

The total annual inflow of the Murray-Darling rivers is reported to average about 24.3 km^3 (including 10. 5 km^3 contributed by the Murray) of which 5.5 km^3 discharge to the sea. Almost all the used river water is for irrigation, with currently only some 5 percent being used for M&I purposes (most of which is drinking water for Adelaide, which is piped to the city from an intake point near the Murray Bridge). The total irrigated area in the basin is reported to be about 1.5 million hectares of which 0.8 million hectares are located in the upper/middle part of the Murray Basin (the "Riverine Plains Zone") and the remainder in the lower part (the "Mallee Zone"). Most of the irrigation water is diverted from the river by gravity but there are also some schemes with pumped supply.

The irrigation development in the basin has led not only to considerable increases to the levels of water tables in the irrigated areas but also to considerable salinization of the lands. The rates of rise of the water table during the last 30–40 years have varied from as low as 5 cm/yr. to as high as 35 cm/yr. The most significant water table rises generally occurred during wet years, indicating that the increased recharge is due not only to irrigation water losses but also to excess rainfall. Studies indicate that if current trends continue unabated, almost all irrigated land will have water tables of < 2-m depth by the years 2010–20. The waterlogging and salinization are especially severe in the Riverine Plains Zone of the Murray Basin where 50–60 percent of the irrigated land suffers from waterlogging and some 40–50 percent from salinity.

River Salinity

The natural salinity of the headwaters of the Murray River as measured upstream of the Hume Reservoir, is generally exceptionally low, only about 30–40 EC units equaling about 20–30 mg/l (in Australia, salinity is traditionally expressed as micro-S/cm; EC units may be converted to mg/l by using a multiplier of 0.64). The salinity levels of the main upper catchment reservoirs are generally still exceptionally low, averaging only about 50–150 mg/l.

In the plains, the Murray River salinity increases downstream, as the river flow diminishes due to diversion and as tributaries and drainage return flow bring in salt (see figure D2). The figure shows that the river salinity varies considerably with the variation in the river flow indicating that the salt influx to the river is not proportional to the inflow. At high flows, when most of the river flow originates from the upper catchment and is generated by rainfall runoff, the salinity is low while it is high at low flows when more of the river flow is generated by groundwater base flow. Due to the proportionally greater impact of the diversions and the proportionally greater contributions of some tributaries, there is also considerably more spatial variation in the salinity along the river during low flow as compared to high flow. At low flows, the salinity of the Murray River may occasionally fall rather than rise as the salinity of some tributaries is so low and the flow so substantial that the main river is diluted.

The Murray salinity data also show a difference in the composition of the river salt between the upper reaches and the lower reaches of the river (figure D2). While bicarbonate is the dominant anion in the upper reach, this is replaced by chloride in the lower reach. On the cation side there are also some changes with sodium becoming increasingly dominant downstream. As sodium chloride is the main constituent of the salts in the groundwater and in the soils in the plains, these downstream changes in the salt composition of the Murray River water are thought to be due to the proportionally increasing contribution of drainage flows from the plains to the river flow. This hypothesis is supported by the fact that these downstream changes in the salt composition are more pronounced during low flows than during high flows. The Darling River water remains bicarbonaceous throughout its length and the flow regime is interpreted as indicating that the contribution of the groundwater drainage flow to the river flow in the Darling Basin is much lower than in the Murray Basin.

The Murray River is separated from the sea by the Goolwa Barrages, which have greatly reduced the salt intrusion and created the Lake Albert and Lake Alexandrina reservoirs. The salinity of these reservoirs at normal flows is around 500 mg/l but these values double or even triple during prolonged dry periods.

Salt Balance

At the rim stations, on average, salt enters the Murray Basin at an estimated 1.1 Mt/yr. (10.5 km^3 river discharge with an average 100 mg/l salinity) while, on average, a reported 5.5 Mt are disposed of to the sea. Including the salt influx by the Darling River (calculated at 0.7 Mt per year, using the discharge and salinity at Weir 32 just upstream of its confluence with the Murray River), the salt balance was arrived at as given in table D1.

Table D1. Average annual salt balance for the Murray-Darling Basin.

	Influx	Outflux (Mt salt/yr.)	Balance
Riverine Plains	1.1	3.2	- 2.1
Mallee Zone	3.9 (3.2 + 0.7)	5.5	- 1.6

It shows that salt-loading of the river occurs both in the Riverine Plains (2.1 Mt/yr.) and in the Mallee Zone (1.6 Mt/yr.). Taking into account that, annually, an estimated 0.3 Mt of salts are being disposed into E-ponds, the net annual mobilization comes to a total of 3.7 + 0.3 = 4.0 Mt/yr. It is reported that of the 5.5 Mt of annual salt outflow to the sea, about 30 percent is human-induced.

Policies and Institutional Arrangements

Under the country's federal structure, the States retain sovereign power over the land and water and all other natural resources within their territories. It is the States that own the water resources, make water allocation decisions, and issue water rights. The early small-scale developments of the water resources in the basin were undertaken separately by each of the

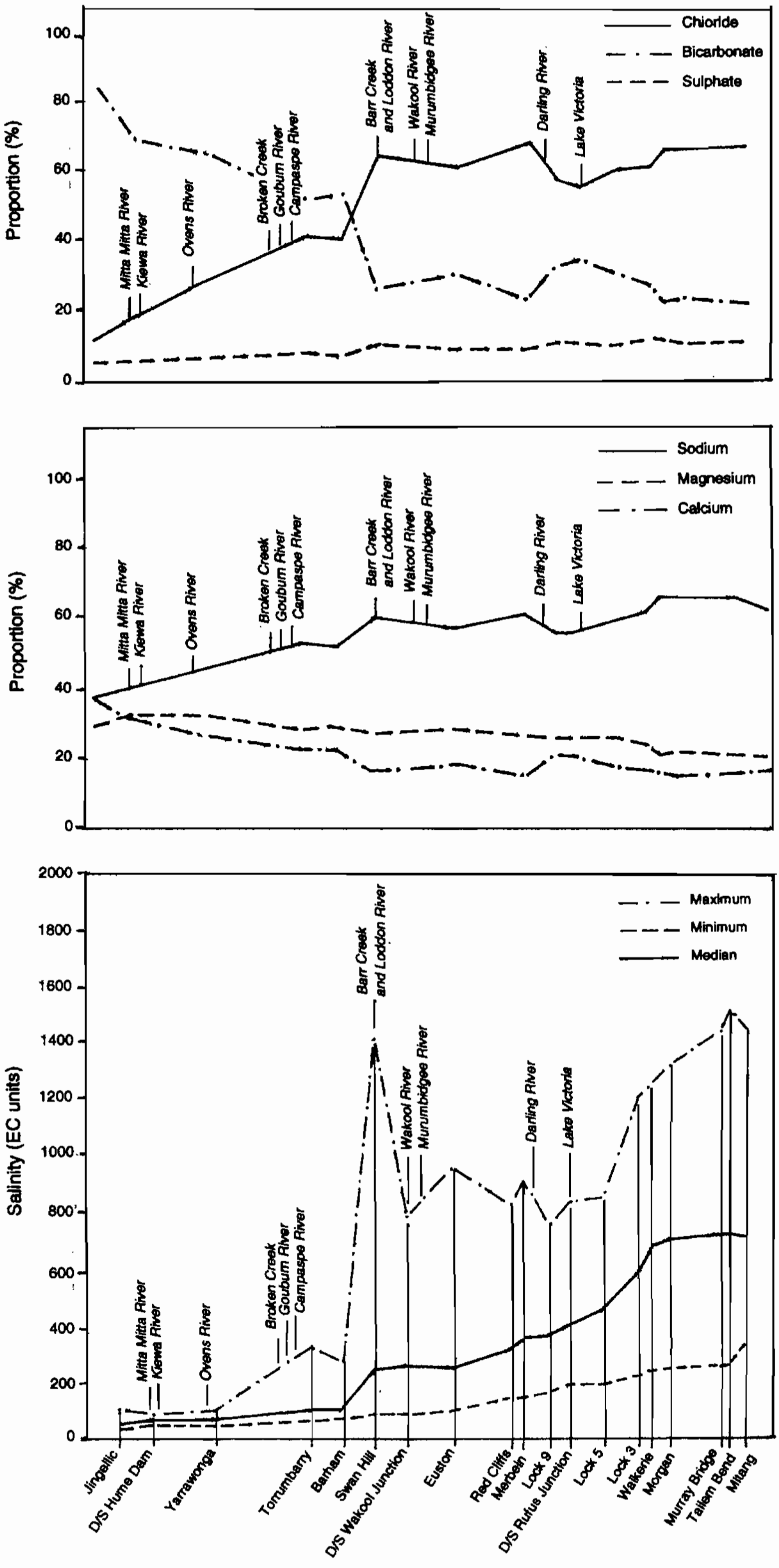


Figure D2. Salinity profiles of the Murray River (MDBC 1990).

States but as the scale of these developments increased, it became necessary to agree on the sharing and cooperative development of the interstate water resources. After several conferences and Royal Commissions, the River Murray Waters Agreement was reached in 1914, which agreement served until the late 1980s.

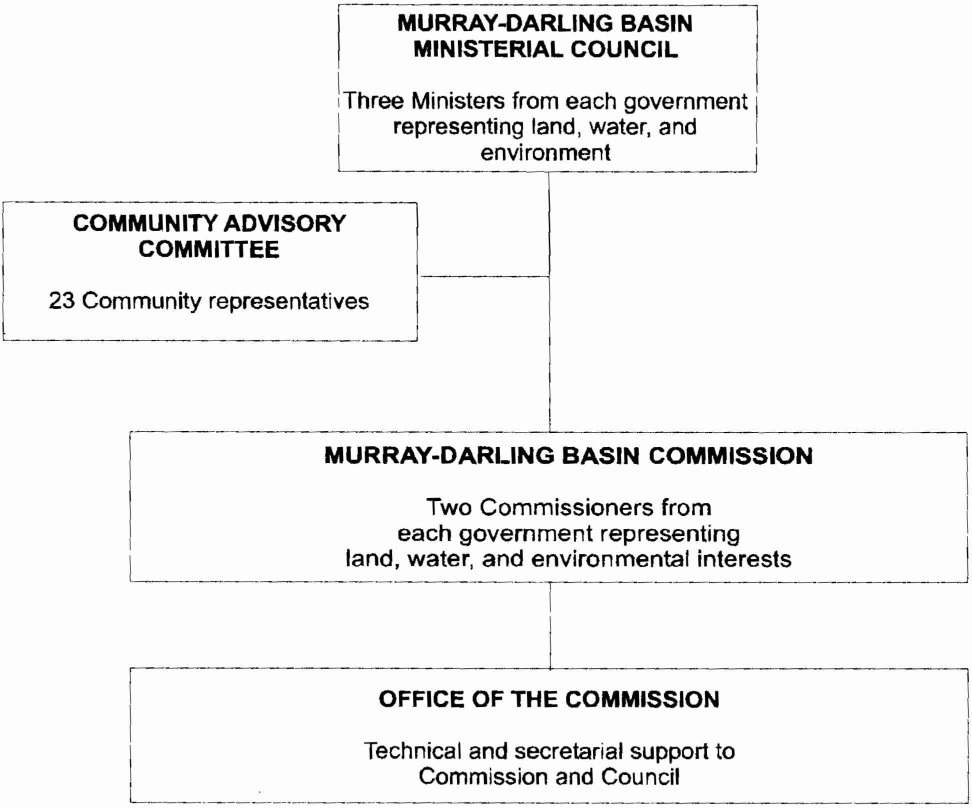
Permanent cooperative structures were not established until 1985 when the involved States and the Federal Government set up the "Murray-Darling Basin Ministerial Council," which is responsible for coordinating and integrating the use of the natural resources throughout the basin. This Council has as its executive arm the "Murray-Darling Basin Commission," which is a commission of senior government officials, typically the senior executives of the involved state agencies (see figure D3). The "Commission Office" assists the Commission in its tasks. The views of the community are heard through the "Community Advisory Council." Through these arrangements, the various stakeholders in the development and management of the natural resources in the basin (various layers of government and various civil, business, farming, and other interest groups) have learned to work in partnership towards common goals. This partnership is known as the "Murray-Darling Basin Initiative."

One of the main tasks of the Council and Commission is to reach agreement on how to control the further increase of the river salinity in the basin. The available data series indicate that the salinity in the middle and lower reaches of the river has steadily increased over the last 40–50 years and conditions have not yet been stabilized. The salinity level in the lower reach has approached levels at which serious damage is being done to the local economy. Currently, the total damage is estimated to be about A$40–50 million (US$31–38 million) per year, most of which is in the municipal use sector (due to the higher salinity of the Murray water, pipe systems in Adelaide have an average lifetime of 9 years as compared to 15 years in Melbourne). It is also estimated that the damage will increase at a rate of some A$130,000 (US$100,000) per year for each mg/l increase in the river salinity at Morgan (located in the center of the lower basin).

Based on commissioned status reports and the results of several rounds of discussion and consultation, in 1989, the Council agreed on a "Salinity and Drainage Strategy," which lays out the basic goals and strategies for the control of the waterlogging, land salinization, and river salinity in the basin. This strategy establishes a framework for a coordinated approach towards solving shared problems as well as for each State to solve its own internal problems. The "Salinity and Drainage Strategy" was later embedded in the broader "Natural Resources Management Strategy."

The approaches adopted for addressing the Murray-Darling Basin problems are strongly influenced by the "National Competition Policy" launched by the Council of Australian Governments in 1995. This policy advocates the enhancement of the role of market forces and competition in society and the economy while preserving environmental values. Inspired by this policy, the States have carried out institutional reforms and formulated new legislation designed to place the management of natural resources in catchments on a sounder and more sustainable financial footing and to give more recognition to environmental values. In most States, the management of the water resources is now entrusted to regional corporate bodies that are obliged to adhere to sound business principles. Many States are also reviewing the existing water rights and drafting new legislation to clarify entitlements and to give due recognition to environmental needs. The new legislation allows for more water trading, which is expected to improve the efficient and economic use of water and discourage waterlogging-and salinity-enhancing irrigation practices. In catchments suffering from waterlogging and salinity or other forms of land degradation, local communities were given the chance to enter into government-supported land and water management agreements with the relevant regulatory bodies.

Figure D3. Management structure for the Murray-Darling Basin Initiative (MDBC 1995).



Salinity Control/Mitigation Measures

The "Salinity and Drainage Strategy" provides a framework for simultaneously addressing the spread of waterlogging and salinization of the land in the basin and the equally alarming increases in the downstream salinity and related environmental degradation in the Murray River. The strategy recognizes the inherent conflicts involved (solving the first problem will generate more saline drainage water that, when disposed of into the river, would further increase the downstream salinity) but it maintains that options are available to solve these conflicts. These are discussed below.

Land Salinization and Waterlogging Control Program

This program covers a wide range of preventive, remedial, and mitigative measures, all of which are designed to restrict the affected areas and the inflicted damage:

- *Recharge control.* These measures address the core causes of the problem, which are the excessive irrigation losses that bring the water table and the salts into the upper soil layers. It promotes such measures as canal lining, water-saving irrigation technologies and irrigation practices, improved surface drainage, land leveling, water-saving cropping patterns, and land use practices.

- *Subsurface drainage.* In areas where, in spite of the implementation of recharge control, the recharge still exceeds the natural subsurface drainage capacity of the land, artificial subsurface drainage will be needed to control the rise of the water table. The installation of subsurface drainage will be limited as the costs will be high and the disposal of the saline drainage water is likely to pose a problem. Some reuse of marginally saline water may be applied but considerable disposal will be needed to assure long-term sustainability.

- *Saline agriculture/forestry.* In areas where the land salinization cannot be easily controlled and/or where no ready salt-disposal solutions are available, the use of the land for salt-tolerant crops, grasses, shrubs, and trees is promoted.

River Salinity Control Program

Under this program the following three broad categories of control measures are being pursued:

- *River flow management.* The downstream river salinity would decrease when, especially during the critical low-flow periods, the downstream river flow could be increased. Measures under consideration include the construction of extra storage, change in existing reservoir operation rules, and reductions in upstream diversions. These reductions may be imposed but may also be induced by pricing and water trading.

- *Interception of saline seepage.* Surveys and studies have confirmed that a considerable part of the river salinity is due to saline seepage inflow. Many of these seepage flows were induced by the water resources and irrigation developments in the basin, which greatly changed the existing natural groundwater regimes. New groundwater mounds were formed and new gradients were established, which generally reinforced the sink function of the incised river. Most of the major saline seepage flows have been identified and measures are being taken to intercept these flows before reaching the river.

- *Non-river disposal.* Many of the above-mentioned measures (drainage, interception, and reuse) only reduce the river salinity when there is an alternative (non-river) means of disposal available. The options seem to be very few. Off-site E-ponds are already being used but the potential for further extension is limited while the environmental acceptability of this solution has not yet been fully confirmed. The disposal of saline water by pipeline or outfall drain directly to the sea or to another safe salt sink, has been studied but judged to be grossly uneconomic. The same conclusion applies to both deep-well injection and desalinization.

- *Land zoning.* Better-planned and more judicious land use, which would reduce the inflow of salts to the river, is promoted. Measures include the reforestation of cleared and degraded land to combat dryland salinity and the retirement of some excessively salt-producing irrigated land.

- *Upstream shifting of intakes.* The harmful impact of high river salinity can, in some cases, be mitigated by shifting the uptake to a further upstream site where the salinity is still at an acceptable level. This solution was investigated for some of the most downstream intakes such as the Adelaide drink water intake, but was found to be infeasible.

Key Features and Components

The key features, components, and mechanisms of the adopted "Salinity and Drainage Strategy" are briefly described below:

Baseline Conditions

It was accepted at the outset that the strategy should aim at maintaining the river salinity at least at the current levels (1989 levels) and that these levels would be the basis for evaluating the merits and impacts of the measures taken and for establishing the responsibilities of the involved parties.

In 1995, the Ministerial Council commissioned an official audit of the current water use in the basin. The results of this audit were used to assess the legitimate needs of the different stakeholders, the balance between diversion of the river water for off-stream use (irrigation, M&I, etc.), and the in-stream needs for water. It was concluded that increased diversion would pose serious risks to the environmental integrity of the river and to the downstream water quality. Consequently, the Council imposed, pending further studies, a cap on diversions beyond the current levels.

Initial Program

Various combinations of the above land salinization, waterlogging, and river salinity control measures were evaluated, taking into account the direct economic costs and benefits as well as the environmental impacts. The costs mostly refer to the capital and O&M costs of the works to be undertaken or the additional costs of adopting new practices but for some measures (changing reservoir operation, land retirement, and others) they refer to foregone opportunities. Benefits mostly relate to the direct agricultural benefits of land salinization and waterlogging control and also direct and indirect benefits of lower river salinity (mostly to the M&I users).

It was agreed that a package of river flow management and interception projects would be implemented over a period of 5–10 years, which are predicted to reduce the river salinity at Morgan by 135 EC units (about 85 mg/l). The capital costs of the interception projects (accounting for the reduction of 80 EC units) was estimated to be A$27 million (about US$21 million) while the annual O&M costs were estimated to be about A$1.7 million (US$1.3 million) per year. These common projects would be supplemented by various State land salinization and waterlogging control projects to be implemented gradually over a period of about 30 years.

Cost Sharing and Salt Credits

After lengthy discussions, the Ministerial Council agreed that the current river salinity levels (the 1989 baseline values) should be used as the basis for assessing the share of the program costs to be borne by the involved States. It was recognized that all States have, in the past, undertaken actions, which have increased river salinity and that some States did so more than others, but it was also recognized that most of these actions were in accordance with the then prevailing agreements. However, it was also agreed that, in the future, States would be held responsible for actions that would increase the river salinity above the agreed baseline level ("polluter pays" principle).

For the initial program, it was agreed that the cost of the common river salinity control projects would be equitably shared between the States and that this, in principle, would also apply to those components of the State land salinization and waterlogging projects, which would have a positive impact on the river salinity or would generate other common benefits. All other costs of these latter projects would, however, be borne by the concerned States that, in turn, may decide to negotiate their own cost-sharing agreements with the communities, the farmers, and other identifiable beneficiaries.

The strategy also recognizes that the upper States would be seriously handicapped in solving their land salinization and waterlogging problems when they are no longer allowed to dispose of some saline drainage water into the rivers, and based on this consideration, each of these States was granted the right of disposing of salt into the rivers over the program period equivalent to 15 EC units (about 10 mg/l) at Morgan (this right is referred to as a "salt credit"). States can earn further credits by taking internal measures at their own costs, which reduce the river salinity. The States may choose to use this credit for actual salt disposal but may also choose to solve their disposal problem without river disposal and trade the salt credit with other States.

Implementation

The agreements between the States described above, and others, have been formalized in the "Salinity and Drainage Agreement," administered by the Murray-Darling Basin Commission. The Commission manages the overall program and assists the States in the preparation and evaluation of projects. An important aspect of this evaluation is the computer simulation of the impacts of proposed projects on the river salinity. The findings of this simulation are accepted by the parties as the basis for assessing how proposed projects change the baseline conditions and how many credit units States would earn or pay for a project.

The Commission also maintains a register of the agreed and proposed projects and monitors their progress and impacts. The common river salinity control projects are mostly prepared by the Commission but all the State projects are prepared by the concerned regular State agencies. The States generally do most of the construction and O&M of all the projects.

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ANNEX E

NILE BASIN

General

The Nile Basin, with a total area of 2. 96 million km^2, covers nine different eastern and northeastern African countries (see figure E1). The main river, the White Nile rises in the humid central equatorial regions of Burundi, Kenya, Rwanda, Tanzania, Uganda, and Zaire and then flows over some 6,700 km through Sudan and Egypt to the Mediterranean Sea (the river length in Egypt is 1,545 km). The Blue Nile, which rises in the Ethiopian highlands, joins the White Nile in its mid-reach at Khartoum. The Atbara, another, more seasonal tributary from northern Ethiopia, joins the main river between Khartoum and the Egyptian border. The contributions of the White Nile, Blue Nile, and Atbara are, on average, some 29 percent, 57 percent, and 12 percent, respectively, of the Nile flow.

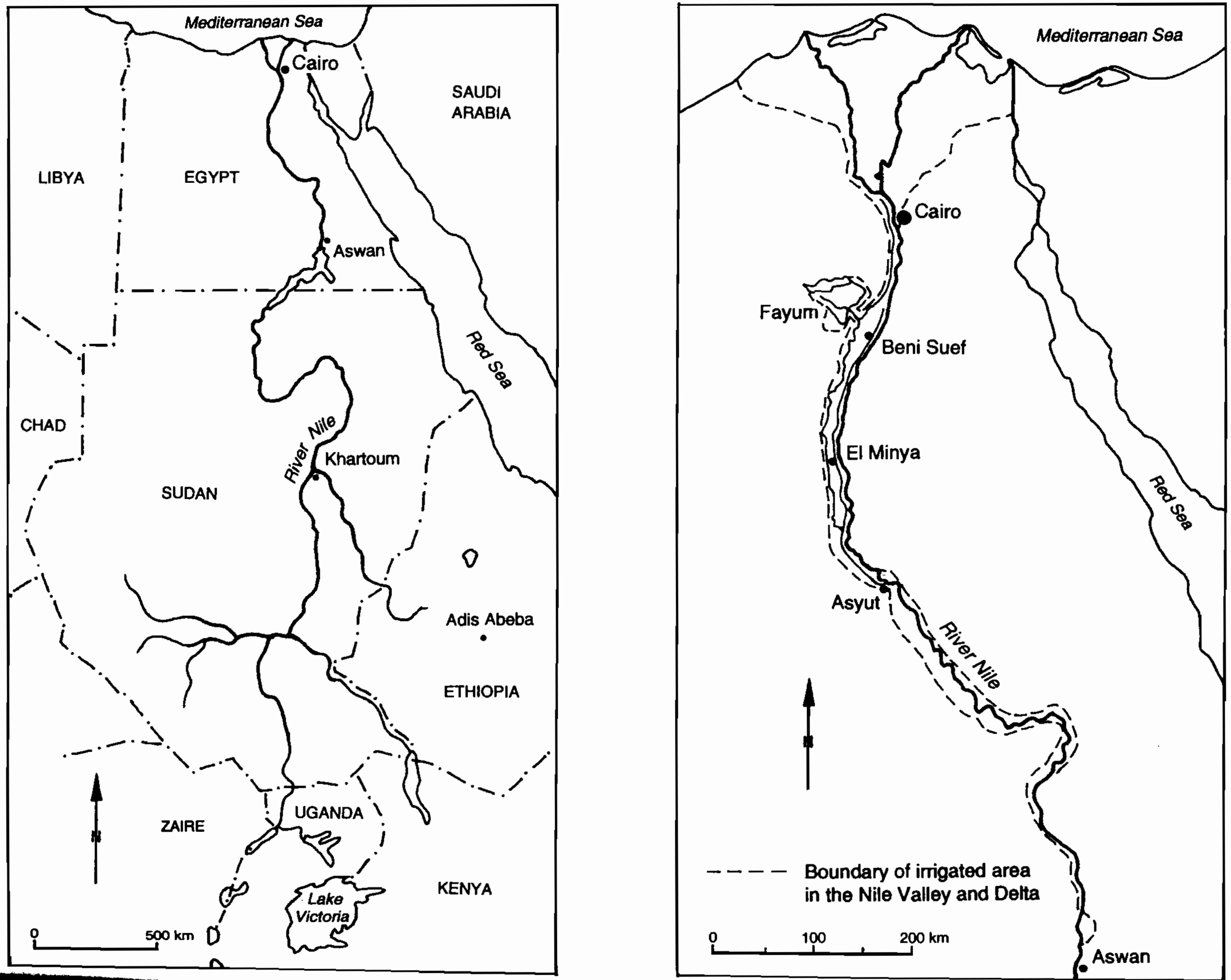
Water Resources Development and Water Allocation

The development and use of the Nile water resources in the countries of its origin in Central Africa and in Ethiopia are still very limited and the principal current uses of the Nile water are in Sudan and Egypt. In both these countries the main use is for irrigation (about 1.7 million ha in Sudan and 3.1 million ha in Egypt). The M&I use of the water in Sudan is still quite negligible but in Egypt it starts to become a factor to be reckoned with. Egypt also has a significant need for Nile water to combat the intrusion of Mediterranean Sea water in the lower deltaic Nile branches.

Both the White Nile and the Blue Nile have a considerable natural lake storage in the headwater regions (Lake Victoria and the other Equatorial African lakes for the White Nile and Lake Tana for the Blue Nile), which provide flow moderation as part of the natural regime. Sudan has constructed four small storage and diversion dams on the Nile system with an estimated total storage capacity of 6 km^3. The main storage facility of the system is, however, the Lake Nasser formed by the High Aswan Dam, which is located on the Sudan-Egypt border and provides some 130 km^3 storage for the benefit of Egypt. This dam, which functionally replaced previously existing lower dams, was completed in 1968.

The first agreements on the use of the Nile water between the riparian countries date back to the early twentieth century and were concluded between the then colonial governments. These agreements were subsequently superseded and the most relevant current agreement is the Nile Water Agreement concluded between Egypt and Sudan in 1959. This agreement is based on an estimated average Nile water availability to the two countries of 84 km^3 per year of which 10 km^3 were estimated to be lost, mostly by evaporation in Lake Nasser. Of the remaining 74 km^3, 55.5 km^3 are allocated to Egypt (measured at the outlets of Lake Nasser).

Figure E1. Map of the Nile River Basin.



At present, almost nearly 85 percent of the water used by Egypt comes from the Blue Nile. Of the considerable water resources of the White Nile, currently more than half is lost as the river traverses the Sudd marshes of South Sudan. Much of these losses could be conserved by the construction of bypass canals and other reclamation works but decisions and implementation are held up by political disagreements between the parties and political unrest in the concerned area.

Construction on one of the prepared projects, the Jonglei-I Canal project, actually started in the seventies but had to be stopped due to security problems. The potential total net gains of these conservation works are estimated to be about 15–20 km^3/yr.

River Salinity

The database on the salinity of the Nile water above Aswan is extremely thin but using the scarce information available, the following picture emerges. The salinity of Lake Victoria, the main origin of the White Nile, is reportedly about 50 mg/l but higher values are reported for some of the other tributary Central African lakes (60 mg/l for Lake Kyoga and about 400 mg/l for Lake Albert) and the average salinity of the Nile water entering Sudan may be plausibly estimated to be about 100 mg/l. Taking into account the large evaporation losses in the Sudd and further losses while passing though Sudan, the salinity of the White Nile water arriving at Khartoum may well have more than doubled to some 200–250 mg/l. The salinity of the Blue Nile at Khartoum is reported to vary between 100 and 200 mg/l and averaging about 140–150 mg/l. On the basis of these values and the relative flows of the two Nile rivers, the average salinity below the junction is estimated to be about 150–175 mg/l.

At and below Aswan, the salinity data become more abundant and reliable. The average salinity of the Aswan outflow is usually given at 200 mg/l. Considering the value given earlier for the incoming river flow and evaporation losses, the salinity of the inflow may reasonably be estimated to be about 170–175 mg/l, which would seem to fairly agree with the estimated Nile water salinity below the Khartoum junction in Sudan. The comparable figure for the Nile at Cairo, at the apex of the Delta, is 350 mg/l while it is about 1,000 mg/l at the outfall of the two Nile branches into the Mediterranean Sea.

Nile Water Use in Egypt

Egypt depends for its water supply almost entirely on the Nile. In addition to the allocated 55.5 km^3 Nile water, the country avails only of some (mostly nonrenewable) groundwater resources in the western desert. Some 2–3 km^3 of groundwater are pumped in the Nile Valley/Delta but almost all of this is percolated Nile water. The rainfall is only of some significance in the coastal zone.

The population of Egypt is currently about 65 million and is growing at 2.5%/yr. Almost all of the population is concentrated in and around the Nile Valley/Delta, which occupies only 4 percent of the country and has a population density of 1,400–1,500 persons/km^2. The Nile Valley/Delta is also the principal site of the country's agricultural production, covering 2.9 million hectares (7.2 million acres) out of the country's total of 3.2 million hectares (7.9 million acres) of cultivated land. Almost all of this land is irrigated. The country is making continuous efforts to expand its irrigated agricultural area by reclaiming land along the Valley and Delta fringes, in and around the oases in the Western Desert, and, more recently, in the Sinai Peninsula. About 0.8 million hectares (2 million acres) of new land have already been reclaimed but the scope for further expansion has now become severely limited by shortage of water for irrigation.

The ultimate authority for the development and use of the country's water resources rests with the Ministry of Public Works and Water Resources (MPWWR). This ministry is directly responsible for the operation of the Aswan Dam and the Nile River system and also for the management of most of the irrigation systems in the country. Its involvement with M&I use of the water, is more a coordinating and regulatory one. The MPWWR is also the principal implementor of the River Nile Water Control Law of 1982, which is designed to protect the Nile water system from pollution. Control of the salinity and other pollution of the Nile water is of great importance in view of the extensive reuse of the water.

Drainage Development

The lands of the Nile Valley and Delta are mostly well-drained. The mostly favorable natural drainage condition of the land has long been complemented by an extensive system of constructed open drains. Several pumping stations have also been installed in the northern part of the Delta to drain low-lying land and to dispose of the drainage water to the coastal lakes and eventually into the sea.

Since the sixties, drainage has been further improved by the installation of pipe drainage. At present some 1.8 million hectares (4.5 million acres) of Nile Valley/Delta land have already been provided with this subsurface drainage technology and further coverage of the land by pipe drainage is in progress.

Salt Balance of the Nile Valley/Delta

The Nile Valley/Delta constitutes a hydrological unit with well-defined inlet and outlet points, which lends itself well for salt balance analysis. The annual balance, based on 1992 data, for the entire area as well as separately for the Valley and the Delta, is given in table E1. It shows that the salt regime of the Valley is quite different from that of the Delta. In both areas the outflux of salt is more than the influx, indicating that in the process of using the water, additional salts are being picked up by the water. The net salt gain in the Valley is calculated to average about 900 kg/acre/yr. (2,200 kg/ha/yr.) and is assumed to be due to a combination of pickup of residual fertilizer salts, disposal of pollutant salts, mobilization of fossil salts, salt release by ongoing weathering of soil minerals, and influx of salts from the newly developed desert land along the Valley edges.

Table E1. Annual salt balance for the Nile Basin in Egypt (1992 data).

	Influx	Outflux (Mt of salt)	Balance
Valley (including Fayoum)	10.9	13.3 *	- 2.4
Delta	12.6	34.1	-21.5
Total area	10.9	34.1	-23.2

*Including 0.7 Mt disposed of into the Lake Karoun E-pond in Fayoum.

In the Delta, the salt pickup is clearly much higher, calculated to average some 4,300 kg/acre/yr. (10,800 kg/ha/yr.). This difference is due to the different geological history and geohydrological nature of the two areas. All of the Delta and probably also part of the Valley were alluviated under marine conditions. While the Valley has, over time, become deeply leached, much of the marine salts in the Delta still remains, especially in the North. These marine salts are continuously being picked up by the subsurface drainage flows. Moreover, due to the sea-induced piezometric overpressure in the deeper groundwater, there is also considerable salt-loading of the drainage water by upward saline seepage in the northern part of the Delta. Along the edges of the Delta, there is also a lateral influx of salts from the newly developed higher-lying desert land.

Meeting Future Water Needs

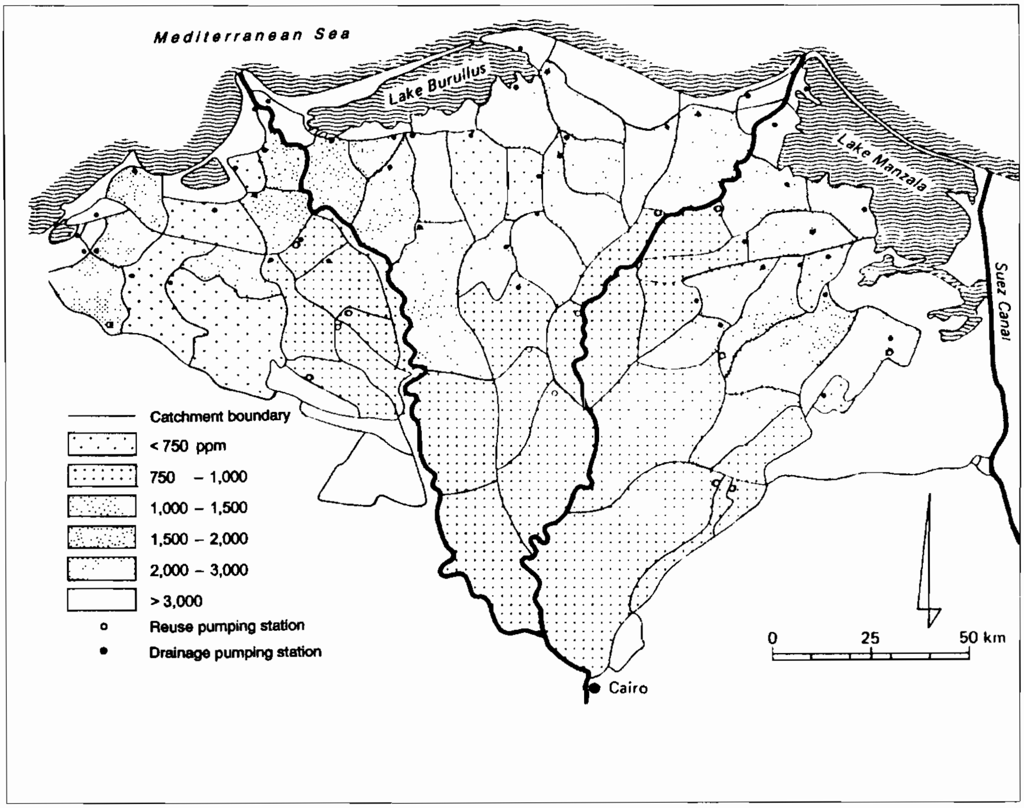
The expected future growth in water demands are planned to be met in the short run by reducing current water waste and losses and by further reuse in the country. In the long run, Egypt intends to work with Sudan and other riparian countries on the implementation of the potential conservation measures, which would increase the Nile inflow at Aswan.

A number of studies recently completed indicate that there is already an extensive reuse of water in the Nile system and that, in spite of the large water losses in the irrigation and M&I systems, the total water use efficiency in the Nile Valley/Delta is exceptionally high. The annual releases of Nile water from the Aswan Reservoir are currently averaging around 55.4 km^3 of which 42.1 km^3 are consumptively used (36.3 km^3 by irrigated agriculture, 2.2 km^3 by M&I, and 3.6 km^3 by others uses) while the remaining water (13.3 km^3) finds its way to the sea. The water use efficiency of the entire Egyptian Nile Valley/Delta thus comes to {(42.1/55.4) x 100 %} = 76 percent.

Of the 13.3 km^3 of water discharging to the sea, 2.1 km^3 flow through the Nile River branches and 11.2 km^3 are discharged through the drainage outfalls (partly by pumping and partly by gravity flow). Although the salinity of the water in the Nile and in the irrigation and drainage systems increases in the downstream direction (see figure E2), part of this water flowing to the sea is of good quality and could readily be reused. The total drainage volume could also be reduced by improving irrigation efficiencies and avoiding over-drainage of agricultural land, notably of rice fields but, as long as the drainage water can and is being reused, these improvements would not provide more water (they may however be cost-effective).

It is recognized that some of the discharge to the sea is essential for the maintenance of the salt balance of the Valley/Delta, for the combat of salt intrusion, and for the maintenance of navigation depth in the Nile branches. Some flushing flow is also required for the control of the water quality and ecological health in the lower Nile branches and in the coastal lakes. Therefore, there are limits to further increasing the reuse and reducing the flow to the sea.

Figure E2. Classification of drainage water salinity.



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