# Hydrological research and water resources management strategies in arid and semi-arid zones

Proceedings of the International Symposium
(Tashkent, Uzbekistan, 25-30 September 1995)

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INTERNATIONAL HYDROLOGICAL PROGRAMME

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# INTRODUCTION

The international symposium on *Hydrological Research and Water Resources Management Strategies in Arid and Semi-Arid Zones* was organized within the framework of UNESCO's International Hydrological Programme, as a contribution to Project H-5.2. Its objectives were to highlight the problems related to water resources development in arid and semi-arid zones, exchange results of scientific research addressing this issue, and propose strategies for the rational management of water resources under water deficient conditions.

The Symposium was held in Tashkent, Uzbekistan, from 25-30 September 1995, and convened jointly by:

The Ministry of Water Resources of Uzbekistan
The Scientific Production Association "Central Asian Research Institute for Irrigation
(SPA SANIIRI)
and UNESCO

with sponsorship from UNEP, IAH, IAHS and ICID.

The Symposium was prepared under the supervision of Prof. V.A. Dukhovny, Director General of SPA SANIIRI and who directed the Organizing Committee, namely:

V.A. Dukhovny (Uzbekistan)
K. Hefny (Egypt)
J. Lloyd (UK)
P. Micklin (USA)
I. Simmers (The Netherlands)
G.V. Voropaev) (Russia)
H. Zebidi (UNESCO)

The scientific programme addressed three main topics which were developed in three successive sessions:

- surface water conditions in arid and semi-arid zones
- groundwater development in arid and semi-arid zones
- water resources management with special reference to the Aral Sea basin

On the basis of discussions and the exchange of experiences of the main problems faced by the arid and semi-arid zones in the field of water resources assessment and management, as well as the needs of the related countries, the symposium prepared recommendations which are presented hereafter.

# Recommendations of the International Symposium: *Hydrological Research and Water Resources Management Strategies in Arid and Semi-arid Zones*

### Recommendations

International co-operation in water resources management holds significant place amongst UNESCO activities and especially those within the framework of the International Hydrological Programme (IHP). UNESCO provides assistance to organising international scientific conferences, symposia, etc. which enable specialists and scientists from different countries to exchange results of their respective works. This Symposium, organized with the assistance of the International Hydrological Programme, is another step in this area. The Tashkent Symposium reflects the international recognition of the contribution of Uzbekistan and other Central Asian Republics to the development of international co-operation in hydrology, water resources management, and other water management sciences.

The Symposium also reflects the concern of the world community for the Aral Sea basin problems. The rationalized use and protection of water resources against pollution and degradation, along with the stabilisation of the environmental situation have become of crucial importance for the economic, social and cultural development of the Aral Sea basin population. The significance of the water problem in the region constantly increases since the natural water resources concerned are limited to an average yearly amount of 120 $km^3 y^{-1}$ which has been observed during several years. These water resources are part of the living conditions for people and animals.

Hydrology-related problems in arid zones are common throughout the world. They may be divided into five main aspects:

1 Scientific study and optimized research on water resources under conditions of shortage
2 Hydrological education and professional training
3 Creation of information networks
4 Provision of technical equipment, and
5 Regional co-operation

Taking into consideration that water is a natural resource, a product of nature and of human society and a source of influence in the social and environmental sphere, the scientific part of the problems should concentrate on the aspects which allow successful development of water management strategy. This means a number of principal considerations, standards, regulations, united in a form of inter-state agreements, treaties and other documents. A combination of the latter with organizational actions and economic measures could become the instruments of and the basis for sustainable development of water supply in arid and semi-arid zones and thereby avoid the dangers of potential conflicts.

The problems of the Aral Sea basin are not unique. They are shared by other zones in the world. Even in the USA we can discover similar examples; in the western states in particular, Tulare Lake, Mono Lake, Pyramid Lake and the Colorado River.

The participants of the symposium noted that:

1. Recent conditions of usage of water, land and other related natural resources require active improvement in management, distribution of water and protection of those resources, together with the implementation of new organisational, ecological and technical principles. The shortage of water resources, increasing population requirements in water supply and the Aral Sea disaster can cause negative social/economic consequences unless improvement of water management is included in the main objective needs of the area.

2 The Central Asian countries, aware of their responsibility in the need to save water for future development, started in 1982 to gradually and systematically decrease the ratio of water used for irrigation needs. As a result, consumption has been reduced from 17,200 $m^3$ $ha^{-1}$ in 1980 to 12,600 $m^3$ $ha^{-1}$ in 1994. The established interstate bodies for water resources management, especially the Interstate Water Coordination Commission and its executive bodies (BWO Syr Darya, BWO Amu Darya, Secretariat, Scientific Research Centre of ICWC), jointly with the Ministries for Water Management of the Riparian States (or the State Committee for Water Resources) now manage Water Resources. This efficiency was proved during the conditions of 1995 which had a low level of precipitation. However, their equipment needs to be upgraded. This is very important in order to increase the quality of management and to achieve an up-to-date technical level. In addition, the poor in-farm water resources management and utilization reflects the need for maximum strengthening of work on water-saving technologies and local management, taking into account the changes in the form of ownership and management of land and water.

The participants of the symposium recommend:

1 Taking into consideration recent difficulties concerning financial support for development of water management, in the scientific and project design field in particular, to ask the EU, UNDP, UNEP and other international donors to provide financial support for the main research and scientific activity expressed in the plan *Scientific and Research Studies of the Interstate Coordinative Commission on Water for 1996-1998* submitted by all the Ministries of Water Management of Central Asian States, together with some new lines expressed at the Symposium.

2. To consider as a priority objective of the ICWC, the creation of an interstate training centre of the Central Asian Countries with the assistance of the international community. The proposals on the centre will be submitted to UNESCO, UNDP, European Union and worked through in the WARMAP Project.

# I

# Surface water conditions in arid and semi-arid zones

# 1. Flash floods in and semi-arid zones

**Xiao Lin**

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## 1.1 Introduction

In arid and semi-arid regions, on the one hand precipitation is rare and areas often experience serious drought while on the other hand, flash floods — if and when they arise — can also cause serious flood disasters. It is almost impossible to prevent flash floods completely since they usually arrive unexpectedly. Nevertheless, we can adopt some effective measures in accordance with local conditions to reduce the loss of lives and property. However, what we should point out here is that continuing economic development and population increase means that the losses incurred through flash floods are also increasing. It has thus become a pressing task for us to take measures to lessen the damage caused by flash floods.

"Sharp and unexpected" are the two best key words to characterize a flash flood and its hydrograph. More formally, a flash flood can be defined as "a flood of short duration with a relativity high peak discharge" (WMO-UNESCO, 1974). The more extensive definition used by the National Weather Service (NWS, USA) is also interesting: "a flash flood is a flood that follows the causative event (excessive rain, dam or levee failure,. . . etc.) within a few hours".

It is useful to consider flash floods under two categories based on the type of the causative event. One is the formation of the "natural" flash floods, i.e. those which result from heavy rainfalls on natural catchments, or where an ice-dam breaks suddenly, or a glacier lake outbursts. The other is the formation of "artificial" flash floods. These can occur through the sudden release of impounded water by the failure of a dam or other man-made barrier.

## 1.2 Flash flood forecasting techniques and models

Flash flood forecasting techniques have no intrinsic difference from those used with normal floods. The key feature of flash flood forecasting is identify quickly when the forecast flow is greater than the flood threshold, and not attempt to forecast exactly the magnitude of peak flow and time of occurence. Hence, flash flood forecasting does not require complex models.

At present, there are many flash flood forecasting methods available, such as simple models based on rainfall intensity, deterministic-conceptual rainfall-runoff models, complex flood routing methods, synoptic radar forecasting methods, etc.

### 1.2.1 Forecasting methods for storm flash floods

The principal techniques are hydrological methods, meteorological techniques, hydrometeorological methods, geographic and topographic methods and other models (rainfall-runoff forecasting models, the Rational formula model, the grey model, hydrometerorological models, etc.).

### 1.2. 2 The peak flow prediction methods for glacier lake flash floods

The magnitude of glacier lake outburst floods depends upon the ice dam height. The formation of a glacier lake is determined entirely by the creation of an ice-dam; the dynamic changes in the height and length of the ice-dam are related to the glacier moving forwards and backwards which in turn is related to changes in precipitation and air temperature. There are simple empirical versions of peak flow equations and numerical modelling of the flood hydrograph.

### 1.2.3 Forecasting methods for dyke-breaks and dam-break floods

Dam-breaks (dyke-breaks) occur in several ways, so we may adopt different methods for forecasting these floods according to the different conditions.

## 1.3 Strategies for flash flood prevention

There have been many articles published in recent years concerning flash flood prevention. The US Corps of Engineers pamphlet *Community Decision* (published in 1974) proposed many practical measures and discussed their advantages and disadvantages. The most frequently used measures may be divided into two kinds: engineering and non-engineering procedures.

### 1.3.1 Engineering measures

Using engineering measures to control flooding and lessen flood damage is a traditional method adopted all over the world in dealing with flood problems. Perhaps with improvements in science and technology and enhancement in financial capacity, engineering measures will play an even greater role. But because of the different natural geographical conditions and flood properties, the specific content of each engineering measure varies from place to place and will also differ from those in other geographic regions.

The major methods are: river basin management, the building of flood diversion storage works and creation of flood retention areas, clearing away obstacles in the water course, building flood protection dykes, etc. An example of river basin management to reduce surface flow is the creation of flood diversion and flood interception shallow ditches along the contour line as the river leaves the mountains and enters the flood plain. We can also make terraces and check dams on slopes and do some contour ploughing as supplementary measures. In this way, on the one hand we can weaken the power of the flood very effectively, reduce the flood peak and lessen the harm to the downstream area; on the other hand, the flood waters can quickly infiltrate into the ground, where some can percolate into groundwater and be stored in the aquifer or underground reservoir. The utilization of the water resource can thus be greatly increased. In the Weigan River, XinJiang, China, we have achieved notable results in flood peak reduction by means of flood diversion and flood interception channels.

### 1.3.2 Non-engineering measures

Non-engineering measures can change the susceptibility and influence of a flood. Land-use planning, flood forecasting and warning, and property protection are the main techniques adopted to change the subsceptibility, while flood insurance, flood rescue and public warnings are the main means of changing the influence of a flood. Thus, to formulate a better flood protection plan, all kinds of protection measures should be combined.

Non-engineering measures have mainly established unified command and disaster management systems, established monitoring, forecasting and warning systems and devoted major efforts in afforestation, establishing systems of flood disaster evaluation and policy-making, flood insurance, and emergency services.

There are many ways to prevent a flash flood but no matter how well each separate method works, its effect is always limited; it has both advantages and disadvantages, and no one method can be used instead of others. The best way is to plan according to local conditions, trying to make the best use of combined methods, and especially be paying attention to non-engineering measures.

## 1.4 Conclusions

One-third of the world's land surface may be classified as arid and semi-arid. Because flash floods are of short duration and such regions have poor vegetation cover and loose surface soils, flash floods bring about much destruction. Research into flood forecasting techniques (in particular, simple methods) and strategies for flash flood prevention (particularly non-engineering measures) are therefore highly important.

## Further reading

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# 2. Hydrological results of cloud seeding in Israel

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## 2.1 Background

Consistent cloud seeding has been carried out in Israel since 1960. It aims at enhancing precipitation over three target areas located in northern, central and southern Israel. Control areas, enabling assessment of the effects, are left west to the northern and southwest to the southern target areas. A buffer area is left between the northern and the central target areas (see Fig. 2.1).

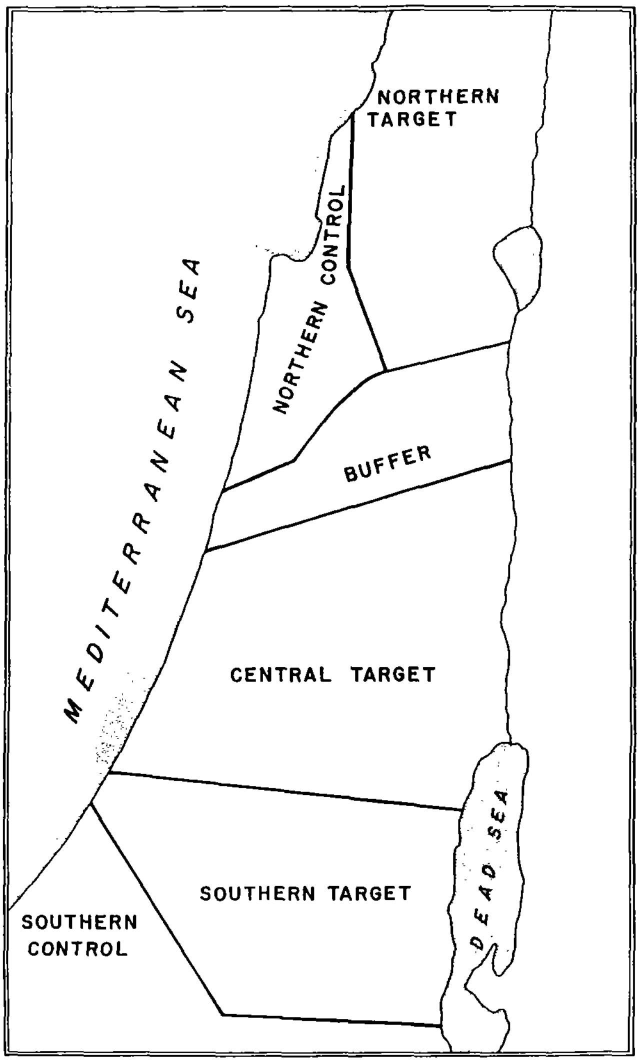

*Fig. 2.1 Map of study area*

***Table 2.1*** *Summary of seeding periods and areas*

| *Years* / ***Area:*** | ***NC*** | ***N*** | ***B*** | ***C*** | ***S*** | ***S7*** |
|---|---|---|---|---|---|---|
| 1960 to 1966/67 | E1 | E1 | U | E1 | U | U |
| 1967/69 t01968/69 | O | O | U | O | U | U |
| 1969/70 to 1974/75 | U | E2 | U | E2 | E2. | E2 |
| 1975/76 to 1994/95 | U | O | U | E3 | E3 | U |

*Legend:* NC is northern control; N is northern target; B is buffer; C is central target; S is southern tarrget; S7 is southern control; E is experimental seeding where following numbers define experiments; O is operational seeding; and U is unseeded.

The seeding is managed in two modes: experimental and operational. Operational seeding is carried out during the seeding season of November through April, whenever suitable meteorological conditions prevail. Experimental seeding is limited also to randomly pre-allocated days. The distribution of seeding activities with respect to areas, modes, and years is presented in Table 2.1.

The effect of seeding on depth of precipitation has been assessed, so far, for the first two experiments and for the operational seeding over the northern target area. Gagin and Neumann (1974) found a statistically significant increase of 15% for the first experiment over the northern and central target areas together. Gagin and Neumann (1981) found a statistically significant increase of 13% for the second experiment over the northern target area. Gabriel and Rosenfeld (1990) confirmed the results of Gagin and Neumann (1981) and added a statistically insignificant small decrease in precipitation for the second experiment over the central and southern target areas together. Nirel and Rosenfeld (1995) found a statistically significant increase of 7% for the operational seeding over the northern target area. The results of the third experiment have not yet been assessed.

## 2.2 Hydrological analysis

The seeding is carried out in order to augment water yield, but the experiments are designed so as to enable efficient assessment of the effects on depth of precipitation. Presuming a monotonic relationship between depth of precipitation and water yield, it can be concluded that a positive effect on the former variable should result in a positive effect on the latter one also. This conclusion, however, can support only qualitative estimation rather than a quantitative assessment of the yield. Owing to the non-uniqueness of precipitation–runoff relationships, preparation of quantitative assessments requires analyses of hydrological data.

Suitable hydrological data should pertain to systems whose replenishment areas lie within seeding target areas, their response times are short with respect to the seeding time units, and whose hydrological behaviour is not subjected to any man-induced change (other than the seeding) during the observation period of the analysed data. Since no hydrological system was specifically instrumented for monitoring results of cloud seeding, the studied systems ought to be selected from those instrumented for other purposes. This situation limits the availability of suitable data series.

Data analyses in Israel were carried out by use of the double ratio and the linear regression models. The double ratio, *DR*, is defined as:

$$DR = X_s C_u / (X_u C_s) \tag{2.1}$$

where $X$ is the mean of the examined variable, $C$ is the mean of the concurrently measured control variable, and subscripts $s$ and $u$ refer, respectively, to data observed under seeded and unseeded conditions.

Application of the linear regression model is carried out through the following equations:

$$D_{si} = X_{si} - (a_u C_{si} + b_u) \tag{2}$$

$$D_{ui} = X_{ui} - (a_s C_{ui} + b_s) \tag{3}$$

$$E = (\text{Mean}(D_{si}) - \text{Mean}(D_{ui}))/2 \tag{4}$$

where $X_i$ and $C_i$ are individual values of the variables, $D$ is the difference between measured and computed data, $E$ is the effect of seeding, $i$ enumerates time units, and $a$ and $b$ are parameters obtained by simple linear regressions carried out separately for seeded and for unseeded conditions. Use of the regression model was limited to cases where the parameter values had been obtained for sufficiently high correlated values of the $X_i$s and the $C_i$s. In most studies this limit was set to $R^2 \geq 0.49$ and in the others to $R^2 \geq 0.36$, where $R^2$ is the squared correlation coefficient.

An agreement between the results of the two models is assumed to exist when:

$$DR - 1 - E/X_u \leq 0.05 \tag{5}$$

Such an agreement was found for almost all of the cases described below yet, it should be mentioned, owing to correlation limitations, the linear regression model was not applied to many data series pertaining to the case studies.

The hydrological systems studied include small catchments, seasonal springs and the Lake Kinneret basin. Owing to shortage of hydrological control systems, depths of precipitation at the control areas served as controls for the hydrological studies. Depths of precipitation over the replenishment areas of the hydrological systems served for distinction between hydrological and meteorological effects. The hydrological assessments obtained are not statistically significant but they are consistent among themselves and with the meteorological results.

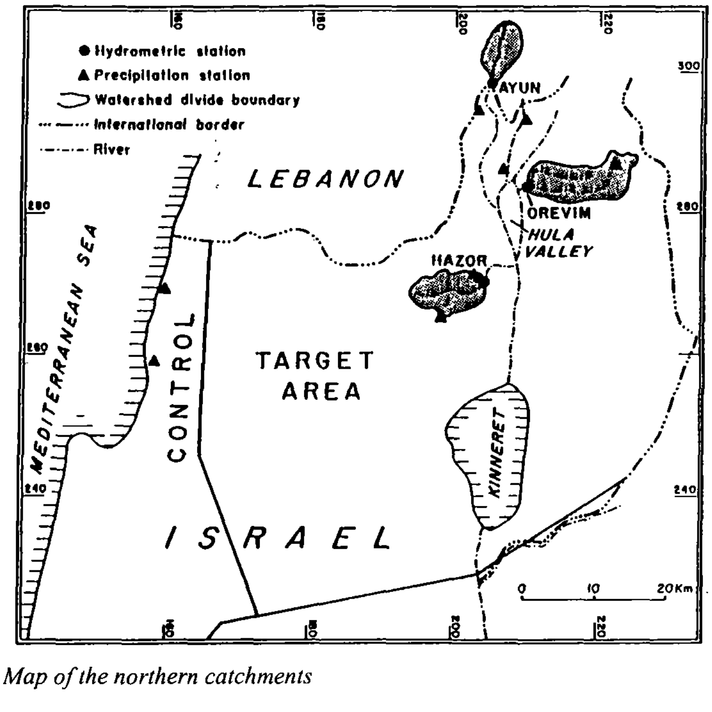

Fig. 2.2 Map of the northern catchments

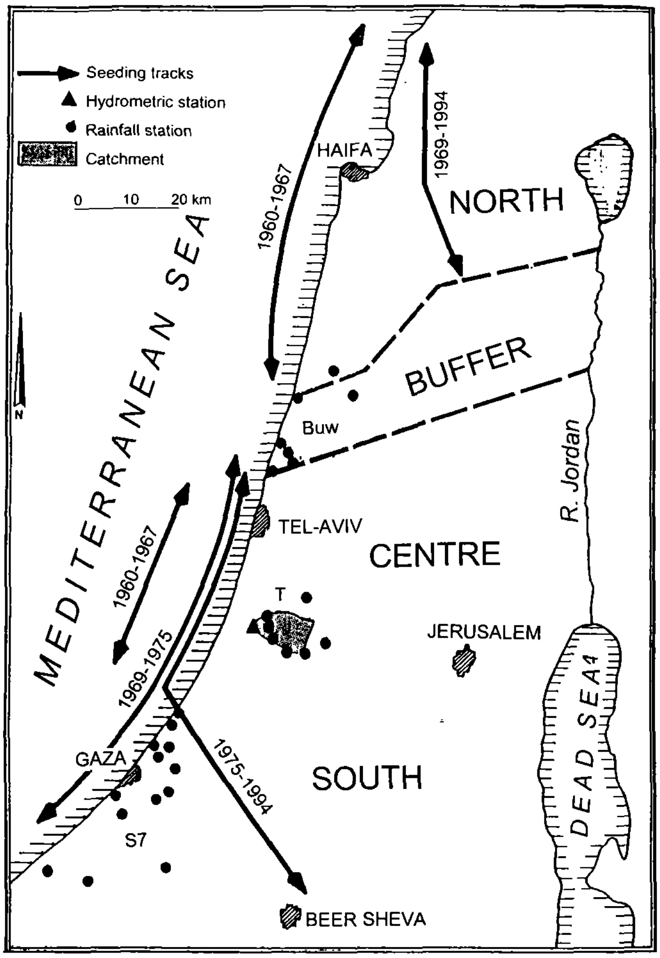

*Fig.2.3* *Map of central catchment*

## 2.3 Direct runoff

Effects of cloud seeding on direct surface runoff was assessed for four small catchments (Ben-Zvi 1988; Ben-Zvi and Langerman 1993; Ben-Zvi and Fanar 1995). Three of the catchments lie within the northern target area and one in the central area, as shown in Figs 2.2 and 2.3.

The response times of the study catchments are a few hours and therefore the assessments could apply daily data observed during experimental periods when the seeding was randomly allocated. The observation period for the northern catchments covered the second experiment and that for the central catchment covered almost 30 years of experiments.

A low baseflow and a certain carry-over flow from day to day were observed in the data for two of the northern and for the central catchment. These components were separated from the immediate runoff by use of a variation of the exponentially decay model. In this variation, the parameter of the model varies with the discharge, thus introducing a certain non-linearity into the computations.

The analyses reveal that the number of runoff days under seeded conditions was more abundant than that under unseeded ones. The ratio of seeded to unseeded runoff days was 2.60 for the watershed with no carry-over flow (Ben-Zvi 1988), 1.33 for the two other northern catchments (Ben-Zvi and Langerman 1993), and 1.17 for the central catchment (Ben-Zvi and Fanar 1995).

Another important result concerns the differences in precipitation–runoff relationships between seeded and unseeded conditions. An example of this difference is depicted in Fig. 4 (Ben-Zvi 1988). In this example, daily volumes of runoff are plotted against daily depths of precipitation over the catchment. The regression lines for non-leading runoff days (i.e. days preceded by other runoff days) differ between seeded and unseeded conditions. A similar difference was

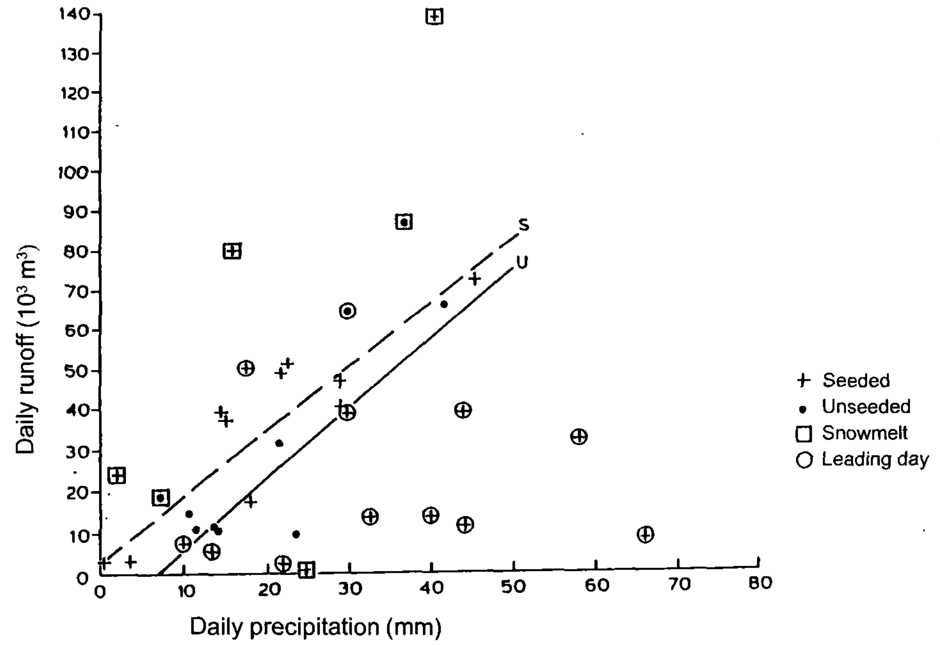

*Fig. 2.4* *Precipitation–runoff relationships for a northern catchment*

found for the regression on the control precipitation. With respect to the control, total volumes of immediate runoff from the three northern catchments are doubled (Ben-Zvi 1988; Ben-Zvi and Langerman 1993). The augmentation is composed of both an increase in the daily volume of flow as well as in the frequency of occurrence of runoff days.

The results for the central watershed are considerably lower. An increase in the number of runoff days and in the daily volume of runoff was found here too, but to a lesser degree. With respect to the controls, augmentation of total runoff is assessed as being only 36% (Ben-Zvi and Fanar 1995).

Analysis of the distribution of daily volumes of runoff from the central watershed revealed

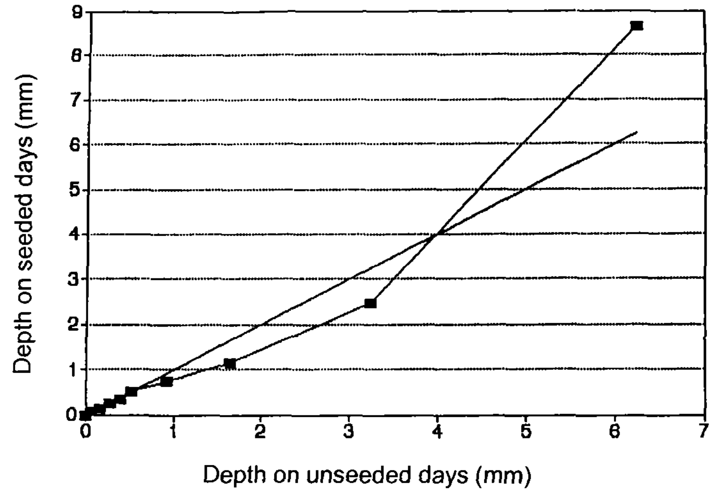

*Fig. 2.5* *Distribution of runoff days for the central catchment*

that the effect of seeding was not monotonic. Despite the 19% increase in the number of runoff days under seeded conditions, the lower 50% of the volumes for seeded days and the lower 50% of the volumes for unseeded days are identically distributed. The upper 10% point for seeded days is almost 1.5 times higher than that for unseeded days. On the contrary, the 20 - 40% points for the seeded days are lower than those for the unseeded days (see Fig. 2.5).

## 2.4 Springflow

Volumes of flow from seasonal springs reflect seasonal replenishment of groundwater sources. The effect of seeding on these sources was assessed by use of Eqns. 2.1–2.5, where $x_i$s and $C_i$s are annual values of the proper variables. The unseeded values had been recorded prior to the initiation of seeding in Israel. Owing to probable variations in climatic, land use, and computational conditions, such historical comparisons of data are weaker than those carried out on randomly allocated data (e.g. Gabriel and Petrondas 1983; Nirel and Rosenfeld 1995).

Data for nine springs, located in the northern target area of Israel, were analysed (Ben-Zvi 1990). Locations of these springs and of the relevant precipitation stations are shown in Fig. 2.6. The results varied between springs and periods of analysis. The assessment was carried out using

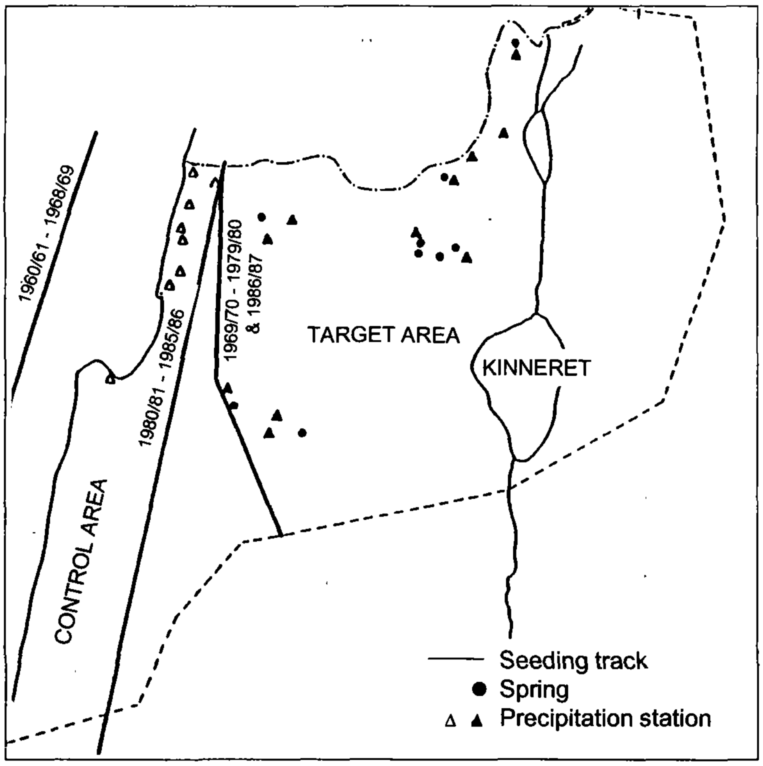

*Fig. 2.6 Map of springs*

a number of averaging techniques. For the operational seeding from 1975/76 to 1986/87, an 11% increase was found through a simple average, a 12% increase through a principal component averaging, and a 22% through a volume-weighted averaging. The last figure is heavily dependent upon the results for the three most northern springs whose total volume is twice as high as that of the six other springs. This difference may reflect a northward increase in the effect of seeding within the northern target area.

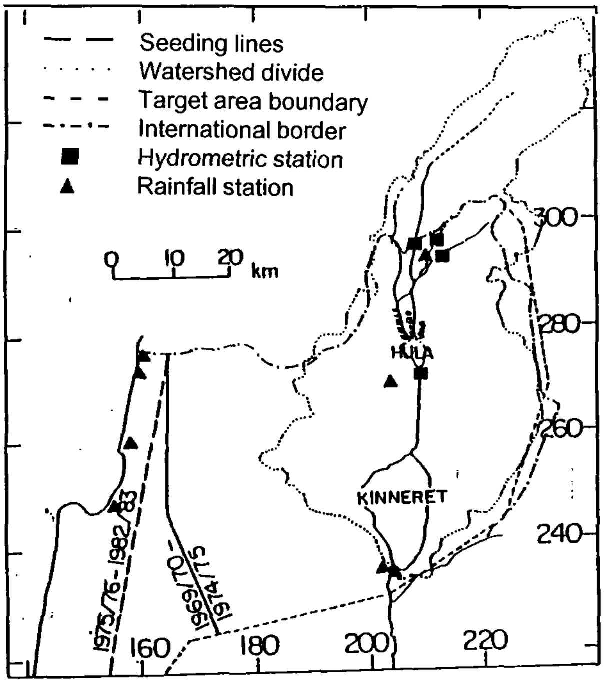

*Fig. 2.7 Map of the Lake Kinneret basin*

### 2.5 Kinneret basin

Augmentation of the water yield of Lake Kinneret is a principal aim for cloud seeding in Israel. Therefore, assessment of this augmentation is important for management of the seeding project. The effects on the total flow to the lake, and from major sectors of the catchment, were assessed by Ben-Zvi and Langerman (1989). Locations of the hydrometric and meteorological stations, whose records were used for this assessment, are shown in Fig. 2.7.

The analysis was carried out on data for the years 1969/70 through 1982/83, which include the second experimental period and a number of operational seeding years. The comparisons were made against precipitation records at the northern control area, at the target area, and at the southern edge of the northern target area where the effect of seeding is marginal.

With respect to the control, a 6% increase was noted for the sectors affected by the seeding during the operational seeding period. Streamflow from a sector which lies to the north of the target area and precipitation at the edge stations decreased by 5% relative to the unseeded period and to the depth of precipitation at the control. Hypothesizing from this decrease that the natural precipitation over the entire watershed would have declined, the rate of augentation from the affected sector becomes higher than the above assessment. However, as long as this hypothesis is not supported by additional evidence, its results cannot substantiate the figure obtained through direct comparisons with the control records.

## 2.6 Discussion and conclusions

The hydrological results of cloud seeding in Israel are found to be consistent with meteorological ones, with the former higher where the latter are higher. The rate of augmentation of flow varies with the type of hydrological system: the more sensitive the system is to precipitation, the higher is the rate of augmentation.

The rate of augmentation of direct surface runoff is about eight times higher than that of its causative precipitation. Gagin and Neumann (1981) found a 26% increase in the depth of precipitation over the central sector of the Kinneret basin during the second experiment. In comparison, Ben-Zvi (1988) and Ben~Zvi and Langerman (1993) found a doubling of direct surface runoff around that area during the same period. Ben-Zvi and Fanar (1995) found a 4% increase in the precipitation over a small catchment in the central target area for almost 30 years of experimentation; they also found a 36% increase in the runoff from this watershed during that time.

Nirel and Rosenfeld (1995) found a 7% increase in the rate of precipitation over the northern target area during the operational seeding period. In comparison, Ben-Zvi (1990) found an 11% increase in springflow in that area during a similar period, and Ben-Zvi and Langerman (1989) found a 6% increase in total flow from the affected sectors of the Kinneret watershed during most of that period. This indicates that the rate of augmentation of springflow is 1.5 times higher than that of precipitation, while that of total flow is similar to the rate of precipitation enhancement.

The non-linearity in the response of hydrological systems to variations in precipitation is based upon well accepted hydrological theories. The differences in the rate of non-linearity can be attributed to two independent processes. One of them is the replenishment mechanism of the flow. Direct surface runoff commences only after infiltration capacity has been fulfilled and percolation towards aquifers has already commenced. Under the Israeli conditions, direct surface runoff comprises on average about 2 to 3% of precipitation volume, whereas groundwater replenishment comprises on average about 25% of that volume. Being a radically residual process, direct surface runoff is highly sensitive to variations in the properties of precipitation.

The other process concerns translation of the effect of precipitation within hydrological systems. Long response times are associated with a large resistance to the flow and a large decaying effect. As a result, systems with long response times are less sensitive to variations in the causative precipitation, and respond more gradually and more linearly. Therefore, detection of non-linear effects on such systems requires analyses of longer series of data.

The difference found in values of the linear regression parameters between seeded and unseeded conditions deserves particular attention. Noting that the seeded values indicate a relatively higher rate of flow with respect to depth of precipitation, that difference ought to be attributed to positive effects of the seeding on properties of rainfall — other than its depth — which are involved with the hydrological processes. Ben-Zvi (1989) related, through mechanical considerations, observed increases in duration, intensity and spatial correlation of rainfall to observed increases in area, depth, precipitation intensity, and precipitation volume of seeded clouds. This relation provides a physical plausibilty for the effect of seeding on the precipitation–runoff relationship. It is advisable, therefore, to consider such effects in applications of models for estimating hydrological results of cloud seeding, and probably of other climatic changes.

Lastly, it should be mentioned here that although cloud seeding has not yet resulted in dramatic augmentation in flow volumes, the values already assessed indicate that the cloud seeding project in Israel is economically feasible. Further research is being carried out in order to improve the effects.

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# 3. Conditions of surface water formation in the arid and semi-arid zones

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## 3.1 Introduction

This paper is a brief accountt of the peculiarities of surface flow prediction in arid climate zones, using as an example the Aral Sea basin, famous for ecological and social impacts. Results from analyses indicate that:

- there are differences in surface flow formation in different parts of the river basin.
- specific components of surface flow were identified for each zone of river basin.
- forecasting of the separate components of surface flow increases the accuracy of assessments.

These results are signticant for the future planmng of water resources management in the framework of the regional water strategy, the further development of which is now being carried out in the Aral Sea basin by specialists from five states with support from the World Bank.

## 3.2 The zoning of a river basin in the arid and semi-arid regions

The peculiarity of the arid zone is that each river basin may be divided into the following main zones: a zone of surface flow formation, then a zone of flow transit and dissipation and finally, the delta zone. The boundary of the flow formation zone is situated in the mountainous periphery and, depending on local conditions, within an altitude of 700-1500 m. In the mountains, where surface and underground flow originates, there are about 12,000-15,000 rivers and ephemeral streams, and a lot of lakes of tectonic origin. In general, there are no significant signs of anthropogenic changes in this flow formation zone but, due to the construction of dams and power stations, the runoff regime changes abruptly at the outlet from this zone. In the flow transit and dissipation zone the runoff and indeed the whole hydrological cycle are changing as a consequence of the anthropogenic interaction between river and land, i.e. in the form of water intakes from the river and the discharge of return flows.

The main factor influencing the hydrological cycle is the volume of non-returnable water consumption, identified as a ratio between water intake and return flow. When the volume of water intake increases in the dissipation zone the runoff to the deltas decreases and ecological damage increases at the outlet from this zone. Today, anthropogenic impacts are influencing this thousands-of-years-old hydrological cycle as various water users, in the interests of their sectors of the economy, accelerate the processes of the natural hydrological cycle.

Accordingly, in each of the three zones, water generates economically and socially valuable products. In the flow formation zone, it is hydropower and recreation; in the transit and dissipation zone, where the major proportion of the population and the economy is situated, it is industry, agriculture and social requirements; at the delta it is fish farming, cattle and other types of production.

The anthropogenic impacts have both a positive and negative influence on the ecology. It should be noted, however, that the biggest part of the negative impacts could be prevented by the implementation of a set of special measures. The greatest success can be achieved by more efficient water resources management. As such measures must be long-term, we have to pay attention firstly to the problem of prospective planning (with the period of prediction being 1-5 and more years). The efficiency of management procedures depends heavily on the accuracy of water resources forecasting. [It was said by Napoleon that he could have achieved victory, if only he could have predicted the situation more correctly.]

From this point of view, the peculiarity of water resources forecasting in the arid zone is the nescessity of elaborating separately the different methods and approaches for prediction of the of natural river flow in the flow formation zone and the particular genetic components of surface water resources in the transit and dissipation zone. The main task in the flow formation zone is to assess the sustainable sources of river inputs, and to estimate the mean values for each source. For the transit and dissipation zone it is to assess the conditions of return flow formation and relationship between the return flow and the river. Particularly, the subsurface component of return flow, which acts as abuffer between the river flow and underground water.

## 3.3 The peculiarities of surface water resources forecasting in the zoneof flow formation

Because of the large number of factors influencing river flow formation (geophysical, geographical and anthropogenic), it has to be considered as an integrated parameter. The variability and mutual relationship of these factors have not been investigated enough and we have to use a more modern technique to assess this process. The river flow in arid and semi-arid zones arises as the result of seasonal snow-melt, glaciers melting and underground water issuing out at the surface. Thus, we may consider river flow to be the aggregation of three generic components: snow, glacier and subsurface. Such differentiation of flow allows a reduction in the quantity of factors to be taken into account in the process of river flow calculation.

There are a few methods available for river flow partition into generic parts but a more simple approach is to draw a line over the lower points on a hydrograph where it passes through a section equal to baseflow. The remaining part of hydrograph is divided into two parts: up to 1st July, it is the snow component; after the 1st July, the glacier component. The tentative halving of the hydrograph at a key date (1st July ) removes the need for assessment of the actual value of these components. Another method for river flow partition into generic components is where the subsurface component is calculated as base flow by an empirical formula such as:

$$U = Qo \bullet t\,(1 - \mathrm{EXP}\,(-T/t)) \qquad (3.1)$$

where : $U$ = the volume of basic underground flow; $Qo$ = average discharge in the month before the beginning of the hydrological year; $t$ = the period of draining the baseflow in $e$ time ($e$ = 2,7182); $T$ = duration of the hydrological year.

Further, by the method of the famous Central Asian hydrologist, V. Konovalov, we can estimate the glacier component. The volume of glacier melting is calculated as:

$$V = [(S - Sm) + f(h) \bullet Sm] \bullet Ms \bullet T' \qquad (3.2)$$

where: $V$ = the volume of glacier component; $Ms$ = the intensity of glacier melting, average for summer; $S$ = the area of glacier without the snow cover, $Sm$ = the area of glacier under morena; $T'$

= time of glacier melting, $f(h)$ function of reaction of glacier melting under morena.

V. Konovalov gave the following formulae for the calculation of the intensity of glacier melting:

$$Ms = a \bullet [TnR(Zo) + \mu \bullet Zo] + b - a \bullet \mu \bullet .Zav \tag{3.3}$$

where : $Tn(Zo)$ = temperature of air at the height of meteostation $Zo$; $\mu$ = the vertical gradient of the temperature of air; $Zav$ = average weighted height of open part of glacier; $a$ , $b$ = parameters of the equation. The difference between the total flow, subsurface and glacier components is the volume of the snow component.

Special investigations were conducted by SANIHU to select the mathematical models for calculation of the total flow and its generic components for the main rivers of Central Asia. The model selection was based on autoregression analysis by the criterion of maximum entropy. In the theory of probability, the entropy is the measure of indeterminacy of a situation (random number). This measure was calculated using the well-known technique.

These investigation showed that the snow component is the most stable factor. The autoregression with exponent number two is the optimal model for the biggest number of rivers of Central Asia. It means that a two-year periodicity exists in the variations of this component. Likewise, the subsurface component is a sufficiently stable factor in the zone of flow formation. However, in the flow transit and dissipation zone, the subsurface component of river flow is fully dependent upon the anthropogenic impacts factor because it acts as a buffer between river flow and subsurface flow, and about 15-60 % of its volume is the return flow. The criterion of maximum entropy showed that very often the optimal model for total flow and glacier component is the autoregression with exponent number zero. It means, therefore, that the variations in these components is "white noise". In the other words, no stable behaviour was found in the variations of these components.

There is thus a wide range of activity on the development of new methods for assessment of the generic components of natural river flow in recent hydrological research. The same problem occurs in the transit and dissipation zone. The peculiarity of this zone is the full transformation of river flow under human activity. It is possible to assess the volume of transformation on the basis of prospective water balances (the river chanel for main rivers and the extent of contributing area). Moreover, as in the case of the flow formation zone, we are able to increase the accuracy of assessment by partition of surface water resources into generic components. After this we can investigate in more detail the formation mechanism of each generic component separately.

## 3.3 The peculiarities of surface flow forecasting in the transit and dissipation zone

The characteristic of arid zones is the full use of river flow in the transit and dissipation zone. The flow in the river channel here is the so-called "lateral flow" that appears as return flow from the active area. By "lateral flow" we understand this to mean the inflow to the river from that part of a catchment situated between two gauging stations on the river. Based on the well-known water balance equation for each separate reach of a river, it is possible to find the lateral flow ($Yl$) as a sum of the following components:

$$Yl = Ym + Ydr \pm Ysub \tag{3.4}$$

where : $Ym$ = disharge of water in the mouth of tributaries; $Ydr$ = drainage flow to the river in a collector-drainage network; $Ysub$ = the component that we call "underchannel flow" – the subsurface flow that outcrops to the suface and into a river as the natural drain. It should be noted that this volume can have both possitive and negative meaning (losses), and carries within it all the errors of measurements and calculations.

It is clear that the structure of lateral flow changes significantly through anthropogenic impacts. For instance, analysis of balances for the Syr Darya river basin, based on the data series up to 1990, shows that in the last 50 years the structure of the lateral flow changed as follows. Up to the 1940s, the volume of the lateral flow constitutes the flow at the mouth of the tributaries, i.e. about 80% of total flow, of which 20% was the underchannel flow. The lateral flow now constitutes (in different regions of basin ) 40-60% collector-drainage water, 30-50 % underchannel flow, and only 10-20 % is tributary flow (often reaching the main river in the form of a flash flood).

The collector-drainage water is the principal pollutant of the surrounding water. It is return water that has an anthropogenic origin and is made up of two components. The surface component of return flow is formed by the drainage from irrigated areas, losses from the irrigation network, and also from water pumping by vertical drainage systems. The subsurface component of these waters is formed as a result of infiltration in the irrigated fields and from the irrigation network, the infiltrated water feeding the groundwater and fully or partly outcropping to the collector-drainage system. Investigation of the mechanism of collector-drainage flow formation showed that there is a very close correlation between water withdrawal for irrigation and return of drainage flow, taking into account the lag time for drainage. There is the explicit trend of the volume of drainage flow increasing with time that depends on increased land use and expansion in drainage construction. Besides this, the volume of collector-drainage flow is not equal year to year because of differing water availability, even if the other conditions are the same.

The investigation of subchannel flow formation showed that its volume depends on, mainly, the relation of water level in the river with that of groundwater. The variation in time of this relationship is caused by either natural or anthropogenic factors. The natural factors concern the water availability of the catchment area (i.e. that which is caused by surface inflow from the upper zone) in the given year and in the preceding year. It is clear that there is water moving into the soil as a result of water level rising in the river channel during a wet year. The reverse process follows after a dry year. Anthropogenic factors take effect as a result of the following:

- increases in groundwater level and decreasing river water level due to expansion in irrigation;
- hydrostatic upthrust in the region of large reservoirs;
- decreasing groundwater level as a result of drainage construction;
- pumping groundwater from the strata connected to the river channel.

The first two factors increase the volume of subchannel flow: the last two have the opposite effect.

As noted above, one of the peculiarities of Central Asia is that subchannel flow acts as a buffer between surface and groundwaters. The regional investigations showed that pumping of groundwater reduces the surface flow in the zone of transit and dissipation. As a rule, this reduction is equal to the volume of pumping from the stratum in hydraulic connection with surface streams. Usually, the biggest reduction in surface flow happens in a wet year that comes just after a dry year. For instance, under recent conditions the maximum reduction in the Fergana valley within the Syr Darya river basin is about 65% of total volume of pumping from groundwater. In the Chircik river valley (near Tashkent) this amounted to about 55%.

The water resources management in the transit and dissipation zone has to take into consideration the re-use of collector-drainage flow. This re-use is limited by the quality of these waters or by the extent of cleansing necessary. The quantity of collector-drainage flow will be reduced due to reconstruction of irrigation systems and implementation of an optimum reclamation regime. At the same time, there will be expansion in industry and further development in sewage collection systems, as a result of which the volume of wastewater outflow will increase. Thus, the total volume of the water resources available for use will be fairly stable in the next 25 years but for planning purposes, we have to take into account the reduction of surface flow under the influence of groundwater pumping.

# 4. Water management strategies for reservoirs in an arid climate (Jequitinhonha Valley, Brazil)

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## 4.1 Introduction

The Jequitinhonha Valley, located in the state of Minas Gerais, Brazil, is characterised by being inhabited by a very low income population. Due mainly to the unfavourable climate (classified as being between arid and semi-arid) with mean annual maximum temperatures between 30 and 32°C and pluviometric precipitation (mean of 800 mm) concentrated in the summer (November-March), the population is subjected to severe problems, such as the periodic lack of water, the inherent difficulties in developing agricultural activities and the absence of an adequate sanitation structure.

The geology of the region is dominated by rocks from the Archeozoic period, partially covered by sediments from the Tertiary/Quaternary periods. Mineral exploitation relates mainly to quartz, lithium, gold and semi-precious stones. Latosols prevail throughout the area, followed by podzolic soils. Over 50% of the drainage basin is occupied by agriculture, characterised by a very low degree of mechanisation and by scarce utilisation of chemical fertilisers. The vegetation cover has a rich floristic diversity due to the fact that the area is situated in a transition zone between *caatinga* (i.e. having small trees, typical of arid areas) and tropical forest.

In the late 1980s the local government began the construction of storage reservoirs, planned to act as multiple-use water bodies, to serve chiefly as permanent sources of water for human supply and agricultural purposes (irrigation). Table 4.1 gives details of these reservoirs.

***Table 4.1*** *Physical characteristics of the reservoirs*

| *Reservoirs* | *Drainage area (km²)* | *Area of the reservoir (km²)* | *Mean depth (m)* | *Water residence time (yrs)* |
|---|---|---|---|---|
| Machado Mineiro | 10510 | 21.3 | 9.5 | 0.3 |
| Salinas | 1180 | 12.7 | 6.7 | 1.2 |
| Bananal | 230 | 3.3 | 7.6 | 1.2 |
| Samambaia | 680 | 3.2 | 8.0 | 1.2 |
| Calhauzinho | 530 | 2.7 | 11.9 | 1.1 |
| Caraíbas | 160 | 1.3 | 7.6 | 1.2 |

## 4.2 Hydrological aspects

The reservoirs were constructed in the region drained by the Jequitinhonha River, whose hydrological characteristics are strongly influenced by a typical precipitation pattern. In the initial stretch of the river the mean specific flow reaches values in the range of 8 to 10 l $s^{-1}$ $km^{-2}$. Through the middle course of the river, where the reservoirs were built, the specific flow oscillates between

3 and 4 l $s^{-1}$ $km^{-2}$.

Groundwater flow, originating from a tertiary rocks system, is not significant because of the small thickness of the saturated layer. The wells drilled in the region rarely show water flows above 25 $m^3$ $h^{-1}$.

The regulated flows for supply purposes are quite variable, ranging from 0.02 to 3.5 $m^3$ $s^{-1}$. The outflow of each reservoir (deep water discharge) is regulated according to local needs and the period of the year.

## 4.3 Surface water conditions

The reservoirs have been monitored since December 1990 at quarterly intervals. The general results of the monitoring point to satisfactory water quality at the surface of the reservoirs but with the opposite taking place in the bottom, as is usually the case in lakes and reservoirs. The most critical situation for the surface waters occurs during the dry period (winter time) when the reservoirs are subjected to an intensive circulation of the water mass. The thermal pattern in the reservoirs shows that they are generally stratified during most of the year. The destratification occurs only during some weeks in the winter period (June-July).

The phosphorus concentration is considerably higher during the rainy period, indicating that phosphorus compounds are washed out from the soil surface. The opposite situation is observed for ammonium, whose maximum concentrations are registered during the dry period, probably as a consequence of good retention in the soil during the rainy season. The ratio between nitrogen and phosphorus, calculated as mean values, varies between 69 and 442, indicating that, in all cases, phosphorus assumes the role of the limiting nutrient.

Analysis of the phytoplankton densities indicates the regular occurrence of intense algal blooms (up to 20,000,000 ind/l) in the summer time, specially after the incidence of heavy rainfall. This phenomenon happens — with different degrees of intensity— in all the reservoirs, highlighting the influence of the transported nutrients in the formation of the blooms. They are all caused by cyanophytes, particularly the species *Oscillatoria sp., Raphidiopsis sp.* and *Microcystis aeruginosa.*

Because of the water quality problems derived from the eutrophication of the reservoirs, a study was carried out to evaluate the nutrient load (especially phosphorus) to the water bodies. With this information, management measures can be taken to prevent or minimise the occurrence of algal blooms. In consideration of the absence of significant point sources of pollution (such as sewage discharges) the study focused on the evaluation of diffuse sources, represented mainly by soil erosion and vegetal matter fallen from trees. Thus soil and vegetation are here the only representative sources for the eutrophication of the perennialization reservoirs.

The methodology developed for the evaluation of the phosphorus load consisted of field work involving the sampling of soil and vegetation. For the vegetation sampling a wooden square of one $m^2$ was placed randomly over each type of vegetation over the ground in the various drainage areas of the reservoirs. This procedure was undertaken in the dry period and immediately after the first heavy rains. The difference in weight between these two samples (loose material within the frame) was considered to be the mass of material potentially transportable to the reservoirs. The composition of the collected material was analysed, with particular interest in the phosphorus fraction, considering that this element is here the limiting nutrient in the eutrophication process. For the estimation of the phosphorus load from the soil, several samples of the A-horizon of each soil type were collected. The Wischmeier equation of soil loss (Walling, 1988) was then applied, considering here the influence of diverse forcing factors (rainfall, soil erodibility, slope, use of soil, conservation practices). The sum of the contributions from the soil and the vegetation thus formed the total nutrient load to the reservoirs, as shown in Table 4.2.

*Table 4.2* *Estimated phosphorus load*

| *Reservoirs* | *P-load (kg $yr^{-1}$)* |
|---|---|
| Machado Mineiro | 63.700 |
| Salinas | 13.200 |
| Bananal | 18.100 |
| Samambaia | 7.600 |
| Calhauzinho | 10.100 |
| Caraibas | 1.800 |

The mass-balance models are currently utilized as a useful tool for the prediction of nutrient concentrations in the water body. The input parameters for the determination of the phosphorus concentration in the reservoirs are the areal nutrient load (from Table 4.2), the mean depth and the water residence time (from Table 4.1). The following mass balance models were compared: Chapra (1975), Chapra-Tarapchak (1976), Dillon-Kirchner (1975), Jone-Bachmann (1974), Larsen and Mercier (1976), Salas-Martino (1991), Vollenweider (1976) and Walker (1977).

The results (Table 4.3) show that the utilisation of models from the literature generally leads to values for phosphorus concentration considerably higher than those obtained from the monitoring of the reservoirs.

*Table 4.3* *Application of mass balance models*

| ***Reservoirs*** | ***L (g $m^2$ $a^{-1}$)*** | ***P-models (mg $l^{-1}$)*** | ***P-observed (mg $l^{-1}$)*** |
|---|---|---|---|
| Machado Mineiro | 3.0 | 0.042-0.067 | 0.043 |
| Salinas | 1.1 | 0.049-0.099 | 0.054 |
| Bananal | 5.5 | 0.245-0.491 | 0.088 |
| Sarnambaia | 2.3 | 0.044-0.183 | 0.111 |
| Calhauzinho | 3.8 | 0.112-0.398 | 0.053 |
| Caraíbas | 1.4 | 0.062-0.115 | 0.019 |

The difference between the observed and the estimated values lead to the following considerations:

- The nutrient load from the soil and vegetation could have been over-estimated, indicating the existence of an even higher retention capacity of the drainage basin;
- The reservoirs could also present an elevated nutrient net sedimentation, conducive to lower phosphorus values in the water mass. This is particularly true for tropical climates, where the more intense metabolism causes an acceleration in the processes of assimilation and sedimentation of nutrients (lower viscosity of the water) (Sperling, 1993)

## 4.4 Management strategies

One of the most conspicuous aspects regarding water resources problems in arid zones is related to management strategies. The scarcity of water is the most important constraint and leads to the necessity of adoption of measures to minimise its consumption.

The reservoirs described in this paper were projected to function as multiple-use water bodies. The main objective is to guarantee a minimum water flow downstream throughout the year. In addition to local usage, such as for bathing and clothes washing, the water should be available for use on a larger scale for irrigation purposes. This activity has a special meaning in the region, due primarily to the low level of nutrition for a majority of the population. Special attention should be paid to operational aspects of the reservoirs to minimise the frequent discharge of deep water during long periods of stratification. The reduced sulphur compounds, such as hydrogen sulfide, accumulated in the hypolimnion are quickly volatilised in contact with the atmosphere. Consequently, extremely bad odours are generated which led in many cases to a belief among the population in the existence of "rotten water". This problem stresses the absolute necessity for the development of educational campaigns, which are closely linked with the management strategies for the reservoirs.

Almost all the reservoirs (with the exception of Samambaia) were also developed for energy generation, with electricity generation ranging from 70 (Caraibas) to 3000 KW (Machado Mineiro). Considering the general good quality of the water, the use of the reservoirs for human supply was encouraged. In most cases only a simplified treatment (filtration and disinfection) was required before the water could be distributed to the population. The recreational aspects were also considered in relation to the management strategies, the main activities being swimming and fishing. In spite of a general lack of protein in the diet of the population living near the reservoirs, the consumption of fish was relatively low as a consequence of concern about the bad odours frequently generated in these water bodies (hypolimnetic discharge). Finally, the reservoirs could also function as flood control water bodies and as an important component of the harmony of the landscape .

## 4.5 Conclusions

The considerations presented here show that the management strategies for multiple use water bodies situated in arid regions should be based on the study of hydrological and ecological aspects:

- *hydrological approach*: scarcity of water, climate conditions, surface and groundwater flow;
- *ecological approach*: intense solar radiation leading to the establishment of productive systems, with high recycling rates and a very good nutrient assimilation capacity; consequently these systems are more resistant to pollutants loads.

The combination of both approaches should form the scientific basis for the implementation of management strategies. In this case the experience accumulated through the management of these reservoirs constitutes a solid contribution to the understanding of the structure and function of aquatic systems situated in arid climates.

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# 5. River flow forecasting in the mountainous area of central Asia using remote sensing data

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**(SANIGMI)**

One of the main objectives in hydrology is searching for remote sensing data application techniques for use river flow forecasting. Its actuality is determined by the fact that sometimes the satellite information is the only source of snow cover data in mountainous areas. This work considers river flow forecasting for the mountainous area of Central Asia (Fig.5.1) including acquisition, expertise, storage and statistical processing of data obtained at three levels of observation: ground — meteorological stations (MS); airborne — gamma-survey, airborne observations (AIRBORNE); space — artificial satellites, Meteorsat, NOAA (AES).

Data obtained at the first two observation levels is subject to preliminary analysis and after correction is put into the "Snow cover in mountains" data bank.

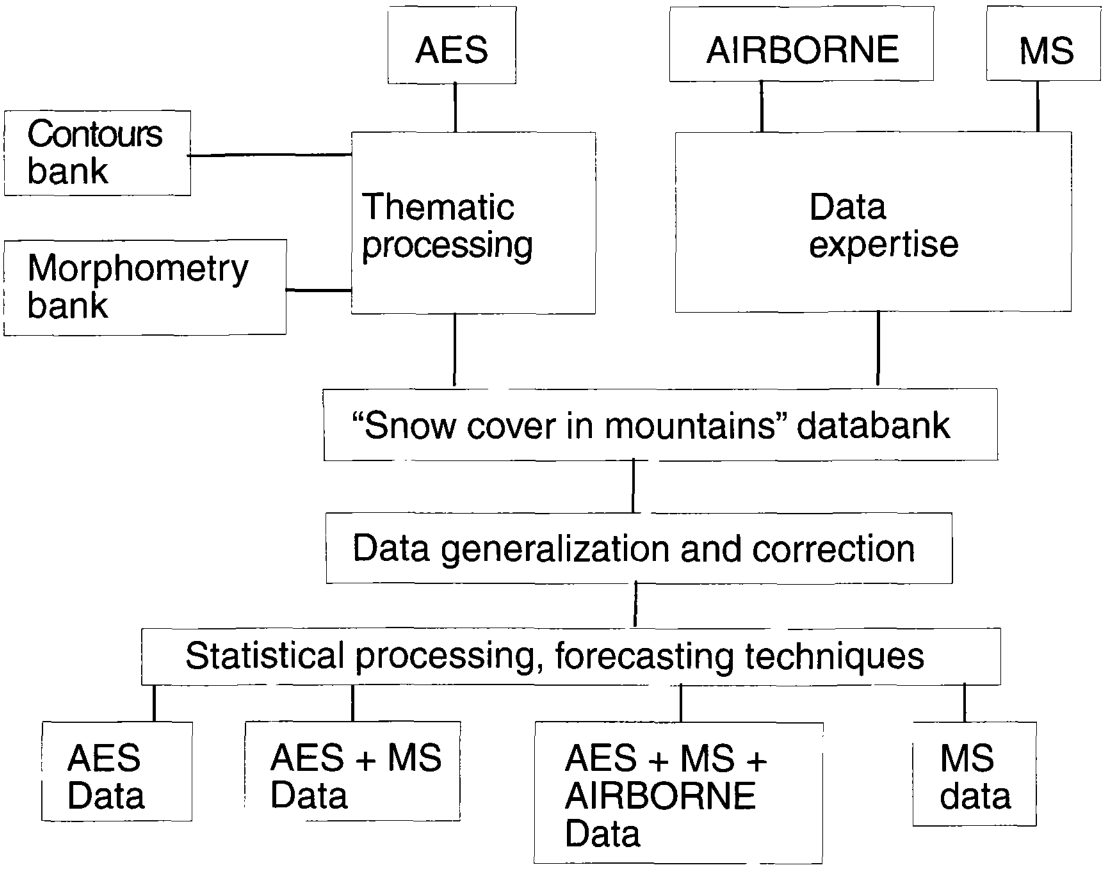

*Fig. 5.1 Svstem for forecasting mountainous river runoff in Central Asia*

Cartographic and morphometric basin characteristics are used in the thematic processing of meteorological satellite data for deriving information on the areal extent of snow cover in the basin, the seasonal snow line elevation at the end of the month and rate of their variation during the snow-melt period.

The techniques of the river runoff forecasting for different periods of time can be divided into four types depending on the combination of the predictors selected: I —satellite-only data; II satellite and ground data: III — data from all three observation levels; IV — ground-only data.

Data on the snow-line elevation obtained at the end of March/beginning of April during the formation of the maximum snow reserves in the basin are the most informative for flow prediction of the rivers. Firstly, it is most relevant to those rivers fed by snow- and glacier-melt. But for the big rivers with catchment areas of more that 100,000 km$^2$ and including dozens of separate sub-basins, it is expedient to use data on snow extent dynamics because even a single image can reveal the large variation in snow limits between separate catchments. Thus, for example, the data on the velocity of the reduction in snow extent ($V$) during snow melt are fairly informative for the upper part or the AmuDarya river basin ($F$ - 309,000 km$^2$ up to the Kerki site).

In this case we have the following equation for river runoff:

$$Q = A/V^B \tag{5.1}$$

where $Q$ = average water discharge for the vegetative period, m$^3$ s$^{-1}$, $V$ = average velocity of the reduction in snow extent in the basin estimated at the beginning of snowmelt (February-April) in % per day; $A$ and $B$ = coefficients selected by the least-squares method. The forecast reliability (%) computed using this approach is presented in Table 5.1.

For some individual basins the correlation equation between discharges and the seasonal snow line (SSL) elevation also has a hyperbolic form:

$$Q = A / (H_{SSL})^B \tag{5.2}$$

where the average water discharge $Q$ for the vegetative period or remaining flooding period is considered as the predictor while the seasonal snow-line elevation $H_{SSL}$ measured at the end of the month (usually March) is used as the predictor. Here $A$ and $B$ are parameters also estimated by the least squares method.

Such equations are used if there are no data (except satellite images of the snow cover in the basin). Similar correlations are derived for the river basins of the Fergana valley (Table 1). It is necessary to use traditional ground-based data on the air temperature and precipitation in the prescribed basin together with satellite data because this improves the correlational accuracy and which then increases the forecast reliability.

In general, the form of correlation between the water discharge and snow extent evaluated by satellite and ground data is unknown, but its non-linear and monotonous character is manifested. This confirms the necessity of the application of the technique of objective alignment and normalisation of the correlations for the calculation of the equation for multiple linear regression.

We can then write the general form of the runoff forecast for the selected period using the normalised variables as follows:

$$C = f(U_Q) = f(\Sigma\alpha_i \cdot U_{Xi}) \tag{5.3}$$

where $f$ = function of the connection between the actual average discharges $Q$ and their normalised values $U_Q$ for the selected period: $\alpha_i$ = regression coefficients: $U_{Xi}$ = normalised values of the variables including the snow line elevation $H_{SSL}$.

The snow extent is evaluated for those areas of more than 2000 km$^2$ using low resolution satellite data. Smaller-sized basins are combined into groups. In such cases the regression equations are computed firstly for the total runoff for the whole group of rivers and then forecasts are computed for individual components. In particular, we have adopted such an approach for the forecasting of river runoff for the south-west slope of the Fergana ridge; for Mailisu up the mouth of the Kairagach River; for Kara-Unkyur up to the Charvak settlement; for Kugart up to the village of Mikhailovskoye, and for Yassv up to theSalamalik site (Pichugina and Tsaryev, 1993).

The snow-line elevation ($H_{SSL}$), precipitation totals from March to October ($X$) or solid precipitation total ($X_T$) from the Ak-Terek-Gava and Chaartash meteorological stations are used as predictors in the multiple regression equations for forecasting total runoff.

Operation snow measurement data, obtained by using all types of snow observations and then analysed and generalised for mountainous catchments, is used for the construction of local correlations between the snow cover depth $h(z)$, density ($\rho z$), snow water equivalent $W(z)$ and the altitude of the locality for $Z \geq H_{SSL}$ and then for the computation of the integral snow reserves (which is presented as the total water mass $W$ accumulated on the basin surface in the form of snow up to some moment in time). The data for snow accummulation for the end of February, March and April are the most interesting because it is these data which determine the timing of the issue of bulletins on current snow accumulation and the runoff forecasts.

Table 5.1 presents information on the predictions used for forecasting Central Asian mountainous river runoff, plus the combinations of the these predictors at different observational levels, and a reliability score.

***Table 5.1*** *River basins, basin areas, forecast technique, predictors andforecast reliabilityfor mean water discharge during the growing season*

| ***River basin*** | ***Area F (km²)*** | ***Forecast technique*** | ***Predictors*** | ***Reliability score (%)*** |
|---|---|---|---|---|
| Amudarya | 309,000 | I | V | 91 |
| Vakhsh | 29,500 | I | V | 73-78 |
| Pyandg | 57,100 | I | V | 70-75 |
| Kafirnigan | 9780 | I | V | 67-83 |
| Chirchik | 9493 | I | $H_{SSL}$ | 80 |
| | | II | $H_{SSL}$, $\Sigma X$, $\Sigma X_t$ | 90-95 |
| | | III | W | 85-86 |
| Pskem | 2830 | III | W | 85 |
| Chatkal | 6291 | III | W | 85 |
| Akhangaran | 1110 | III | W | 88 |
| Chadak | 850 | II | $H_{SSL}$, h, w | 80-90 |
| Gavasai | 657 | II | $H_{SSL}$, h, w | 75-80 |
| Kassansai | 1206 | I | $H_{SSL}$ | 73 |
| | | II | $H_{SSL}$, $\Sigma X$ | 71-77 |
| Fergana Ridge | 26,110 | II | $H_{SSL}$, $\Sigma X$, $\Sigma X_t$ | 80-91 |
| Murgab | 27,380 | I | $H_{SSL}$ | - |
| Tedgen | 26,110 | I | $H_{SSL}$ | - |

# Reference

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# II

# Groundwater development in arid and semi-arid zones

# 6. Planning and management strategies for major deep aquifers

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## 6.1 Introduction

Extensive sedimentary basins conceal major deep aquifers containing large groundwater reserves. In arid areas such reservoirs can be the only source of water. Examples are found in North Africa in Algeria, Tunisia, Libya, Egypt, Sudan, Niger, Chad; in Asia in Saudi Arabia, China, the northern Siberian basin and also in the United States and in the east-Australia Artesian basin. Table 6.1 shows some of major groundwater formations and their physical properties.

In the arid regions of the Middle East and Africa the population growth rate is 2-4% per year and with an increasing *per capita* water demand, the total water requirements of these countries will increase rapidly; the ever-increasing demands may constitute a severe threat for over-exploitation of fresh groundwater reserves in such major aquifers.

Dating by radio isotopes indicates that the groundwater in most of the major deep aquifers is mainly paleo-water that has accumulated during one or more intervals of the pluvial periods of the late Quaternary (30,000 to 40,000 BC). The term "fossil" is often used to describe water which has thus been present in an aquifer for thousands of years. This does not mean, however, that the water is stagnant or that there is no renewal of water in such major deep aquifers. In absolute terms hardly any groundwater exists independent of or cut off from the natural water cycle. Any groundwater basin in nature attains a state of dynamic equilibrium although the motion may be very slow. Each of the formations that constitute a groundwater basin is connected through any direction with one another, depending on geological and hydraulic characteristic of the water-bearing formation.

The sandstone complex in North Africa has been deposited in extensive geosynclinal basins, which act as regional hydrogeological basins. In age, they range from Cambrian to upper Cretaceous, commonly known in West Africa as Nubian Sandstone and in Arabia as Saq-Tabuk-Walid-Minjur, with a thickness varying between 500 to 3000 m. The whole of the sandstone aquifer system covers an area more than 15 million km$^2$. These large basins are in part separated by regional upward structures, which act as barriers and do not completely isolate the hydrogeological basins and hydraulic connection can be found in the region of North Africa. The Nubian sandstone basins of north Egypt and Libya continue into the El-Kufra Basin, the Mursuq Basin, the Chad Basin and the Jiado Basin.

In the Arabian area, the El-Hamad Basin, located between Jordan, Iraq, Syria and Saudi Arabia, continues southward into the Riyad basin and then into the Rub Al-Khali Basin. The eastern and western Nubian systems are separated by the Arabo-Nubian Massive. There are similarities for many of these major basins, such as the water in storage which was recharged *in situ* during one or more of the rainy periods of the Quaternary. Other authors suggest that there was an initial phase of replenishment in the early Palaeogene and Neogene when heavy rains occurred. The volume of water in storage in the major deep aquifers is huge (Table 6.1). Water in storage in some of the basins in North Africa can be in the order of $6 \times 10^{13}$ m$^3$ to $14 \times 10^{13}$ m$^3$.

***Table 6.1*** *Some major groundwater formations in arid or semi-arid zones*

| *Country, Basin* | *Aquifer formation* | *Area* $10^3$ *km*$^2$ | *Total theoretical storage, m*$^3$ | *Present recharge (renewable resource) mm*$^3$ *y*$^1$ | *Chemical quality of water T.D.S. in g l*$^1$ | **Exploitation**<br>*Present rate of withdrawal mm*$^3$ *y*$^1$ | <br>*Total volume withdrawn (period) m*$^3$ | *Observation* |
|---|---|---|---|---|---|---|---|---|
| Australia Great Artesian Basin | Sand; sandstone Triassic Cretaceous | 1700 | 2 × $10^{13}$ | 1100 | 0.5-1 | 600<br>(1975) | 35.1 × 106<br>(1880-1973) | Max. fall in level: 120 m in 83 years |
| Algeria Tunisia Northern Sahara | Terminal Complex sand, sandstone limestone Upper Cretaceous to Miocene | 350 | | 580 | 1.5-6 | 400 | 6.7 × 106 | |
| | Continental Intercalary sand, sandstone Lower Cretaceous | ~600 | 6 × $10^{13}$ | 270 | 0.5-6 | 200<br>(1970) | 1.26 × $10^6$<br>(1950-70 | Max. fall in level: 29m in 14 years |
| Libyan Arab Jamahiriya Kurfrah Basin | Sand, sandstone Cambrian Upper Cretaceous | 1800 | 6 × $10^{12}$ | ~1000 | 0.15-0.25 | 160*<br>(1970) | 360<br>(1990) | Max. fall in level: 15 to 20 m in 4 years<br>*Projected: 220 mm$^3$ y$^{-1}$ |
| Egypt, Nubia ('New Valley') | Nubian sandstone | 850 | 14$^{\times 13}$ | | 0.1 to 0.8 | 360* 718<br>(1975) (1990) | | Projected: 2400 mm$^3$ y$^{-1}$ |
| Niger, Mali Nigeria | Sand, sandstone Upper Cretaceous Continental Intercalary | 500 | 'Exploitable': 4 to 8 × $10^{10}$* | ~800 | <0.5 | | | *with max. falls in level: 100m (Mali, Niger |
| Senegal Mauritania | Sand, sandstone Maastrichian | 200 | 1.5 × $10^{12}$ | 1300 | <1* | 9<br>(1971 | | *Over two-thirds of the area |
| China Plain of Hebel | Alluvium Quaternary | 136 | ~5 × $10^{11}$ to 1 × $10^{13}$ | ~35000 | | ~17000<br>(1960) | | Annual growth (1973-780: ~600 mm 3 y$^{-1}$. Max. fall in level: 30-40 m in 8 years |
| Hoi-long jing* | | 62 | | ~12000 | | ~10000<br>(1978) | | *Central part of the Hebel Plain |

## 6.2 The Nubian Sandstone basin

This is considered to be one of the most important groundwater basins in North Africa. It extends across the borders of four African countries — Egypt, Sudan, Libya and Chad with an area of 2.25 million km$^2$). The geology of the Nubian Basin has been subjected to a series of studies for the last 50 years. However, the complexity of the structures prevailing in the basin precludes adequate identification of the hydraulic continuity between the various Nubian sub-basins although this continuity is emphasised in each sub-basin within individual countries; the hydraulic interconnection between these sub-basins is also pronounced at the regional level. The Nubian basin is described as a multi-layered artesian basin and behaves as a single hydrogeological system in hydraulic continuity with other systems in Libya and Sudan. It is important to point out that all the detailed studies which have been undertaken on the hydrogeology of the basin are almost always restricted to localities representing only a small portion of the basin's gross area, where our knowledge about its regional hydrogeology remains vague.

## 6.3 Discharge and recharge

In North Africa and in Arabia, the discharge from what are generally described as "dynamic basins" occurs by evapotranspiration from natural depressions connected directly or indirectly (e.g. the Qattara Depression in Egypt, the Wadi El Shatie depression in Libya, Chott El Jerid in Tunisia, and El Hofof oases in Arabia). The estimate of total natural discharge in Egypt is about 1.75 billion m$^3$ y$^{-1}$, while in Sudan is in the order of 2.5 billion m$^3$ y$^{-1}$. Under the present arid conditions, recharge to such basins is insignificant and production of groundwater is essentially from storage, resulting in lowering groundwater pressures in the aquifer systems. The estimate of groundwater extractions from the regional Nubian Basin is in the order of 2.68 billion m$^3$ y$^{-1}$ of which 0.72 billion m$^3$ y$^1$ is withdrawn in Egypt, 0.54 billion m$^3$ y$^1$ in Sudan and 1.42 billion m$^3$ y$^{-1}$ in Libya.

Groundwater movement, direction and piezometry is determined so as to identify the manner and degree of the hydraulic continuity within the regional flow system. The generalised piezometric contour maps indicating a regular continuous movement of groundwater through the whole basin can hardly be justified under the current hydrogeological conditions.

The origin of groundwater in the Nubian basin is still a controversial issue, for which various concepts have been presented. A recent concept has been presented by Sudan which can be explained by the following two complementary concepts:

- The allochthonous concept which postulates a regional flow of groundwater, from intake areas to points of discharge in the aquifer. This concept can be justified from the regional piezometric map which indicates that the groundwater is renewable and that the basin is receiving some recharge at intake areas, estimated in the Sudan report to be about 1.6 billion m$^3$ y$^{-1}$.
- The autochthonous concept which infers that the bulk of the groundwater mass within the basin was deposited *in situ* during the pluvial periods of the Holocene.

These two concepts seem justified, taking into consideration the age of the groundwater which depends on sampling location and its distance from the intake areas. The hydraulic properties of the Nubian Basin have been mainly estimated from field pumping tests only in developed areas where it was found to vary greatly; in some individual sub-basins the volume may range from 100 to 1000- m$^3$ d$^{-1}$ and storativity from $1\times10^{-5}$ to $1\times10^{-1}$. The large difference in magnitude is due to many hydrogeological and pumping well properties.

## 6.4 Exploitations

The exploitation of major aquifer systems in arid regions where groundwater is the only source of water depends on the following factors:

- the need for water;
- the availability of financial resources;
- the calibre of technical staff involved;
- eagerness to integrate efforts with neighbours and bi-lateral and international cooperation.

In some countries of the Sahel exploitation is minimal, usually because of socio-economical and socio-environmental reasons. In other countries where funds are available over-exploitation is more likely. Examples are: the great man-made river in Libya, the extensive extractions from the Umm El-Radhume aquifer in East Arabia and the New valley in Egypt. In Australia, only 35 billion $m^3$ were extracted during 90 years, with 70% of this amount coming from storage while in Arizona, where 225 billion $m^3$ were extracted in 60 years, 90% of this amount is from storage.

It is expected that in north Africa, extractions from storage will reach more than 200 billion $m^3$ in 100 years in Algeria, Egypt and may be in Libya also. The evaluation of a dynamic reserve which reacts to exploitation is more complex. Mining costs rise as water levels decline or production of wells decreases as a result of compaction of aquifers. Also, water quality may change due to movement masses of water of different quality from adjacent layers or boundaries.

## 6.5 Strategy for management of major deep aquifers

The strategy for exploitation of groundwater from major aquifers under mining conditions depends on two criteria:

- Extraction of groundwater should be economical and rational
- The process should be sustainable to assure prosperity for generations to come.

As the rate of extraction increases, the hydraulic head in the aquifer drops and the cost of raising water to the surface also increases. Generally, it is rational to exploit a resource when marginal costs to bring one extra unit of water do not exceed the additional marginal revenues. However, a country may have other goals which may be more important, e.g. settling populations and allowing them to gain income. The resources provided for such incomes should not necessarily be exploited at maximum profitability.

The maximum economic extraction depths are not necessarily the same in different locations of the basin since many factors influence the cost of supplying the water, such as:

- geological aquifer conditions;
- pumping capacity;
- energy cost;
- crop water requirements;
- soil suitability.

The second criterion to be met for sustained prosperity is related to the time over which maximum pumping depth must not be exceeded. In order to meet the objective of sustained prosperity, it is assumed that several generations of people should be able to exploit the groundwater resources economically. The time horizon can be set arbitrarily at 100 years for it is difficult to foresee groundwater development.

Groundwater development for large-scale agricultural projects will depend upon the available recoverable water from the aquifer which, in turn, will be directly proportional to the induced draw-down during exploitation. Intensive cultivation, although feasible and acceptable from a socio-economic point of view, results in many hydrological problems. A drop in the piezometric pressure creates a sort of artificially deep watersink under cultivated areas. The ultimate result of such water use strategy is a reduction in the amount of water available and an increased pump lift. As a result, the well yield and/or the pumpage lift, will be subjected to change affecting the productivity of the reclaimed areas. The agriculture project will gradually become uneconomic unless the method of water delivery changes periodically. Hence, as a steady-state can never be reached under the present boundary conditions of both the aquifer characteristics and the high rates of water exploitation, thus the hydrologic problems will never be resolved.

Therefore, a change in some of the present strategies of water use seems to be unavoidable, if huge water reserves are to be used both technically and economically in the long run. An approach towards isolated, distant, limited-area farms may constitute an appropriate alternative from the present intensive cultivation envisaged. It is believed that such an approach will relieve the hydrological problems besides possibly prolonging the life of the aquifer and/or maintaining the water lifts at economic levels. Such an approach may, however, create other problems but of a different nature e.g. socio-economic, which should be carefully studied in order to avoid any eventual drawbacks. The quality of life for small communities — education, heath care, transport and roads, crop marketing, etc. — are among the problems to consider.

Simultaneously, an alternative approach, denoting isolated wells at large distances and transferring water to irrigate collective cultivations, may also be considered. The Libyan experience through the execution of the great man-made river may form a good basis for this approach.

It is important to avoid creating undesirable huge water sinks resulting from intensive water production from enclosed wells in a small surface area. This can be achieved by expanding the area of water production, thus prolonging the life of the reservoir, minimising the hydrological problems, and securing steady-state and more stable hydraulic conditions.

## 6.6 Planning considerations for groundwater

Planning for groundwater extraction and use from major deep aquifers requires much information and faces serious difficulties, as does the integration of supply and demand, where the application of techniques of water conservation and water demand management are necessary.

- In most water resource management situations some form of planning exists but the subjects and the approaches may vary widely. Planning and decision-making are continuous processes. All inputs to groundwater resource systems are subject to changes, especially on the demand side.

Groundwater resources are interrelated with other areas, such as agriculture, urbanisation and industrial development. The planning process takes place at different administrative levels where it has to be hierarchically linked to each other. It is essential to consider constraints which have important roles in the planning process and which may have disastrous results. It is essential to consider these factors in an early stage. Such constrains can be: natural hydrogeological factors, socio-economic and technical factors (e.g. wells or well fields).

- Groundwater planners should look at the capability of resources first, rather than just plan and summarise the adverse impacts later on.

- Sustainable development will be the main factor for planners who have to deal with expected future scarcity of the resource. Integration of disciplines in groundwater planning is required.

Different experts should cooperate during the planning process, such as engineers, geologists, ecologists, agronomists, etc.

The concept of integration of supply and demand in water resource planning is at present receiving increasing attention. Where the application of water conservation and water demand management techniques is necessary, an integrated approach is essential, with careful consideration of the several steps in the planning cycle.

- The continuous monitoring of groundwater: computerised databases are a powerful tool with which to store and process data within the plan or not. The supplementary data from the monitoring network also provide hydrogeological inputs to regularly update the plan.

Groundwater models are one of the powerful tools in the prediction of the effects of groundwater development policies. The reliability of these models is highly dependant on the availability of the necessary input. Sophisticated models for regional groundwater evaluation of a major aquifer require large amounts of data in order to benefit from its potential capabilities. A good approach is to design a groundwater model in accordance to the available input rather than fill in missing input with estimates. The model can be extended and refined later when more data become available.

- Hydrogeological maps are an important tool for development and management of major aquifers. These maps are used by engineers, planners and decision makers in order to allocate and develop groundwater within a national or regional policy.

Good storage, retrieval and presentation of hydrogeological data are indispensable nowadays due to the complexity of planning and management of groundwater resources. Using an integrated remote sensing/GIS approach, manipulation and handling of a large amount of data can be easy and efficient.
Satellite images and hydrogeological mapping experience allow relatively cheap and factually accurate base maps to be produced. GIS may also be linked with numerical as well as environmental and economic models

- Non-renewable groundwater reserves in major aquifer systems constitute most of the water resources reserves in arid regions. In many cases those major aquifers extend across the borders of two or more countries, hence their development and exploitation require bilateral consultations. In many countries in arid regions mining could be a feasible solution to solve some of the economic and social problems created by water scarcity. .

- The increasing demand for water requires an efficient use of the resource available. Fresh groundwater of good quality should not be used for purposes where lower quality water would be appropriate, for example brackish groundwater and wastewater may substitute for the extraction of fresh groundwater for agricultural use. In such cases, good quality sources should be reserved for domestic water supply for both present and future generations. As the agricultural sector is the main consumer of water in arid countries, the greatest savings can be made in this area. Also, savings can be obtained by making domestic and industrial water sectors more efficient; such savings may reach more than 50%.

- Water pricing has a beneficial effect on water consumption in all sectors and could generate additional funds for better operation and maintenance of the water systems. While in principle water pricing is a desirable option, however, the associated legal, social and political aspects should be carefully considered before its introduction.

- Existing legal instruments should be reviewed in their entirety to ensure their effectiveness for rational groundwater planning and management. Regulations by themselves are not enough for sustainable groundwater management. Often for social, economic and political reasons, such regulations are not implemented. Such constraints should be overcome.

- Environmental impact analysis should be integrated in an early stage of the planning process. For rational groundwater planning the assessment should involve a balanced attention to positive and negative environmental impacts. Attempts should be made to maximise positive environmental impacts and to minimise negative impacts.

- Economic evaluation of costs and benefits provide a sound base for comparing different alternative plans for groundwater development. Benefits and drawbacks that cannot be translated into economic terms (public health, socio-cultural aspects, etc.) should be expressed in qualitative terms. The decision-maker can then make the final decisions on the basis of both quantitative data and qualitative information available.

- Planning and decision-making is a continuous, dynamic process to accommodate changing conditions and circumstances. This is valid for both demand and resource considerations (population growth, land use, etc. — quantity and quality changes due to natural or human interferences, etc.).

- Water users' participation is required to get people motivated and willing to take necessary and sometimes unpleasant decisions about water use and distribution. Users' involvement is desirable from the early stage of planning process since they are both the ultimate beneficiaries and managers. National and regional plans have to be presented at appropriate levels of detail to different users as well as to the general public.

## 6.7 International cooperation

Planning the development of the international aquifers require good cooperation between the countries concerned as many of the major aquifers of arid and semi-arid regions are shared by two or more countries. Because of their international character, their development and management are more complex when compared with aquifers which are totally contained within one country. While many issues are political in nature, much can be done at the technical level. The following case study illustrates a good example of cooperation in north-east Africa.

### 6.7.1 Case study: north-east Africa

Several meetings were held between representatives of countries sharing similar major aquifers in North Africa and the Arabian peninsula. These were organised by international agencies, initiated by UNESCO and followed by UNEP, UNDP, IFAD and currently by CEDARE. Egypt and Sudan, with the cooperation of international organisations, began activities in 1982 with Libya joining the project latter on.

In the beginning the project focused mainly on regional coordination of hydrogeological studies on the Nubian aquifer. The project consisted of material components plus a regional mechanism for the coordination of activities and a joint working groups secretariat.

The main recommendations stated that availability of water is not a constraint in the development of the Nubian sandstone. Future activities should be oriented to water management and the use and exchange of previous experience of the three countries in different existing project development (e.g. the Great Man-made river in Libya, the New Valley in Egypt and the Dongola project in Sudan, etc.). Project proposals using groundwater from the major Nubian aquifer have been discussed and approved by AMCEN-UNEP in Nairobi and at a meeting in Algeria in 1990.

It is worthwhile mentioning herewith that it will be useful for countries sharing an aquifer to answer the following questions before formulating bilateral or multi-lateral research programmes:

> Is there a national coordinating mechanism that would coordinate the interests and inputs of various sectors involved in the project. What are the responsibilities and power of that agency?
>
> Are there any intentions to finance the national components of this programme?
>
> Is the respective national government agreeable to regional coordination and a coordination committee, and what is the mandate of such a committee?
>
> Is the government agreeable to the introduction of a common system and standardised methodologies to be developed during the execution of the programme, for smooth communications, and for technical coordination within the regional networks?

# 7. Groundwater recharge principles, problems and developments

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## 7.1 Introduction

Groundwater use is of fundamental importance to meet the rapidly expanding urban, industrial and agricultural water requirements in (semi-)arid areas. To quantify the current rate of groundwater recharge is thus a basic prerequisite for efficient groundwater resource management in these regions, where such resources are often the key to economic development. It is indeed unfortunate that of all the factors in the evaluation of groundwater resources, this rate of aquifer replenishment is one of the most difficult to derive.

Attention in the present discussion focuses on recharge of phreatic aquifers, often the most readily available and affordable source of water in (semi-)arid regions; not all can bear the cost of, or even require deep boreholes. These aquifers are also the most susceptible to contamination, with the recharge rate determining their level of vulnerability.

## 7.2 Historical framework

The above aspects serve to illustrate the growing international demand for reliable quantitative information on arid and semi-arid zone groundwater recharge estimation and the determination of its variability both in time and space.

Early responses to these demands are typified by the *ad hoc* norms for estimating groundwater recharge introduced by the Government of India (1984). Initial guidelines (1972) were based on use of the Chaturvedi formula (for rainfall recharge) and recommended loss values from other sources (canals, storage tanks, irrigation return flow). A 1979 update proposed estimation of rainfall-derived recharge from specified, lithology-determined percentages of “normal rainfall”. This approach was again reflected in the 1984 norms presented by the Groundwater Estimation Committee with the additional advice that, given sufficient data, the groundwater level fluctuation method is preferred (specific yields were defined for a range of geological formations).

Such norms, despite their (now) obvious shortcomings, have proved of value to India. However, the data are the result of a pioneering study based largely on empirical information and are country specific; the international community requires guidelines for wider application.

Since the mid-1980s there has been a relative explosion of recharge studies reported in the scientific literature. Recognition of the growing need for reliable recharge estimation has also been reflected in the active support by international agencies / NGOs, and the publications which have emerged from various international meetings (e.g. Simmers, 1988; Sharma, 1989; Lerner *et al.*, 1990).

As further response, it is expected that the IAR / UNESCO contribution by Simmers *et al.* (1997) [*Recharge of Phreatic Aquifers in (Semi-)Arid Areas*; ICH 19] which results, *inter alia*,

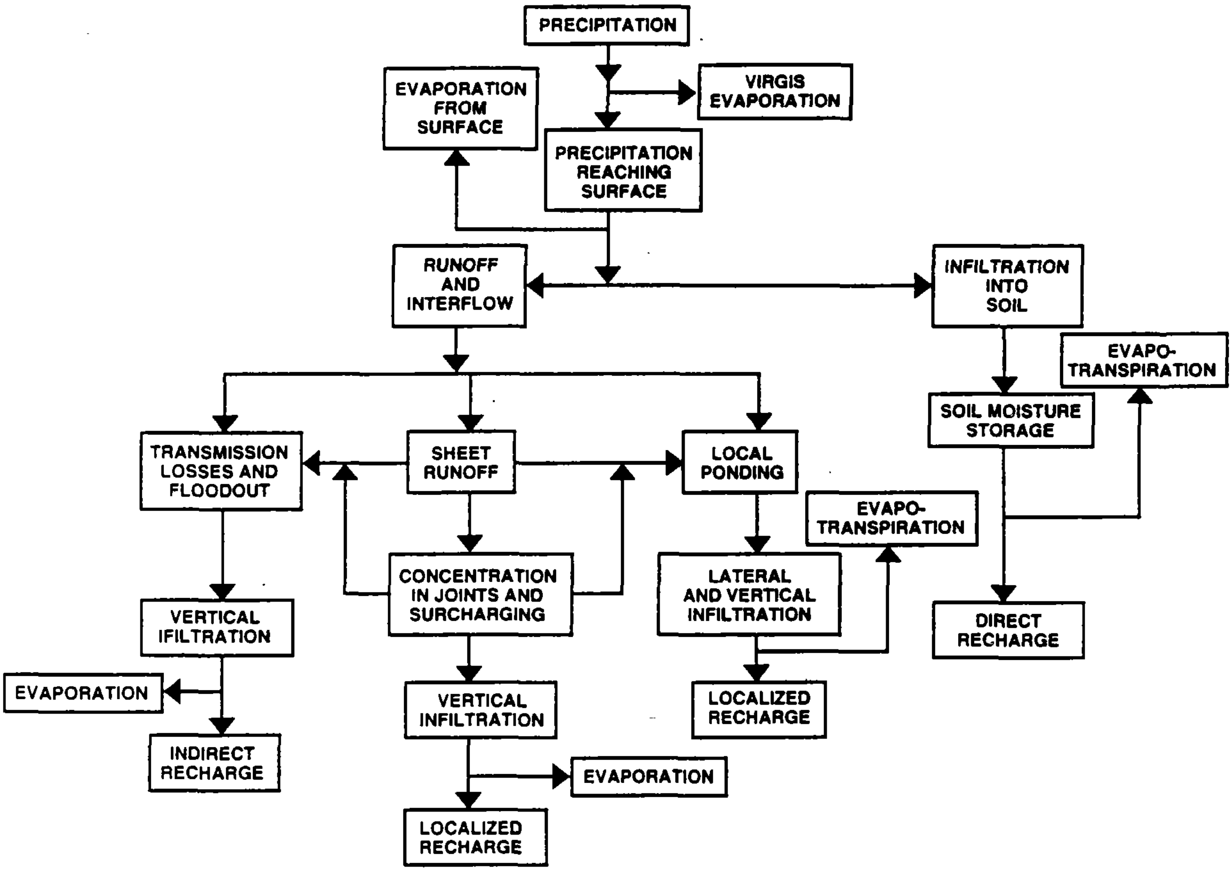


*Fig. 7.1* *The various elements of recharge in a (semi-)arid area (after Lloyd, 1986)*

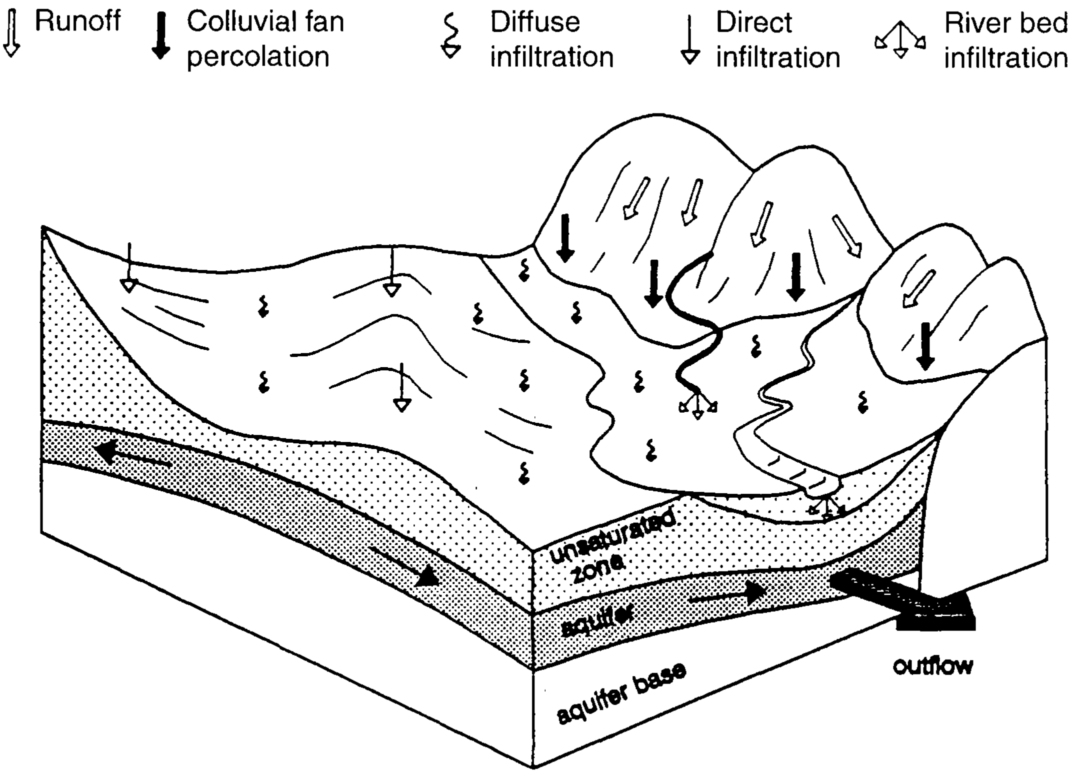


*Fig. 7.2* *Recharge mechanisms in the Pitsanyane and Nnywane basins, Botswana; groundwater outflow is in a northerly direction (Gieske, 1992)*

from the 1994 International Workshop held in Hyderabad, will offer additional guidance to the practitioner engaged in (semi-)arid zone water resources exploration and development. This new book updates and supplements ICH 8 (Lerner *et al.*, 1990) and should not be considered as an alternative text. The volume comprises three principal sections, i.e. Recharge from Precipitation, - Intermittent Flow, - Permanent Water Bodies; each is self-contained and closes with illustrative case studies. The present summary is intended to introduce and review the concepts and problems considered in more detail by the book [scheduled for publication in early 1997 as a contribution to UNESCO / IHP-IV, Project H-5.21] and relies heavily on the readily available post-1990 literature.

### 7.2.1 Recharge processes

The various sources of recharge to a groundwater system are of course well known, i.e.

- precipitation recharge;
- river recharge, including perennial, seasonal and ephemeral flows;
- irrigation losses, both from canals and fields;
- inter-aquifer flows; and
- urban recharge.

Principal recharge mechanisms from these sources have been defined by Lerner *et al*, (1990) as direct, localised or indirect; Fig. 7.1 from Lloyd (1986) presents a conceptual illustration. The definitions are of course a simplification of reality, since in many locations combinations of the various types will occur (Gieske, 1992; Fig. 7.2). It is clear from the literature, however, that:

(1) recharge occurs to some extent in even the most arid regions (Gee *et al.,* 1994);
(2) as aridity increases, direct recharge is likely to become less important than localised and indirect recharge in terms of total aquifer replenishment (Johnston, 1987; Gee and Hillel, 1988; Stephens, 1994; Wood and Sanford, 1995);
(3) estimates of direct recharge are likely to be more readily derived than those of either localised or indirect recharge.

Successful groundwater recharge estimation depends on first identifying the probable flow mechanisms and important features influencing recharge for a given locality. Further, the actual frequency of recharge events and the transit time until recharge takes place are also important, i.e. infrequent major recharge is a totally different proposition from smaller but more regular events (Barnes *et al.,* 1994).

It is clear that differences in sources and processes of groundwater recharge will mean that the applicable value of available estimation techniques will also vary. Although *direct* recharge is known to be of decreasing significance with increasing aridity, the processes are conceptually the easiest to define and still form the basis of numerous recharge estimation techniques in common (at times inappropriate) use. The quantification of groundwater recharge is fraught with problems of varying magnitude and hence substantial uncertainties. It is therefore desirable to apply and compare a number of independent approaches.

### 7.2.2 Recharge estimation

The procedures which may be used to quantify recharge from the various sources (i.e. direct measurement, water balance methods, Darcian approaches, tracer techniques, empirical methods) and the problems encountered with each, are addressed in detail by, *inter alia,* Gee and Hillel (1988) and Lerner *et al.* (1990).

Gee and Hillel (1988) note, for example, that: (a) water balance methods to estimate recharge are inherently difficult because of errors involved in determining the required inputs (e.g. runoff, precipitation, actual evapotranspiration, change in soil moisture storage, soil hydraulic conductivity); (b) lysimeter measurements are potentially useful, but suffer from the problems of expensive construction and maintenance, disturbance of the vegetation and soil, confinement of drainage and modification of the bottom boundary condition, and the localised nature of the data obtained; (c) Darcian flux calculations are dependent on reliable measurements of the hydraulic gradient and unsaturated hydraulic conductivity; (d) conservative environmental tracers such as chloride and bromide offer promise for recharge estimation, as do the stable isotopes $^{18}O$ and deuterium.

In brief, Gee and Hillel (1988) conclude:

> *"Errors in estimating recharge for desert or semi-arid sites using conventional techniques will generally be high. Direct measurements are seldom possible and water balance methods are of limited use. Errors of similar magnitude arise using Darcian-flux calculations. In addition, topographic effects, spatial variability, and unstable or concentrated flow are often ignored, furthering the uncertainty in estimating recharge. Lysimetry and tracer tests offer the best hope to evaluate recharge at arid sites".*

These conclusions are echoed by Allison, *et al.* (1994). As a general note, Lerner *et al.* (1990) emphasise that there are five ingredients to a "good" recharge estimation method:

- A recharge estimate should explicitly account for the water that does not become recharge.
- Most estimation methods rely on a knowledge of the processes that convert source water to recharge and on flow mechanisms for that water. A "good" method will reveal if the conceptual model underlying the method is correct.
- A "good" method will have low associated errors and will not be sensitive to parameters which are difficult to estimate accurately.
- Ease of use.
- Methods that can use readily available monitored data (e.g. rainfall) to extrapolate estimates are more useful than those which require specialised observations.

There is, in fact, very little published work on how realistic recharge estimates may be made by the water resources practitioner. Further, model development is too often seen as an alternative to careful fieldwork and the model applied may be inappropriate to the actual field situation.

## 7.3 Practical challenges

(Semi-)arid zone recharge, while generally low, can be highly variable — the greater the aridity, the smaller and potentially more variable the natural flux. In addition to the perennial difficulties associated with sparse information, numerous recharge estimation "problems" recur in a scan of the literature to the early 1990s. These include:

- The assessment and hydrological consequences of localised and indirect recharge.
- Recharge time and space variability (*inter alia*: effects of climatic and land use changes on tracer profiles / mass balances; the spatial translation of "at-point" data; determination of reliable (representative) water balance and soil hydraulic parameters).
- The impacts of urban development on groundwater recharge.

It is clear from a review of the more recent literature that not all the above "problems" have been satisfactorily resolved. Equally evident, however, is that progress has been made.

## 7.4 A review of some recent developments

### 7.4.1 Recharge from precipitation

Much of the readily available recharge literature deals with the movement of precipitation through the vadose zone, with accumulating research results indicating that this is an extremely heterogeneous realm where flow is transient and almost always spatially variable. This complex zone and its relative inaccessibility, as well as the importance of the processes taking place through it, present a serious challenge in attempts to estimate either local or regional recharge (Gee and Hillel, 1988; Stephens, 1994).

The present discussion addresses developments in the determination of *direct* (diffuse) and *localised* (preferential flow) recharge (as defined by Lerner *et al.*, 1990); comprehensive recent reviews are provided by Stephens (1994) and Allison, *et al.* (1994). Aspects relating to indirect recharge via ephemeral channels are considered in section 7.4.2.

***Direct (diffuse) recharge estimation***: Given the potential for direct recharge, water movement through the vadose zone is usually a one-dimensional process. Stephens (1994) identifies several mechanisms which need to be considered in field measurements and modelling, i.e.

- hysteresis in the unsaturated hydraulic conductivity-pressure head relationship (moisture is available to plants for longer periods of time);
- downward water movement below the root zone often occurs as a piston displacement process (recharge comprises infiltrated water from older events);
- the influence of immobile water (reduces the vadose zone transit time);
- multidimensional flow induced by (*inter alia*) profile anisotropy and vegetation;
- the effects of land use changes (see, for example, Walker *et al.*, 1991).

In principle, one can determine recharge in the vadose zone by direct measurements of water fluxes or by establishing a vadose zone water balance on the basis of soil, climate and vegetation data. However, in arid and semi-arid climates such methods are not straightforward; the size, spatial and temporal variability, and frequently even the direction of water balance fluxes are distinct from those encountered in more humid environments. In their review of the range of techniques available, Allison *et al.*. (1994) state:

> *" .... indirect, physical approaches, such as water balance and Darcy flux measurements, are the least successful, while methods using tracers (e.g. Cl, $^3H$ and $^{36}Cl$) have been the most successful in estimating groundwater recharge in dry regions. Of the tracer techniques available, Cl balance methods appear to be the simplest, least expensive, and most universal".*

The same authors also show that mutually supporting, multiple tracer approaches, or a combination of tracer and physical methods, are now the norm rather than an exception [e.g. Walker *et al.*, 1991 (Cl, matrix suction profiles); Cook *et al.*, 1994; Phillips, 1994; Tyler and Walker, 1994 (all using Cl, $^3$H, $^{36}$Cl); Leaney and Herczeg, 1995 (Cl, $^2$H, $^{18}$O, $^{13}$C, $^{14}$C); Liu *et al.*, 1995 (Cl, $^2$H, $^{18}$O, $^{36}$Cl); Nativ *et al.*, 1995 (Cl, Br, 2H, $^{18}$O, $^3$H,); Wood and Sanford, 1995 (Cl, $^2$H, $^{18}$O, $^3$H)].

The fundamental difficulty with Darcy's Law solutions for water movement in the unsaturated zone is that they require knowledge of the soil water retention and unsaturated hydraulic conductivity curves; direct determination of these hydraulic properties is difficult. However, indirect methods for estimating soil hydraulic properties have now been developed from easily measured soil data (Rawls *et al.*, 1991; Van Genuchten *et al.*, 1992), which yield sufficiently precise information for many practical applications without increasing costs. The statement by Allison *et al.* (1994) relating to such procedures should therefore not be rigidly accepted, particularly if concern is with the determination of preliminary recharge estimates.

A further technique which is re-emerging, with reported success, uses upper vadose zone changes in soil temperature. As example, Taniguchi and Sharma (1993) derived recharge rates from the method which corresponded closely to those estimated using natural Cl and artificial Br tracers.

***Localised (preferential flow) recharge estimation:*** Recharge along preferential flow paths has received considerable attention in the past decade, with an increasing number of studies verifying the significance of the process and attempting to quantify its relative contribution to the groundwater body. The literature also makes very clear that local groundwater recharge models which ignore the possibility of such phenomena may be highly misleading. A summary overview of the topic may be found in Stephens (1994).

Gee and Hillel (1988) visualise localised recharge as occurring on three spatial scales, i.e:

- 'micro-scale' pathways, several centimetres or decimetres apart, such as those formed by shrinkage cracks, roots and burrowing animals;
- 'meso-scale' flow paths, with a spacing of several metres or tens of metres, initiated by local topographic or lithological variations;
- 'macro-scale' flow paths, spaced hundreds (or more) metres apart, caused by major landscape features such as karst sinks, playa basins, or stream beds (see section 7.4.2).

The immediate discussion focuses on micro- and meso-scale events, and is intrinsically related to that below on spatial variability. The key to both issues for the practitioner is project scale. If concern is with acquiring good recharge estimates over a limited area (e.g. for waste disposal or local water supply purposes), then the need for detailed information is evident. In this situation multiple 'at-point' investigations are appropriate, with identification of the preferential flow contribution a prerequisite. Conversely, for projects on a regional scale, or those requiring only preliminary recharge estimates, area- or groundwater-based methods are relevant and small scale variability in local recharge ceases to be an issue. This second situation is considered in more detail below.

Small-scale variations in local recharge have been demonstrated and quantified for many soil types. Examples of experimental plot studies are those by Johnston (1987) [700 $m^2$ research plot; recharge variability 2.2-100 mm $y^{-1}$] and Gieske (1992) [200 × 200 m plot; recharge 3-26 mm $y^{-1}$; Fig. 7.3]. Other recent studies are detailed by Scanlon (1992), Nativ *et al.* (1995) and Wood and Sanford (1995) all used isotopic ($^2H$, $^{18}O$, $^3H$) and/or chemical tracer (Cl, Br) techniques to gain solutions to their specific problems.

In brief, Scanlon (1992) investigated fissured sediments in the Chihuahuan Desert, Texas, and found that minimum moisture fluxes in the fissures (1-8 mm $y^{-1}$) were 350 times greater than those derived for adjacent ephemeral stream and inter-stream locations. Nativ *et al.*. (1995) focused their study on water flow through unsaturated chalk in the northern Negev Desert, Israel; their results showed, *inter alia*, that the combination of arid conditions and fractured chalk cannot be deemed a suitable shield against contaminant migration. The Wood and Sanford (1995) isotopic and geochemical study on the High Plains of Texas and New Mexico is particularly interesting, since it addresses both surface runoff and spatially variable vertical fluxes. Although the research had a regional perspective, much of the effort focused on recharge processes in and around a *ca.* 400 m diameter ephemeral playa lake. The results confirm a regional recharge to the High Plains aquifer of ca. 11 mm/year, with nearly 50% of this occurring as piston flow through playa basin floors that occupy only 6% of the area. The remaining recharge flux, from 94% of the area, comes from macropore recharge near the basin floors and diffuse infiltration over the region.

An alternative approach to solving the variability problems inherent in localised recharge estimation is the combination of frequency-domain electromagnetic (EM) measurements and "at-point" Cl mass balances. The method is not new conceptually, but more recent studies (e.g. Cook *et al.,* 1989, 1992; Salama, *et al.*, 1994a) have shown some promise.

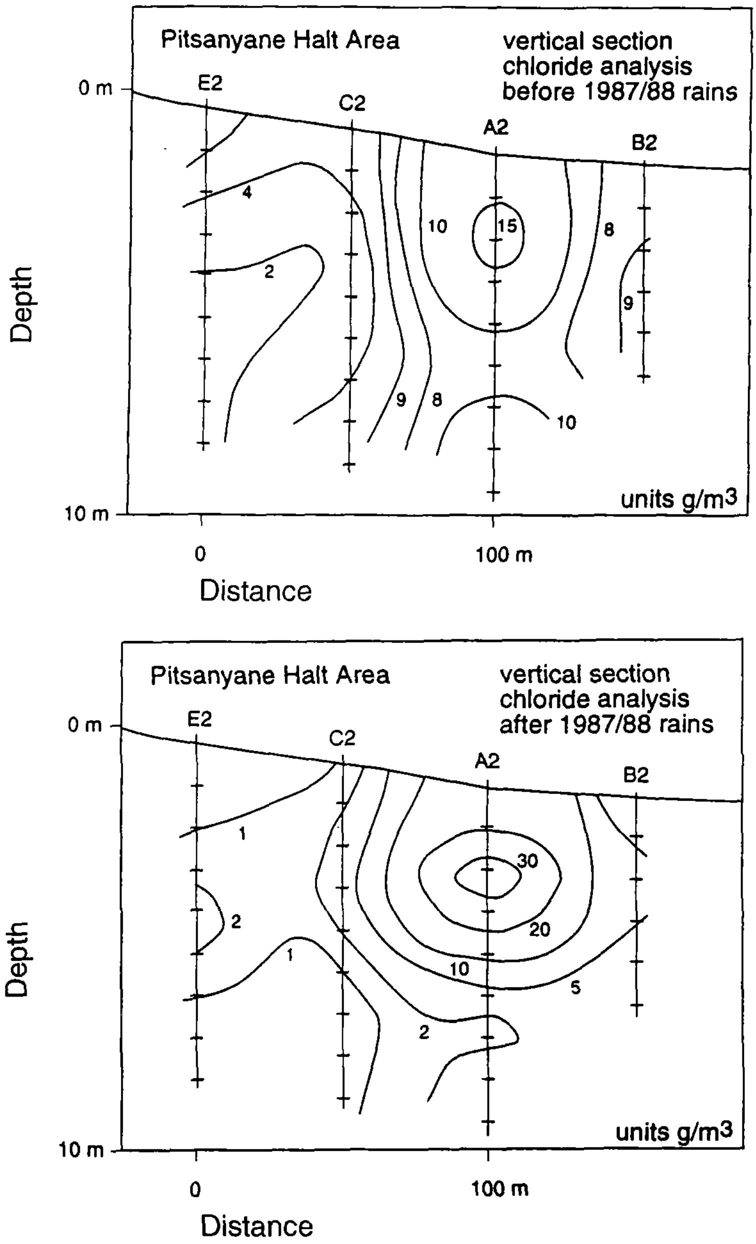


*Fig. 7.3* *Vertical transect across a 200 × 200 m plot near Pitsanyane Halt (Botswana) showing chloride concentrations in g* $m^3$*, before and after the rainy season 1987/88; recharge varies from 3 to 26 mm* $y^1$ *across the plot ( Gieske, 1992).*

***Recharge time and space variability***: Variations in groundwater recharge with time are well documented (e.g. Lerner *et al.*. 1990); Fig. 7.4 offers a further example from work recently completed in Botswana (Gieske, 1992; De Vries, 1994). Although the figure illustrates model output using measured daily rainfalls, comparable results were also obtained from an 80-year stochastically generated rainfall sequence. An obvious implication from these studies is that when significant recharge results only from infrequent large events, it is highly misleading to talk of mean annual recharge, or of recharge as a proportion of mean annual rainfall (Gee and Hillel, 1988). Barnes *et al.* (1994) further propose: one implication of this episodic mechanism is that a climatic variation which results in an increased mean rainfall could be offset by a decrease in variability, leading to a reduction in mean annual recharge. Such speculation assumes, however, that the decreased variability is accompanied by fewer major (recharge-causing) events.

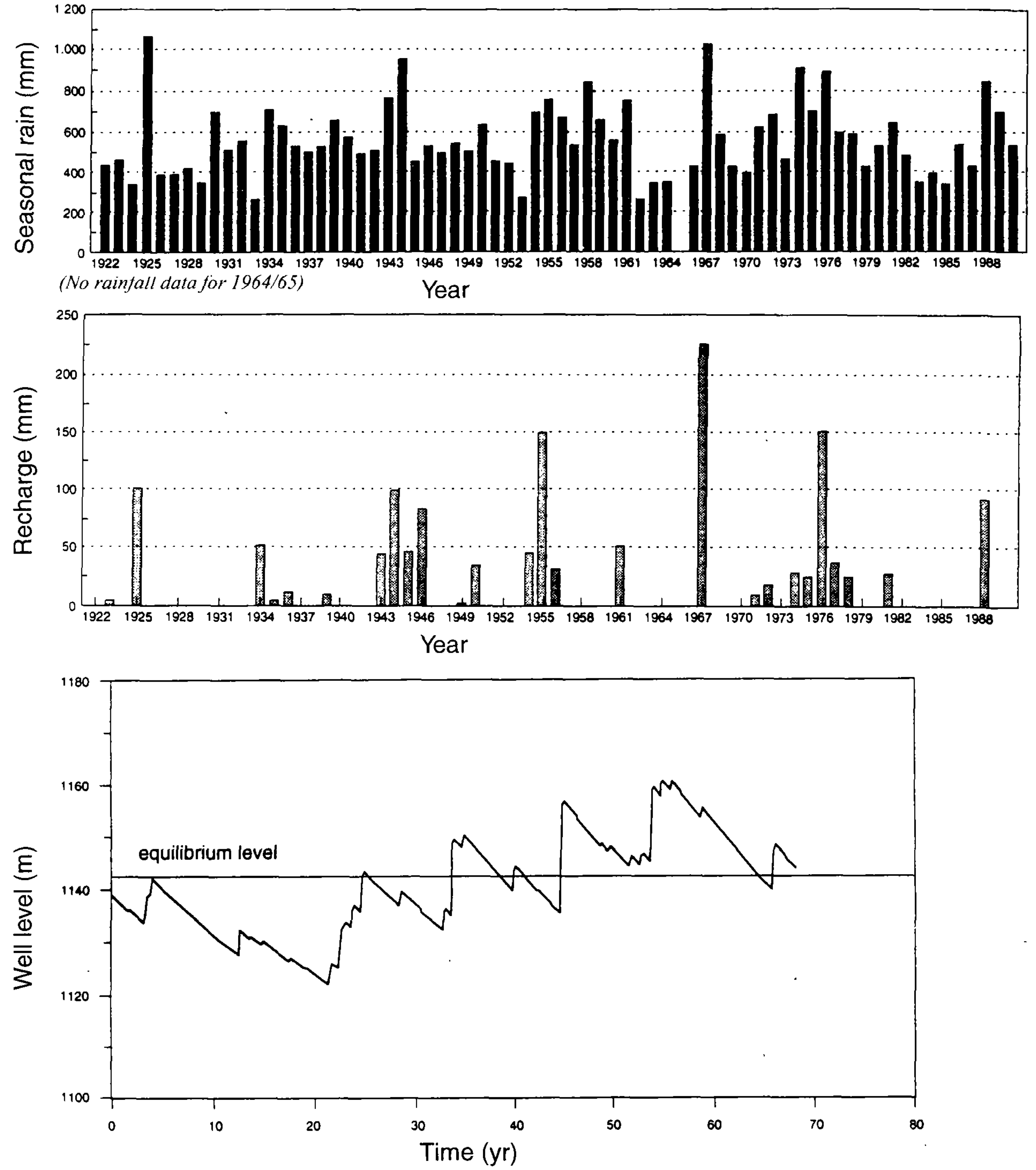


*Fig. 7.4* *Results from a 68-year recharge simulation using the model EARTH and Lobatse (Botswana) daily rainfalls (Gieske, 1992).*

Many earlier attempts to estimate recharge have generally assumed that evapotranspiration and precipitation are the only time-variant factors affecting the various processes. The obviously related issue, however, is when transit time until recharge is long and land use changes are known to have occurred in an area prior to current data collection programmes (Lerner *et al.*, 1990). In this situation the hydrological system is in a state of dynamic evolution; numerous examples are cited in Allison *et al.* (1994) and Phillips (1994). Solutions have usually been sought from interpretations of "at-point" Cl profiles which, under non-steady state conditions, typically display complex (bulged) shapes. An example of this approach is the comprehensive study by Walker *et al.* (1991) using a combination of tracer (Cl) and physical (suction profile) methods. The described procedure preserves essential features of the chloride front displacement technique, accounts for transient movement of Cl, and does not rely on piston-flow assumptions. The presented examples show that the method remains valid even when the chloride profiles become distorted; it also allows an estimate to be made of the probable time delay before effects of the land use change reach the water table.

Of the two variability aspects (time and space), it has often been stated that the more important problem yet to be overcome for practitioners is the assessment and prediction of recharge spatial variability. The issue has obvious practical importance; if recharge estimation is based on point measurements, water resource managers will need to know how or whether these relate to values over a specified area of interest. However, as proposed above, the degree of 'problem' is directly related to project objectives (and hence scale).

As illustration, several regional studies have shown that it is quite possible to derive what appear to be very reasonable initial estimates of recharge over extended areas, using readily derived low cost field data, without considering the complicating aspects of small-scale (local) variability: Athavale *et al.* (1992) present results for 19 Indian basins (ranging in size from 40 to >50,000 km$^2$), Edmunds and Gaye (1994) consider a 1600 km$^2$ area in north-west Senegal, and Leaney and Herczeg (1995) target a 3000 km$^2$ strip in South Australia. This last study is interesting in that it deals with a karstic aquifer overlain by soil of variable permeability and combines several mutually supporting techniques, i.e.

- vadose zone chloride profiles (to estimate diffuse recharge for the different soil types and through the base of an ephemeral swamp);
- temporal changes in groundwater salinity (to investigate the results of land use changes);
- the stable isotopes $^2$H and $^{18}$O (to fingerprint potential recharge sources);
- groundwater $^{14}$C and $^{13}$C concentrations of total inorganic carbon (to indicate the areas of enhanced recharge).

Other recent methods used to estimate recharge over extended areas reflect, to some degree, a proposal by Lerner *et al.* (1990) that "some potential lies in a combination of field measurements, remote sensing and geostatistics". In a study which aimed to derive regionalised recharge estimates for central Kansas, Sophocleous (1992) first used multiple linear regression analysis to develop a simple relationship between annual recharge from 10 sites and four easily measured independent variables. Regional recharge was then determined by GIS overlay analysis based on the weighted recharge-related variables. Kennett-Smith *et al.* (1994) adopted a conceptually similar approach for the south western Murray Basin, Australia; recharge estimates were related to soil type, rainfall and land use by combining data sets from 18 field locations with a simple daily water balance model. A more recent contribution by Salama *et al.* (1994b) showed that recharge areas in a 2000 km block of Western Australia could be readily identified using aerial photographs and Landsat (TM) colour composites; conclusions were verified by hydrogeological field studies.

Results from (*inter alia*) the Kennett-Smith *et al.* (1994) study indicate that despite its present shortcomings, the areal water balance method can be a powerful tool to understand the main features of recharge processes if short time periods are considered and the variability of the water balance components are taken into account. To this end, it is expected that procedures arising from (e.g.) the ongoing FIFE programme (Sellers *et al.* 1992) will make a valuable contribution, particularly with respect to determining evapotranspiration and soil moisture status over an extended target area.

Dedicated readers are referred to Blöschl and Sivapalan (1995) for a comprehensive review of the numerous, complex theoretical and practical issues relating to 'scaling' in hydrology.

### 7.4.2 Recharge from intermittent flow

The two principal mechanisms of natural groundwater recharge under conditions of ephemeral flow are mountain front- and channel recharge; in (semi-)arid regions both types frequently occur in the same drainage basin and are difficult to separate in practice. Descriptions of their respective physical and hydrological characteristics are given by Lerner *et al.* (1990).

***Mountain front recharge***: With respect to mountain front recharge, estimates of this component are vital for management purposes in areas where total recharge is small and development may lead to overdraft conditions. Determination by water balance calculations is unreliable, and methods based on either hydrochemical mass balances or environmental isotopes are shown to be associated with large uncertainties. An alternative approach has recently been proposed by Chavez *et al.* (1994a, b), who develop and test an analytical seasonal streamflow model which includes mountain front recharge as one of the parameters. The model is formulated in terms of parameters with physical significance, makes use of normally recorded climatic / hydrometric data and favours remotely sensed input of basin characteristics.

***Recharge from ephemeral channels** (wadis)*: The most common approaches to determining recharge from wadis have been by water balance methods, empirical formulae, isotope tracer studies and Darcian approaches; numerous examples are summarised in Lerner *et al.* (1990). None could be thought of as straightforward and the empirical formulae, in particular, are site specific. Examples of recent detailed studies to refine local ephemeral channel recharge estimates are afforded by Abdulrazzak *et al.* (1989), Parissopoulos and Wheater (1992), Hughes and Sami (1992), Sorman and Abdulrazzak (1993) and Scanlon (1994). All target the unsaturated response of wadi alluvium under field conditions and required an intensive data collection programme; with the possible exception of the Tabalah study, none addressed the issue of spatial heterogeneity in bed material. As concluded by Parissopoulos and Wheater (1992), it is clear that the relationship between hydraulic properties at a point and reach transmission losses requires further investigation.

### 7.4.3 Recharge from permanent water bodies

Typical examples of seepage recharge from permanent water bodies are losses from rivers or lakes and irrigation losses from canals or through the bunds of flooded fields. In urban situations recharge occurs from water mains, sewers and drainage ditches. Since the processes involved and the numerous techniques used to estimate recharge from such line sources are well documented in the readily available literature (e.g. Lerner *et al.* 1990), the present discussion emphasises aspects which are either new or innovative. These more recent significant advances include:

***Seepage recharge from rivers, canals and flooded rice irrigation:*** Realistic estimates of seepage recharge from rivers rely primarily on field measurements of flow losses. Recent examples of this approach are detailed by Knighton and Nanson (1994) for a >400 km reach of Cooper Creek, Australia, and by Zellweger (1994) in Colorado using multiple tracer (lithium, sodium, chloride and bromide) continuous injection.

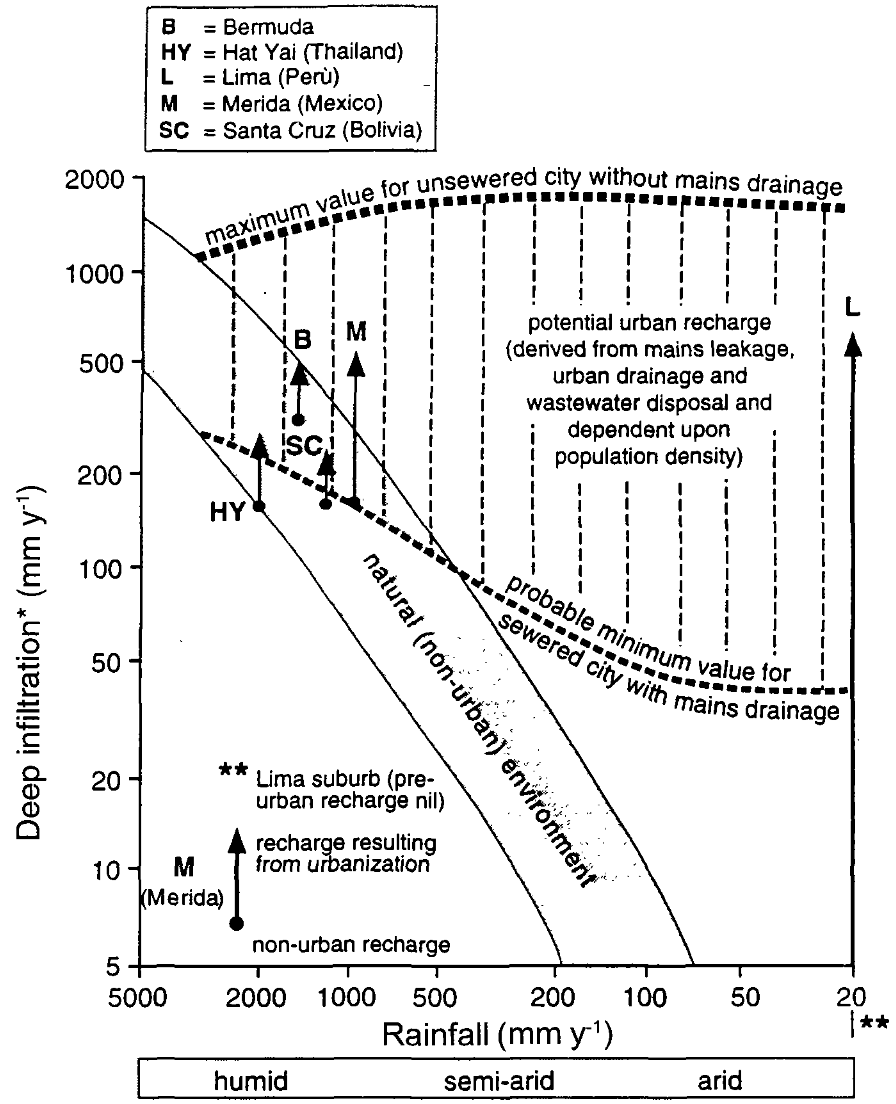
With respect to canals, earlier guidelines such as those proposed by the Government of India (1984) have assumed minimal losses from lined canals. However, more recent ponding tests and water balance studies have demonstrated that large losses can occur which are rarely less than 25% of the water supplied. It has also now been shown that time-varying losses in excess of 50% are typical from unlined canals and form an important component of the recharge in areas where there are canal irrigation schemes.

A similar situation has been demonstrated for flooded rice irrigation, with field and modelling studies indicating typical recharge water losses of 2 mm/day as vertical flow through the plough layer and 8-13 mm/day through the bunds. This last result is particularly surprising when one considers that bund width is generally in the order of 1/100th rice field width, but has recently been confirmed by Tuong *et al.* (1994) during a comprehensive study at the International Rice

Research Institute in the Philippines. First estimate irrigation loss design charts have now been developed by Rushton (in Simmers, 1997) which require only simple field measurements. Two practical recommendations from the Philippines study, with regard to reducing water losses, were to lower ponding water depths and to seal bund walls with mud from the plough layer.

***Recharge in urban areas***: Urban development can have a profound impact on the hydrological cycle and hence water balance of an area. Increased recharge is commonly reported, often resulting in rising groundwater levels, widespread and costly damage to structures and services, and a deteriorating quality of local water supplies. The changes are even more marked when major water imports from outside the urban limits are involved, particularly when combined with a lack of (sub)surface drainage; in such cases, as much as 90% of the imported water may be recharged. The effects vary with the type and stage of urbanisation and between advanced and developing countries, giving similar problems irrespective of climatic region.

Although urbanisation can induce an increase in surface runoff and a reduction in direct recharge, new sources of recharge water are introduced. These include: leaking water mains;



* to unconfined or semi-confined aquifer recognising that surface runoff becomes more frequent in high rainfall situations, but not making any allowance for phreatic evapotranspiration.

*Fig. 7.5 Potential range of increase in recharge due to urbanization (Foster,* et al.*, 1994).*

septic tanks and leaking sewers; over-irrigation of compounds, parks and roadside verges. The most common net effect of these is to increase recharge to at least pre-urbanisation rates (Foster *et al.* 1994; Figure 7.5). To consider briefly each of the above recharge sources:

***Recharge from leaking water mains***: Two facts are clear from the literature on this aspect of urban recharge, i.e. (a) in terms of a local hydrological balance the amount of water circulating in distribution systems can be large in relation to excess rainfall, even in relatively humid climates, and (b) since water mains are normally pressurised, leakage will occur from any location where there is a weakness, even if the pipes are below the water table.

Few authorities claim to be able to reduce leakage below 10% of the water supplied and rates of 65% have been reported. This source alone can thus create a potential recharge which is orders of magnitude greater than natural rates. Results from several of the more recently reported studies show that mains leakage is rarely less than 20% and more typically in the order of 30% of supply. Published figures also indicate that this component can account for up to 45% of total urban recharge, though approximately 30% is again more usual.

*Recharge from septic tanks and leaking sewers*: Septic tanks, latrines and cesspits are an obvious source of polluted recharge, particularly in developing countries where the provision of mains sewage lags considerably behind urban population growth. For example, such sources are thought to contribute almost 40% of total urban recharge in Riyadh (Saudi Arabia), 30% in Bermuda and 20% in Doha (Qatar).

*Recharge from over- irrigation of parks/gardens and other public amenities*: Contributions from this source vary widely, but are typically in the order of 20-40% of total urban recharge. As illustration, detailed field- and modelling studies in Lima (Peru) showed local irrigation rates of up to 15 mm/day in an area where daily potential evapotranspiration reaches 5 mm at maximum. Similarly, application rates of about 23 mm/day are reported for Riyadh, with ET demand at 8 mm/day. Such over-irrigation is particularly important in cities where high rates of urban recharge are associated with rising groundwater levels (e.g. Doha, Riyadh).

Many detailed data can be needed to determine the effects of urbanisation on recharge. Whether the effort to be invested justifies the resulting improvement in accuracy of a groundwater model depends on the precision required, the size of the urban area, the ratio of imported water supply to precipitation and other recharge, and on the nature of the city. The most direct method to estimate urban recharge is to carry out field measurements for each of the component processes. However, to consider each individually, with their associated errors, can lead to a large error in the final estimate. Alternative procedures are discussed by Lerner *et al.* (1990).

## 7.5 Concluding remarks

The principal aims of the present review are to supplement and update the wealth of information contained in Lerner *et al.* (1990) and to offer further guidance to the practitioner engaged in (semi)arid zone water resources exploration and development. With respect to the latter, readers are encouraged to explore the identified recent techniques. It should be noted, however, that many of the reported studies are in response to specific local issues; it cannot be concluded that all the procedures described will prove equally reliable elsewhere.

Groundwater recharge estimation is an iterative process, with progressive aquifer response data collection and resource evaluation. There is a need to use more than one technique in order to verify results. Further, some recharge models are complex and have large data requirements; others are relatively simple and concentrate on dominant features which control the quantity of water that reaches the main aquifer. The important criterion for all models is that they must represent the essential features of likely flow mechanisms.

The research literature repeatedly illustrates that the estimation of recharge fluxes in arid and semi-arid regions is fraught with uncertainty. Multiple tracer approaches appear to offer the best potential for reliable results in local studies which require 'at-point' information. It is also clear, however, that sufficient advances have been made in recent years to show that the value of water balance and Darcian methods should not be underestimated. Field measurements are a necessary component of a recharge investigation, at any scale, as they form the only means to realistically investigate recharge processes.

The frequently investigated issues of localised recharge and spatial variability need not be a problem if concern is with regional estimates. The key for the practitioner, therefore, is the project objective; this will dictate whether multiple 'at-point' or area-based estimation methods are appropriate. It is further concluded that the combination of reliable local data, remote sensing, GIS technology and geostatistical techniques offers considerable promise for a better understanding and quantification of recharge over extended areas in (semi-)arid regions.

At a workshop in 1987 answers were sought to the following questions posed in the opening session (Simmers, 1988):

- Is sufficient known about the mechanisms of recharge?
- Under what limiting conditions is each recharge estimation method of value?
- What are the present deficiencies in information between recharge theory and application? How best can these be bridged for the practitioner?

As a 1995 reaction, the present summary review and other recent recharge literature clearly show that considerable progress been made in the past decade on this issue of fundamental importance for (semi-)arid zone water resource management

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# 8. Fresh groundwater resources from artificial recharge in the Amu Darya delta

**Albert M.Shapiro, Uzbekistan**

The Amu Darya delta includes the densely populated areas of the Karakalpakstan Khorezm and Tashaus oases. Examination of the territory shows that a large part of the populated area has fresh groundwater deposits, connected with the Amu Darya river and the main irrigation canals. At the same time almost the whole of the delta, including the north-west area on the left bank of the river, can be provided with potable water supplies through the help of treatment plants based on a deep cretaceous aquifer, which is very convenient for desalinisation and protected from pollution. The population of the Karakalpakstan and Khorezm oasis is 2.3 million: about 1600 thousand people are supplied from the Amu Darya through the Tujamujun pipeline, 100-150 thousand from 130 treatment plants, and about 300 thousand from groundwater deposits (mainly in the south of Karakalpakstan where the Tujumujun pipeline has not yet been connected). There are a further 300-400 thousand people, mostly in the northern part of Karakalpakistan, who have no source of drinking water.

There are 65 fresh groundwater deposits in the region, so-called river and canal lenses, 40 of which are located in Karakalpakistan. Two lenses are located along the river (Beruny and Chalish) while others are along the main irrigation canals such as Kegaily, Kuvanishjarma., Shumanay, Khavat, Palvan-Gazavat, Bogjab, etc. When first adopted, the fresh groundwater resources for Karakalpakistan were 364.2 thousand $m^3$ $day^{-1}$ from 37 deposits, followed by 446.5 thousand $m^3$ $day^{-1}$ from 25 deposits for Khorezm. Following a water quality assessment in 1989-90, the resources required for Karakalpakstan were estimated at 187.4 thousand $m^3$ $day^{-1}$ from 35 deposits and for Khorezm 381.4 thousand $m^3$ $day^{-1}$ from 25 deposits. In 1990, the annual average discharge was 33.1 thousand $m^3$ $day^{-1}$ in Karekalpalotan from 19 deposits and 37.7 thousand $m^3$ $day^{-1}$ in Khorezm from 12 deposits.

During the last six years the situation grew worse because of the setting up of the Tujamujun pipeline and most of city supply sites were preserved (Urgench, Nukus, Shavat, Chimbay, Kegeily, Akmangit, etc.). The main reasons for the low level of groundwater use were (1) an underestimation by local authorities of the role of groundwater as a healthy source of potable water for the population and (2) shortage of finance for skilled professionals and pump equipment.

Fresh groundwater lenses are located along the river and irrigation canals in alluvial sandy depositions of ancient riverbeds and streams of the Amu Darya. The formation of lenses requires the following conditions:

- a source of fresh water (such as an irrigation canal);
- the crossing over of such depositions by a canal;
- the canal's water horizon to be higher than the groundwater table;
- a large volume of sandy porous media;
- and some drainage on a boundary for the outflow of saline groundwater and its removal by fresh water.

The dimensions of lenses are usually not more than as follows: width — 600-700 m, thickness — 30 m, length — 2000–10,000 m. Only river lenses have a very large width of up to 2000 m. and thickness of 70 m. The water table depth is usually 1.6–3.0 m. Sandy deposits are covered by salts with a thickness of 0.5-3.0 m and underlaid by neogene or cretaceous sandstones with saline water. One such deposit's average capacity is 5-10 thousand $m^3$ $day^{-1}$, with the groundwater intimately connected with surface water. This is why it is necessary to compare some of the water quality parameters in the river, irrigation canals and groundwater supply sites for 1990 because this year had average river discharge. If the water supply facility near the city of Termez sets allowable concentrations for the chemical components of the water, and total hardness concentrations for the Tujamujun reservoir, the mineralization and total hardness standards for the River Samanbay near the city of Nukus and the groundwater supply sites observation points are higher than the standard allowed throughout the year, excluding a 3-4 month period (June-August), when river water quality meets the standard required. During these months river water can be used for artificial recharge of groundwater resources.

All groundwater deposits are classified according to the extent of artificial recharge technology adopted. The conditions necessary for its usage are primarily:

- a source of potable water available for at least three months;
- a sandy collector with minimum thickness of 16-20 m;
- a coefficient of permeability not less than 10 m/day;
- overall dimensions of: length —1000–1500m, width — 700–800 m, thickness of silt layer — more than 3m.

According to such criteria, the groundwater deposits have been classified as follows: ten deposits are invalid for artificial recharge, two deposits are river-related lenses and others canal-related, and among the rest, three are two-layer deposits. All deposits are separated according to base and analogue type. Base deposits are the largest and typical lenses, where special works were implemented. For the analogue deposits, resources were adopted by comparison with base deposits.

At the present time the resources of all the base deposits in Karakalpakstan are adopted on the basis of the artificial recharge technology. Additional work was done on the supply sites using operational wells in an experimental segment. Located along the canal at a distance of 30-50 m from it, experimentation was successfully implemented on 11 of the city and agricultural settlements supply sites at Urgench, Turtkil, Chimbay, Khalkabad, Akmanget, and others.

The technology for artificial recharge of groundwater resources operates according to a common principal but which may change according to the specific conditions of a deposit. At the outset of such schemes, some basic requirements must be met:

- accumulation of an estimated volume of fresh water during high river flow periods;
- increasing the distance between the canal and the line of the wells to avoid bad quality water being input from the canal to the wells;
- regulation of exploitation according to canal flow, surface water quality and the speed of the movement of the saline groundwater boundary.

To meet these requirements, the supply site has the following configuration. Two or three lines of wells, depth 25-30 m, are located along the irrigation canal and are separated by a system of artificial canals. The length of the site depends mostly on water demand. The distance between the lines of the wells and the canals is 60 m. The width of the artificial canal is 15 m, depth <3.5 m. In the summer time, when river flow is high and water quality is good, all wells at the site are in operation, with maximum discharge and full canals. From experience, it is known that about 50-75% of the filtrating water discharged by the wells accumulates in the sandy porous media. After a high river flow period, two outer lines are closed and only the middle line continues to discharge, possible from the accumulated volume of water up to the next high flow period.

Water discharge in the summer time equals 10-12 thousand $m^3$ $day^{-1}$; in winter time — 3.4 housand $m^3$ $day^{-1}$, which is three times less than in summer because of changes in water demand between summer and winter under arid climate conditions. The average discharge from our wells is 3-6 l $sec^{-1}$. For the two-layers deposits, the difference is as follows; winter pumping is operated from the lower aquifer where fresh water has accumulated and which is isolated from the upper layer. Artificial recharge is used in the upper aquifer to develop discharge, decrease the pressure on the lower aquifer and avoid saline water outflowing from the upper to the lower aquifer. In this case, wells are drilled into the two aquifers separately.

The problem of maintaining water quality can be demonstrated by the example of the supply site for Turtkul city. Experimental works were implemented during two years on one segment, consisting of six wells and two artificial canals. Summer discharge was 5 thousand $m^3$ $day^{-1}$ during two months (July-August). Winter discharge was 1 thousand $m^3$ $day^{-1}$ because of a very short filtration cycle time. The main water quality parameters for the irrigation canal, the line of traditional wells near the canal and the experimental wells were all quite different. The water dry residue was 0.6-1.7 g $l^{-1}$ for the irrigation canal, 0.6-1.3g $l^{-1}$ for the line of traditional wells, and 0.8-0.95 g $l^{-1}$ for the experimental wells. These last figures were stable throughout the year and meet the standard required. Total hardness was 5-13 mg.env $l^{-1}$ for the irrigation canal, 5-11 mg.env $l^{-1}$ for the traditional wells, and 6-9 mg.env. $l^{-1}$ for the experimental wells, which were the lowest and more stable values. Water temperature in the experimental wells was 17°C; turbidity, odour and taste were absent. A large amount of chemical analysis demonstrated good biological conditions and absence of pesticide and fertiliser pollutants. This phenomenon is due to the effectiveness of a natural sandy screen.

The potential for artificial recharge usage is defined not only on the principal possibility of maintaining good water quality but also for economic advantages. For example, one supply site reconstruction on the basis of artificial recharge technology cost the equivalent of US$ 300 000 and its annual running costs about US$ 30,000. Thus, the price of 1 $m^3$ $d^{-1}$ of water will be 0.26 cents. At the same time, 1 1 $m^3$ $d^{-1}$ of water from the Tujumujun pipeline costs 1.6 cents and from the treatment plant 1.87 cents. The groundwater price is thus six times less compared with pipeline or treatment plant produced water. Other advantages are the following:

- the cyclical character of the artificial recharge system; the greater capacity in comparison with treatment plants;
- the possibility of reconstruction of operating sites with minimum expense and time.

Groundwater deposits could provide about 25% of potable water demand in Karakalpakstan and can be also used as a reserve source of drinking water in the case of a Tujumujun pipeline failure.

# 9. Quasi-3D mathematical model for groundwater resources management in the Gurguéia Valley, Piauí State, Brazil

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**(Italy/Brazil)**

## 9.1 Introduction

Within a project financed by the Italian Ministry of Fioreign Affairs, a hydrogeological study was conducted in the Upper Gurguéia Valley, Piauí State, Brazil (see Fig. 9.1 and CEPRO-IBGE, 1990; CPRM, 1978; DNOCS-SCET SIRAC, 1976; DNOCS-DIPRO-ATEPE-LABHID-UFPE, 1990; DNOCS-COTEP, 1973; DNOCS-COTEP, 1976; DNPM-CPRM, 1973; Marinho de Oliveiras *et al.*, 1990; Mebus, 1976; RADAMBRASIL, 1973 and SUDENE, 1978) involving geological, tectonic, hydrogeological, hydrological and chemical-isotopic investigations (Catani *et al, in press).* A preliminary modelling approach (Crestaz *et al.*, in press) pointed out the key role of the vertical

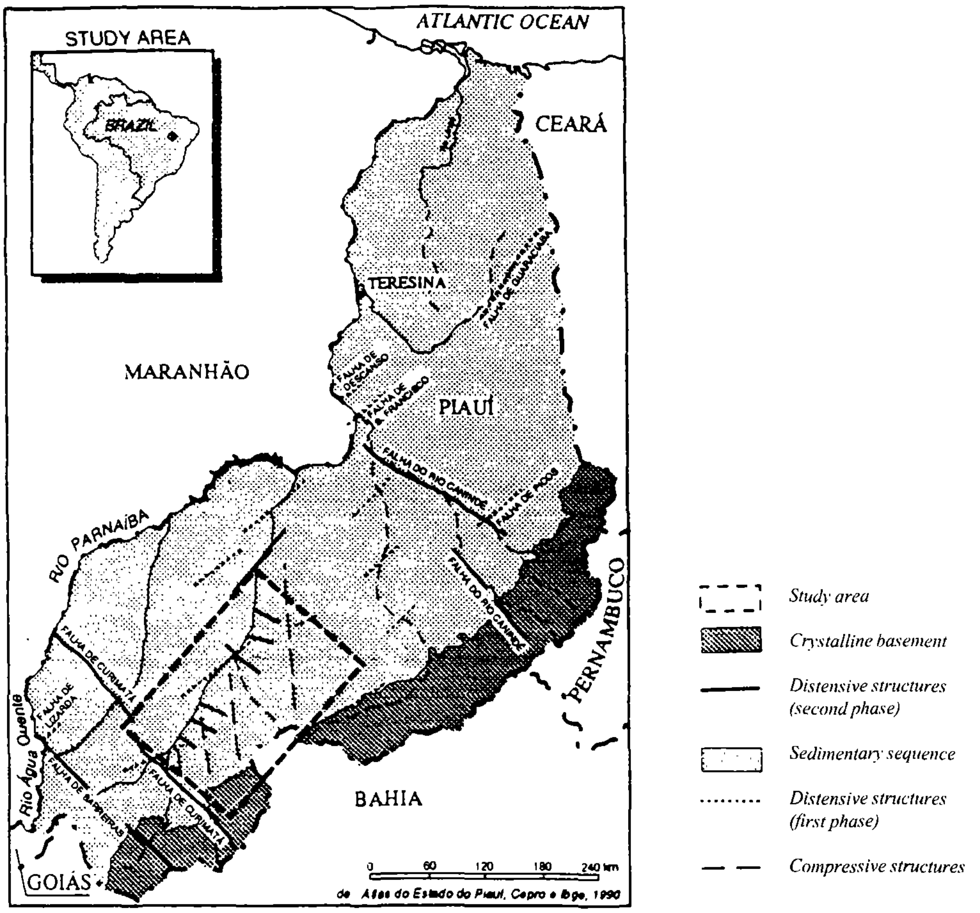

*Fig. 9.1* *Study area and main regional tectonical structures*

fluxes through the aquitards, the related influences of the Gurguéia River on the piezometries and the hydrogeological implications of the tectonic structures, both at large and at the local scale. The final target, focussed on in this paper, was the implementation of a multi-aquifer model (Anderson, 1992; Aral, 1989; Bear and Verruijt, 1987; de Marsily, 1986, Kinzelbach, 1986 and Kruseman and de Ridder, 1990) to be used by the Brazilian groundwater management authority in planning exploitation activities and in the evaluation of development policies.

### 9.1.1 Geology

Two original hydrogeological maps, one at scale 1:250,000 (Fig. 9.2) and one at scale 1:100,000 covering the Gurguéia River valley, revealed a fairly thick stratigraphic sequence which, from the Precambrian crystalline basement at the south-east border of the study area, includes:

- Serra Grande aquifer (coarse quartzitic sandstones);
- Pimenteiras aquitard (silty sandstones with thick clay interbeddings);
- Cabeças aquifer (medium-fine grained quartzitic sandstones);
- Longá aquitard (silts and fine-grained sandstones);
- Poti-Piauí aquifer (sandstones with thick interbeddings of silt in the upper part of the series).

A detrital cover, prevalently silty, non-fractured, with thickness varying from 10–35 m, extends over a large part of the Cabeças outcroppings, thus reducing the effective permeability. Intense fracturing affects the crystalline basement and the sedimentary sequence up to Cabeças. The overlying formations and the detrital cover are slightly or locally fractured along the main tectonic trends involving geomorphological evidences.

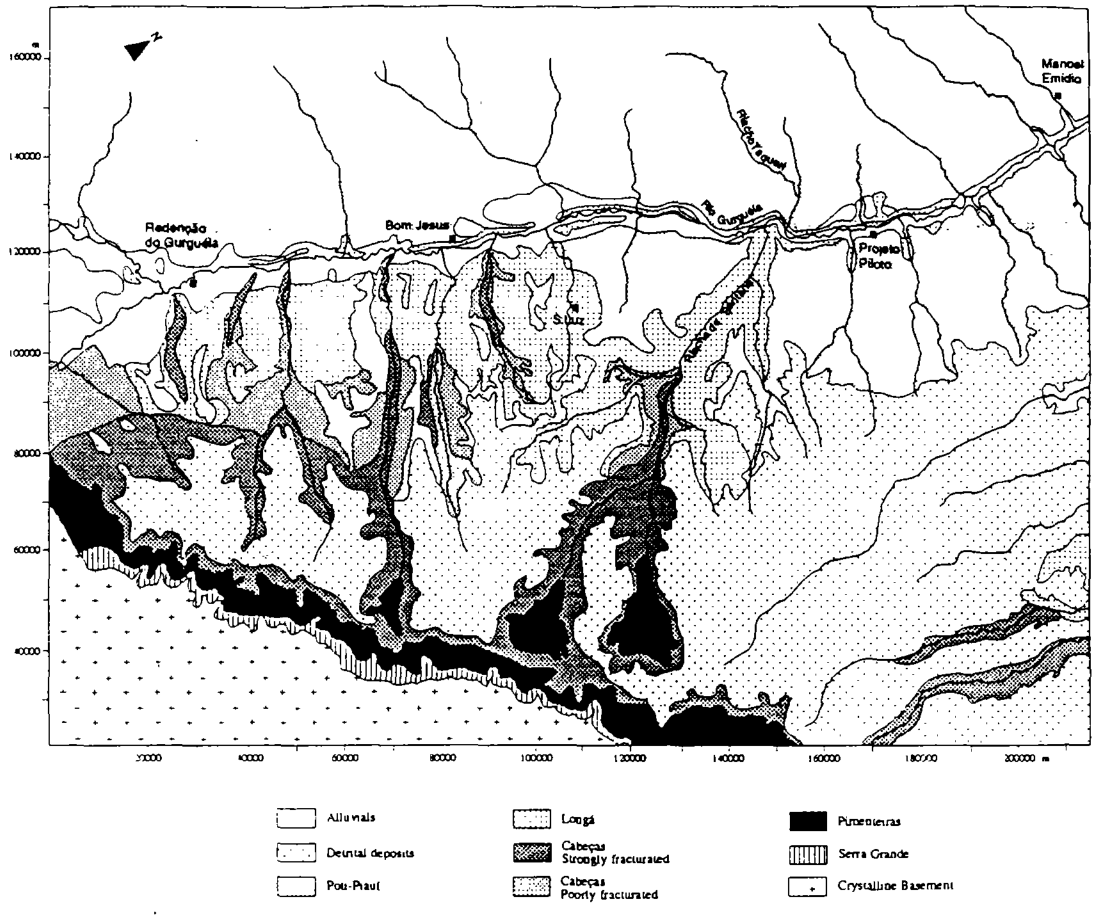

*Fig. 9.2* *Schematic geological map*

## 1.2 Tectonics

At the regional scale (Fig. 9.3), we observed (Marinho de Oliveiras *et al.*, 1990):

- NE–SW oriented faults, parallel to crystalline outcroppings (e.g. Guaraciaba and Lizarda faults) that can be linked to a pre-Mesozoic distensive phase, responsible for formation of a large graben in the Parnaiba basin;
- SE–NW oriented faults (e.g. Curimatá and Barreiras faults) related to a second pre-Mesozoic distensive phase;
- comprehensive Mesozoic structures oriented NS (e.g. structural high of Canto do Burití in the study area).

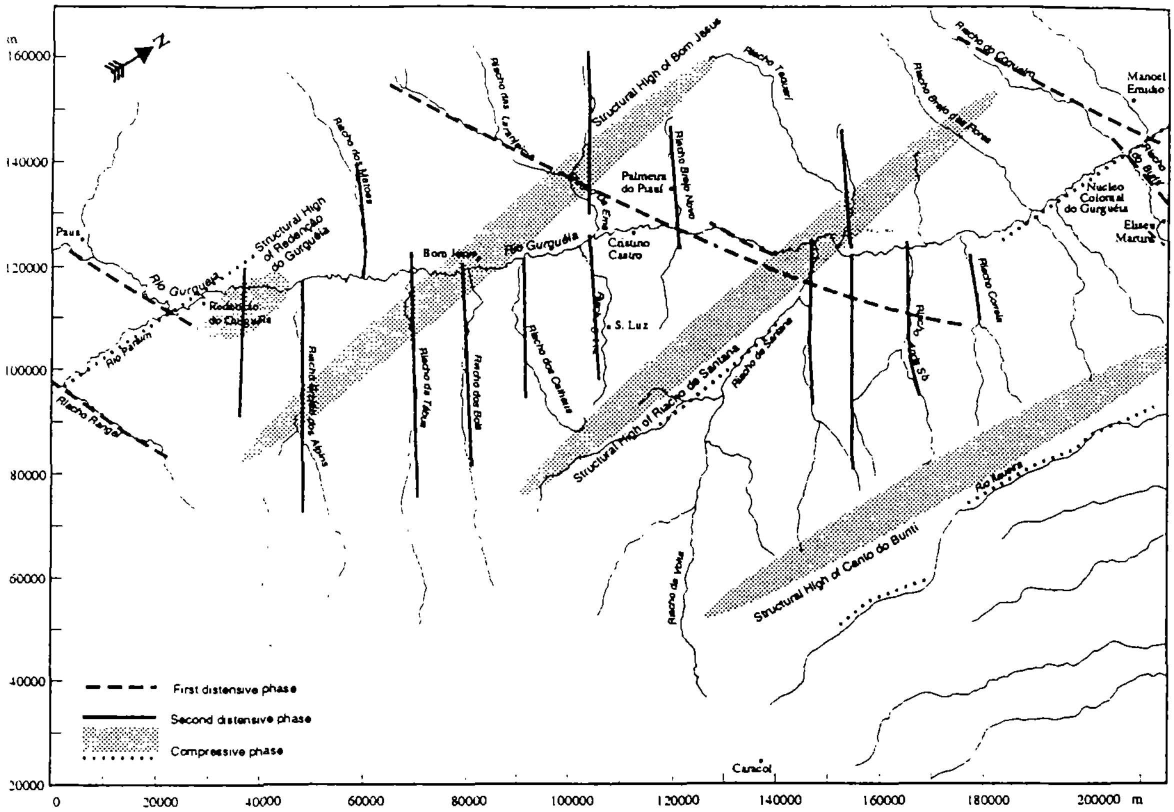

*Fig. 9.3* *Main tectonic structures*

### 9.1.3 Hydrogeology

The most important hydrogeological information is the following:

1. *Historic piezometric data.* They indicate variations of 2–3 m for Cabeças and 30–40 m for Serra Grande (Violeto, Fazenda Santa Fé and BP-6 wells);
2. *Present piezometries for the three regional aquifers.* The piezometries of Cabeças and Serra Grande are analogous near the crystalline outcropings and totally different near the centre of the valley (+30–50 m in Serra Grande). The Poti-Piauí piezometry indicates runoff towards the Gurguéia River and substantial drainage along the tributaries (Riacho do Matoes and Riacho das Laranjeiras);
3. *Local Cabeças piezometries in the Piloto project area referring to 1991-92.* The annual piezometric variations are in the order of 10–15 m, with the lowest piezometry occurring in

July under maximum exploitation for irrigation purposes. Original conditions are restored fairly rapidly (1–2 months) at the end of the irrigation period;

4 *Thickness, hydraulic conductivity and storage coefficient of the aquifers.* Maximum thickness is 200–350 m for Cabeças and Serra Grande along the valley bottom. The Poti-Piauí, mainly present on the hydrographic left, is 300–350 m thick near the watershed, along the north-west border of the study area. Hydraulic conductivity is relatively low in Serra Grande due to cementing, and in Poti-Piauí owing to the fine-grained lithology. Higher values were recorded in Cabeças through the effect of fracturing.

5 *Thickness and permeability data for the Pimenteiras and Longá aquitards.* Maximum thickness is respectively 30 and 150 m. Permeability is in the order of $1 \times 10^{-7}$ m $s^{-1}$, as indicated by pumping tests carried out on the silty layers of the aquitards, and is not representative of equivalent vertical permeability. The latter, governed by finer-grained interbeddings (40–50 m of clay within Pimenteiras) must be evaluated from the literature.

### 9.1.4 Hydrology

The hydrological study provided effective infiltration estimates for each aquifer, for sub-areas and for various probabilistic time periods (Table 1) (Frischorn and Santiago, 1992; Huyakorn and Pinder, 1983; Mather and Thornthwaite, 1957; Shaw, 1985 and Walton, 1987; 1989). Values are low for Serra Grande due to the limited outcropping area in the south-east recharge zone, to the topographic trend and to the semi-arid climatic conditions typical of higher elevation areas. Higher infiltration was calculated for Cabeças and Poti-Piauí on extensive outcropping areas. In Cabeças, a major difference exists between fractured areas and areas covered by low-permeability, fine-grained detrital formations.

**Table 9.1** Effective infiltration estimates *($10^6$ mc)*

| *Aquifer* | *Wet year*<br>*Return period = 5 y* | *Normal year* | *Dry year*<br>*Return period = 5 y* |
|---|---|---|---|
| Poti Piauí (12055 $km^3$) | 69.2 | 62.5 | 13.4 |
| Cabeças (3107 $km^3$) | 209.45 | 86.57 | 50.27300–100 |
| Serra Grand (412 $km^3$) | 10.54 | 4.42 | 2.52 |
| Total (15574 $km^3$) | 289.19 | 153.49 | 66.19 |

### 9.1.5 Chemical and isotopic analyses

In all three aquifers the chemical composition is very similar but the chemical-physical characteristics (pH, electrical conductivity, temperature) and isotopic composition differ substantially. Major physical-chemical variations were observed in the Serra Grande circuit, depending on the age.

The isotopic study has differentiated present and ancient recharge, specifying that the age of waters along the valley bottom is 21,000 for Serra Grande and 6000 for Cabeças (absolute datings using Carbon-14; AIEA, 1990 and 1992). It also pointed to low circulation rates.

## 9.2 Numerical code

The finite element numerical code OSM (Oxford Geo Technica Ltd., 1991 and 1992) was adopted on PC hardware under the MS-DOS operating system. It is a multi-aquifer model, particularly well suited for continuous aquifer and aquitard systems, and represents the 3-D extension of other well-known models (Geo Trans. Inc., 1988; Oxford Geo Technica Ltd., 1989). Every aquifer is modelled according to a two-dimensional rectangular grid, where each element is assigned a group of hydrogeological parameters (thickness, permeability and storage coefficient) and a pumping rate. The aquifers are connected by vertical linear elements that permit simulation of flow tied to leakage, even in transient conditions.

## 9.3 Steady-state calibration

The historical piezometric data of the Cabeças indicate small variations of about 1–2 m in the last five years, while no significant data are available over the same time interval for both Serra Grande and Poti-Piauí. Due to discharge concentration in the Cabeças, the hypothesis that steady-state conditions were satisfied by the system in 1991 appears to be quite reasonable.

### 9.3.1 Conceptual scheme, boundary conditions, properties distribution

The aquifers are characterised, from the top of the stratigraphic sequence, as follows:

- *Poti-Pianí aquifer.* All of the outcropping area is recharged. The north-west boundary of the modelling area is a null flux boundary (except for a small inflow at the northern limit) as it is along the water divide. The same condition is adopted along the north-east and south-west limits. The Gurguéia River and a few tributaries with clear drainage behaviour (Riacho dos Matoes and das Lanranjeiras) represent the natural basin of confluence of the Poti-Piauí aquifer. They are consequently modelled with fixed head nodes. The thickness varies from a few tenths of metres in the proximity of the Gurguéia up to 300 m along the water divide. The calibration permeabilities are in the order of $2\text{-}3\times10^{-6}$ m s$^{-1}$.

- *Cabeças aquifer.* The recharge is characterised by high values over the highly fractured outcrop area and much smaller values where a low-permeability thin eolian formation overlies the aquifer. The S limit, along the crystalline basement outcroppings, is the natural water divide at regional scale and it is obviously modelled as the no-flow boundary, as well as being part of the south-west limit. Inflows are assumed at the southern limit, associated with the Gurguéia and Paraim Rivers and along the structural high along the eastern limit. A few right-hand tributaries of the Gurguéia play a strong role in aquifer piezometry control and they are assigned constant heads. The north-west limit is again assigned a fixed head condition and it is not critical to the system due to the distance from both well fields and the main river (30–50 km). The thickness ranges from a few metres up to 300–350 m at the northern limit of the study area, according to gradual thickening of the stratigraphic sequence to the north. The calibration permeability is in the order of 10 m$^{-5}$ m s$^{-1}$ but it increases along the Gurguéia River and north of Cristino Castro ($6\times10^{-5}$ m s$^{-1}$), because of the effect of fracturing along the main regional tectonic trends. A few tectonic structures, ranging north-south and related to the Mesozoic compressive phase and others, ranging south-east–north-west and delimiting the Projeto Piloto sector, are basically permeable barriers ($2\text{-}5\times10^{-6}$ m s$^{-1}$).

- *Serra Grande aquifer.* The outcropping and recharge area is quite limited and close to the crystalline basement outcroppings. According to the conceptual scheme for the Cabeças, the southern limit is a nullflux boundary, the eastern limit is a fixed inflow and both north-east and north-west limits are fixed head boundaries. The thickness varies from a few tenths of metres to a maximum of 300 m at the northern limit, and the calibration permeabilities ($6\times10^{-6}$ m $s^{-1}$) are usually less than those of the Cabeças. For analogy with Cabeças, high permeability areas are assumed to occur along the Gurguéia River, while low permeabilities are adopted along the structural highs, trending north-south, and in the Projecto Piloto area. The aquitard-problem is a difficult one to solve because the vertical fluxes are a function of both thickness and equivalent vertical permeability. From the top of the series we have:

(1) *Longá aquitard.* The estimated vertical permeabilities are quite low ($10^{-10}$–$10^{-11}$ m $s^{-1}$), avoiding head losses in the upper Poti-Piauí aquifer. Instead, wide areas along the Gurguéia River are characterised by much higher values ($10^{-6}$– $10^{-9}$ m $s^{-1}$) due to fracturing. This would imply strong interconnection between aquifers and mainly between Cabeças and the river; the thickness ranges from 10–60 m along the Gurguéia River up to about 100 m.

(2) *Pimenteiras aquitard.* The strong fracturing causes recharge at the regional scale from Cabeças to the deep Serra Grande at the southern limit of the study area, and opposite behaviour along the valley due to the higher piezometric head of the Serra Grande. The thickness, according to general trends, varies from a few tenths of metres at the southern limit up to 300 m, while the calibration vertical permeabilities are in the order of $10^{-9}$–$10^{-10}$ m $s^{-1}$.

### 9.3.2 Recharge

The calibration values of the recharge are 3.2 mm $y^{-1}$ for the Poti-Piauí (a total of $43\times10^{6}$ $m^3$ $y^{-1}$), 2 and 20 mm $y^{-1}$ for the Cabeças outcroppings and for the overlying low thickness eolian deposits (a total of $58\times10^{6}$ $m^3$ $y^{-1}$) and 5 mm $y^{-1}$ for the Serra Grande (a total of $4\times10^{6}$ $m^3$ $y^{-1}$). These values are consistent with the estimates from the hydrological study (see Table 9.1).

### 9.3.3 Discharges

After the drilling of the first wells in 1967, the discharges increased gradually up to estimated values of $213\times10^{6}$ $m^3$ $y^{-1}$ for the Cabeças. Much lower values are estimated for the Poti-Piauí ($0.5\times10^{6}$ $m^3$ $y^{-1}$ in 1991), outcropping in an area of little interest for agricultural activities, and for the Serra Grande ($3\times10^{6}$ $m^3$ $y^{-1}$ at three wells along the valley).

### 9.3.4 Validation cross sections

A few piezometric sections (Fig. 9.4) indicate a good degree of correlation for observed *vs*. computed data, which means that the calibration target is satisfied. Among the main simulation capabilities should be noted:

- piezometric head differences between Serra Grande and Cabeças along the valley;
- influence on the Cabeças piezometry of the permeability barriers located in the proximity of the Piloto Project;
- strong interconnection between the Cabeças piezometry and the Gurguéia River, north of the Piloto Project;
- difference in the Cabeças and the Poti-Piauí piezometric trends on the left side of the Gurguéia.

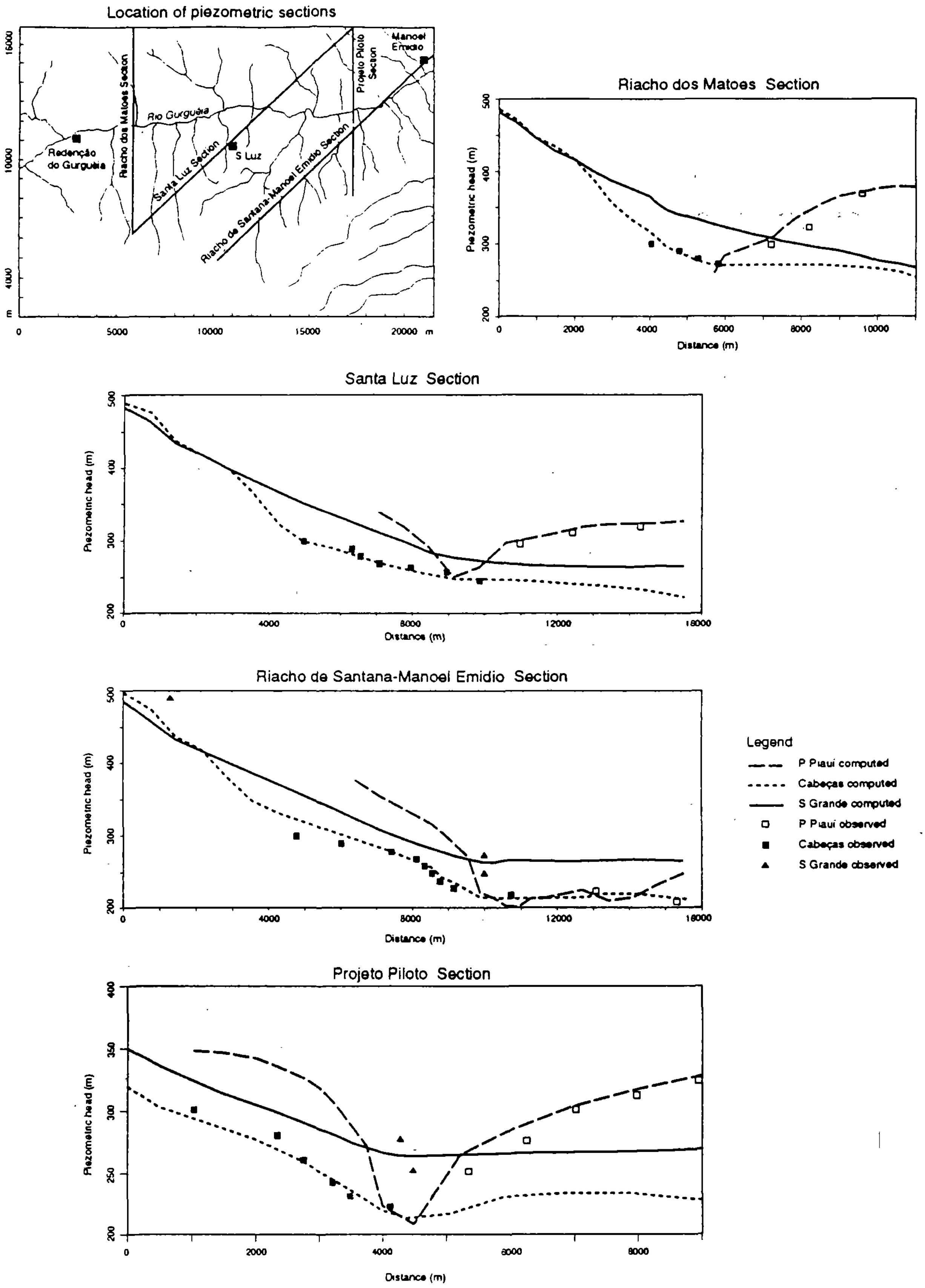

*Fig. 9.4* *Calibrated piezometric sections: computed* vs. *observed*

## 9.4. Unsteady state calibration

The historical piezometric data set is very small, basically pointing to limited piezometric variations for the Cabeças (4-5 m) and also a few tenths of metres for the Serra Grande (40 m at the Violeto well). The model, calibrated under steady-state conditions, has been used to simulate the hypothetical initial conditions with no discharge in 1967 (there being no data available at that time). Gradually incrementing the discharges (according to the available estimates) and with constant discharge (in the absence of data on climatic variations), the piezometric head distribution was computed in unsteady state conditions for the period 1967-1991). The satisfactory correlation of observed *vs.* computed values indicates that calibration requirements are satisfied while, on the other hand, the piezometric stability in the last five years states that the initial hypothesis of stationarity at 1991 is acceptable.

## 9.5 Model validation at local scale: Piloto Project

The Piloto Project area is affected by significant, but discontinuous, discharges, with maximum values achieved in July and minimum ones in the wet period October to March. The piezometric data, collected at a monitoring network from March 1991 to August 1992, point to significant drawdowns (10–15 m) and quick recoveries at the end of the pumping period. The calibrated model was used to simulate the behaviour of the Cabeças aquifer in the Piloto Project for a one-year period. The computed drawdowns in the area between the Anda So and Correia Rivers are in the order of 7–8 m and practically nil outside of the area, both situations being satisfactory with respect to the observed data.

## 9.6 Hydraulic balances at 1967 and 1991

The hydraulic balance under steady-state conditions (i.e. the summation of total inflows and outflows) is obviously nil. In detail, the hydraulic balance for 1967 (Table 9.2) shows a large deficit for the upper aquifer, Poti-Piauí, and the surface hydraulic network ($-29\times10^6$ m$^3$ y$^{-1}$).

The hydraulic balance for 1991 (Table 9.2) is characterised by the discharges located mainly in the intermediate aquifer Cabeças. Consequently, the water losses from the Cabeças to the rivers reduce to one-half at the regional scale ($12\times10^6$ m$^3$ y$^{-1}$). Locally, it is also possible that inversions in leakage fluxes occur (i.e. contributions from the rivers to the aquifer in the Piloto Project area).

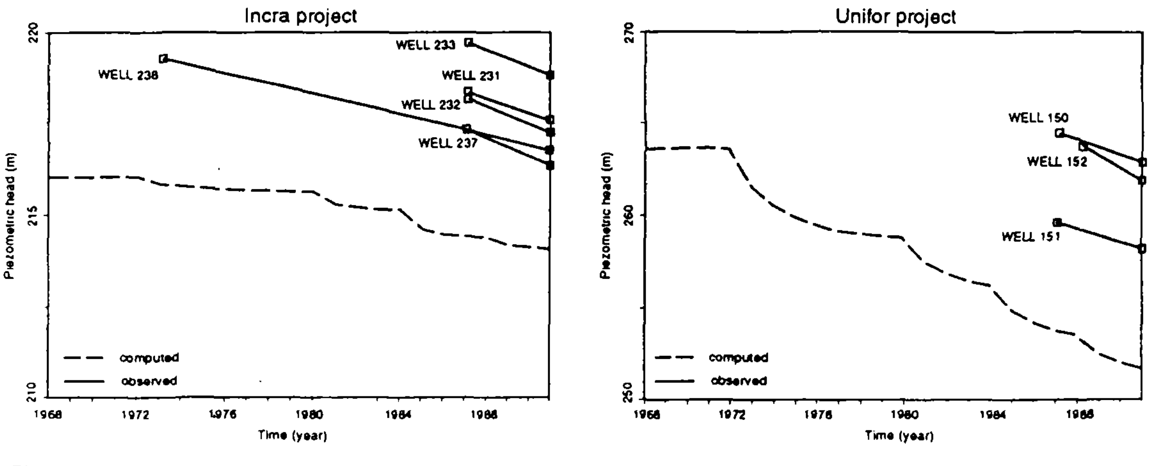

*Fig. 9.5* *Cabecas transient piezometric behaviour at regional scale: computed vs. observed*

**Table 9.2** *Hydraulic balance; 1967* vs *1991 (flux in $m^3 y^{-1}$)*

| | | *Boundary Condition* | *1967* | *1991* | *Differences* |
|---|---|---|---|---|---|
| Poto-Piaui aquifer | Effective infiltration | Neumann | 41424870 | 4142870 | 0 |
| | NE limit | Neumann | 1219120 | 1419120 | 0 |
| | Gurgueia River | Dirichlet | -61114624 | -48350932 | 12763692 |
| | Tributaries | Dirichlet | -11-53548 | -9667074 | 11386474 |
| | Wells | Neumann | - | -539461 | -539461 |
| | **Aquifer balance** | | **-29324182** | **-15713477** | **13610705** |
| Cabecas aquifer | Effective infiltration | Neumann | 58264904 | 58264904 | 0 |
| | SE limit | Neumann | 2391690 | 2391690 | 0 |
| | NW limit | Dirichlet | -11209345 | -8862127 | 2347218 |
| | NE limit | Neumann | 2668324 | 2668324 | 0 |
| | E limit | Neumann | 122253628 | 12253628 | 0 |
| | Paraim River | Dirichlet | -7577785 | -7524805 | 52980 |
| | Tributaries | Dirichlet | -31567536 | -26373746 | 5193790 |
| | Wells | Neumann | 0 | -20694837 | -20694837 |
| | **Aquifer balance** | | **25223880** | **12123031** | **-13100849** |
| Serra Grande aquifer | Effective infiltration | Neumann | 4013713 | 4013713 | 0 |
| | NW limit | Dirichlet | -4349407 | -2874896 | 1474511 |
| | NE limit | Dirichlet | 893563 | 1655631 | 762068 |
| | E limit | Neumann | 3541682 | 3541682 | 0 |
| | Wells | Neumann | 0 | -2920378 | -2920378 |
| | **Aquifer balance** | | **4099551** | **3415751** | **-683800** |

## 9.7 Preliminary predictions

The model has been used to simulate the system behaviour for different hypotheses of agricultural development:

1 Strong increases in discharges in a few areas north of Christion Castro city (+6×$10^6$ $m^3 y^{-1}$, +5×$10^6$ $m^3 y^{-1}$ and +4.1×$10^6$ $m^3 y^{-1}$ at the Piloto, Unifor and 500 Hectares projects). The model shows a strong reduction in leakage fluxes from Cabeças to the Gurguéia River through the Longá aquitard. The Cabeças piezometry is affected by important drawdowns 20 m between the Unifor and Piloto Projects, while the increase in leakage fluxes from the underlying Serra Grande also induces significant drawdowns (8-10 m) in this latter aquifer. Already the conclusion is that this hypothesis of increased discharge should be treated with great care by the local planning authority and maximum attention should be devoted to localisation and dimensioning of the wells.

2 Drilling and/or deepening of existing wells down to the deeper aquifer, Serra Grande, in order to adopt a differentiated exploitation policy. This is a theme of great interest because of the drilling (down to the Serra Grande) of the Violeto, Fazenda Santa Fè and BP-6 wells in a valley where the Pimenteiras aquitard has a thickness greater than 300 m. For the same total discharge at the system scale, but one-half being concentrated in the Serra Grande,

enormous drawdowns occur in this last aquifer and still 16-17 m drawdowns are computed for the Cabeças. The conclusion is that large increases in exploitation of the Serra Grande do not seem reasonable.

3. Gradually varying increments in exploitation of the Cabeças aquifer according to an hypothesis of agricultural activity development along the valley, north of Cristino Castro (Unifor, Jobex, 500 Hectares, Piloto, Incra and Terra Santa Projects). The total amount of increments varies from $13.6 \times 10^6$ $m^3 y^{-1}$ up to $68 \times 0^6$ $m^3 y^{-1}$. Very high drawdowns are computed both on the Serra Grande and the Poti-Piauí, due to water losses by leakage, while the impact on the Cabeças piezometry appears to be very high already for a discharge of $13.6 \times 100^6$ $m^3 y^{-1}$ (quite close to that of the first hypothesis).

## 9.8 Conclusions

A quasi 3-D finite element flux model of the Gurguéia Valley, Piauí State (Brazil) has been discussed. This model is the first attempt to provide the Brazilian Planning Authority with a provisional tool to manage the water resources of the system as a whole (the complete system has three aquifers – Poti-Piauí, Cabeças and Serra Grande – and two aquitards – Longá and Pimenteiras).

The calibration conditions were discussed in detail, both in the steady and unsteady states for the period 1967–1991, highlighting both the final distribution of the hydrostratigraphic unit properties (thickness, horizontal/vertical permeability, storage, effective infiltration) and the boundary conditions. The application of the model at local scale (Piloto Project area) and over a one-year period was satisfactory with respect to the observed data. At regional scale, the model revealed the key role of the vertical drainage fluxes, strongly affecting the Cabeças piezometry with respect to the main river (with prevalently draining behaviour).

A few preliminary predictions are made, outlining problems of great interest to the Brazilian Planning Authority:

1 *Exploitation increases made on the basis of increased agricultural development*; the intermediate and principal aquifer, Cabeças, would already be affected by important drawdowns at the regional scale as well as for discharge increases of $10–20 \times 100^6$ $m^3 y^{-1}$. Maximum attention should be devoted to well localisation and dimensioning.

2. *Differentiated exploitation of both Cabeças and Serra Grande aquifers*, by drilling new wells or deepening existing wells down to the deeper aquifer (three deep wells – 700 m – already exist down to the Serra Grande aquifer in the valley). The model points out important drawdowns in the Serra Grande and also small increments in the discharges. New drillings down to the deep aquifer are not advisable.

## 9.9 Acknowledgements

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# III

# Water resources management strategy in the Aral Sea basin

# 10. Water resources management in the Republic of Uzbekistan

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Uzbekistan is situated in the central part of the Aral Sea Basin. The Republic covers 44.8 million hectares, of which 79% are lowland and 21% are foothills and mountains. The climate is extreme continental, with hot dry summers and cold winters. Precipitation is sparse, ranging from 70-300 mm (over the plains) falling in the form of rain and snow in the autumn-winter-spring period. Potential evaporation exceeds precipitation considerably which predetermines that agriculture relies on artificial irrigation.

Farming has been practised in the region of Uzbekistan for several thousand years and thus a great deal of experience has been accumulated in irrigated land cultivation, irrigation construction and water resources management. At the present time, 4,300,000 ha within the republic is irrigated, using more than 90% of the total volume of water supply, such that almost all irrigation, land reclamation systems and hydrotechnical structures have been built and operated to maintain irrigation needs.

There are more than 50 reservoirs in the republic, with a total capacity of 16 billion $m^3$, 200,00 km of irrigation channels, a 130,000 km collector-drainage network, 1500 pump stations, about 10,000 wells for irrigation and vertical drainage, and several thousand various hydrostructures. There are 4500 water users of various sectors, out of which about 3000 belong to the agricultural sector. Every second more that 4000 $m^3$ of water is controlled (delivered for use) during the growing season. All this demands that water resource management personnel be mobile, highly skilled and up to date with the water resources situation so as to be able to apply appropriate adjustments to older water plants.

Management of water resources in the Republic of Uzbekistan is carried out through a complex system of local government and catchment personnel. General management comes under the Ministry of Land Reclamation and Water Management which annually establishes limits appropriate both for the national economy and, within the framework of the provinces, estimates of total water intake volume, including that from the Amu Darya and Syr Darya rivers. The Department of Inter-Regional Canal Operation also has management responsibility and delivers water to the provincial borders according to established limits.

In all 13 provinces there are Province Water Management departments which control water resources on the border of regions through confirmation of intake limits for regions and sectors of a province within the framework of the limit allotted by the state.

Water delivery to consumers is carried out by regional water management departments which establish decade limits for all consumers within the Province intake limit which takes account of the system efficiency. Water delivery is carried out using water offtakes which must be registered and equipped with water measuring units. Regional water managements are the main link in the chain of water resources control since they alone deliver water to consumers and thus directly control rational water use. Water distribution is implemented in accordance with agreements between the regional water management departments; water measurement is executed twice a day with participating water consumer representatives. The obligatory condition for agreement to be reached over supply to consumers is evidence of permission for special water use.

All issues to do with water resources management are regulated by two general directives:

- "*Water and Water Use*" law, which came into force through Supreme Council Decree, Republic of Uzbekistan, dated 06.05.93. Pursuant to this law, water is in state ownership and the state management body in the sphere of water (surface) specially authorised to control its use is the Ministry of Land and Water Management. Also, limited water use for all water consumers is determined by and its volume established by the Ministry of Land Reclamation and Water Management. The needs of the public utilities are provided for first.

- "*Limited Water Use in the Republic of Uzbekistan*" Cabinet Minister Decree No. 385 dated 03.08.93. By this Decree and pursuant to the "Water and Water Use" law, limitations on water use have been introduced in Uzbekistan from 1993. According to this decree, all water consumers have the right for water delivery only through a registered water intake, permission for special water use and an agreement with regional water management. Violation of this order means that the infringers are subjected to penalties and other punishments within republican legislation.

The Ministry of Water Management is given a right to reduce the water limits depending on the capacity of the resources. Established limitations regarding intake volumes is obligatory on all consumers, independent of their departmental subordination.

Water protection measures are carried out in accordance with the "Confirmation of Rule for Water Protection Zones" Cabinet Minister Decree No. 174, dated 07.04.92. Pursuant to this Decree, a riverside area is determined on the banks of every water body (reservoirs, rivers, canals, collectors, lakes) where all economic activity (except essential technologies) are prohibited, and also a water protection zone in which economic activity is limited to that which will not cause the water body itself or the water quality to deteriorate.

Improvements to water resources management still require the following issues to be resolved:

- Discrepancy between the administrative border for regions and that of the servicing area of irrigated systems. This occurs in all the provinces and makes it difficult to convey water to the furthest canal stretches in dry years.

- The technical level of a number of irrigation systems are still too low to permit the introduction of advanced automated control and management systems.

- In general, an unreadiness in water consumers, particularly in agriculture, to permit the introduction of more progressive methods for rational water use and insufficient watering equipment and facilities, both of which preclude the departure from traditional methods of water resources management.

# 11. Water resources and socio-economic development in the states of the Aral Sea basin

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When considering the problems of socio-economic development in the Aral Sea region with regard to limited water resources and a worsening of ecological conditions, we must have clearly realisable aims. Further, these must consolidate the long-term friendly relations of the States within the basin and be harmonious with the interests of all the people living in this area.

As is well-known, the basic hydrographic network of Central Asia comprises the basins of the Syr Darya and Amu Darya Rivers. To aid the rational use of water resources, the region has been divided into 11 water-use districts, three in the Syr Darya basin and eight in the Amu Darya basin.

The available water resources of the basin can only irrigate about 7.3 million ha out of the 58 million ha of the area currently devoted to irrigated agriculture: this is some 13%. About 80% of all water resources are spent in this way, the rest going to industry, public utilities and other needs. The water-economic situation of the region and some of the main problems defining the strategy for future socio-economic development may be estimated without the need for retrospective analysis of the principles behind the formation of the modern infrastructure of the national economy.

As many will be aware, during the period 1960-1980, the Republics of the Aral Sea basin have not developed any water-consuming initiatives, mainly because of the increasing reduction in the volume of water flowing out to the Aral Sea; nevertheless, part of the deficit in water resources has been compensated for by the increased use of sewage discharge. Thus, the ecological situation in the region has worsened, connected not only with the drying out of the Aral Sea but also through the deterioration in water quality.

In modern times, the Central Asian Republics make considerable efforts, with the assistance of the inter-state bodies, to increase the amount of water flowing to the Aral Sea region and also to improving the quality of the water resources. Principally, a new situation has arisen through the changed priorities for the use of the limited resources. Alongside increased water use for social purposes and industrial development, we now have equal demands from ecological systems.

Even under the conditions of highly effective use, the increased consumption by the priority demands listed above of the naturally limited water resources will increasingly restrict the limits on water for irrigated agriculture. The trends in redistribution and use for available water determines the necessity for a total change in strategy in the socio-economic development of the region.

The rise in water consumption by priority domains and the reduction in water supply limits, even at the highest level of technical perfection of hydro-ameliorative systems and the transition to more effective methods and technologies in irrigation practice, will result in the need to reduce the area of irrigated land in the near future. This is a very important point and is the principal conclusion which must be taken into account during the elaboration of future socio-economic development strategy for the region.

Side by side with the changes in integrated use of water resources, the reduction in the limits for water for irrigation needs will, in both the short and long-term perspectives, be affected by such factors as the changing regime in the use of runoff for hydropower development in the upstream runoff formation zones (Kirgizstan and Tadjikistan) and also the increase in water intake by Afghanistan (within the limits of international law). It is also necessary to take into account the possible change in the water resources of the region's rivers through global climate change. All the factors stated above indicate fairly substantially that one of the main problems in socio-economic development of both the individual States and the region as a whole is that of reorganisation of irrigated agriculture.

What are the main ways out from this complicated situation?

We have developed a conceptual scheme which provides assistance with decisions for the problems of steady water supply, the socio-economic development of the States and the rehabilitation of the ecological systems of the region. The scheme has the following main aims:

- Maximum possible mobilisation of available water resources. The basis of this objective is a mix of practical, technical and economic measures providing for the reduction in non-productive losses of water through filtration, physical evaporation and hi-tech water transfers;

- A realisation of a mix of organisational investments, technological, and economic-legal measures oriented towards a reduction in water consumption and protection of water quality in both industrial and social spheres;

- Elaboration and implementation of hydrological, hydrogeological and some technological measures involving the transformation of water resources in non-irrigated, desert-pastures to meet industrial and social needs. The sources of water in this zone (precipitation, highly mineralised groundwater, ephemeral streams, sewage reservoirs, etc.) do not contribute to the formation of resources for traditional usage.

The problems described acquire important scientific and practical significance under our conditions of virtually complete utilisation of all available water resources. As is well known, rich reserves of minerals and other sources of raw materials are exploited very intensively in this region, creating new zones of high population densities.

The process of creating industrial-agrarian and social infrastructures in the desert zone has great prospects for raising the economic potential of the States and resolving the problem of employment for the increasing population. The main limitation is water supply which, in our opinion, must be considered as an integral part of the complexity of water resources in this territory.

A full consideration must be made of the way in which the use of non-traditional sources of water could be substantiated and thus help to compensate for the water deficit. One such direction is to manage glacier-melt within the limits of the long-term variation in glacier volumes; others are artificial precipitation, or the use of atmospheric moisture. Naturally, such possibilities should be considered with great care, without violation of the existing ecosystem balances.

A conceptual scheme for the stable water supply to meet socio-economic development in the States of the Aral Sea Basin arises from the following assumption: regional water resources are physically limited even under rational use and decisions on the problems of the water supply for the region must be made by 2010-2020. After this time, as noted earlier, there will be a need to replenish the water resources of the region through donations from neighbouring river basins.

The importance and urgency of the Feasibility Study (FS) on supply from donors was featured in the programme of urgent actions, already adopted by the leaders of the States of Central Asia in 1994. It was also considered in the declaration of the International United Nations Conference, 18-20 September, 1995. However, financing of the FS has not yet been decided. The World Bank, referring to the inter-state nature of the problem, considers this to be a task for the UN but the latter do not appear to show proper attention to the problem.

We profoundly believe that we cannot defer the development of any such schemes or the FS for the future. We have practically no time left to conduct inter-state investigations, or to adopt certain decisions and their implementation. The strategy for socio-economic development of the region will depend on the directions taken which determine the development of the water economy, the level of stable water supply and the rational use of water in the territory.

In conclusion, we wish to emphasise once more that for a region such as the Aral Sea basin where, unlike other states, there is a profound imbalance between land reserves, manpower and water supply, new approaches are needed. It is necessary to consider the problem of socio-economic development of the region within the complete system of long-term development of the water economy.

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# 12. Development of a GIS for the Amu Darya region using remote sensing data

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## 12.1 Introduction

The basis for a Geographical Information system has been set up for the Amu Darya delta. Information layers describe natural parameters such as soil type and condition, salinity, vegetation, the status of desertification, administrative boundaries, natural and anthropogenic hydrologic networks, infrastructure, major cities, etc. The availability of relevant data and information is not consistent, sometimes is of poor quality and, in the case of critical maps, is at different scales. Additional statistical data for portions of the delta is being gathered . Satellite data such as NOAA-AVHRR and high resolution imagery like Landsat-TM and Resource MSU-SK and MSU-E are being used to derive full coverage and up-to-date information.

## 12.2 GIS structure and information layers

### 12.2.1 Digital topographic mosaic

The basis for several information layers have been 15 military maps at a scale of 1:200,000. All maps have been scanned and digitally merged to produce a continuous topographic digital mosaic for the delta. This information is essential to reference high resolution satellite information and to rapidly obtain data about geographic location and topographic features. All maps have been geo-referenced to UTM, so that the mosaic can be directly linked to other information in the GIS. The military maps were used to derive several GIS layers, which can be essential for future landuse and water management planning in the delta.

### 12.2.2. Irrigation network

A crucial information layer for future water management in the Amu Darya delta has been created by digitising about 8000 irrigation channels, which show the main irrigation network. The channels have further been separated into major irrigation channels, secondary or tributary channels and collectors (which carry return runoff from irrigated field back to rivers or to other places of disposal). Further associated properties of the channels have been added to the database where available such as channel depth, channel width and the bottom conditions of the channels. This information will be essential for the proper organisation for future irrigation reconstruction, as the irrigation system is old and of poor quality. A digital database will help to organise the information.

### 12.2.3 Transportation

The main transportation networks of the region have been digitised and incorporated into the GIS. Railroad tracks, main streets and country roads are identified. This layer is useful for describing the capability of the transportation network and as an aid for organising road construction measures.

### 12.2.4 Hydrographic network

One layer has been set up showing the natural and anthropogenic hydrographic features such as lakes, ponds and rivers. Anthropogenic lakes and ponds have been formed from collector drainage water and created for fishery purposes. Creation of this database should help avoid uncoordinated flooding of vast areas within the delta as happened in recent decades. Additionally, it should help fisheries development by providing more optimal means of selecting appropriate locations for new artificial lakes and ponds within the delta.

### 12.2.5 Additional information layers

A variety of information layers in different scales have been incorporated into the GIS. The most important ones are soil maps including details about soil type and degree of salinization. Also an ecology layer shows soils along with the geomorphology and the flora of the region. To provide information on administration and political responsibilities the administrative boundaries of districts (***rayony***) as well as 300 major cities within the delta have been incorporated into data layers. Point location information has been added such as endangered fauna in the region and pesticide loads on irrigated fields.

### 12.2.6 Auxiliary statistical data

Agricultural data about groundwater availability, agricultural productivity, crop yields, water consumption for irrigated fields, salinization degree, etc. have been collected for major portions of the delta and will be incorporated into the GIS database. Also, agro-meteorological data such as long term precipitation, temperature, relative and absolute humidity, and wind speed and direction will be interpolated from point data for the region and added to the data base as contour maps. The data will be used to describe the natural growing conditions for the different crops and to calculate their potential water requirements. In conjunction with other layers of the GIS an optimised land use model will be created as described further below.

### 12.2.7 Satellite-derived information

**NOAA - AVHRR**
Time series satellite images have been processed by the receiving station of the DLR for 1994 and 1995 on a monthly basis. The data were used to produce time series profiles of NDVI to determine the absolute extent of irrigation of the delta and the percentage of irrigation within each administrative district. Further, the cumulative NDVI over the growing period was used to distinguish between the natural vegetation, such as Tugai forests and reeds, and irrigated areas. Additionally, NDVI values of selected locations with ground truth data will be used to derive coefficient data in combination with standard crop parameters to determine phenology stages of crop types and their associated water requirements

**High resolution satellite data**
Basically, Russian Resource MSU-SK and MSU-E data for 1995 will be used to create an accurate, recent land-use classification of the whole delta. Standard classification routines will be utilised

in combination with ground truth data for 1995. The land-use classification will focus on the determination of the main and most important crop types. Additionally, Landsat TM for 1994 and MSS data will be applied to enhance the classification results. The classification will be used as the basis for the calculation of irrigation requirements for the current land uses.

## 12.3 GIS structure and interactive user interface

All data layers will be implemented in a Geographical Information System (GIS) for the delta. This will include raster data, vector data, statistical information, and new layers derived from manipulating and combining these. The data will be made accessible by an easy to use interactive user interface which will provide the user with a graphical menu driven surface. All data will be in a uniform projection, facilitating layer combinations and geographical modelling. It is proposed to implement the GIS on several workstations at several locations within the delta to provide decision makers with the necessary information for their future land use and water management. On-the-job training is also planned in order to train the potential users to make the fullest possible use of the system and the data.

## 12.4 Optimisation of the landuse in the Amu Darya delta

The GIS database will be used to derive an optimised land-use model by combining a variety of information. The main focus will be on identifying those areas where crop substitution (i.e. replacing high water consumption, low suitability crops with low water consumption, high suitability crops) makes the most sense. For this purpose agrometeorological data will be evaluated to calculate reference evapotranspiration using Penman's equation. Specific crop coefficients will be derived regarding their individual phenology using standard reference values and satellite information (AVFM) to determine water requirements for each growing period related to crop specific evapotranspiration. The information will be used to model area data for evapotranspiration of the entire delta, combining the current land-use classification with other crop variables. Physical conditions such as soil fertility, soil salinization, groundwater availability and mineralisation, etc. that are determinants of crop growth will be evaluated using the GIS database and the degree of suitability for the main crop types will be determined. The next step will be the substitution (in the model) of the least suitable crops (defined in terms of water consumption, productivity and other factors) by more suitable varieties.

The chief goal is to formulate a "model" of the optimal distribution of crops within the delta to minimise water consumption but taking into account certain constraints. The potential water consumption for the different "crop distribution models" will be calculated and evaluated by comparing it to the current water consumption for irrigation in the delta.

## 12.5 Problems and future requirements

One of the crucial problems to build up a Geographical Information System for the Amu Darya delta is the lack of consistency in the available data. Most of the existing maps do not show any kind of co-ordinates and are sometimes of poor quality. Furthermore, existing maps are at a variety of scales which makes it difficult to combine the information of the different layers due to generalisation at small scales. Therefore, all maps have been rectified to the large-scale military topographic maps using ground control points. Also, the administrative division of the irrigated area during the Soviet era into two Republics (Uzbekistan and Turkmenistan) and one Autonomous

Republic creates problems, as the thematic maps used for creating layers in the GIS are sometimes only available for one or two of the three republics.

The implementation of the GIS at several locations in the delta will be dependent On future co-operation between these republics (now two new nations, Uzbekistan and Turkmenistan, and one republic, Karakalpakstan, within Uzbekistan) in order to develop a co-ordinated approach to water management in the delta. Potential irrigation water pricing schemes will have to be considered to promote the efficient use of water. This will require a change in attitude of decision-makers, with less emphasis being placed on increasing crop production and yields and more on promoting ecological stability.

## 12.6 Summary

So far, an extensive database for the Amu Darya delta and the surrounding region has been developed, which includes a variety of information. Agrometeorological data, as well as data layers describing physical geographic parameters, such as soil type, soil salinity, natural and anthropogenic-influenced vegetation etc. and satellite data have been created and integrated into the GIS. Besides adding additional information layers to the GIS, further scientific work will focus on the optimisation of the land use in the delta to minimise water consumption and to increase the efficiency of future irrigation planning. Conventional data as well as high and low resolution satellite data will be used to create thematic information layers which will be employed to model a reasonable crop distribution under current circumstances. All information from the GIS will be made accessible and available to key decision-makers in and for the delta. In the future, the GIS for the Amu Darya delta could be used as a prototype GIS for other major irrigation areas within the Aral Sea region (assuming, of course, that the Amu Darya delta GIS has proven to be a useful tool for land use and water management for this area).

# 13. Lessons for Central Asia from the terminal lakes and rivers of the western United States

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Americans are properly disturbed by the destruction of the planet's fourth largest inland body of water, the Aral Sea, in the Central Asian republics of the former Soviet Union (FSU). The Sea has been sacrificed by central government decisions of the past four decades to strengthen national and regional economies by growing cotton. More than the Sea has suffered: local lifestyles, customs and cultures are being lost in the process.

Is restoration of the Sea possible? Can restoration begin soon? Is the Mono Lake case in California a lesson for the Aral Sea? For the lakes and rivers of the world?

Destroying terminal desert lakes smaller than the Aral Sea in the U.S. West has been part of the American way of progress for more than a century. Four examples are reviewed here. Tulare Lake of California's San Joaquin Valley, Pyramid Lake of Nevada, and Owens and Mono Lakes of California's eastern Sierra. A man-made terminal lake, the Salton Sea near the California-Mexico boundary, is also included.

Many lesser known lakes of the original West have also been lost as progress came West. Some were replaced with managed wetlands that are now becoming known as dangerous places for birds, fish and other wildlife due to irrigation drainage. Conversely, there is the modem Salton Sea, created first by a flooding Colorado River breaking through levees during a construction accident in 1906, and later maintained as a drainage sump for the lands irrigated by the waters of the same river in the deserts of Imperial and Riverside Counties of California. Now efforts there focus on maintaining the simple food chain of the Salton Sea despite an ever-rising salinity level. The Sea's fishery was introduced in the 1950s by transfer of biota from the Sea of Cortez. The Salton Sea has physical, chemical and biological analogs useful for analysing the Aral Sea's predicament.

The loss of the Colorado River's inflows to the Sea of Cortez (the Gulf of California) cannot be quantified today, biologically or economically. The only Colorado River reaching the Sea of Cortez now is a saline byproduct of the original river. For decades the Colorado's once extensive delta has been barren and dry; these waters now underwrite the economies of seven states. In Central Asia, the Aral Sea's deltas of the Amu Darya and Syr Darya rivers dried out more than a decade ago; the waters of these rivers, diverted upstream in five new nations, primarily grow cotton on desert lands never before irrigated.

The similar fates of the Aral Sea and the Colorado River delta, as well as the declining conditions of the Ganges and the Nile rivers, were compared in the May-June 1995 issue of *World Watch*, the magazine of the Worldwatch Institute.

"Progress" everywhere seems to ride on the backs of fish, wildlife, native vegetation, and indigenous peoples. The demise of our western US lakes, rivers, marshes and estuaries may be useful to Americans trying to understand the destruction of the Aral Sea.

Conversely, changes in the physical, chemical and biological conditions of waters and lands here may provide useful information to Central Asians struggling with recovery from the Aral Sea disaster. Political and legal system changes in the American West may also be instructive for the developing democracies of the Central Asian states — Uzbekistan, Turkmenistan, Tajikistan and developing democracies of the Central Asian states — Uzbekistan, Turkmenistan, Tajikistan and Kyrgyzstan — and Kazakhstan, as these new nations assume control (1991) over their own waters, lands and peoples. This is worth consideration by the international bodies now applying mostly "northern" solutions there.

## 13.1 History

Land development in the US West started about 1850. Gold discovery in California triggered the exodus from the Eastern Seaboard and Middle West states. Early federal laws made the public lands available for mining, for "homesteading" and even for draining "swamp and overflow" lands. The indigenous peoples and Spanish land owners were simply over-run. Miners moving water great distances, for placer and hydraulic mining operations, established the first "water rights." States became established, carved from federal "territories" as mining booms brought settlers and a need for law and order. Statehood moved in a west-to-east direction: e.g. California in 1850 (gold), Nevada in 1864 (silver), Colorado in 1876 (silver), Utah in 1896 (gold-silver-religion), and New Mexico and Arizona not until 1912.

Scientific explorations of the 1870s and 1880s established the need for government-sponsored water projects to develop and populate the "arid lands" of the West. These are the lands west of the 100th meridian, where rainfall is less than the 20 inches per year that supports dryland farming. Under federal laws such as the Homestead Act, irrigation of private lands was already developing in locations all over the West favourable to small projects. Generous land grants to private corporations spurred railroad construction, linking east and west coasts in 1869.

New states assumed land administration control, though large blocks of federal lands remain to this day in all western states. States were required to develop educational systems — including the "land-grant colleges" so important to developing scientific agriculture and "farm extension" (advisor) systems in the decades following statehood. Federal 'swamp and overflow lands' laws encouraged diking, draining and farming of natural wetlands.

Federal water projects did not come to the American West until the beginning of the 20th century. These early federal water projects in the American West were primarily for encouraging small-scale private and cooperative farming enterprises During the 1890s Westerners developed the political momentum prompting this investment. The federal Reclamation Act of 1902 was the vehicle for land and water development for the 17 Western states.

The reclamation act contained strong anti-monopoly and acreage limitation features. And it reserved to the states the authority to allocate waters among conflicting users, the power to determine individual and corporate "water rights" of all private lands within their boundaries. The federal land in the unsettled mountains were the source of most of the waters flowing to users of the West. Other federal lands were the vast deserts and rangelands not suitable for irrigation.

The political experience getting the Reclamation Act passed by Congress served the western states well 25 years later. Organisationally, at least, they were prepared to deal with the drought and depression of the 1930s. The seven Colorado River states, under pressure from California development, agreed to dividing the river into Upper and Lower basins in the Colorado River Compact of 1922. This divided the river, with the Upper Basin obligated to provide 7.5 million acre feet (9.248 $km^3$) in most years to the Lower Basin and the Lower Basin claiming 7.5 maf. Mexico's share of the river, 1.5 maf, came later. So today 16.5 million acre feet (20.345 $km^3$) of the river are allocated annually to the seven US states and Mexico —when the water is available. The annual flow of the Colorado only rarely reaches the annual amount in the compacts and treaties. The original estimates of the Colorado's safe yields were overly optimistic, due to a series of wet years in the first two decades of the 20th century. The annual flow of the river varies widely, with an average since 1930 of about 12 million acre feet. Of course, no amount of flow was set aside for the good of the river itself — its fish, wildlife, water quality or renewability. And no flow, except rare floods, can move saline river waters all the way to the Colorado River delta and the Gulf of California.

## 13.2 The big dam era

The Boulder Canyon Project Act of 1928 produced the world's first large multi-purpose dam, now called Hoover Dam, where the Colorado River provides the boundary between Arizona and Nevada. During the Depression of the 1930s, many large water projects were started as emergency civil works in the West and also in the upper Midwest and other depressed areas of the country such as the Tennessee Valley. Dam builders were not only the Bureau of Reclamation but also the US Army's Corps of Engineers, especially active in the non-western states including the Missouri River and Mississippi River basins. Many small dams were financed by the Soil Conservation Service of the Department of Agriculture. A special agency with unique powers, the Tennessee Valley Authority, was established to develop the Tennessee Valley.

These much bigger projects were designed to control water movement within entire river basins. Generating hydroelectric power, previously a mostly private activity, was an important feature of these new big dam projects, especially in the Pacific Northwest and in the Tennessee Valley. The vast drainages of the Missouri, Columbia, Colorado, Arkansas-White-Red, Rio Grande and Sacramento rivers were brought under man's control. Unknowingly, the United States was also readying resources for the extreme production demands of World War II.

Both of California's large federal dams, Shasta and Friant, began storing water in 1944. System-wide projects of this period included the Missouri Basin Project (Pick-Sloan Plan) approved by Congress in 1944. The Colorado River Storage Project, for the Colorado's Upper Basin, was approved in 1955, following the agreement of the four Upper Basin states (plus Arizona) to the Upper Colorado River Compact in 1948. The US Congress authorised new big dam projects, or extensions of earlier-approved projects, into the 1980s.

In several respects the historic eras of really "big dam" construction in the USA and in Central Asia under the USSR are comparable. In the USA the big dam era lasted from 1928 (Hoover Dam) until, roughly, 1968, when the long-delayed Central Arizona Project finally (Water Education Foundation).

In Central Asia the USSR's big dam period lasted from the mid-1950s (Kara Kum Canal) to the end of the USSR itself in 1991. So in both countries the eras lasted 40-plus years, and in both countries the big dam era was preceded by years of developing small irrigation projects. (In Central Asia irrigation goes back at least 2,000 years; in the pre-1917 period there were 967 "irrigation systems" operating there.)

In 1994, before the interested audience of the International Commission on Large Dams at Durban, South Africa, the Commissioner of the US Bureau of Reclamation, Daniel P. Beard, explained the end of big dam construction in the USA. He gave reasons for this change, and even described how the legendary Bureau of Reclamation was adapting to the new conditions.

There is a lesson here for Minvodkhoz, the powerful USSR Ministry of Land Reclamation and Water Resources. Minvodkhoz built the canals, dams and diversion structures of Central Asia between 1950 and 1990. Actually, the entrenched power of Minvodkhoz began waning in 1986, when the Gorbachev administration cancelled the long-promised Siberian rivers diversion schemes that were to add even more cotton fields to Central Asia. Later the Siberian diversion schemes were revived briefly as the only way to "save" the Aral Sea. This panacea died with the collapse of the USSR, but some Central Asians insist it is the only physical and moral solution. Today Minvodkhoz functions as separate units within the five Central Asian governments. Its former employers are now major players for the five new nations in working with the international aid organisations restoring Central Asian's lands and waters.

In an earlier period in the US West, from 1902 to 1928, the US Bureau of Reclamation and many local public, private and municipal interests constructed many small dams for urban and agricultural water supply systems throughout the 17 western states. The US Army Corps of Engineers built many small dams for flood control in this same period.

At that time California's Mono Lake, more than 300 miles from Los Angeles, was not yet threatened. It lived in a glorious isolation, with shacks and other buildings from the mining era boom days the only decoration added by man. Unfortunately, the headwaters of its tributary streams were not included within one of America's earliest national parks, Yosemite, true also for the headwaters of the Owens River across a divide from Mono. But before we turn to Mono Lake let us look at an earlier time and a larger place — the Tulare Lake Basin in the rich San Joaquin Valley, the southern half of the Great Central Valley of California.

## 13.3 Tulare Lake

Diversion and impoundment of west-flowing streams on the "Valley side" of the Sierra Nevada began with the first miners and farmers. The 400-mile long Central Valley offered both land and water to a hungry, bustling frontier society. The Sacramento River divides the Central Valley into major north and south sections — the Sacramento River Valley to the north and the San Joaquin River Valley to the south. Both rivers flow to the delta of San Francisco Bay. The San Joaquin River drains the northern half of the San Joaquin Valley, joining the larger Sacramento River in the delta. The southern half of the San Joaquin is the Tulare Lake Basin, an internal drainage that only rarely, as in 1983, overflows into the Sacramento-San Joaquin-delta system.

Originally, lakes dominated the floor of the Tulare Lake Basin. But by 1900 the lakes were gone, diked and drained for farmland irrigated by the very waters that once sustained Tulare Lake, Kern Lake, Buena Vista Lake, and Goose Lake. Today the legal Tulare Lake bed is a dry rectangle of sand. The valley floor is covered with irrigated crops, including cotton, and punctuated in some areas with oil wells.

Before settlers began diking lands and diverting the west-flowing streams from the Sierra, say in the 1850s, Tulare Lake was the largest freshwater lake west of the Mississippi River, in surface area. The basin's rich fish, wildlife and vegetation resources once supported the most dense concentration of native peoples to be found in pre-1850 California. The migratory birds, fish and freshwater mammals (e.g. river otters) of Tulare Lake astounded early settlers — and nourished them. Land development and irrigation got under way in earnest in the 1870s and 1880s.

After the Tulare Basin's surface waters were captured for irrigation, the ample groundwaters were tapped. After the groundwaters were taken, a major reason for federal and state water projects there was to maintain the agricultural economy that had grown in the Basin's first 94 years of irrigation — roughly from 1850 to 1944. In the 1950s planning began by these same agencies to supply more surface flows, exported from the Sacramento River to the north. Predictably, in the 1970s came planning to construct a master drainage system to serve the lands supplied by the two large public projects (one state and one federal) that had brought the Sacramento River water to these lands in 1968. Construction of the San Luis Drain began. The goal was to discharge the "harmless" drainage wastes into the upper reaches of San Francisco Bay, 200 miles away.

Already delayed, construction of the San Luis Drain ended conclusively with the 1983 discovery — the "Kesterson National Wildlife Refuge Disaster" — that the drainage flows it was designed to dispose of were highly toxic to fish and wildlife. The toxicity was traced to the element selenium, leached and drained in dangerous amounts from the lands lying along the west side of the San Joaquin Valley. As this is written (1995), for the past 12 years various drainage alternatives, including what the official report terms "cessation of irrigation" for the most selenium-rich lands, have been the subject of more than $100 million in studies. This applied research included construction of test facilities for removing selenium from the drainage wastes. No practical physical, chemical, financial — or political — solution has been found. In the spring of 1995 the regional board in charge of water quality control for the Central Valley began requiring farmers and public agencies to produce and submit specific timetables to abate the selenium pollution. But dogged farming interests even then still pursued a court solution to force the federal government to complete the San Luis Drain.

Tulare Lake and its three smaller companions (Kern, Buena Vista and Goose Lakes) disappeared decades ago. No fish have been able to survive there in about 100 years. At its largest size known to history (the 1862 flood), Tulare Lake covered about 486,000 acres (196,682 hectares, 790 square miles). More commonly it spread over 200,000 acres, in normal weather years, with the flows coming from Sierra snowmelt in springtime and early summer. The lakebed today is filled with farms, some of which can get flooded in very wet years (1982-83). Now cotton grows and oil wells pump where fish and wildlife once multiplied in one of the planet's lushest habitats.

Such drastic changes in the USSR are explained as the result of Stalin-era policies that endorsed the “transformation of nature” to serve man. Reportedly, Lenin was more generous toward nature; the Communist Party fought out the ideology of man *vs* nature about 1930. Man won.

The labour of man dominated the economic balance sheets of state planning. Nature's contribution of water, soils, minerals, and timber were free givens. Values were never calculated for nature's contributions to economics. The environmental devastation dotting the former USSR is one product of this shift in dialectics 65 years ago. However, the general condition of the planet today indicates that most other ideologies also endorse transformation of nature for man — instead of transforming man to live with nature. It is not only a Communist failing.

The Tulare Lake Basin of today has been described as “the most altered landscape on earth”. In addition to vast agricultural enterprises, the basin supports an extensive oil field. Its three counties (Kern, Kings and Tulare) are usually found among the nation's top ten agricultural counties. However, the Tulare Lake Basin's prosperity, in historic terms, may be brief. Its natural resources, including clean and healthy air, are disappearing. The problem list includes serious land subsidence from overdrafting the groundwaters, serious aquatic pollution by selenium and other toxic constituents unleashed by irrigation of the marine shales of its west side, serious pollution of the groundwaters of its east side by over-application of pesticides and chemicals on the better farm lands located there, and serious air pollution from the combined effects of its large-scale agriculture, oil production and urban expansion. (Mono Lake escaped the attention of utilitarian Americans for a century longer than Tulare Lake.) Yet to come are blowing salt dust storms from the Tulare Lake Basin's 13,000 acres (5,261 hectares) of evaporation ponds now storing brines from the toxic farm drainage.

And the wetlands. The Tulare Lake Basin once contained the largest portion of the Central Valley's original four million acres of wetlands. These were the overwintering habitats for the millions of birds of the Pacific Flyway — the migratory corridor stretching from Alaska to Central America. Today a century of progress has reduced those vast wetlands of the entire Central Valley of California to only 300,000 acres (121,408 hectares). Many of these habitats are mere “postage stamps floating on a sea of agriculture” (F. E. Smith). Sadly, the water supply for half of these remaining wetlands comes from agricultural drainage or farm runoff. Many of them have no guaranteed water rights, and thus are the first habitats to suffer in drought years. The fish of Tulare Lake were not able to reproduce after 1900, a sacrifice to the unstoppable expansion of irrigation there as in many other areas of California. (Today 65 percent of California's native fish species are ‘...extinct, endangered, or need special protection to stop them from becoming endangered”, according to California freshwater fish experts Peter B. Moyle and Michael D. Morford.)

The Tulare Lake Basin's analogs to the Aral Sea Basin are apparent, ranging from extirpated fish to toxic airborne dust.

## 13.4 Pyramid Lake

The first project that the Bureau of Reclamation completed in the West, in 1906, diverted most of the Truckee River that flowed naturally from Lake Tahoe in California to Pyramid Lake in Nevada. This was America's deepest natural, desert, terminal lake at the time. At the other end of this short and beautiful river system, Lake Tahoe, a six-foot (2 metres) high dam was built to add storage. Even then Tahoe had its partisans, who opposed a higher dam. Ephemeral desert "lakes" — overflow lakes and wetlands — near Pyramid Lake included Lake Winnemucca and the Carson Sink at the terminus of the Carson River.

Predictably, the level of Pyramid Lake began dropping, year by year as the new lands around Fallon, Nevada, were brought under irrigation. Sixty years later the Pyramid Lake's level was about 50 feet lower than in 1906. The irrigated lands promised the Northern Paiute Indians who owned the Pyramid Lake reservation were never developed.

Actions taken by the US Department of the Interior in the mid-1960s began restoring some of the Truckee's flows to Pyramid Lake by the late 1960s. It was too late to save the Lake's trophy sport fish, the Lahontan cutthroat trout which stopped reproducing naturally in the 1940s. Both the cutthroat and the Pyramid Lake Paiutes' traditional staple-food supply, the Cui-ui, needed access to the Truckee River to spawn. The long-lived Cui-ui survived the 60 years of impact of reduced river inflows. The Endangered Species Act was too late to help the Pyramid Lake species of Lahontan cutthroat but the Cui-ui was certified as endangered in 1967.

As the Lake declined the Truckee's meagre inflows to it became braided and too shallow to permit fish migration from the lake to the river. Now an extensive and expensive fish facility has been built at the Lake to help spawning of Cui-ui and the trout in very wet years only. They cannot go up river very far: Derby Dam, though only about 20 feet high, never has been fitted with fishways or ladders to accommodate spawners of either species. A Sierra Pacific power plant on the lower river elevates water temperatures.

The Cui-ui, a long lived species, survived the 60-years of declining lake levels. Today the Cui-ui is the most important fish in northern Nevada, and its preservation 'drives' water allocation and water right decisions. Hatchery production of both species, managed by the Pyramid Lake Paiute Indians — plus a federal hatchery for the trout — keeps populations of both species at harvestable levels in Pyramid Lake and thus provides an important source of income for the tribe.

A new chapter was added to the Pyramid Lake story in the late 1980s. Gigantic fish kills began occurring at the Stillwater Wildlife Management Area, a wetlands developed at the original Carson Sink to take advantage of farm drainage flows and any excess river waters from the combined Truckee and Carson river waters serving the Fallon area. The source of the toxic problem was constituents in the drainage water coming from the irrigated desert soils around Fallon, including selenium as in a dozen other locations in the West where drainage has been applied to create wetlands as "mitigation" for multi-purpose federal projects.

Thus the Bureau of Reclamation's first completed project — officially the Newlands Project, named for the US Senator from Nevada who was the leading proponent of the Reclamation Act of 1902 — had many predicted and unpredicted impact on fish and wildlife and indigenous peoples. With the changing culture of the U.S., and of the West especially, it is conceivable that the farmlands around Fallon will be purchased by public agencies, with their Carson and Truckee River waters favouring the fish, birds, wildlife and Indians that once used them but lost them to progress.

## 13.5 Owens Lake

Diversion of the Owens River in eastern California, by the City of Los Angeles starting in 1913, dried up Owens Lake. The waters that once supported this desert aquatic ecosystem — featuring a lake whose surface reflected Mount Whitney, the highest peak in the conterminous USA, and even sported commercial steamboats in the earlier mining era — were taken to supply a budding city rising on the coastal plain 233 miles away.

As with the wetlands surrounding San Francisco Bay and the delta of the Colorado River, Owens Lake disappeared so early and so completely that its wetlands habitat values to nature and man were neither studied nor evaluated. Even if the values had been documented, the political environment of that day would not have allowed Owens Lake to be saved. Growth was in the wind. Later the same winds were to blow the sandy bottom of Owens Lake over hundreds of square miles, a foretaste of what is to come someday to the Tulare Lake Basin when drainage ponds there fill up, dry out and blow away.

Blowing toxic salts and dust from the dessicated bottomlands of the Aral Sea now spread over hundreds, probably thousands, of square miles of Central Asia. In the past 15 years new arrays of illnesses, mostly respiratory, have plagued the people who live near the Sea's former shoreline in Karakalpakstan, Turkmenistan and. Kazakhstan.

Owens Lake died in 1928, only 15 years after the completion of the Los Angeles aqueduct. The Owens River was captured totally, transported by tunnel, canal and syphon, to serve as the first imported supply for what was to become the world's only megalopolis located on a desert seacoast. A different future held for California's next natural desert terminal lake to be targeted by the Los Angeles Department of Water and Power — Mono Lake

## 13.6 Mono Lake

The stark setting of Mono Lake, on the eastern side of the Sierra, downslope of Yosemite National Park, has fascinated travellers for almost two centuries. Mark Twain and John Muir were among its earliest chroniclers. Ansel Adams' photographs that catch its haunting beauty and light are famous. Perhaps one million years old, the lake's bed was scoured by glacier and torn by volcanoes. Its salty waters are, or were, fed by five streams flowing down the eastern flanks of the Sierra Nevada, concentrating the minerals of the. mountains in the ancient landscapes of the Great Basin.

Mono Lake's "waters" are really a brine of dissolved carbonates, sulphates, chlorides and other minerals — 80 times more alkaline than sea water. The chemicals concentrate in "tufa" towers that rise from the lake's shores and bottom. Brine shrimp and brine flies — but no fish — thrive in the lake's mineral soup, and they attract millions of birds.

In spring months Mono Lake is host to migrations of intercontinental shorebirds and is California's largest rookery for seagulls. Eighty species of water birds use Mono Lake's shores, mudflats, waters, brine shrimp and brine flies at some time during each year. When it was first surveyed in 1857, Mono Lake's surface elevation stood at 6,407 feet above sea level. A series of wet years in the early decades of the 1900s brought the level to 6,428 in 1919 — the same wet period that produced the overly optimistic flow estimates for the Colorado River.

Diversions of several of the streams feeding Mono Lake, by the Department of Water and Power of Los Angeles, began in 1941 when a six-mile tunnel was completed connecting Mono Lake basin to the Owens River basin. Along with the new water, generation of more hydroelectric power for Los Angeles was a project bonus. In 1963 the City started building a second aqueduct (the "second barrel") from the Owens Valley to Los Angeles to "salvage the water in Mono Basin being lost into the saline water of Mono Lake." The new aqueduct was completed in 1970, when diversion of Mono Lake's waters increased from 51,000 acre-feet per year to an average of 100,000 acre feet per year. The lake level dropped 45 feet (16.5 m) by 1981, and its salinity level doubled. The dropping lake level soon linked nesting islands to shore, making it easy work for four-footed predators to prey on the eggs and young of the two-footed residents of the previously safe rookeries. The City's water rights for its projects were considered to be untouchable.

Thanks to dedicated individuals, especially biologist David Gaines, and the support of local, the state legislation to find alternative supplies, mostly to come from water conservation and recycling, and gets technical and other assistance from federal and state water agencies. (The federal agencies, especially the US Forest Service, avoided the water fight for years but began recognizing Mono Lake's unique values about 10 years ago. The Forest Service has constructed an impressive visitor centre at the lake.)

The final referee in this David *vs* Goliath struggle is the State Water Resources Control Board. The Board's hearings concluded with a decision on September 18, 1994, that committed Los Angeles to reduce diversions of water from four of the inflowing creeks to provide the water needed to raise the lake level. The goal is to stabilise the lake level permanently between the 6,388- and 6,392.6-foot elevation levels. At the time of the decision the level was at 6,374.6. The Committee, the City and other parties to the decision such as California Trout, have agreed to accept the State Board's decision. They are now working cooperatively on various creek and lake restoration projects.

Thus, finally, 17 Years after the effort began, the Mono Lake situation has been turned around. The process has been reversed from draining the lake to filling the lake. Money, political power (especially inside the City of Los Angeles), and access to the court system made these changes possible.

Unfortunately, none of these factors are yet at work on restoring the Aral Sea of Central Asia. There international agencies have begun to plan to develop a sustainable economy for the peoples of the Central Asian republics of the FSU. But giving the region a democratic system that can produce a rational, equitable use of water and land there — use that respects nature's needs also — is not on the horizon. The oldgovernmental ways of the past 75 years resist change, despite the new management.

## 13.7 Mono Lake's water "right"

So what happened to Los Angeles "untouchable" water rights? What happened may be useful to water around the world.

Because of the scientific evidence generated by the Mono Lake Committee — backed by public support and an inspired legal approach — the burden of proof was shifted. The water right-holder, the largest municipal utility in California and possible in the world, learned that its rights could be, and were, re-opened and re-evaluated by the State authorities. Thus they could be modified as necessary to protect the natural values of ancient Mono Lake. This "public trust doctrine" policy approved by the State Supreme Court in 1983 applies to all water rights of California. In legal circles the case is referred to as "Audubon".

In law there is always precedent. "Audubon's" major impact on the arcane laws and practices governing water rights in California was an extension of the State Supreme Court's "Public Trust Doctrine" decision governing use of the states tidelands — as "lands" — in the Marks *vs* Whitney case (1972). So now public trust applies to both water and land in California: water as allocated to private and public use by the State; land where the State's sovereign interest in title to the land still exists (tidelands, lake bottoms, riverbeds, coasts, offshore, etc.).

The Mono Lake court decision, and favourable follow-up in administrative law, is more than a smoke signal rising from the world's most hydraulicised society. The Public Trust Doctrine has roots that reach across continents and time to 1500 years ago and the Code of Justinian, the Roman emperor and law compiler. Now this is working law, revived to serve both ancient and modern needs of working nature and working man. In essence, the Mono Lake decision re-opens all water rights in California for "balance". The decision is cited now in other western states also — many of them with more progressive water rights' systems and histories than California. (Both riparian and appropriation doctrines flourish in California; most western states use the appropriation "first in time, first in right" doctrine only.)

Organisations such as the Bay Institute of San Francisco, for example, may apply principles of the Mono Lake decision to obtain legal entitlement to remaining "unregulated" flows of the Sacramento River to benefit the San Francisco estuary. In the pre-Mono California water ethic, the estuary's fish and birds could have the river water they needed but only if they could find a way to buy it from some upstream user or force the state's two huge public projects to provide it at a cost to the projects' budgets or their contractors' entitlements.

Under the Public Trust Doctrine, fish do not have to carry credit cards. Fish and wildlife advocates have pressed successfully for reform legislation, such as the Central Valley Project Improvement Act of 1992, to reallocate the Central Valley Project's water supplies to benefit fish, wildlife, water quality and people.

For California, the Mono Lake lesson is that the needs of nature and man that have been unmet or ignored by past legislatures, courts and self-perpetuating construction agencies can now be addressed and re-appraised. Water rights are now recognised for what they always were: temporary permits, called "usufructs", from a state authority for the use of a public resource as long as the benefits the public receives are visible, useful to man, safe for nature, and periodically re-evaluated.

The worldwide Mono Lake question might be:

> "Can international forces develop new, locally accepted programs to rescue world peoples and resources now being destroyed by abuse of natural water systems?"

The Aral Sea catastrophe offers a first-class, world-class test of this question. Only time will give the answer, but at least the question has been raised.

# 14. An improvement regime and flushing pattern for salinized land in the low Aral region

**Farid M. Rakhimbaev**

The question of how to choose optimal improvement regimes remains insufficiently understood under the conditions operating in the complex reconstruction of irrigation systems. The principles for optimising an improvement regime are elaborated here. Optimisation assumes a conscious choice of parameters which will change the irrigation regime and groundwater in such a way as to create favourable conditions which will ensure soil desalinization or the halting of salinization processes from occurring on uncontaminated land with the least waste in water, materials or labour.

A combination of irrigation and drainage management techniques are understood to take place under the best improvement packages which safeguard the water-flushing regime (or desalinization regime during the transition period) and which increases the fertility of the soil to maximise investment in land improvement schemes and the complex reorganisation of old irrigated areas.

Under modern conditions, with the development of irrigated agriculture, inconsistency is often observed between the results of man's activities directed to soil improvement and agricultural development, and the consequences for the environment. It has been noted, in the context of the changes in the Aral Sea Basin, that it is necessary to understand why, in spite of considerable growth in drainage in the region, extensive desalinization of the soil did not take place. According to physical-chemical hydrodynamic theory and soil statistics from the numerous and continued investigations on various irrigation initiatives, the increase in artificial drainage by the flushing action arising from irrigation ought to lead to improvement in desalinization.

We have noted the number of common features, characteristic of linear models, which were applied to the struggle against soil salinization over the last 50-60 years, particularly those popular in projecting the dependence for the calculation of rising groundwater table on the irrigation of separate strata. At the same time, it has been noted that estimation equations are mainly intended for local use during this period since widespread irrigation practice had not yet begun. The common approach to such calculations as derived from traditional scientific techniques has a fundamental weakness. For example, the dynamic calculation of subterranean waters is based upon hydrological conditions but the model for salt transference is a unified system. In all cases, anthropogenic activity will be excluded; understanding infiltration and augmentation of groundwater, for example, are continuing within the natural sciences, mainly at the expense of more complicated calculation techniques. Inconsistencies have thus been noted between statistics on soil desalinization based on drainage (on individual systems and for a whole region) which will arise on regional and local levels because the scale of irrigation over the last 30 years has led to an alteration of regional conditions.

We should like to identify several aspects of the input to the soil water regime in the unsaturated zone and to calculations of water use under the agricultural cultivation of the Lower Amu Darya region (the northern zone of the Republic of Karakalpakstan and southern Korezm) during the years 1969-1990.

The formation of the water regime within different soil/hydrogeological horizons and their change during vegetative periods have an important theoretical and practical significance in the development of ameliorative regimes. On the basis of research results from eminent hydrologists and agronomists, and also on personal observations and statistical analysis characterising the formation of groundwater regimes (level and chemical) in the Amu Darya, we have identified a mixture of horizons in the unsaturated zone for the irrigated area of the Khoresm oasis: $h1$ - variable moisture; $h2$ - potential moisture; $h3$ - active capillary moisture; $h4$ - active seasonal oscillation in groundwater levels, equal to the height of the seasonal amplitude of the oscillation of the groundwater table. At the limit of horizons $h3$ and $h4$, an active process of deposition occurs which we denote in the $h1 + h2 = hn$ subzone of active ground deposition development; $h3 + h4 = hgw$ - subzone of active groundwater recharge.

If we adopt $hgw/hn = Ku$ for irrigation salinity, $Ku=1$ will mean stabilisation in the process of irrigation salinity (= critical coefficient for irrigation salinity). The result of the analysis of long-standing research into the subterranean water regime (in the Amu Darya) has revealed that the intensive irrigational salinity of the main irrigated region and the necessity for active measures to be taken ($Ku$ on average oscillates around 2.7-2.8 metres). For major flushing of strongly salinized soils, it has been suggested that flushing norms be based upon:

$$N = 10\,000 * \lg(S1/S2)^a \qquad (14.1)$$

where $N$ = the flushing norm ($m^3$/ha)
$a$ = index of salt return
$S1$, $S2$ = beginning and permissible maintenance of salts.

The flushing norm depends first of all on the mechanical structure of the soil and the relative humidity of the air.

From the results of well-established determinations, we recommend :

$$N = 1000 * w * S * Wb \qquad (14.2)$$

where $w$ = the mass of a soil stratum, 0-100 m, g/$cm^3$
$S$ = necessary degree of toxic salt flushing, %
$Wb$ = relative humidity of air at the time of flushing, %

Calculations based on relative humidity of the air at 63% are shown in Table 14.1, where it follows that the flushing norm must grow in proportion with the increased soil volume.

**Table 14.1** *Calculated flushing norm ($m^3$ per hectare)*

| ***Flushing norm of toxic salts*** | ***Volume mass of soil*** (g/$cm^3$) | | | | | |
|---|---|---|---|---|---|---|
| | *1.0* | *1.1* | *1.2* | *1.3* | *1.4* | *1.5* |
| 0.010 | 630 | 693 | 756 | 819 | 882 | 945 |
| 0.020 | 1260 | 1386 | 1512 | 1638 | 1764 | 1890 |
| 0.040 | 2520 | 2772 | 3024 | 3276 | 3528 | 3780 |
| 0.060 | 3780 | 4158 | 4536 | 4914 | 5292 | 5670 |
| 0.080 | 5040 | 5544 | 6048 | 6552 | 7056 | 7560 |
| 0.100 | 6300 | 6930 | 7560 | 8190 | 8820 | 9450 |

The average long-standing value of 63% for the relative humidity of air was obtained from records of a Dhimbuy meteorological station for the period 1969-1991, for March, April, October and November; this is the period in which will be carried out the mass flushings in the northern zone of the Karakalpakstan's cotton crops.

The flushing norm based on Equation (14.1) may be based on a soil mass of $w = 1.10$ g m$^3$. However, there are more concentrated soils in nature. This is why we must use Equation (14.2) for calculating the flush volumes required where the mechanical structure of the soil and the climatic conditions of the concentrated period are taken into consideration.

For the major flushing we recommend calculation of the flushing norm on the following basis

$$N = m * 1000 * 1g(S1/S2) \tag{14.3}$$

where $N$ = capital fluishing norm m$^3$ per hectare
$m$ = percentage clay content in the soil
$S1, S2$ = initial and permissible percentage salt content

From Table 14.2 it is clear that the largest index of salt-return of the soil in Equation (14.1) formula corresponds to the clay index $m$ = 30%. This is why for the purpose of ameliorating improvements in flushing soil strata it is necessary to base calculations on Equation (14.3).

*Table 14.2*

| *lg (S1/S2)* | *Soil clay content (%)* | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | *10* | *20* | *30* | *40* | *50* | *60* | *70* | *80* |
| 0.052 | 520 | 1040 | 1560 | 2080 | 2600 | 3120 | 3640 | 4160 |
| 0.086 | 860 | 1720 | 2560 | 3420 | 4280 | 5140 | 6000 | 6860 |
| 0.120 | 1200 | 2400 | 3600 | 4800 | 6000 | 6200 | 8400 | 9600 |
| 0.300 | 3000 | 6000 | 9000 | 12000 | 15000 | 18000 | 21000 | 24000 |
| 0.360 | 3600 | 7200 | 10800 | 14400 | 18080 | 21600 | 25200 | 28800 |
| 0.420 | 4200 | 8400 | 12600 | 16800 | 21000 | 25200 | 29400 | 33600 |
| 0.520 | 5200 | 10400 | 15600 | 20800 | 26000 | 31200 | 36800 | 42000 |

In connection with the flow regulation of the Amu Darya on the sea-ward side of the delta, intense aridisation is observed. This process will increase in all the deteriorating soils and increase the process of salt-marsh formation.

It is necessary to take into consideration the intensive development of sedimentation and also necessary to develop a full range of protective measures and to initiate an optimum ameliorative programme for irrigatable soils, based on forecasts of evapotranspiration and chemico-biological regimes of these soils for different versions of the corrective measures and well-known conditions of improved territories.

# 15. Optimisation of multiple-reservoir systems operation under semi-arid climatic conditions

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## 15.1 Introduction

Dynamic programming (DP) has long proven broad applicability in water resources management, and especially in reservoir operation. However, the discrete nature of DP induces considerable computational load when applied to complex systems. This, so-called "curse of dimensionality" phenomenon, can result in prohibitive computer storage and processing time requirements by increasing the number of system elements under consideration. This is directly reflected in optimisation of multiple-reservoir systems operation where a number of state and decision variables can easily reach these limits. The methodology presented in this paper attempts to resolve these dimensionality problems by combining system decomposition with stochastic dynamic programming (SDP) based on optimisation, simulation, and release allocation of a single-reservoir operation. The application of the method with a particular emphasis on tackling reservoir operational problems under semi-arid climatic conditions is demonstrated on a seven-reservoir system in Northern Tunisia.

## 15.2 System operation

Optimisation of a multiple-reservoir water resources system operation is confronted with a series of difficulties; even more so if uncertainty inherent in systems' operation is to be taken in consideration. The complexity of the problem is perhaps best described by a single word: "dimensionality". For instance:

(i) reservoirs may interact by means of both serial and parallel interconnections;
(ii) water transfer from one basin to another should also be allowed;
(iii) possible supply-demand patterns may include a single reservoir supply towards multiple demand targets while any of the demand centres could be associated with more than one reservoir.

Each new system element and all the aforementioned facets of a complex reservoir system require additional (state and/or decision) variables and sets of constraints to describe the system, thus introducing new dimensions to the problem. This may subsequently result in prohibitive computational requirements imposed by any straightforward optimisation application.

The proposed algorithm aims at reducing the dimensionality of an optimisation problem while trying to preserve some important aspects of a multiple-reservoir operation. It is based on a physical decomposition of a system into a series of single-reservoir subsystems, thus reducing a multi-dimensional decision problem to a sequence of one-dimensional optimisation tasks. Subsequently, a combined optimisation/simulation procedure is applied to each reservoir. The sequence in which reservoirs are introduced into analysis is mainly determined by their physical position in the system. The adopted ordering is based on the algorithm named "sequential downstream moving decomposition". Namely, reservoirs are initially clustered into so-called "cascade levels" to distinguish between groups of reservoirs with respect to the determination of the sequence in which those reservoir subsets should enter the computational procedure. Further on, reservoir selection order within a "cascade level" could be determined according to rules imposed by the analyst. These principles may include firm water allocation schemes, water quality, economical, social, or environmental aspects, thus fostering the flexibility of the scheme.

The algorithm is essentially an iterative procedure. One iteration cycle comprises optimisation and simulation of operation of each reservoir within the system. These principle iterative cycles are repeated until a stable system return is reached. Next to the linkages due to the physical layout of the system to be decomposed, data transfer between two consecutive iteration runs consists of sets of individual reservoirs' supply shortages derived in the preceding iteration. These deficits are to be considered as additional demands associated with each reservoir situated directly upstream of the reservoir in question.

The stochastic dynamic programming optimisation procedure is based on Loucks *et al.*, 1981. It derives the optimal, expectation-oriented, long-term operational strategy for a single reservoir defined over 12 monthly stages within an annual cycle. The state variable selected to describe a system (reservoir) is the volume of water stored at the beginning of a time stage (month). Uncertainty is explicitly incorporated into the optimisation procedure: monthly inflow to a reservoir represented by a set of different classes with their respective independent or transitional probabilities is considered as an additional state variable in the SDP-based optimisation procedure. Thus, and regardless whether the inflows are considered random or Markovian, the system's state is described by two state variables: (1) reservoir storage at the beginning of the month, and (2) the inflow to the reservoir during the month.

The decision to be taken at each stage is the storage volume of the reservoir at the end of the time interval. Thus, the operating policy is defined for each month and it is expressed in terms of the optimal decision to be taken as a function of system states. Having these three variables defined and assuming that reservoir losses could be derived for each stage, both the consumptive and non-consumptive releases could be estimated from the continuity equation which describes the balance of water in the reservoir during the given stage.

A multiple-decision problem that arises from the envisaged complex water allocation pattern is reduced to a single-objective optimisation by aggregating individual requirements for water from a reservoir into a single composite demand. This simplification is justified by the arrangement of individual demands with respect to a predetertnined priority order which is conformed with in the subsequent allocation of available releases from the reservoir. The objective pursued in optimisation is to minimize the expected value of an annual sum of squared shortage of releases towards the corresponding demands for water.

Following the optimisation, simulation takes place to evaluate the derived policy and its impact on the operation of the system as a whole. As part of the simulation outcome, the updated values of the expected remaining demands, available non-utilised releases over the whole simulation period, and the expected supply shortages of the reservoir, are passed through to computational cycles involving reservoirs whose operation is directly influenced by these factors. Finally, the release volumes obtained by simulation are allocated to individual users according to the predetermined priority assigned to each demand associated with this particular reservoir.

## 15.3 Analysis and results

The proposed methodology to derive and to assess long-term operation of multiple-reservoir systems has originally been developed within the water resources master plan for Tunisia, executed through the project EAU2000 (Agrar-und Hydrotechnik, 1993). Extensive analyses thereafter resulted in further improvements and modifications of the original approach (Bogardi *et al.*, 1995; Bogardi and Milutin, 1995; He *et al.*, 1995; Milutin and Bogardi, 1995). However, the core of the method which combines decomposition, SDP-based optimisation, simulation, and release allocation, has not been changed significantly.

In this paper, the analysis framework has been devised to concentrate on the impact of discretization and the level of the "hypothetical demand" imposed upon reservoirs on the performance of a system operated under the derived SDP policies. The analyses have been carried out on the existing seven reservoirs in Northern Tunisia interconnected into a complex water resource system with the main purpose of providing water for domestic, tourist, irrigation, and industrial consumption (Figure 15.1). The main characteristics of the system are given in Tables 15.1 and 15.2. Note that the sequence in which reservoirs are listed in Table 15.1 reflects the order of their consideration in the computational procedure.

Semi-arid climatic conditions dictated that the resulting operational strategies should reflect the emphasized need to utilise the maximum of the available surface water resources. This is achieved by pursuing the so-called "hypothetical demand" in optimisation rather than striving to satisfy actual demands associated with a reservoir. Namely, the actual demand imposed upon a reservoir is only used to form the shape of the demand curve. The final values of the "hypothetical demand" are oriented to the value of the annual median inflow to the reservoir: the annual median inflow is redistributed with respect to the real (monthly) demand distribution within an annual cycle, i.e. the "hypothetical demand" values reflect the monthly distribution of the components of water supply requirements. This alternative arises from the intention to create an overwhelmingly large demand

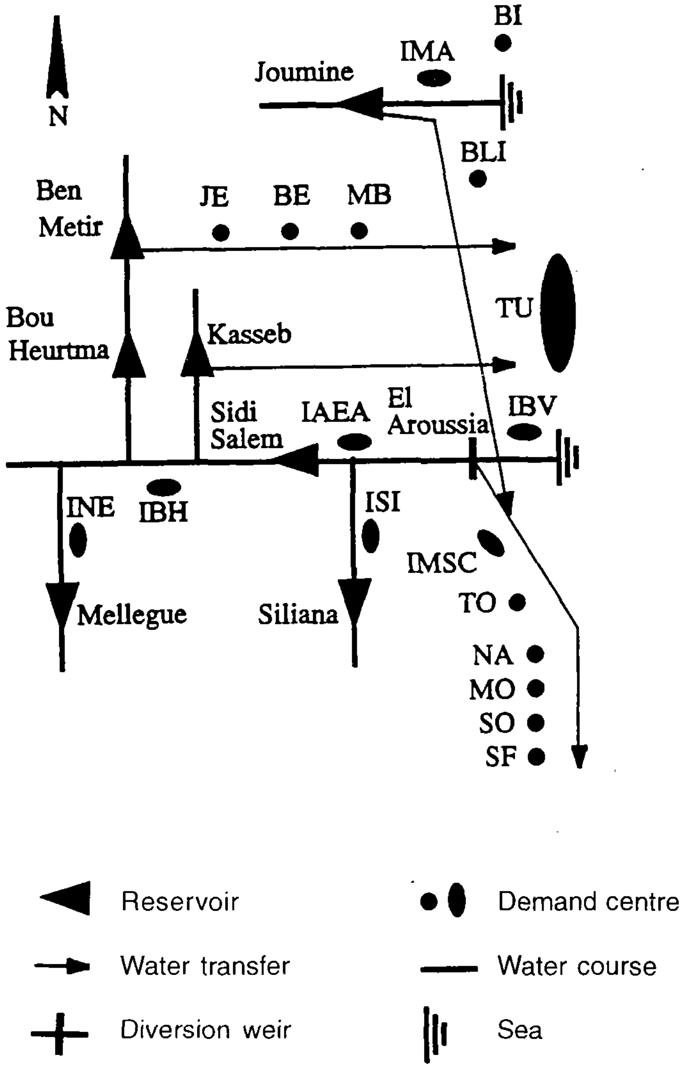

*Fig. 15.1* Seven-reservoir system in Tunisia

*Table 15.1* *Salient features of the seven reservoirs*

| *Reservoir* | *Active storage ($10^6$ $m^3$)* | *Mean annual natural inflow ($10^6$ $m^3$)* | *Median annual natural inflow ($10^6$ $m^3$)* | *Demand targets (coded names)* |
|---|---|---|---|---|
| Joumine | 121.3 | 132.959 | 113.585 | BI, IMA, BLI, TU, TO, NA, MO, SO, SF |
| Ben Metir | 44.2 | 42.325 | 40.440 | TU, BE, IE, MB |
| Kasseb | 72.2 | 48.389 | 43.375 | TU |
| Bou Heurtma | 102.5 | 92.015 | 76.210 | IBH |
| Mellegue | 89.0 | 175.859 | 141.290 | INE, IBH |
| Sidi Salem | 510.0 | 429.188 | 338.805 | IAEA, TU, TO, NA, MO, SO, SF, IBV, IMSC |
| Siliana | 61.51 | 43.0991 | 29.450 | I ISI, IAEA, TU, TO, NA, MO, SO, SF, IBV, IMSC |

*Table 15.2* *Estimated monthly water demands ($10^6$ $m^3$)*

| Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 47.982 | 26.343 | 19.842 | 10.854 | 16.258 | 20.174 | 28.509 | 40.406 | 46.981 | 66.360 | 78.578 | 65.237 |

Estimated annual water demand from the whole system: 469.504

which is assumed to constitute a theoretical maximum demand a reservoir of unrestricted size, while having no losses whatsoever, would be able to fulfil without any shortage to occur. It is obvious that these prerequisites are not met by real-world reservoirs. Thus this "hypothetical demand" might be approximated but never achieved. This transformation provides maximum challenge towards the utilisation of the reservoir storage capacity, while the within-year distribution of the demand remains unchanged.

The operation of the system has been derived and assessed for four distinctive sets of initial assumptions (Table 15.3). Sets *S*1 and *S*2 assume a fixed number of 25 discrete storage classes to represent reservoir volumes, whereas 49 discrete values were used to describe storage in sets *S*3 and *S*4. This in fact means that the reservoir storage class sizes in sets *S*3 and *S*4 are exactly a half of the respective classes used in sets *S*1 and *S*2. In addition, when generating the respective "hypothetical demand distributions", approaches *S*1 and S3 rely on constant (unregulated) annual median inflow values of each reservoir throughout all iterations. On the other hand, sets *S*2 and *S*4 allow that the

*Table 15.3* *Initial assumptions for the four computational setups*

| *Setup* | *Number of storage class* | *Anual median inflow estimate* |
|---|---|---|
| S1 | 25 (all reservoirs) | constant (unregulated inflow) - all reservoirs |
| S2 | 25 (all reservoirs) | Bou Heurtma - variable (unregulated inflow + free flow from Ben Metir); the rest - constant (unregulated inflow) |
| S3 | 49 (all reservoirs) | constant (unregulated inflow) - all reservoirs |
| S4 | 49 (all reservoirs) | Bou Heurtma - variable (unregulated inflow + free flows from Ben Metir); the rest - constant (unregulated inflow) |

annual median inflow estimate for Bou Heurtma reservoir be evaluated in each iteration upon the inflow time series which is obtained as the aggregate of Bou Heurtma's unregulated inflow and additional flows that result from non-consumptive excess releases from Ben Metir. Similarly in approaches SI and S3, annual median inflow estimates for the remaining six reservoirs are assumed constant throughout iterations.

It should be stressed that this modification is applied only to Bou Heurtma and not to Sidi Salem (Sidi Salem and Bou Heurtma are the only two reservoirs that can expect additional contribution of flows from reservoirs situated upstream). This is due to the results of the preliminary analyses of the estimates of the actual annual demands associated with each reservoir throughout the iterations. Table 15.4 compares the ranges of annual demands against the respective annual unregulated and potential augmented (i.e. as a contribution from upstream reservoirs) median inflow values. However, Sidi Salem annual unregulated median inflow is already much greater than the estimated actual demand. Thus, no significant improvement in its operation, if any, can be expected by increasing the level of its "hypothetical demand" which is based on the median inflow. On the other hand, additional flow contribution from Ben Metir to Bou Heurtina is quite substantial. However, although the aggregated annual median inflow estimate for Bou Heurtma results in almost 50% increase in the respective unregulated flow value, the augmented annual "hypothetical demand" still falls short of the actual demand imposed upon Bou Heurtma. Thus, there are reasons to believe that the augmented "hypothetical demand" would result in better performance of Bou Heurtma and consequently the whole system as well. It is to be noted that Bou Heurtma would be simply overchallenged, should Mellegue reservoir not be able to make up the difference in supply towards their common (IBH) demand.

***Table 15.4*** *Annual demand and median flow estimates throughout five iteration* ($10^6 M^3$)

| *Reservoir* | *Annual real demand* | *Annual (unregulated) estimates (min; max)* | *Annual augmented median median inflow inflow (min; max)* |
|---|---|---|---|
| Bou Heurtma | (133.772 ; 133.894) | 76.210 | (109.546; 110.568) |
| Sidi Salem | (197.869 ; 197.879) | 338.805 | (517.791 ; 522.537) |

***Table 15.5*** *Expected annual supply deficits of the entire system and Siliana reservoir* ($10^6 m^3$)

| *Reservoir* | *Setup S1 (iteration 3)* | *Setup S2 (iteration 2)* | *Setup S3 (iteration 2)* | *Setup S4 (iteration 5)* |
|---|---|---|---|---|
| the entire system | 7.181 | 6.634 | 6.034 | 5.595 |
| Siliana | 5.411 | 5.259 | 4.521 | 4.690 |

The maximum number of iterative cycles executed in each of the four approaches has been limited to five. Table 15.5 shows the expected annual supply deficits of the entire system and for Siliana reservoir only in the respective "best iterations". It is obvious that both the assumption of refining storage discretization (comparing *S*1 to *S*3, and *S*2 to *S*4) and augmenting the "hypothetical demand" of Bou Heurtma (comparing *S*1 to *S*2, and *S*3 to *S*4) bring about some improvement into the system's operation. It may seem at first glance that very little could be gained by augmenting the "hypothetical demand" of Bou Heurtma. However, it is not quite true. Namely, it is obvious that a large portion of the system's supply deficit originates from Siliana reservoir. The major part of Siliana's deficit is due to shortage towards its local irrigation demand ISI (about 90% of the estimated deficit values in Table 5). Thus; in all cases Siliana contributes significantly to the overall supply deficit. Therefore, it can be concluded that the bulk of the improvement has been achieved by Ben

Metir, Bou Heurtma, Mellegue and Sidi Saleni, whose operation is directly influenced by augmenting Bou Heurtma's "hypothetical demand" (note that the operation of Joumine and Kasseb is largely independent of the proposed changes in Bou Heurtma's "hypothetical demand" — see Table 15.1).

## 15.4 Conclusions

The presented methodology to derive and to assess optimal operation of multiple-reservoir systems is believed to be a solid foundation for planning in water resources management. It is very flexible as to accommodating different configurations of reservoir systems, various objectives pursued in optimisation and even incorporating different (external) optimisation and simulation models.

The results in this paper and those from other applications (e.g, *Agrar-und Hydrotechnik,* 1993) show that the proposed "hypothetical demand" concept has certain advantages in optimisation of the operation of multiple-reservoir systems in semi-arid regions. As for further research, it would be sensible to analyse in more details the role of discretisation as well as to assess the impacts of extremely high actual demands imposed upon reservoir systems when optimised and operated under the "hypothetical demand" concept.

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# 16. Towards rational usage of water resources in a lower drainage zone of the Aral Sea

**I.B. Ruziev, A.K. Chernishev. and U.I. Shirokova**

The Aral Sea depression is an enormous basin where the fresh waters providing a source of life for fish-breeding and also act as a natural regulator for the irrigated territories lying in the middle of the desert soils of Kizilkum, Kharakum and Usturt are being degraded in both the drainage zone (below the 53 m mark) and outside. On the depression floor left by the sea there are vast regions of salt-marshes, over-salinized soils, and salt-dust transfer points which accompany the devastation process.

On the sea shore of the delta zone (above the 53 m mark) and along the strip of the sea-shore, the complex ecosystem formed earlier has been destroyed completely by the mineralised water which had stayed in the basins (dried-up lakes) and then risen; instead of dried swamps there now appear salt-marshes, fish stocks and fur-bearing animals are reduced significantly, nesting places for migratory birds have disappeared, the flora and the fauna has changed as has also the local climate of the pasture lands.

The altered ecological situation troubles all nations who live in the Aral Sea basin and on its boundaries. The catastrophic situation has made it necessary to decide on how to soften the influences of the processes described. A number of projects have arisen which try, in one degree or another, to solve this complex problem.

A project has been proposed for:

- the protection of the population from the unfavourable influences arising as a result of the fall in level of the Aral Sea;
- the creation or re-establishment of the maximum (useful) biological diversity of the animal world.
- the creation of employment opportunities for the population by the re-establishing fish-breeding, ondatre-breeding, cattle-breeding, etc.
- the creation of better social conditions for the population and an improved economy through the installation of technologies directed to highly productive water use and soil resources, and
- the prevention of the development of negative natural processes and the restoration of the ecological balance of the Aral Sea region.

Formerly, these problems were solved naturally within the two interconnected stable ecological zones based on the hydrogeological regimes of the Amu Darya and the Syr Darya, and the Aral Sea and Aral sea-shore. Here, near the Sea and in its delta, man's economic activity was tied tightly to the regimes of these zones and did not encroach on the vital natural conditions.

It is now necessary to create a new steady-state nature-anthropogenic profile for the diminished Aral Sea and its sea-shore under the changed conditions of the water regime and the negative trends which have ensued.

The irregular input of water resources into the Amu Darya delta induces the need to look for economies in the accumulation, systematic regulation and distribution in the dried-up part of the Sea.

Analysis of satellite photos for different years shows that, depending on the wetness of a particular year, irrigation areas supplied with water (basins and sporadically flooded regions) oscillate within wide bounds. Thus, in September 1990, the general water surface on the sea-shore of the former Aral Sea bottom was more than 3100 km$^2$: in June 1995 the area was no more than 650 km$^2$.

The hydrological situation is evident from the general ecological surroundings of the sea-shore zone and in the desiccation zone. It is necessary to maintain the optimal level in the existing basins and limit the extent of water-mineralisation emanating from their usage.

The current state of the main group of inter-river reservoirs does not allow it to carry out its main function — retention and distribution of water in the lower basins. Following the reconstruction of the Sudatchi and Jiltirbus lakes, it will be possible to achieve a cascade of basins and improve the ecological conditions in the delta and in the dried-up bottom of the Aral Sea.

Studies of the nutritional status of the lakes of the delta zone will need to solve questions about reduction of conflicts in the basin's hydrochemical régime where the water is to be used for drinking needs.

The proposed SANIIRT option considers the question of creating two ecological systems. *Ecological system level 1* which will arise at the junction at the base of the solid dam (220 km) with a dry zone between the 47 m (lowest) and 57 m (highest) mark. This should result in the creation of an uninterrupted buffer zone from the water surface. The average depth of the basin is defined as 3 m; the overall area of the basin of stage 1 is 2200 km.

The lower part of stage 1 is expected to accommodate stage 2 of the basins: in the Adjibuy the dam will be put at the 44-45 m mark, lower on the Tigroviy cape of the Amu Darya delta at 39 m and north of the Giltirbus gulf at the 45 m mark.

The height of the dam can be up to 4 m and the maximum depth of the 2nd range of basins 2 m. The complete water surface of the first basin does not permit regulation of the water regime in the individual parts of the submerged territory but rare faults in the erection excludes the possibility of irrigating the area between the water bodies. The safety of the enlarged system depends on the dam's durability.

The first ecological zone is the delta and adjoining territory of the remote cattle-breeding pastures. It will be accommodated provisionally between the 60th and 53rd marks. This zone includes all soils, some influenced by the river waters and through the formation of Akhbush, Khipchakdarya, Khundarya, Kazakhdarya, Erkindarya, Injenerazek and Akkat canals. The terrain consists of channels, meadows, marsh-meadows and intermittent accumulations of channel spoil some 2 m thick, within strongly jagged residual dried-up channels.

For 30 years the vegetation in these areas has undergone changes as the marsh-meadow communities have been substituted by species capable of accumulating moisture. The territorial heterogeneity of the existing water regime with unstable seasonal variation means that forage reserves for cattle-breeding vary considerably, depending on the wetness of any particular year. To achieve stability for the food industry, considerable improvement in the quantitative indices of pastures created for cattle-breeding is required for which it is expedient to carry out a number of measures directed to irrigation of the area, supplying water through the canals identified above and water courses from regulatory structures.

The overall area, minus the large-scale lake systems, covers about 2000 km$^2$ and it is assumed that the volume of water used is some 0.5-0.9 km$^3$. The organisation of the water distribution requires the building of different types of structures totalling 70-80 million dollars.

The second ecological zone is the protective zone of the districts Muynak, Porlatau, Shege, Kazakhdarya, etc. and the organisation of public services and amenities, recreation, and improved social conditions. This zone consists of the reservoirs: Mejdurechenskoe, Muynakskoe, Ribachiy zal, Maypot and Dautkul.

It is necessary to consider the following:

- regulation of seasonal reserves of more fresh waters in the main reservoirs (Dautkul, Mejdurechenskoe, Ribachiy and Muynakskoe).

- for the Sudatchi lakes, the Kharajar systems, the Dumalak systems and the Jiltirbus lake, canals to provide supplementary nutrition by the collectors and river waters to regulate volumes, maximise the flow of basins and minimise their mineralisation.

***Table 16.1*** *The water balance*

| *Water balance indices* | *Dautkul* | *Mejdurechenskoe* | *Ribachiy* | *Muynakskoe* | *Dumalak* |
|---|---|---|---|---|---|
| Max. area (km$^2$) | 150 | 400 | 135 | 123 | 350 |
| Average 2.0 m depth | 1.5 | 1.2 | 2.0 | 1.25 | 1.1 |
| Volume (km$^3$) | 0.225 | 0.480 | 0.205 | 0.154 | 0.38 |
| Exhalation (km$^3$) | 0.145 | 0.388 | 0.126 | 0.120 | 0.34 |
| PRV Channel | 0.350 | 9.145 | 0.370 | 0.300 | 8.75 |
| KDV Channel | —— | —— | 0.200 | 0.200 | —— |
| GV Channel | 0.018 | 0.024 | 0.010 | 0.010 | 0.02 |
| Sediments | 0.015 | 0.04 | 0.014 | 0.012 | 0.03 |
| Total balance | 0.238 | 8.773 | 0.468 | 0.402 | 8.51 |

*Note*: artefacts are present on two lakes — Ribachiy and Makpalkol.

The measures proposed for Mejdurechenskoe and Dumakskoe for the Mejdurechenskoe reservoir are:

- to raise the height of the dam by 1-2 m to allow an increase in the reservoir volume to 360-720 million m$^3$ and move to 2-3 years' regulation with the water resources.
- to raise the existing spillway by 1-2 m.
- to permit changes in water distribution as well as increase pasture, and in the same reservoir system to reconstruct the Khipchakdarya channel to provide a buffer for the upper inflow from the reservoir, and to build one or a number of regulating structures.
- to raise the level of the Maypot Dumalak lake system to the 55 m mark, after the building of the reinforced dam 15.5 km from the River Amu Darya to the River Khundarya (from Bayniyazawl, Marat sources) by an average height of 3-3.5 m. The volume of the building works is about 2 million m$^3$, but the useful volume can increase up to 210 million m$^3$.
- to establish the Dumakskoe source level at the 54 m mark after the construction of the reinforced dam with a height of 2 m, by which the former river-bed of the left channel of Khundarya Basin has an area of 115 km$^2$ and an average depth of 1.5 m.

The length of the dam is 12.5 km, its height is 1.5-2 m and its operational volume is 0.5 million m$^3$.

The third dam of the Dumalak system is proposed for even distribution of waste masses over the whole Akkala penisula. This dam may have a height of 1.5 m and a length of 8-10 km.

Taking into consideration the dynamics of the changes in water resources over a long period, and prognosticating the minimal volume of water entering the Mejdurechenskoe reservoir to be 4.7 km$^3$, it is then advisable to create a reserve volume of about 1.2 km$^3$ at the base of the lower basins, which may expediently be done by increasing the volume of the Mejdurechenskoe and Dumalak lake systems. This provides an opportunity to:

- permit irrigation from the estuary along the shallow parts of the permanent basins;

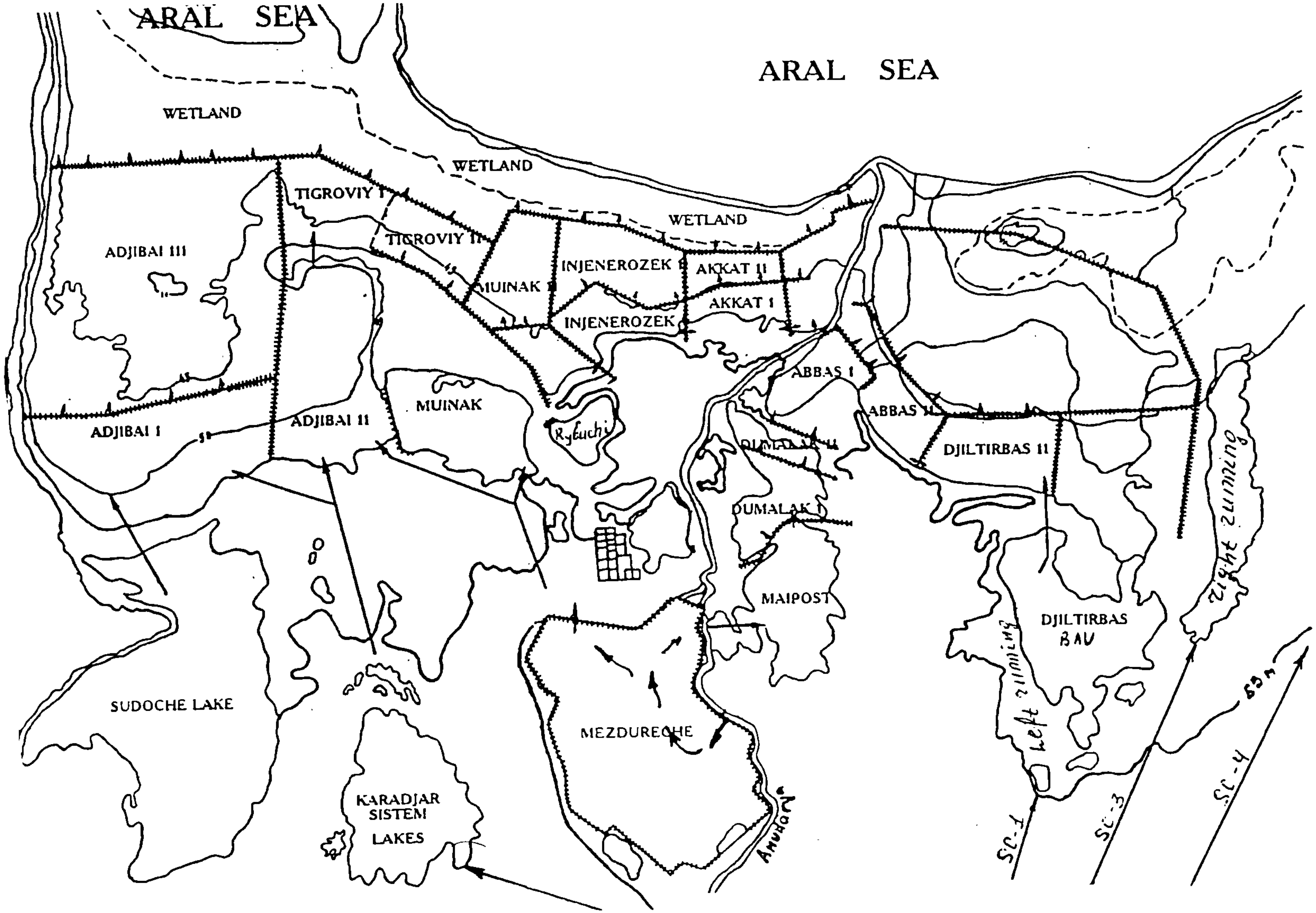

*Fig. 16.1* *Sketch of SANIIRI proposals for the creation of man-made reservoirs in the region of the dried-up bottom of the Aral Sea and in the delta of the Amu Darya river*

- to increase stocks of fish and fur-bearing animals;
- to support a minimal level of artificial storage basins during water-scarce years;
- to raise the Maypot lake level and thus feed the Khundarya; to provide for periodical flooding of the right-hand flood plains where the dried-up canal of the Khundarya appears.

*Ecological zone 3* (first variant) includes a system of two circular secluded basins of scale type (VST). A biological purification zone (bioplateau) will be created before the basins to provide an opportunity to regulate the quality of the water in the VST basins.

The total area of the VST is 904 km$^2$. The size of the VSTs with freshwater input can be within the limits of 5-20 thousand ha and present a system of independent economies in fish-breeding, hunt-breeding, cattle breeding and agricultural production.

The upper circle from the 53-54 m mark and to 51 m mark can be used for different types of agricultural production under conditions of soil improvement and for cattle-breeding.

The fourth ecological zone includes all northern systems (Sudatchy, Adjibay, Jiltirbus, Kharajar, South Kharateren and a number of others).

*Table 16.2*

| *Balance indices* | *Kharajarsk* | *Jiltirbus* | *Sudatchy* |
|---|---|---|---|
| Maximum area | 60 | 500 | 600 |
| Average depth (m) | 1.5 | 1.5 | 1.2 |
| Volume (km$^3$) | 0.09 | 0.750 | 0.720 |
| PRV channel (km$^3$) | 0.110 | 2.0 | |
| KDV channel (km$^3$) | - | 1.2 | 0.7 |
| GV channel (km$^3$) | 0.003 | 0.036 | 0.36 |
| Sediments (km$^3$) | 0.006 | 0.05 | 0.06 |
| Exhalation (km$^3$) | 0.058 | 0.485 | 0.582 |
| Total balance | 0.061 | 2.801 | 0.214 |

From the table it follows that the volume necessary to preserve the ecological zones 1-5 is 11.1 km$^3$ and under these conditions the 100-km region of the 5th ecological zone will receive 5.6 km$^3$ of water which will promote intensive salinity of the territory and favourable processes will follow.

# 17. Managing water and salt regimes in irrigated lands to increase water productivity

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More than 2 million hectares of irrigated land in Uzbekistant is salinized. The salinization of irrigation water is much increased and amounts to some 1.5-2.0 g $l^{-1}$. Since 1989, the Republic of Uzbekistan has had the *Law for Limited Water Use* for different regions and farms for both the cropping and the fallow seasons. The key the region's future improvement lies in the importance of salinity regimes and their relationship with thermal, nutrient and microbiological regimes , i.e. fertility.

The water-salt management regime consists of the following main technological problems: appraisal of the possibility for high crop capacity with rational water and land use; definition of the land reclamation measures required, and existing technical conditions of the irrigation and drainage systems; analysis of the sources of improvement; forecasting the amelioration conditions and ecological impacts; choice of different measures for water and land improvement; and choice of the optimum ameliorative regimes.

An approach such as a joint consideration of both the agricultural system on the irrigated land and the water-salt management, allows us to control all land-reclamation and water-economy activities with the purpose of increasing crop capacity and decreasing the ecological impact.

The main topic of this chapter is a consideration of the connection between land reclamation, water use and crop capacity. The management targets are:

- the most favourable water-salt regimes for soil and groundwater with reference to crop capacity;
- the water supply necessary for the irrigated areas in both harvest and fallow periods with due regard for drainage;
- decreasing ecological impact;
- definition of the socio-economic conditions of the irrigated areas.

**Efficiency criteria:** in our opinion, the best criterion to reflect the most economic process of both control of expenditure and the results of the activity (its effects) within the necessary conditions and limitations, may be written as follows:

$$E = GOV - (Ua + Uw + Ue) \rightarrow \max \qquad (17.1)$$

where: $E$ = increase in economic effect
$GOV$ = increase in gross output value
$Ua$ = agricultural expenses
$Uw$ = water-economy expenses
$Ue$ = ecological expenses

Equation (17.1) should be executed according to the following conditions:
*salt regime:*

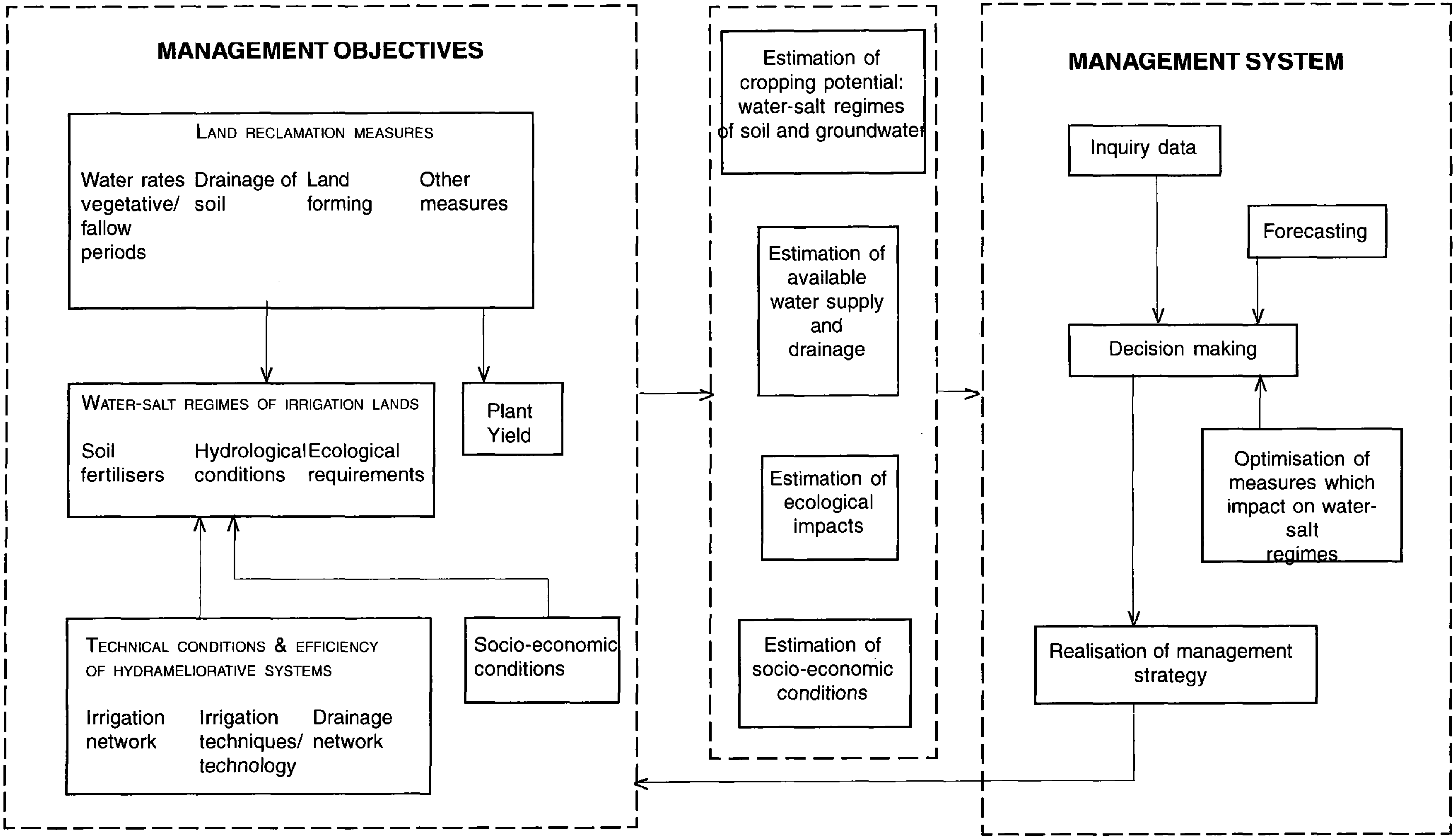

*Fig 17.1.* *The technological structure of the hydro-ameliorative management systems function*

(a) during the land-reclamation period:

$$S[n,i]/S[n,i+1] \rightarrow \max \qquad \text{or } M[p,i]/M[<p,i+1] \rightarrow \max \qquad (17.2)$$

(b) during the exploitation period:

$$S[i] < [S] \qquad \text{or } M[p,i] < [Mp] \qquad (17.3)$$

*water regime*:

$$alfa1*ppV < Wi < alfa2*ppV \qquad (17.4)$$

*available water supply*:

$$Op + N = B \rightarrow \min \qquad (17.5)$$

where:

$S[n,i]$, $S[n,i+1]$, $M[p,i]$, $M[p,i+1]$ - are the percentage of salt in the soil at the beginning of year ($i$) and at the beginning of the year ($i+1$);
$[S]$ - is the permissible salt concentration in the soil;
$alfa1$, $alfa2$ - constants;
$Op$ - is the irrigation demand;
$N$ - is the flushing demand.

The water-salt management regime for the irrigation lands consists of scientific, technical, and organisation sub-systems. Here, we will consider first the scientific sub-system, which should come before the technical and organisation sub-systems.

The management problem should be considered from the point of view of management theory with due regard for cybernetics, computer support and information theory. The methodological basis for this consideration is system analysis.

The hydro-improvement technique for the irrigation lands is a complicated subject and consists of various natural and technical elements. The evaluation of the land-reclamation management techniques was based on hydrochemical balances which are specific to all physical systems. The interactions of the management influences and the technical conditions of water-salt processes and crop capacity are shown in Fig. 17.1.

A water management strategy for irrigation lands should be based on an analysis of main factors which govern effective water use. The Syr Darya region of Uzbekistan (the Golodnaya Steppe) with an irrigation area of about 286.77 thousand hectares is typical of such a problem. This region is situated on the I-st, II-nd and III-rd terraces of the Syr Darya River and on the part of the Turkestan mountain ridge in the proalluvium plains. Irrigation has been provided via irrigation networks from the Syr Darya River (the large canals named Kirov and Sarkisov). The littoral conditions are: first stratum (1.5–45 m) — sand, loam and clay; below the first stratum — gravel and sand strata from 5–10 to 80 m and more. The hydrological conditions are characterised by very difficult outflow and an absence of natural drainage in the north of the region. The present situation is that the depth of groundwater is 1.5-3.5 m (mainly 2-3 m). Groundwater mineralisation — 1.5-15 g $l^{-1}$ (mainly 3-7 g $l^{-1}$). About 78% of the land is salinized from a weak to a strong degree.

In connection with the introduction of limited water use in the Central Asian Republics, at the present time the Syr Darya region has a limit on its water resources of about 2240 million $m^3$ (during the growing season) and 460 million $m^3$ (in the non-vegetative season) making a total volume of 2700 million $m^3$.

The following table shows some of the characteristics of the hydro-remediation systems for the Syr Darya region of Uzbekistan (Golodnaya Steppe).

*Table 17.1*

| ***Areas*** | ***Irrigated surface (000 ha)*** | ***Discharge from vertical wells*** *(l* $s^{-1}$*)* | ***Specific drainage per irrigated surface*** *(m* $ha^{-1}$*)* | ***Percentage subsurface drainage*** | ***Overall efficiency of irrigation system*** |
|---|---|---|---|---|---|
| Central | 46.9 | | 62.0 | 45 | 0.78 |
| South-east II | 38.4 | | 105.0 | 85 | 0.80 |
| South-east I | 43.04 | | 97.2 | 45 | 0.77 |
| Farkhadsky | 9.6 | 64<br>(30.5) | 44.0 | | 0.77 |
| Poimenny | 37.9 | | 27.4 | | 0.69 |
| Bayautsky | 37.8 | 87 | 28.3 | | 0.70 |
| Shuruziaksky | 50.5 | 318<br>(41-61) | 26.3 | | 0.69 |
| Sardobinsky | 22.63 | 216<br>(29.8-44.3) | 38.9 | | |
| Total | 286.77 | 685 | | | |

Agricultural irrigation is carried out by surface irrigations — furrows, bunds, check-dams. The most wide-spread is furrow irrigation. At present, the effectiveness of irrigation is 65-68%.

Eight large irrigation areas in the Syr Darya region were chosen for analysis (geomorphological conditions, water-salt balances, inflows, outflows, and soil conditions). On the basis of 10 and more years of investigations of the data (agricultural, water use, scientific and technical developments, etc.) the following parameters were identified: the quantity and quality of groundwater, extent of soil salinization; water mineralization; available water supply in both growing and fallow seasons (in accordance with crop composition) and the technical conditions of irrigation and drainage systems; and crop capacity. From this information and joint consideration of the moving forces and trends in soil condition and influences, the cause and effect relationships between scarce water and land productivity in each area were determined. Also determined were the necessary measures for improvement of the present situation and decrease in the ecological impact for soil and irrigation sources.

The quality and quantity estimations for return flow and vertical drainage systems allow us to carry out the recommendations for effective water use in these areas. During the past three to five years in these areas there has been a tendency for a decrease in cotton productivity. The main causes for this situation are soil salinity, an increase in water mineralisation (0.88–1.57 g $l^{-1}$ at the present time against 0.55–0.65 g $l^{-1}$ in 1960), insufficient available water supply (0.8– 1.0 in the growing season and 0.15– 0.73 in the non-vegetative season).

The depth to groundwater is lower in all areas than that accorded by the Cadastre of Central Asian Water Resources. But in 1992-93, an increase in groundwaters had been observed, which means that the effectiveness of the drainage systems is insufficient and these systems should be improved.

An analysis of the salinization trends in the various soils showed that desalinization has stopped because the flushing regimes have ceased. The study of cause and effect relationships between the ameliorative conditions, available water supply and the technical conditions of irrigation systems, allows us to determine that to achieve an increase in available water supply what is necessary is: an increase in water intake in the non-vegetative period; meet the requirements for flushing and agricultural irrigation demand according to the recommended regimes; speed up the reconstruction of canals K-9 and K-9a in the Sardoba area; increase the average supply in the canal ("debit moyen d'un canal") K-1; reconstruct the Left Canal with the purpose of increasing water supply in the Bajaut area.

At the present time, the conditions of the drainage systems are satisfactory but at some periods it does not meet the requirements because of the small volume of repair works and insufficient outflow for the header lines (collectors). It is for these reasons that groundwater levels are increasing.

The existing vertical drainage system in the old areas of Golognay Steppe were built about 20-30 years ago and the in the new areas about 15-20 years ago. They all use metal filters. With the help of such vertical drainage systems, these areas benefited from both land reclamation and increased agriculture during the 1970s and 80s. At the present time the effectiveness of the vertical drainage systems is decreasing because of filter corrosion and a number of repair works are necessary to improve their effectiveness.

Measures for rational water use to increase soil and water effectiveness including the following:

- Improvement in land smoothing, land forming, irrigation technology, field optimisation, decrease in non-effective wastewaters;
- Organisation of inter-farm rotation of water use; use of the return waters; improved agricultural techniques — harvesting, ploughing, flushing, optimisation of crop composition;
- Improvement in the information systems at the different levels of "field", "farm", "irrigation system" etc. Improvements in the gauges and control devices which permit the estimation of the volume of water supply and the quality of soil improvement regimes to increase crop capacity.

Furthermore, lining and reconstruction of the inter-farm and farm water-improvement schemes are a long-term major repair commitment for capital investment.

# 18. Ecological-economic substantiation and selection of technical measures for stabilisation of interaction between a river and irrigation lands using multicriterial analysis

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## 18.1 Introduction

The increase in population and the rapid growth of industry in the second half of the twentieth century has led humanity to exhaust many natural resources, provoking their destabilisation and straining social and ecological requirements of populations. This tendency has also been displayed within water resources management, especially in the arid zones which are characterised by rapid population growth and are deficient in water resources. The necessary demand for land to meet population requirements needs supplementary water capture and the subsequent increase in the volume of drainage water which inflows to river basins.

The intensive inflow of polluted waters in rivers leads to a decrease in the quality of the land. For both stabilisation and to improve this situation, we must develop techniques which do not change the natural situation for the worse or lead to a deterioration in social development.

The basis for ecological-economic techniques which decrease the volume of water use and water losses through modification of irrigation systems, water distribution technology, optimisation of water management and other such measures is a very difficult multi-criterial problem. To solve it, we use system analysis.

## 18.2 Statement of problem

It is first necessary to work out the complexity of the water-protection and water-saving measures which consist of:

$X_1$ optimisation of the amelioration regimes;
$X_2$ water allocation;
$X_3$ improvement in the irrigation regime and technology;
$X_4$ increasing irrigation network efficiency;
$X_5$ organisation of the collector network;
$X_6$ water cleaning;
$X_7$ water freshening.

Thus system analysis is required of the regimes and parameters of the irrigation network and remedial technology to determine which measures provide for the most effective ecological-economic development. The application criteria may be defined as:

(a) WC = cost of:
$Wc1$ - capital investments
$Wc2$ - exploitation expenditure
$Wc3$ - working resources (manpower)
$Wc4$ - energy (fuel, electricity)

(b) WQ = quality of:
$Wq1$ - water mineralisation
$Wq2$ - water salinisation
$Wq3$ - return-waters pollution
$Wq4$ - return-waters salinization

(c) WT = technology
$Wt1$ - complexity
$Wt2$ - availability of necessary resources
$Wt3$ - Reliability of the technology
$Wt4$ - lasting for use

(d) WM = macro-economic effect
$Wm1$ - economic effect
$Wm2$ - ecological effect
$Wm3$ - social effect

On the basis of these criteria, we can solve a number of problems with the help of economic-mathematical methods and determine the efficiency of the various versions of a complex system.

## 18.3 Method of solving

For the application of quantitative analytical methods it is necessary to construct a mathematical model of the object under investigation. Such a model allows the expression of one or several efficiency indices through the appointed conditions. If the number of feasible versions $X = \{x1, x2, ..., xn\}$ are not too large, it is possible to calculate the optimal value of the efficiency index W with the help of the "simple sorting" method or the analytic Hierarchy Process (AHP) method, a multi-criteri decision-making process that was developed by the mathematician Thomas L. Saaty at the Wharton School of the University of Pennsylvania, USA. The AHP method makes it possible to look a the elements of a problem in isolation: one element compared with another with respect to a single criterion (see: *Multicriteria decision making: the analytic hierarchy process*, vol I, AHP series, by Thomas L. Saaty, 1990, 478 pp).

In our case, the number of alternatives is $n$=7, and the number of different feasible techniques is $(2^n – 1 = 1) = 127$. Taking into account the complication of the ecological-economic basis (substantiation) of each of the 127 projects, from a practical point of view, the use of special sorting methods is preferable. Such special sorting methods are based on application of the logical approach whereby an optimal variant is defined by a number of priorities in consecutive order. Furthermore, it should be noted that a problem so defined is a multicriterial problem where the maximum number of criteria necessary is

$$W\max = \max_{x \in X} \{WQ(a, x); WM(a, x)\}$$

or in others a minimum:

$$W\min = \min_{X \in X} \{WC(a,x)\}$$

Then, the Pareto optimal set is:

$$Wp = W\max \cap W\min$$

whence, from systems analysis theory, we can determine the optimal variant:

$$W\text{opt} = \text{opt}\{W\text{p}(a,x)\}$$

where $a$ is an appointed limitation.

Obviously, the synchronous achievement of an optimum for all local criteria is very difficult owing to the choice of a common strategy X and it is necessary to compromise between local criteria. The main complication in such mutlicriterial problems is the choice of optimum principle to determine the characteristics of the optimal variant Wopt and to show in what sense this variant is preferable to others.

also, the multicriterial problem (in contrast with monocriterial problems) has many different compromise principles, the most frequently applied being:

(i) "Weight coefficients" method where the global efficacy index $W$ consists of a number of local indices $W1$, $W2$, ... with the determined "weights" a1, a2, ...:
$W = a1*W1 + a2*W2 + \ldots.$

It should be added at this point that a main difficulty is a correct and exact determination of a "weight" for each index.

(ii) the method of main index isolation where, for a number of criteria $Wi$, we are isolating the main criterion $W1$ to be maximised; while for other criteria $W2$, $W3$, ... we will determine the special limitations $w2$, $w3$, ...

(iii) Method of consecutive concessions, where the indices $W1$, $W2$, ... are situated in accordance with their importance, with the first index being maximised (in preference to other indices) then the second index, etc. The main complication with this method is the difficult calculation when the number of variants is very large.

Thus the method for solving multicriterial problems consists of formulation of the global criterion. This may be constructed as an additive or a multiplicative unification or as a "weight" combination of the local criteria. The method for solving this problem is as follows:

(a) On the basis of expert estimations, all local criteria are situated in accordance with their importance: $f1, f2, \ldots fk$;

(b) Step by step we solve the following problems:

1. Determine $f1 = \max_{x \in \Omega} f1(x)$;

2. Determine $f2 = \max_{x \in \Omega} f2(x)$, on condition that:

$$\begin{cases} x \in \Omega \\ f2(x) = f^* \end{cases}$$

k. Determine $fk = \max fk(x)$, on condition that:

$$x \in \Omega$$
$$fr(x) = f^*r \qquad r = 1, 2, ..., k\text{-}1.$$

where $\Omega$ = field of alternative variants.

(c) The alternative variant $x1$ is preferable to $x2$ ($x1 > x2$), if:

$f1(x1) > f1(x2)$; or

$f1(x1) = f1(x2), f2(x1) > f2(x2)$; or

..................................................

$f1(x1) = f1(x2), ft(x1) > ft(x2)$, 1 = 1, 2, ..., $t$-1; or

..................................................

$f1(x1) = f1(x2), fk(x1) > fk(x2)$, 1 = 1, 2, ..., $k$-1.

(d) The alternative variant $x1$ is equal to $x2$ ($x1 \sim x2$) if:

$F(x1) = F(x2)$, $F = \{f1(x), f2(x), ..., fk(x)\}$

(e) For any variants $x1$ and $x2$ implemented always one of the three correlations: $x1 > x2$; $x1 < x2$; or $x1 \sim x2$.

(f) According to Pareto's axiom, the multicriterial problem is characterised by the rule: strategy $x1$ is always preferable to strategy $x2$ if $x1 > x2$ or $x1 \sim x2$. Thus, for all possible alternatives we can determine Pareto's optimal subset $F^* \subseteq F$.

(g) Finally, we can determine (with the help of additional information) the optimal strategy $F$opt $\in F^*$.

## 18.4 Example

On the basis of this method we can show an example of the ecological-economic basis for selection of technical measures for the stabilisation of interaction between a river and irrigation lands.

Let us suppose that, it is necessary to estimate alternatives ($x1, x2, ..., x7$} on the following indices: cost - *Wc*, quality - *WQ*, a technology - *WT*, a macroeconomic effect - .

The estimates provided by the experts are shown in the following table where *Cij*, *Qij*, *Tij*, *Mij* are the experts' estimates (in points).

On the basis of Table 18.1, we construct the generalised Table 18.2:

***Table 18.1***

| ***Criteria*** | | ***Alternatives*** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | *x1* | *x2* | *x3* | *x4* | *x5* | *x6* | *x7* |
| WC: | Wc1 | c11 | c12 | c13 | c14 | c15 | c16 | c17 |
| | Wc2 | c21 | c22 | c23 | c24 | c25 | c26 | c27 |
| | Wc3 | c31 | c32 | c33 | c34 | c35 | c36 | c37 |
| | Wc4 | c41 | c42 | c43 | c44 | c45 | c46 | c47 |
| WQ: | Wq1 | q11 | q12 | q13 | q14 | 15 | q16 | q17 |
| | Wq2 | q21 | q22 | q23 | q24 | q25 | q26 | q27 |
| | Wq3 | q31 | q32 | q33 | q34 | q35 | q36 | q37 |
| | Wq4 | q41 | q42 | q43 | q44 | q45 | q46 | q47 |
| WT: | Wt1 | t11 | t12 | t13 | t14 | t15 | t16 | t17 |
| | Wt2 | t21 | t22 | t23 | t24 | t25 | t26 | t27 |
| | Wt3 | t31 | t32 | t33 | t34 | t35 | t36 | t37 |
| | Wt4 | t41 | t42 | t43 | t44 | t45 | t46 | t47 |
| WM: | Wm1 | m11 | m12 | m13 | m14 | m15 | m16 | m17 |
| | Wm2 | m21 | m22 | m23 | m24 | m25 | m26 | m27 |
| | Wm3 | m31 | m32 | m33 | m34 | m35 | m36 | m37 |

*Table 18.2*

| ***Criteria*** | ***Alternatives*** | | | | | | |
|---|---|---|---|---|---|---|---|
| | *x1* | *x2* | *x3* | *x4* | *x5* | *x6* | *x7* |
| WC | C1 | C2 | C3 | C4 | C5 | C6 | C7 |
| WQ | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 |
| WT | T1 | T2 | T3 | T4 | T5 | T6 | T7 |
| WM | M1 | M2 | M3 | M4 | M5 | M6 | M7 |

where the estimates are:

$$Ci = \sum_{j=1}^{4} c[i,j]\ /\ 4; \qquad Qi = \sum_{j=1}^{4} q[i,j]\ /4;$$

$$Ti = \sum_{j=1}^{4} t[i,j]\ /\ 4; \qquad Mi = \sum_{j=1}^{3} m[i,j]/3.$$

From the available projects $\{x1, x2, ..., x7\}$ it is necessary to choose the most preferred project $xi$. Note that all seven projects should have the greatest total estimates. Therefore, we have a multicriterial problem with four criteria and seven alternatives. Let us choose the best solution in two steps:

*1st step*: On the basis of the method shown above, determine Pareto's optimal set $F^* \in F$, where $F = \{x1, x2, ..., x7\}$. For this we compare the solution for $x1$ with that for all the others (x2, $x3$, ..., $x7\}$ on the following principle:

If $[C1 > C2)$ and $Q1 > Q2)$ and $(T1 > T2)$ and $(M1 > M2)]$ => $x1 > x2$.
In another case: $x1 \sim x2$,
and in a consecutive order to determine the Pareto's optimal set of a possible solution for $F^*$.

*2nd step*: On the basis of the additional information (which is not always clearly formulised) we determine the concrete optimal variant Fopt ∊ F. This optimal variant Fopt is a final decision. This algorithm may be solved on a computer using PROLOG programming language or with the use of some of the logical operators from C++ or Pascal programming languages.

## 18.5 Example calculation

For complete understanding of the method suggested, let us carry out an actual calculation. For example, the expert estimates were determined on the 10-numbers scale (from 0 to 9). The results of these estimates are shown in Table 18.3.

***Table 18.3***

| ***Criteria*** | ***Alternatives*** | | | | | | |
|---|---|---|---|---|---|---|---|
| | *x1* | *x2* | *x3* | *x4* | *x5* | *x6* | *x7* |
| WC | 9 | 4 | 6 | 8 | 3 | 3 | 2 |
| WQ | 2 | 7 | 8 | 2 | 1 | 5 | 6 |
| WM | 8 | 3 | 3 | 5 | 0 | 3 | 2 |
| WT | 4 | 1 | 3 | 2 | 7 | 2 | 7 |

*1st step*: let us assume that $F1 = F = \{x1, x2, .., x7\}$.
To compare the solution for $x1$ with other solutions from $F1$:

x1 and x2: 9>4 => + |
| => $x1 \sim x2$
2<7 => – |

$x1$ and $x3$: 9>6 => + |
| => $x1 \sim$ x3
2<8 => – |

$x1$ and $x4$: 9>8 => + |
2=2 => + |
| = x1>x2 => x1 ∊ F*
8>5 => + |
4>2 => + |

x1 and x5: 9>3 => + |
2>1 => + |
| = x1~x5
8>0 => + |
4>7 => – |

$$\begin{array}{lll|l} x1 \text{ and } x6: & 9>3 \Rightarrow & + & \\ & & & \Rightarrow x1 \sim x6 \\ & 2<5 \Rightarrow & - & \end{array}$$

$$\begin{array}{lll|l} x1 \text{ and } x7: & 9>2 \Rightarrow & + & \\ & & & \Rightarrow x1 \sim x7 \\ & 2<6 \Rightarrow & - & \end{array}$$

From this, evidently, $x1 \in F^*$ because $x1 > x4$. Moving off the solution $x1$ and $x4$ from $F1$, we get:
$F2 = \{x2, x3, x5, x6, x7\}$.
By analogy, compare now the solution for $x2$ with the other solutions from the set $F2$, yielding:
$(x2 < x3; x2 \sim x1, i=5, 6, 7\_$.

Therefore, $F3 = \{x3, x5, x6, x7\}$. By comparing the solution for $x3$ with the other solutions from set $F3$, we get $F4 = \{x5, x7\}$. Furthermore, $x3 \in F^*$ because $x3 > x6$. In the end, comparing the solutions for $x5$ and $x7$ from the set $F4$, we get $x5 \sim x7$ and $F5 \neq 0$!

Thus we have two Pareto's optimal solutions (decisions):

$F = \{x1, x3\}$.

The other solutions — $\{x2, x4, x5, x6, x7\}$ — are not optimal.

*2nd step*: It is necessary to choose the more preferable solution from the alternatives of $x1$ and $x3$. The concept of "more preferable" is impossible under strict mathematical rules and so is a very difficult basis from which to make a final decision. In this case it is necessary to gain additional information about the interactions between $x1$ and $x3$, for example, additional criteria (such as ecological influences, the time for project completion, reliability, etc.) On the basis of this extra information we can determine the final optimal decision for selection of appropriate technical measures to stabilise the interactions between the river and the irrigation lands.