4.5 Sustainable water resources management in arid and semi-arid regions

SUSTAINABILITY

Sustainable water resources management is a practice, which avoids irreversible (and quasi-irreversible) damages to the resource water and all resources linked to it (e.g. soil and ecosystems). It conserves in the long run the ability of the resource to extend its services including ecological services. Water scarcity and poverty are usually the reasons for non-sustainable behaviour. They lead to overexploitation and wastage.

What are the globally relevant problems of sustainability in the water sector? In order to identify the big and potentially existential problems of whole regions we have to look for globally spread negative trends. In this sense the most important non-sustainable development trends are:

- the overexploitation of groundwater basins
- the reduction of low flows of rivers,
- the destruction of wetlands,
- the salinisation of soils and
- the pollution of aquifers with persistent pollutants

World-wide about 800 km³/year of freshwater are abstracted from aquifers. About a quarter of this abstraction is not sustainable in the sense that it is not replaced again by recharge. That means it is covered by emptying the storage. On the Arabian Peninsula, in North Africa, Northern China, or the dry west of the United States large quantities of water have been abstracted for large scale irrigation. They cannot be recharged again under present climatic conditions in the foreseeable future.

Due to the consumptive use of water (i.e. use during which water is evaporated) in irrigation of the upstream regions of catchments, the remaining flows in the downstream are considerably reduced. Even big rivers such as the Yellow River in China become ephemeral. In recent years the Yellow river did not flow for more than 100 days on a stretch of several hundred kilometres. The most extreme example is probably the Amu Darya, which has so little water left that the Aral Sea is drying up. The shift of availability of water from the downstream to the upstream contains considerable conflict potential in international catchments.

A related problem is the drying up of wetlands. The global wetland area has been halved between the year 1900 and today. This has a dramatic impact on biodiversity. The tendency is a direct consequence of the competitive allocation of land and water resources to nature and agriculture, which continues undiminished.
Of the world-wide 260 million ha of irrigated agricultural land about 80 million ha are more or less affected by soil salinisation. Salinisation is a common phenomenon in hot and dry climates. It occurs if evapotranspiration deposits more salt than can be carried away by drainage. The most common mechanism responsible for salinisation is based on the groundwater table rise associated with the seepage of irrigation water. If the groundwater table comes within a distance of less than 2 m from the surface, capillary rise leads to direct evaporation of water from the groundwater table and consequently deposition of salts dissolved in it at the top soil level.

Finally the pollution of groundwater by persistent pollutants has to be mentioned. One might think of chlorinated hydrocarbon solvents, which is probably still true for the industrialised countries. World-wide, however, salt is the most important pollutant, especially in arid regions and in coastal areas where salt water intrusion occurs.

In principle all these violations of the principle of sustainability are reversible, however on time scales of several generations. Therefore they are for all practical purposes irreversible.

In the following paragraphs two examples from projects of the Institute for Environmental Engineering (formerly Hydromechanics and Water Resources Management) at ETH Zurich are introduced which illustrate the sustainability problems and show possibilities for solutions. The examples have 4 points in common:

- There is a situation of water scarcity (both examples are from arid or semi-arid regions),
- a model is developed with which the system is to be analysed and understood,
- the model is used to test management strategies and/or optimise the resource management and finally
- the connection to the socio-economic environment is important

**Overexploitation of the North-West Sahara aquifer system**

The North West Sahara covers an aquifer system which has twice the area of France. It consists of two main aquifers, the deeper Continental Intercalary (CI) and the shallower Terminal Complex (CT) (Fig. 4.5-1). The water resources of these aquifers are used by three countries: Algeria, Tunisia, and Libya. Today the system has practically no natural recharge anymore. The maximum estimate of recharge is about 30 km$^3$/year in the outcrops of the aquifers in the Atlas Mountains. It drains to the chotts or terminal salt lakes, which are at the lowest points of the endorheic basin. There, about 10 m$^3$/s are evaporated. A small portion of not more than 5 m$^3$/s goes into the Mediterranean in Libya.

Till 1959 the water abstraction was small. Since then, however, the population has tripled and the water abstraction for irrigation increased by the same factor. Today, about 180 m$^3$/s are abstracted.

As a consequence, the large springs close to the Chotts ran dry (Fig. 4.5-2). The Artesianism vanished and over large areas where formerly the water flowed out without any energy input now pumping has become necessary.

The present situation is characterised by an abstraction which is at least 6 times as large as the natural recharge. This leads to the question whether non-renewable water resources should be exploited at all.

Taking into account the size of the system and its storage coefficient, a huge water reserve of about 100,000 km$^3$ can be derived. About one tenth of it can be exploited, if the economically feasible lift height is set at maximally 250 m. At a predicted abstraction of 500 m$^3$/s in the future, the resource theoretically can last for about 600 years. But this water comes at a price. Energy is needed for pumping, investments are necessary for the infrastructure of roads, wells and power lines. Water quality is another issue. It is

![Fig. 4.5-1: Overview over the North West Sahara Aquifer System and its water balance (ERESS 1972).](image-url)
threatened by salinity. In the vicinity of the chotts large drawdowns lead to the inversion of the piezometric gradient between chott and oasis. In the natural situation flow is always directed from the Oasis to the chott. If an inversion occurs, salt brines are attracted from the chott to the oasis, leading finally to the die-off of the date palms or other irrigated vegetation. A similar phenomenon is observed at the Libyan coast, where overpumping leads to seawater intrusion. Finally saltwater of the underlying Turonian can be mobilised if the pressure of the CT is diminished by the well fields’ drawdown.

A numerical model of the aquifer system was constructed, which shows that at the pumping rates required in 2050, large portions of the now strongly pumped regions will show drawdowns which are economically no longer feasible, at least for irrigation water (red areas in Fig. 4.5-4 in comparison to Fig. 4.5-3). At the same time the requirements for water quality cannot be fulfilled anymore.

The groundwater model was coupled with an optimisation algorithm in order to find a distribution of abstractions, which at a given demand will fulfill the constraints on drawdown and water quality while simultaneously minimising the total cost (SIEGFRIED 2004, SIEGFRIED & KINZELBACH 2006). The suitable optimisation procedure for a problem with so many degrees of freedom is a genetic algorithm. In the optimal schemes the wells are more evenly distributed over the area in order to reach an equilibrium between production cost and distribution cost. The abstractions also move from the already strongly utilised CT to the deeper CI. Two variants were analysed. In the first one the existing well fields were used. The pumping rates at these locations were the decision variables. In cells near the chotts the inversion of the hydraulic gradient was forbidden by a constraint. On the whole, cost of water exploded over 50 years by a factor of 30. In a second variant the choice of well positions was arbitrary. The results showed that compared to the first variant, well distributions with a relative total cost increase of a factor of 4 over the coming 50 years are feasible. Interesting as such scenarios may be, they require time to build new infrastructure. A realistic road of development would be a transition from the present infrastructure to a more favourable distribution with respect to total cost. The 50 years must be used to find alternatives as the salinity problem cannot be contained indefinitely. All optimisations were done without consideration of the national borders. It can be seen that co-operation between the countries, especially in the chott region brings some cost advantages with water transfers on the order of 10% of the total pumping rate. In the long run, the conservation of the oasis culture, however, requires high subsidies.

**Water resources management in the Okavango Delta, Botswana**

The Okavango originates on the Benguela Plateau in Southern Angola and flows in south-east direction through the Caprivi strip into Botswana, where an inland delta is

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**Fig. 4.5-2:** Development of flow of two springs in Southern Tunisia (1887–1985) (MAMOU 1990).

**Fig. 4.5-3:** Modelled piezometric heads in CI-aquifer, 1950 (Isolines from 530 m asml (1) to 70 m asml (2) in steps of 35 m) (asml = above mean sea level).

**Fig. 4.5-4:** Predicted piezometric heads in CI-aquifer, 2050 under planned abstractions (Isolines from 530 m asml (1) to -250 m asml (2) in steps of 55 m).
formed (Fig. 4.5-5). There almost the total flow is consumed by evapotranspiration. The Delta is one of the biggest animal reserves in Africa and an attraction for numerous tourists. The annual floods of the river turn the Delta into a seasonal swamp (Hutchins et al. 1976, Thomas & Shaw 1991, McCarthy et al. 1986, 2003, Ellery et al. 1993, McCarthy & Ellery 1994, Gumbrecht et al. 2001, 2005).

As the annual flood wave takes 3 months to proceed from the inflow at Mohembo to the distal part of the Delta at Maun, it is out of phase with the local rainy season. This leads to an essential prolongation of water availability.

The countries in the upstream are discussing plans to abstract water from the Okavango or build dams for both power generation and irrigation. In Botswana several sectors of the economy have proposed a more intensive utilisation of the Okavango water both for agriculture and mining. All these measures threaten the Delta in its existence. Abstraction in the upstream and acceleration of the flood propagation by canalisation lead to a decrease and a redistribution of the seasonally flooded swamp area.

In order to assess the impact of hydraulic measures on the flooded area a numerical model with a 1 km by 1 km raster was constructed (Bauer 2003, Bauer et al. 2006), which couples surface and groundwater in two layers separated by the topography. In the surface water layer the flow is described by the Darcy-Weissbach law, while in groundwater and dense growths of papyrus Darcy’s law is used. The average water level in a cell determines whether the cell is flooded and therefore transports also surface water, or whether there is only groundwater flow. The exchange between the surface and groundwater layers is essential as groundwater is supplying the trees on the islands with water. Satellite data on the time varying size of the flooded areas over 20 years were used in the model calibration. Other data applied were the inflow at Mohembo, precipitation from Meteosat data (according to Herman et al. 1997), evapotranspiration from the multispectral NOAA AVHRR sensor (with the method from Bastiaanssen et al. 1998a,b) and finally local hydrographs which are measured routinely by the Department of Water Affairs. The model is capable to reproduce the seasonal dynamics both in the average flooded area of the Delta as well as in its temporal variation (Fig. 4.5-6).

The final sink for all the water is evapotranspiration via the vegetation or evaporation from water surfaces. These processes determine also the distribution of salt in the Delta. Salt crusts in the centres of islands show where the natural storage sites for salt are. Their continued functioning is essential for keeping the rest of the Delta fresh.

An example of measures with potentially serious repercussions on the Delta is the abstraction of water in the upstream. Computation runs comparing the evolution of the seasonal swamp area with and without abstractions are shown in Fig. 4.5-7.
Computations show that an abstraction is magnified as the relative reduction of swamp area is twice as large as the relative reduction of the inflow. Dams in the upstream have both the effect of inflow reduction as well as a temporal redistribution of flood water. Morphological changes by dredging of channels or cutting of the papyrus also have a pronounced effect, not so much on the total area of the Delta as on the redistribution of the flooded area within the Delta.

The local abstractions for private households both from the aquifer and directly from surface water are so small, that their impact is negligible. If one ranks the anthropogenic and natural impacts on the Delta’s size by influence and magnitude, the following list in direction of decreasing impact can be given:

- abstraction larger than 20 m$^3$/s in the upstream,
- climate change to drier climate,
- large dams in the upstream,
- morphological change (Canalisation, cutting of papyrus, tectonics)

The model provides a quantitative basis for the political debate between the riparians of the Okavango. The water comes from Angola while the income for tourism is mainly generated in Botswana. It is clear that for the conservation of the Delta part of the income from tourism has to be redirected to the upstream in exchange for a guaranteed inflow at Mohembo. The key parameter for an administrable, negotiated solution is the guaranteed minimal inflow at Mohembo and its temporal variability.

**Conclusions**

In arid countries and regions the problems of sustainability are essential and a solution is urgently needed. This requires massive efforts as for example the consequent utilisation of the water savings potential of irrigation in agriculture, the development of new resources such as sea water desalination, the substitution of agriculture by other economic activities, or the resettlement of people. Some of these items imply a substitution of water by capital investment or energy. We probably have to get used to the idea that in a sustainable mode the cost for food worldwide will have to increase and require a larger portion of our income again.

Water problems are not really global problems. They have to be solved region by region. The natural system boundary is the catchment which can include territories from different nations. The analysis must be broad enough with respect to the subjects to be included, e.g. in arid regions besides the water balance the salt balance has to be considered. But also ecology and economy cannot be separated from water issues.

Modern tools of hydrology such as remote sensing, geophysics, environmental tracers and modelling help especially in regions with weak infrastructure to quantify the impacts of human interventions and to judge the sustainability of present practices. The resulting models allow to evaluate the efficiency of measures and to optimise management strategies with respect to sustainability. This process has to be carried out in a dialogue with many actors involved. In this process the transparent and trustworthy representation of a problem and the options on a scientific basis are very helpful. Even if the theoretically derived optimal solutions often remain idealisations they still represent points of reference which can develop some attractive potential. While science can offer advice and decision support, the decisions for or against sustainability are made in the political arena.