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3.2.10 Irrigation induced soil salinisation in the Yanqi Basin, China-modelling approaches and possible solutions

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SUMMARY: *Intensive irrigation with river water in the semi-arid Yanqi Basin has caused several environmental problems, the most severe one being soil salinisation. The Yanqi Basin is a typical example for the misuse of water in a semi-arid region. Irrigation has caused a substantial rise of the groundwater table, followed by soil salinisation. Agricultural production can only be maintained by means of over-irrigation. However, this triggers off a vicious circle, as over-irrigation again contributes to a rising groundwater table, leading to an ever higher salinity and water consumption at a given production level. Conjunctive use of ground- and surface water, as well as an improvement of the efficiency of the irrigation systems are measures that would contribute to both a reduced salt concentration in the Basin itself as well as an increased amount of freshwater in the downstream systems. To evaluate the feasibility and to find optimal solutions, a hydrologic model simulating surface water, groundwater and the coupling between them was constructed.*

World-wide, about 17% of the agricultural area is irrigated, but its production amounts to over 40% of the global agricultural outputs and to 60% of its grain production (FAO 2004). Irrigation techniques have been designed to permit crop production in areas where rainfall is either insufficient or poorly distributed over the year (HILLEL 1987). Compared to an agricultural system which is completely dependent on the weather, irrigation helps to ensure a stable production. In wide areas of Asia, Australia and Africa as well as Russia, productive agriculture is only possible with irrigation. In a global ranking, China has with 32% of its total cultivated area (approximately the area of France) the largest portion of irrigated farmland (FAO 2004). The ever-growing population and the ongoing loss of arable land have led to a significant increase of irrigation in the semi-arid regions of China.

However, even though the irrigation of large areas can contribute to a stable and productive agriculture, it comes at a cost. The expansion of the irrigated areas significantly influences the local supply and demand balance of water. In eastern China (e.g. in Hebei province), the gap between the limited, renewable water sources and the continuously increasing water demand is, to a large extent, compensated by groundwater pumped and used for irrigation. If the abstraction rate of an aquifer is above the recharge rate, the groundwater table inevitably drops. If the drawdown cones become too deep, the remaining water resources are difficult to access. It is clear that in areas where more water is used than recharged, agricultural production will diminish, as the available resources get scarce. Ironically, abundant water resources do not guarantee sustainable production. In the semi-arid regions in western China such as Xinjiang or Inner Mongolia, irrigation water is not pumped from aquifers, but mostly drawn from rivers. In these areas, the intensive irrigation has led to several negative impacts on crop production. Besides water logging, soil salinisation is the most important one.

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Irrigation and soil salinisation

Salinisation occurs naturally (primary salinisation) or due to human activities (secondary salinisation). As water evaporates (be it through transpiration or evaporation), the salts dissolved in the water accumulate in the evaporation zone. If rainfall or the amount of irrigation water applied is not sufficient to flush the salts out of the root zone, the salts will accumulate. The impact of salinisation on different kinds of crops is well known. An excellent database summarising the impact of salinity on crop growth is provided by the US-SALINITYLAB (2004). Changes in the structure of the soil due to salinisation have been observed and described. Different forms of irrigation and their influence on salinisation have been widely studied (HILLEL 1987, RHOADES et al. 1992). A good overview of these different aspects of salinity can be found in (HILLEL 2000, HILLEL & WORLD-BANK 2000, JAKEMAN et al. 1995, RICHARDS 1954, US-SALINITYLAB 1954).

Irrigation can accelerate the process of soil salinisation. If irrigation takes place without adequate drainage, the groundwater table rises. If the depth to groundwater (the distance between the soil surface and the groundwater table) reaches a critical minimum, groundwater will evaporate continuously through capillary rise. This evaporation rate can be of the same magnitude as the transpiration rates of plants. Salts stored in the unsaturated zone are dissolved and can, by capillary rise, be transported to the root zone. *Fig. 3.2.10-1* shows the mechanism leading to irrigation induced soil salinisation.

Only if these accumulating salts are removed, either by surface drainage to a downstream system or by flushing down the accumulating salts, (leaching) can production be kept at the same level. The leaching of the soil triggers a vicious circle. If more irrigation water is applied to keep the salinity of the soil at a low level, the groundwater table rises and phreatic evaporation is additionally increased. This mechanism has been observed in the Yanqi basin.

The Yanqi basin in China (*Fig. 3.2.10-2*) is a typical example of the misuse of the resource water in a semi-arid region. The dependency between water resources management, soil salinisation and agriculture are illustrated with this example.

Soil salinisation and water management in the Yanqi Basin

The agriculture in the Yanqi Basin started in the second half of the last century with the construction of irrigation channels. The main agricultural products are wheat, cotton, chilli pepper and fruits such as watermelons and grapes. At present, the irrigated area covers about 1.2×10^5 ha. If it weren't for irrigation, no agriculture would be possible as rainfall amounts to only 20 mm/year. The main water source is the Kaidu River. Surface water is sufficient, but unevenly distributed. A large amount of water is wasted through supply systems and on farm irrigation practices. Flood irrigation is the most common irrigation technique applied in the Yanqi basin. A field is simply flooded with water. Even though a drainage system has been installed in the Yanqi basin, its efficiency is by far not sufficient to receive the high infiltration rates under fields irrigated by flood irrigation. In the lower regions of the basin, the groundwater table has reached a level as close as 1 metre below the surface. The lowest point of the basin, Bostan lake, is the terminal sink of the aquifer. The Kaidu river flows into Bostan lake and leaves it as the so called Kongque river. The runoff from Bostan lake to the Kongque river is regulated by pumps. The Kongque river supplies the so-called Green Corridor between Korla and the now dried out Lop Nor with water. Before irrigation in the Yanqi basin and along the Kongque River took place, Lop Nor was the terminal salt sink of the Kaidu-Kongque system. Nowadays, the salt transported by the Kaidu and Kongque rivers is distributed over irrigated areas, the final sink is moving upstream towards the water consumers.

In 2002, 60% of the entire irrigation area exhibited a groundwater table of less than 2 m below the surface and therefore is at risk of turning saline. One could argue that the applied irrigation techniques and efficiencies in the Yanqi Basin are sustainable, as a steady state has been reached (the amount of salt transported out of the Yanqi Basin is equal to the amount of salt imported by the Kaidu) and production has stabilised on a level which is still profitable.

This of course cannot be called sustainable because only the needs of the farmers in this particular irrigation system are satisfied. The reduced amount of available surface water as well as the increased salt concentration endanger the downstream ecosystems and worsen the economical situation for the Green Corridor. Consequently, the spatial system boundary to evaluate the sustainability and its cost benefit analysis of such a groundwater abstraction has to include the downstream systems.

However, alternatives to today's practices exist. Possible structural strategies include the limitation of irrigation water, the increase of the efficiency of the irrigation channels or the reduction of the irrigated area. The measures could contribute to a more economical use of water. A change of the irrigation techniques as well as an expansion of the drainage net would again reduce

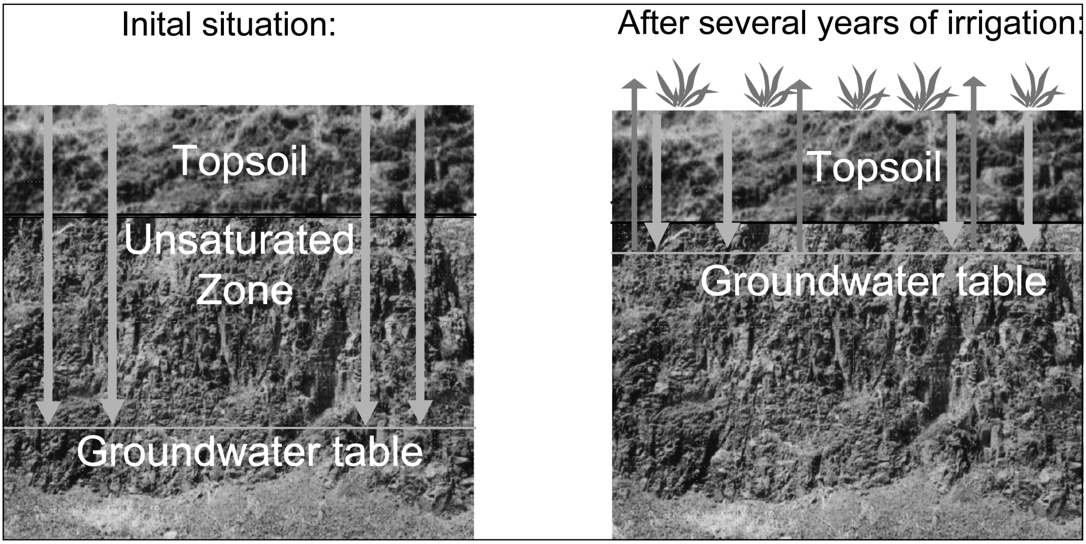

Fig. 3.2.10-1: In the initial stage of irrigation, the infiltrating irrigation water raises the groundwater table. After the groundwater table has reached a critical depth, water continuously evaporates from the groundwater table.

groundwater recharge. Adapting the choice of crops planted to the climate conditions in the Yanqi basin is another option. One of the most promising options, however, is keeping the groundwater table below a critical level by pumping groundwater. If a part of the irrigation water directly drawn from the rivers is substituted by river water pumped indirectly from the aquifer, the groundwater table will drop and the process of salinisation will be slowed down. If the groundwater table drops sufficiently low, the process will even be reversed by flushing down the salt. The major decision variables to steer the system into a desirable state are the extent of the irrigated area and the ratio of irrigation water pumped from the aquifer to irrigation water drawn from the river. Groundwater is hardly used today, as due to energy requirements groundwater is a factor of 10 more expensive than surface water. However, if the water table can be kept low by pumping groundwater, the conservation of soil for continued agricultural use along the Kaidu river might strike the balance with a higher price of water. The ideal ratio was determined with a coupled model of groundwater and surface water flow. Such a model has been constructed and verified by using spatially distributed input data derived from remote sensing (Brunner 2005).

Modelling the water and salt balance in the Yanqi basin

Soil salinity can be modelled with different model types and on different scales. The simplest way to model the water and salt balances is to set up a 1-box model. In order to get an overview of the relevant salt fluxes through the basin such a model was set up for the Yanqi basin. The amount of infiltrating water was quantified, the initial conditions in the pre-irrigation era were assumed. The output fluxes considered were phreatic evaporation as well as drainage rates. Both rates depend on the groundwater table. With the 1-box model, the principle feasibility of groundwater abstraction can be simulated. The box model has shown that irrigation in the Yanqi basin can be carried out by using less surface water, reducing the danger of salinisation and thereby increasing the available resources for the downstream systems. However, to develop concrete measures, a spatially distributed model is required. Such a model must be based on spatially distributed input and verification data.

Recent developments in remote sensing have opened up new sources for distributed spatial data. Examples of such data sets are a digital elevation model or the

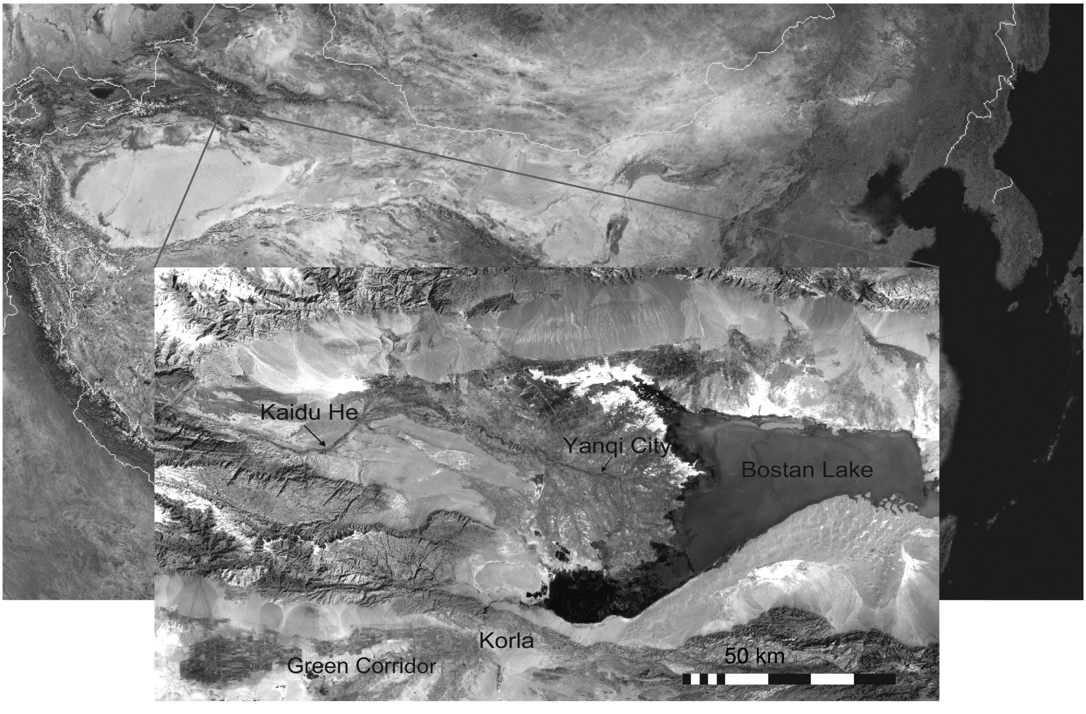

Fig. 3.2.10-2: Location of the Yanqi basin. The detailed picture of the Yanqi basin is a Landsat image.

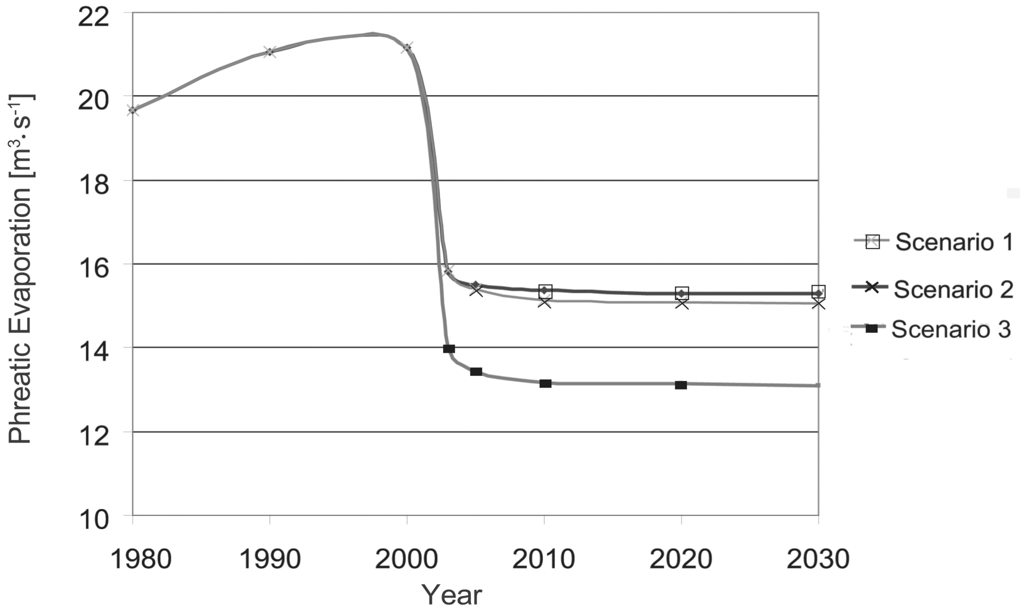

Fig. 3.2.10-3: Development of phreatic evaporation in time. Pumps are installed after the year 2000.

distribution of the infiltration rates. These data sets were obtained by correlating measurements on the ground with the parameters measured with the satellites' sensor. The constructed model simulates surface water as well the groundwater and the coupling between them. Phreatic evaporation is one of the waterfluxes computed by the model. The relationship between the depth to groundwater and phreatic evaporation has been measured in a field campaign and is used as an input function. The model was verified in a distributed manner as well as with point data. Verification data included measurements of the groundwater table in the available boreholes as well as the infiltration rates of the rivers and the observed efficiency of the surface drainage system. An example of distributed verification data is phreatic evaporation. A map of phreatic evaporation was obtained by the combination of measurements of stable isotope profiles in the unsaturated zone and processed multispectral satellite images. Including the distribution of phreatic evaporation, the model was able to reproduce all verification data.

In order to simulate the conditions in the Yanqi basin before irrigation was introduced, a model was set up without any diversion from the rivers and without any recharge. This zero-irrigation scenario clarified where phreatic evaporation is caused by irrigation and where it occurs naturally. This scenario revealed that high groundwater tables are found in many areas even without irrigation. The comparison between the distribution of phreatic evaporation in the zero-irrigation scenario and in the calibrated model allows to identify areas where phreatic evaporation is irrigation induced. It is in these specific areas that pumps should be installed. Three different pumping scenarios have been tested with the model. Scenario 1 and 2 simulate the same abstraction rate but with a different distribution of pumps. Scenario 3 simulates an increased abstraction rate. *Fig. 3.2.10-3* plots the development of phreatic evaporation in time for all three scenarios. Within only 5 years, phreatic evaporation drops rapidly for all three scenarios. The downstream resources are increased by up to 20%.

The model showed how the Yanqi basin can be managed in a more effective way without reducing the present intensity of agriculture. The partial substitution of irrigation water drawn from the rivers by pumped groundwater helps to reduce the phreatic evaporation and prevents further (or even reverses) soil salinisation. It augments the downstream fluxes up to around 20% and keeps their mineralisation low. However, this comes with the cost of installing and maintaining pumping infrastructure ♦