Sustainable groundwater management - Problems and scientific tools

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Sustainable groundwater management — problems and scientific tools

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Groundwater is a strategic resource due to its usually high quality and perennial availability. However, groundwater management all over the world often lacks sustainability as evidenced by falling water tables, drying wetlands, increasing sea-water intrusion and general deterioration of water quality, As groundwater cannot be renewed artificially on a large scale, sustainable management of this resource is vital. A number of scientific tools are available to assist in his task. Three items are discussed here. They include methods for the determination of groundwater recharge, groundwater modeling including the estimation of its uncertainty, and the interfacing to the socio-economic field. Generally the quality of water management work can be largely enhanced with new tools available, including remote sensing, digital terrain models, differential GPS, environmental tracers, automatic data collection, modeling and the coupling of models from different disciplines

Introduction

Ground water contributes worldwide about 20% of people's fresh water. Despite this relatively small proportion its role is important for two reasons: On the one hand, ground water is well suited for the supply of drinking water due to its usually high quality. On the other hand, ground water basins are important long-term storage reservoirs, which in semi-arid and arid countries often constitute the only perennial water resource. The storage capacity is evident if one compares the volumes of surface and ground water resources. Globally the volume of fresh water resources in rivers and lakes is about 100,000 km^3. With about 10,000,000 km^3, the volume of ground water is two orders of magnitude larger (e.g. Gleick, 1993, Postel et al., 1996). For sustainable water management, however, the renewal rate is more relevant, and for this quantity the situation is reversed. The renewal rate of surface water resources is 30,000 km^3/a, that of ground water only about 3,000 km^3/a. Worldwide, about 800 km^3 of ground water are utilized by mankind annually. This number still looks considerably smaller than the yearly renewal rate. However, the global comparison does not do justice to the real situation. Average figures hide the fact that of the yearly withdrawal rate about one quarter is supplied by non-renewable fossil ground water reserves (Sahagian et al., 1994).

Similarly, in a globally averaged analysis the average pollutant concentrations of ground water become negligible. The natural balance unit for water resources is the catchment of a river, a spring or a well. And on that scale things look very different on a case-by-case basis. Ground water resources are degraded in the long term by overpumping and pollution, and the local and regional utilization of ground water is impaired or even has to be abandoned. As ground water cannot be renewed artificially on a large scale its non-sustainable use is a serious danger. This will be illustrated in the following with various examples.

Sustainable water management

For an assessment of the ground water situation in a catchment, a definition of sustainable resource utilization is necessary as a starting point. In the following we will define it as a set of management practices, which avoids an irreversible or quasi-irreversible damage to the resource water and the natural resources depending on it such as soil and ecosystems. Such management allows the resource water to extend its service, including ecological service, over very long periods of time.

The abstraction from a ground water reservoir should in the long term not be larger than the long-term average recharge. The storage property of course allows temporary overpumping. As the quantities abstracted may be used consumptively (e.g. by evapotranspiration in agriculture) and reduce the downstream flows, sustainable management with respect to quantity requires that abstraction is limited to a fraction of recharge in order to guarantee a minimum availability of water in the downstream. These principles are violated in many aquifers all over the world.

Overpumping of an aquifer

Steadily falling ground water levels are an indicator of overpumping. A famous example is the Ogallala aquifer in the United States. Up to 1990, 162 km^3 of water above the natural recharge were abstracted from this aquifer. Finally, the pumping had to be reduced drastically as the pumping costs rose to a level which made irrigation with ground water unfeasible (HPUWC, 1998). In Northern China, Eastern India and North- and South Africa ground water levels drop at a speed of 1 to 3 m/yr. The abstractions in the Sahara and in Saudi Arabia empty aquifers, which since the last ice age have not had any recharge worth mentioning. It is estimated that by 2010 the water reserves of the deeper aquifers of Saudi Arabia will contain less than one half of what there was in 1998.

The cause of overpumping is in all cases the large-scale irrigation with ground water. The quantities pumped for drinking water are small in comparison. Globally, the water use in households is only 8% of the total consumption, while irrigation accounts for 70%. In arid and semi-arid regions, the proportion of irrigation in total water use may be as large as 90%.

Long before an aquifer is dried up by overpumping other phenomena occur, which indicate a non-sustainable situation.

Consequences of ground water table decline

Large drawdowns of the ground water table or pressure head lead to increased pumping costs, which will limit pumping rates for economic reasons. But increased cost is not the only consequence of drawdowns. Pressure reduction may lead to land subsidence in soft strata, as happens in Bangkok and Mexico City for example. Long before an issue of water supply develops, the stability of buildings requires the reduction or even halt of ground water abstraction.

If a ground water table is declining too quickly or to a too-deep level the roots of trees relying on ground water (Phreatophytes) may not be able to follow, which leads to their dying off. This is critical in dry areas such as the Sahel, where the loss of the capability of trees to withstand wind leads to an increase in aeolic soil erosion. In wetlands and swamps, in which the visible water table is often a manifestation of a ground water table above ground, a drawdown will lead to their drying up.

Sea water intrusion and upconing of salt water

A special consequence of ground water level decline is shown in coastal areas. Due to the density difference between fresh water on the land side and salt water on the sea side a salt water wedge develops, which progresses inland until the pressure equilibrium at the salt-fresh water interface is reached. Every perturbation of this equilibrium by reducing the fresh water flow will lead to a further progression of the salt water wedge inland, until it eventually reaches and destroys the pumping wells. Sea water intrusion is notorious along the coasts of India, Israel, China, Spain and Portugal, to mention just a few. In the Egyptian Nile Delta, the zone where ground water quality is impaired by sea water, reaches up to 130 km inland. On islands in the sea the fresh water lens formed by recharge from precipitation is often used for drinking water supply. In this situation the drawdown due to pumping can cause a rise of the salt-fresh water interface (upconing). If the interface reaches the well, the well has to be abandoned.

Similarly, saline water from salt lakes (Chotts) in Tunisia and Algeria, in the vicinity of which ground water is pumped, can be attracted to the wells. A ground water level decline inland can lead to the rise of saline water from underlying aquifers. This tendency is seen in Brandenburg, Germany. It can also not be excluded in the Upper Rhine Valley.

Degradation of ground water quality

The discussion of seawater intrusion shows, that the definition of sustainability must include both quantity and quality aspects. The available resources are diminished by pollution. Sea water intrusion is certainly the most widely spread pollution of ground water worldwide. It is followed by pollution by nitrates and pesticides from agriculture. In industrial areas, chlorinated hydrocarbons and mineral oil hydrocarbons are still the main problem.

Ground water pollution is in principle not irreversible. In the case of sea water intrusion, a diminishing or abandoning of abstractions will in the long term let the system return to the original state. In other pollution cases eradication of the source will lead to cleaning up within the typical renewal time of the resource. But this time span may be so long that the aquifer cannot be used for drinking water purposes for several generations, or alternatively money has to be spent on the processing of this water to make it suitable for drinking.

The experience of industrialized nations shows that aquifer pollution is a lengthy affair even if active remediation measures are taken. The remaining option of treating the water to bring it up to drinking water quality is not available for small and decentralized ground water users in the third world.

Soil salination

A further non-sustainable practice, which must be mentioned here due to its connection with ground water, is soil salination. It is caused by too high ground water tables. If in arid climates the ground water table rises (e.g. due to irrigation) to a distance of 1 to 2 m below the ground surface evaporation of ground water through capillary rise starts. The dissolved salts precipitate and accumulate in the topsoil, finally leading to infertility of the land. In regions with very small gradients and little permeable soil, this problem can usually not be solved by artificial drainage. Of the irrigated 230 Mio. ha agricultural land worldwide around 80 Mio. ha are in one way or the other afflicted by soil salination.

Soil salination is not irreversible, but the time spans for rehabilitation of the soil can be very long. Soil salination is a problem in all irrigated areas. Strongly affected countries are Iraq, Egypt, Australia, the USA, Pakistan and China, to mention only a few.

Scientific methods

The implementation of water resources management strategies is in the end a political and economic question. Still, in the analysis of sustainability and the search for solutions, modern methods of water research can make a contribution. Three areas are discussed further:

1. The quantification of ground water recharge
2. The use of ground water models including the estimates of uncertainty; and
3. The incorporation of economical aspects of sustainability

Determination of ground water recharge rates

Ground water recharge is the most important parameter for sustainability in arid and semi-arid regions. Despite that fact, it is not yet possible to measure this important hydrological quantity with sufficient accuracy. Recharge is not directly measurable, and indirect methods introduce various uncertainties. To make things worse, rain and recharge events in dry climates are of an extremely erratic nature. Integral methods such as the Wundt method, based on low flow analysis of rivers are very useful in humid climates, but do not work in arid zones, where the low flow is usually zero. The method of hydrological water balance is notoriously inaccurate: In the long-term, average and under neglect of surface runoff recharge is the difference between precipitation and evapotranspiration. As these quantities are both of the same magnitude and inaccurately known, their difference is even more inaccurate. Only if long time series of balance components are available is the balance method feasible, as in this case systematic errors accumulate, and can be identified as such.

The methods based on Darcy's law, in which the flow Q through an aquifer cross-section is computed from the cross-sectional area A, the hydraulic conductivity K and the hydraulic gradient I as

$$Q = A*K*I \qquad (1)$$

are very inaccurate, as it is extremely difficult to find a representative effective value on the large scale for the usually abnormally distributed hydraulic conductivity K.

Both methods can easily be a factor of 10 to 50 off. Better estimates can be obtained at least in sand-gravel aquifers using environmental tracers. The classical tracer for recharge estimation is Tritium from the nuclear bomb experiments in the 1960s. The atmospheric peak of those years reaches the springs and pumping wells with a delay. The interpretation of the concentration observed in the well requires a model for the residence time distribution in the aquifer. Often, simple black box model concepts are used. In the simplest case a plug flow is assumed. If more information on the geometry of the aquifer is available, more realistic residence time distributions can be derived by means of numerical ground water flow models, which are able to take into account a more realistic aquifer structure. It has to be remembered however that the interpretation leads to pore velocities and not specific fluxes. Both are connected by the effective porosity, a quantity, which in sand gravel aquifers is reasonably well known and much less variable than the hydraulic conductivity.

In principle, every non-reactive trace substance in the atmosphere with a well-known concentration history and distribution can be used in a similar fashion as Tritium. This is of great interest, as the Tritium peak has lost much of its usefulness by decay. A new group of tracers are the freons and SF_6, the atmospheric concentrations of which have been growing exponentially since the middle of the last century. The freon concentrations have been stagnating or declining for the last few years due to the ban on their production. These molecules are however not a complete replacement for Tritium, as Tritium moves as part of the water molecule, while freons as gases diffuse much faster through the unsaturated zone and only in the ground water are they transported with the velocity of the water in which they are dissolved.

In Southern Botswana we used freon tracers for a crude test. In this desert-like region one can occasionally find fresh water in the middle of a very saline environment. The question is now whether this water has been formed recently or whether it is a just a nest of fossil fresh water, which would not survive a prolonged pumping test. Freons were found only in wells in which another method — the chloride method — which is described below, also indicated relatively large recharge. But while the chloride method cannot say anything about the time of recharge, the presence of freons confirmed that these aquifers have had recent recharge, and pumping them makes sense.

In combination with its decay product Helium-3, Tritium can be employed as a stop watch. The ratio of the concentration of both isotopes allows a direct age determination over a time of up to 40 years. In the beginning, there is no Helium-3 as long as it can escape as gas to the atmosphere. As soon as a water drop reaches the saturated zone, Helium-3 can no longer escape, and is enriched relative to Tritium. This method is independent of source strength. Corrections are necessary due to oversaturation of ground water with air and possible inputs of Helium from mantle and crust (Schlosser et al., 1989).

Stable isotopes such as oxygen 18 and Deuterium can also yield information on recharge and relevant processes. Their concentration in water is determined by phase transitions. In the project in Botswana we could have, for example, very reliably determined the proportion of water in a well coming from the nearby river or from the native ground water as the river water has a clear evaporation signature. Stable isotopes can be employed as mixing tracers as well as transient tracers. For very old water, carbon 14 can be used as an age tracer. The progress in mass spectroscopy will in future make many more tracer groups available for hydrology e.g. isotope ratios of rare earths or metals.

A method often employed successfully in arid regions is the chloride method. This method uses the deposition of wind-blown sea salt aerosol. The resulting chloride concentration in soil water increases by evaporation and transpiration. If the surface runoff is negligible, the concentration increase is proportional to the evapotranspiration rate and the recharge rate can be derived from

$$R = (c_P * P + D)/(c_B) \qquad (2)$$

where c_P is the chloride concentration in rain water, P the precipitation and D the dry deposition of chloride. c_B is the chloride concentration below the zero upward flux plane. It can be approximated by the concentration in shallow ground water. The method requires the long term observation of wet and dry deposition of chloride, and of course there must not be any other source of chloride such as evaporates in the subsoil.

Contrary to the inaccurate large-scale water balance methods, the chloride method yields more accurate but very local estimates of recharge rates. Because of this complementarity a combination of the two methods is promising. In northern Botswana the difference between precipitation and evapotranspiration was determined using satellite images over 10 years (Brunner et al., 2002). This difference indicated a recharge potential. The precipitation can be obtained from METEOSAT data, and the evapotranspiration can be estimated from NOAA-AVHRR data using for example the SEBAL algorithm (Bastiaanssen et al., 1998). The result (on the basis of 97 utilizable NOAA images) its shown in Figure 1. While the numerical values themselves are unreliable the pattern is stable, and shows up every

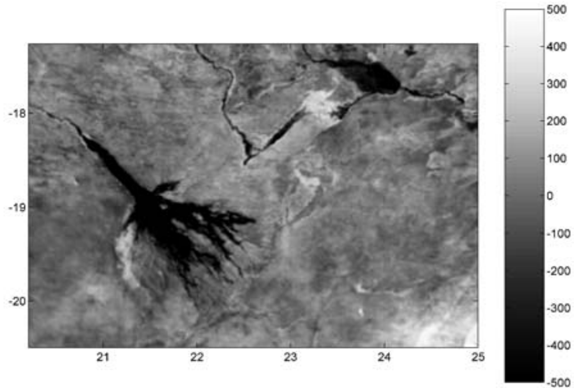

Figure 1 10-yearly mean of the difference between precipitation and evapotranspiration in (mm/a) from remotely sensed data.

year in similar fashion. This can be proved by principal component analysis. The spatial information from satellite images therefore already allows a more realistic spatial distribution of recharge than would be arrived at with the assumption of homogeneity over the whole region. But the absolute value must be adjusted, and it can be obtained from an average of all chloride values of the region. That this procedure makes sense can also be seen from a comparison of recharge rates obtained from remote sensing data and the recharge rates obtained from well clusters in the same pixels. These show a correlation coefficient of about 70%. The correlation can be used to calibrate the recharge map obtained from remote sensing. It is encouraging to see that the sub-region with the highest computed recharge rates is also the region with the highest observed ground water levels.

Generally, remote sensing, be it from an airplane or a satellite platform, opens up new avenues for water resources management especially in large countries with weak infrastructure. Local hydrological research can be interpolated and completed into more areal data sets. Generally, remote sensing data are always of interest if they allow reduction of the degrees of freedom of a model by an objective zonation of the whole region considered. We use satellite images not only in the determination of precipitation and evapotranspiration; from the vegetation distribution and the distribution of open water surfaces after the rainy season hints of the spatial distribution of recharge can be abstracted. Multi-spectral satellite images can show the distribution of salts at the soil surface. For large areas, the GRACE mission will allow the contribution of soil water balances calculated from variations in the gravitational field of the earth. New developments in geomatics allow us to obtain accurate digital terrain models on small scales from laser scanning or stereophotometric methods and on a large scale from radar satellite images. In both cases, checkpoints on the surface are required which can be obtained with differential GPS. Digital terrain models are important in all cases where the distance to ground water table or a flooded area at varying water surface elevation play a role. The combination of remote sensing, automatic sensors with data loggers, GPS, and environmental tracers in combination with the classical methods of hydrology and hydrogeology allows us to introduce into water resource studies a new quality, especially in those cases in which in earlier times lack of infrastructure and poor accessibility were limiting.

Ground water modeling

Modeling is indispensable in the field of ground water, as in the geosciences in general, as the accessibility of the objects of study is very limited. Because of the rather slow reactions of a ground water system to changes in external conditions, a tool for prediction and planning is necessary. Ground water models allow us to bring all available data together into a logical holistic picture on a quantitative

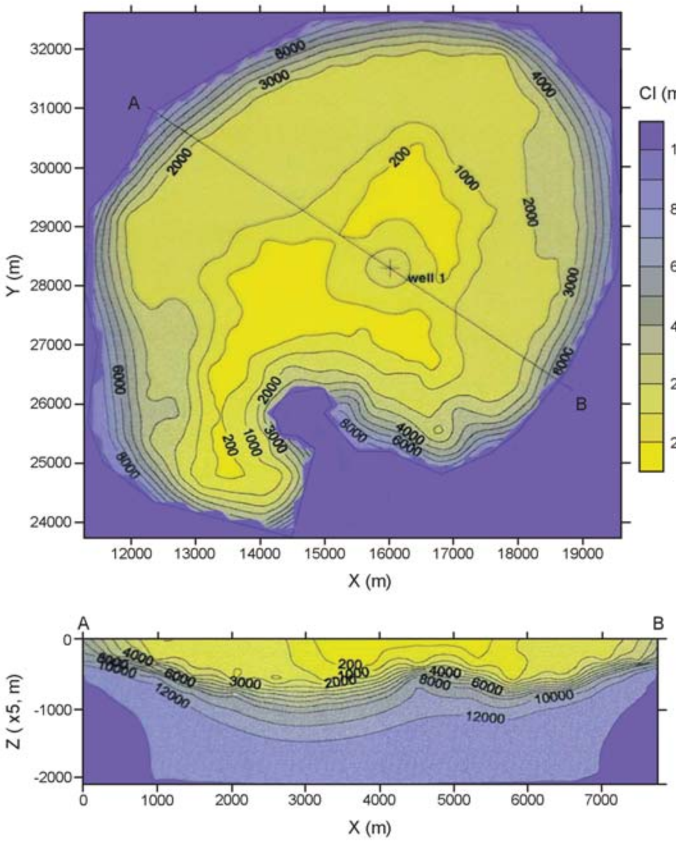

Figure 2 Computed horizontal and vertical distributions of the freshwater lens under Weizhou Island (In the vertical section the upconing caused by the central well is visible).

basis. As the first step, the system with all its dominant processes must be understood. In this calibration phase observation data are integrated and parameters identified. Only a calibrated model can be utilized for predictions. In the prognostic application the strength of models lies in the ease with which scenarios can be compared to each other. Finally, the integrative effect a model can develop in a project should not be underestimated. It forces the participants to undertake disciplined and goal-oriented cooperation.

An example of a model application done in cooperation with Chinese colleagues is given in Figure 2 (Li, 1994). A ground water model is used to study the sustainability of ground water abstraction. On the island of Weizhou, off the South China coast, an increase of ground water pumping for the extension of tourism is planned. About a third of the available recharge is required for the additional water supply. In principle, shallow or even horizontal wells would be advisable in order to avoid saltwater upconing. But due to the unfavorable conductivity of the upper strata, the fresh water lens on Weizhou is best pumped in a deeper aquifer layer. If the pumping is concentrated in one well, within a few years, the salinity of the pumped water becomes unacceptable due to saltwater upconing. If the pumping is distributed over two wells at a 4 km distance, an acceptable final salinity is reached. It the pumping rate is distributed over four wells sitting on a square with side length 1 km, the chloride concentration stays below 200 mg/l all of the time (Figure 3). The model in this case allows us to find a technical solution to the problem, as the total pumping rate stays well below the total recharge. If the pumping rate is higher than total recharge the best model in the world can not find a pumping strategy that avoids salt water intrusion.

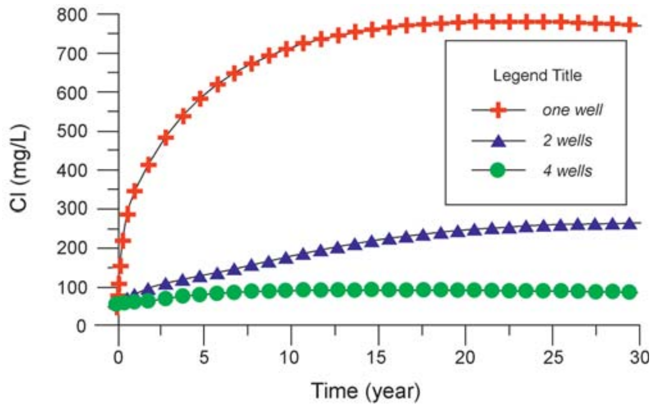

Figure 3 Development of chloride concentration in the pumping wells for different configurations of wells with the same total abstraction rate.

Despite the widespread use of models, care is advisable. Models are notoriously uncertain, and their prognostic ability is often overestimated. The necessary input data are usually known only partially or only at certain points, instead of in their spatial distribution. Lacking input parameters have to be identified during calibration, which, as a rule, does not yield a unique solution. Ground water models are usually overparameterized, and good model fits are feasible with different sets of parameters, which in a prognostic application of the model however would yield different results. A responsible use of models acknowledges their uncertainty and takes it into account when interpreting results. For the estimation of model uncertainty, several methods are available today, which go far beyond the classical engineering philosophy of best case-worst case analysis. The spectrum of stochastic modeling methods contains error propagation, as do Monte Carlo simulation and many others.

Let us look for example at the often-used formula (1) which estimates the flow through an aquifer cross-section with Darcy's law. None of the three factors is known exactly, and would therefore be considered a stochastic variable with uncertainty. The hydraulic conductivity for example is usually lognormally distributed and even if we know the value of this variable at several points in the aquifer the spatial average value estimated from those still allows for a considerable estimation variance. The measured hydraulic gradients are also not exact numbers, not so much due to the measurement accuracy of the dipper, but due to inaccuracies in the leveling of the well and temporal variations of heads. Finally there is some leeway in the cross-sectional area, which might be obtained from a geophysical method. The product of three stochastic variables is again a stochastic variable into which the uncertainties of the factors propagate. In a numerical model this process takes place in every cell of the discretized model domain, as every flux across a finite difference cell for example is also calculated by (1). It is therefore advisable to show modesty when heading towards prognostic use of models. How a

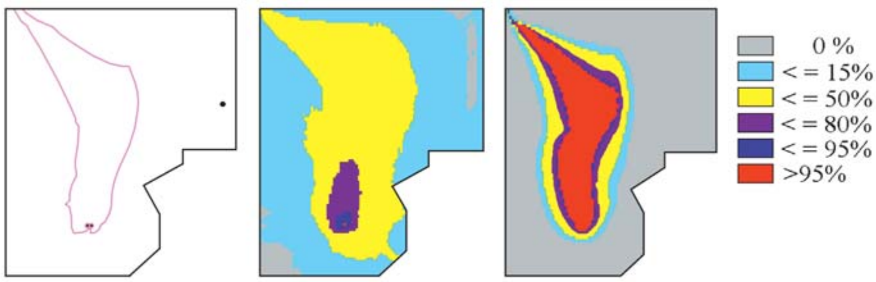

Figure 4 Catchment area of a well: deterministic and stochastic approaches, a) Result of deterministic modeling, b) Unconditional stochastic modeling, c) Stochastic modeling with conditioning by 11 long term observed heads.

more appropriate stochastic procedure could look like is discussed with the example of the determination of catchment areas of wells (Vassolo et al., 1998, Stauffer, et al., 2002).

It is reckless to draw the catchment of a well by a precise line, as shown in Figure 4a. It will never be possible to determine a catchment with this precision. A stochastic approach calculates all catchments which result from parameter combinations within the uncertainty limits of the parameters (e.g. transmissivities of n zones and recharge rates of m zones). In the simplest procedure, this is possible by sampling the parameter combination from the individual distributions. Then, for each set of parameters a catchment is computed, yielding a set of catchments which can be analyzed for their statistical properties. By superimposing all catchments, every point on the surface can be assigned a probability of belonging to the real catchment of the well. This distribution is usually rather broad (Figure 4b). It does not yet take into account measured data for state variables such as heads, spring flows or tracer concentrations. Through this information the distribution can be conditioned. Only the subset of catchments is selected which is compatible with the observations. Incorporating 11 long-term observation data of piezometric heads the distribution of Figure 4b is narrowed considerably (Figure 4c). This is the typical way we gain knowledge in the earth sciences. In the beginning, almost everything is conceivable. Measurements allow us to filter the realistic cases which are compatible with the data from the set of imaginable cases. This procedure corresponds to the Bayes principle. From an a priori distribution, an a posteriori distribution is obtained by conditioning with data. Data are valuable if they lead to a reduction of the width of the stochastic distribution. To be fair, it has to be mentioned that stochastic modeling needs data to yield reasonably narrow distributions. These data are however of a slightly different nature than usual. What is required besides the usual scarce observation data of state variables are distribution characteristics of parameters.

The usefulness of models need not suffer from the admission that they are uncertain. The resource engineer is not interested in every detail of nature; he wants to propose a robust solution which will function also if the underground does not exactly look as anticipated. For this type of decision the stochastic approach is adequate. It allows even the quantification of the risk to take a wrong decision.

Socio-economic aspects

Decisions on sustainability take place in the economic-political sphere. Models are therefore more useful the more they manage to interface with socio-economic aspects. The aquifer exploitation problem is a typical common pool problem. Consider the situation of n users of an aquifer, which receives a total recharge Q_N.

As long as the pumping rate of the n users is smaller than Q_N, the difference between recharge and consumptive use will flow out of the basin to a receiving stream. It is clear that in the long term the total abstraction cannot surpass the recharge rate. Sooner or later, the abstraction has to adapt to the availability of water. It is however wise to get to that equilibrium at an early stage, i.e. at a relatively high water table. First, the higher water table allows larger short-term overpumping to overcome a drought, for example. Secondly, the higher water table reduces the specific pumping cost for all users. If every user goes for a large drawdown and a deep well, all users will in the end have to shoulder higher specific pumping costs. Ground water is a resource which rewards partnership and punishes egotism. Negri showed (Negri, 1989) how a collective decision in the common pool problem leads to a better solution than the sum of all independent, individual decisions. In the soil salination problem, the situation is similar, only with the opposite sign in the water table change. All irrigators infiltrate water and cause the ground water table rise. At a depth to water table of less than 2 m, the already saline ground water starts to evaporate, leading to rapid salinization. Collective self-restraint will again lead to a better solution. The soil salination problem in the Murrumbidgee Irrigation District in Australia is of this type. The irrigation of rice leads to considerable percolation, and results in ground water table rise. If the present practices are continued, up to another 35% of the arable land could be salinized before an equilibrium between the input of irrigation water from the river, the outflow from drains and the output by evaporation is reached. With model calculations it has been shown (Zoellmann, 2001) that reducing the rice growing area by one half will basically halt the salination process at present levels. Figure 5 shows a comparison between the ground water table rise after 30 years for the present rice growing area and for a 50% reduced rice growing area.

In a project of our institute in Xinjiang, China, it was investigated how far the pumping of ground water for irrigation could keep the water table at a suitable depth in order to prevent salination. Again, this is primarily an economic problem, as the pumped ground water costs about 10 times as much as river water, which has been used exclusively up to now and which has led to considerable ground water table rise. The choice of the system boundary for optimization is crucial. If downstream ecological benefits are taken into account, the higher cost of ground water may be bearable.

The soil salination problem illustrates another basic economic aspect. If one applies the classic economic principle of optimizing discounted net benefits, the discount rate plays an important role. At a discount rate of 5%, costs and benefits in 40 years' time are already so small that they have no impact on the optimization. The short-term gain has much more weight. For slow processes such as salination, the time scale of which can be easily 40 years or more, the usual economic optimization is unable to take those future penalties into

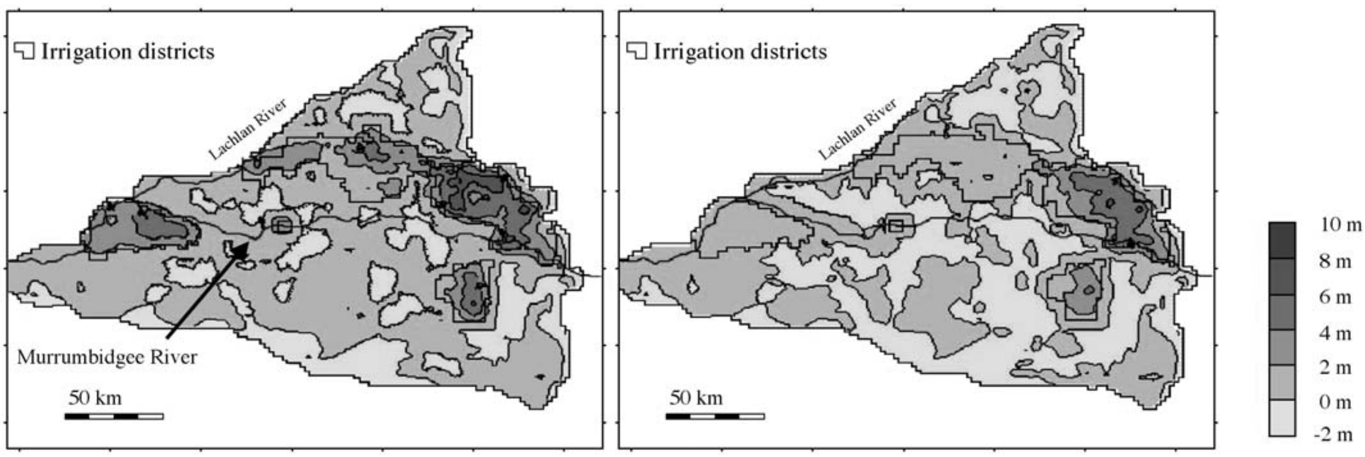

Figure 5 Modeled groundwater table rise over 30 years in Murrumbidgee Irrigation District, Australia, a) at present rice growing area, b) at 50% reduction of rice growing area.

account. Alternatives to the classical optimization are required which give a greater value to the future, e.g., by constraints on the final value of the agricultural land and its salinity. Of course the state can repair this deficiency by regulations, which enter the optimization problem as constraints.

Conclusions

The sustainable management of aquifers is a burning problem in many countries. New scientific tools can assist in its solution, both in the analysis of whether the present management is sustainable and in the definition of strategies and measures to achieve sustainability. Models will always play a role in this task. A new model generation can use new data sources such as environmental tracers, remote sensing data and geophysical data. It must however not only simulate an average deterministic situation but also analyze the uncertainty of its predictions by a stochastic approach in order to remain credible. Finally, the natural and engineering sciences have to interface much more with economics and politics to be of real practical use.

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Peter Bauer *is developing model concepts for the sustainable water management in the Okavango Delta, Botswana. He received his Diploma at the Swiss Federal Institute of Technology thesis in 1999.*