6th International Conference on Water Resources and Arid Environments (ICWRAE 6): 256-265
16-17 December, 2014, Riyadh, Saudi Arabia

Managing Overpumped Aquifers - A Road to Sustainable Water Use

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Abstract: The most visible sign of unsustainable water use is the overpumping of aquifers. About one quarter of groundwater pumped worldwide is not replenished by recharge. Falling groundwater tables do not only increase the energy needed for pumping, they also diminish the aquifer's capability to buffer drought years, lead to decline of base flows in streams and possible degradation of water quality. Despite the energy cost, groundwater is a convenient resource available year round and at the point of use. While surface water is easily controlled at a reservoir outlet, groundwater pumping wells are so numerous that control is a challenge. The main obstacles to rational management are wrong incentives, lack of transparent fee systems and lack of real sanctions. We suggest that modern technology combined with drought insurance provides a vision towards a solution. An example from China illustrates that vision.

Key words: Groundwater depletion ・ Groundwater management ・ Drought mitigation ・ Optimal control

INTRODUCTION

Worldwide Situation: In arid and semi-arid regions, agriculture is only feasible with irrigation. Contrary to surface water, groundwater is available all year round, which has made it more and more attractive for agricultural water users to guarantee reliable yield. Groundwater extraction has tripled over the last 50 years [1] and severe overpumping of aquifers has become common worldwide. Groundwater as an open access resource is prone to the "tragedy of the commons", a phenomenon by which each user pumps egoistically regardless of the others, depleting the resource collectively to everybody's detriment in the end. Defining a sustainable pumping rate is not easy. We will for simplicity define the sustainable yield of an aquifer by its recharge both natural and induced [2], although in reality only a fraction of that amount can be safely pumped due to downstream commitments. Present global groundwater extraction is about 1000 km^3/yr, of which 67% are used for irrigation, 22% for domestic water supply and 11% for industry [1]. Wada *et al*. 2010 [3] estimate that unsustainable groundwater depletion is about 280 km^3/yr (in 2000), up from 126 km^3/yr in 1960. The global distribution of regions where irrigated agriculture is not sustainable at present levels of groundwater withdrawals is shown in Fig. 1 [4]. The depletion of aquifers over the last 10 years has been so substantial that it can be seen in changes of the gravitational field of the earth, as it is measured by the satellites of the GRACE mission. Figure 2 (taken from [5] shows the changes in the earth's gravitational field between 2003 and 2009, which are mainly due to changes in water storage. Blue areas are areas with increases in water storage while red areas indicate loss of water, mainly snow and ice in mountains and the North Polar Region, but also water from aquifers as is visible for example in the Ganges plain, in the North China plain and Spain. (Of course oil, coal and ore abstractions of sufficient size will also show up in a gravitational change). The consequences of aquifer depletion are manifold. The possibly most important one is the loss of buffer capacity. Aquifers can store water over many years and are therefore particularly well suited for mitigation of droughts, even over prolonged periods of time. Farmers are well aware of this and increasingly turn to groundwater pumping to mitigate droughts and heat waves. A recent household survey in China [6] shows that drilling new wells accounts for 33% of engineering mitigation measures taken. To be available for drought mitigation aquifers must however be allowed to recover in times of above-average rainfall. Only under strict management, aquifers will be able to serve as storage for drought relief. A rational practice is conjunctive use of surface water and groundwater: While surface water is

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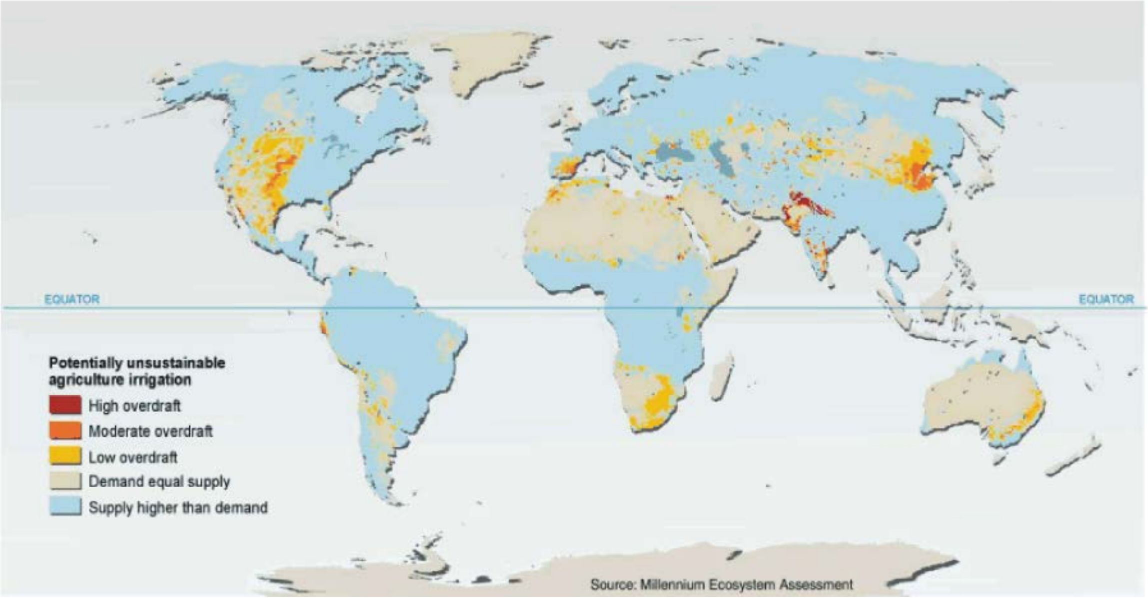

Source: Millennium Ecosystem Assessment

Fig. 1: Regions with potentially unsustainable agricultural irrigation due to overexploitation of groundwater resources [9]

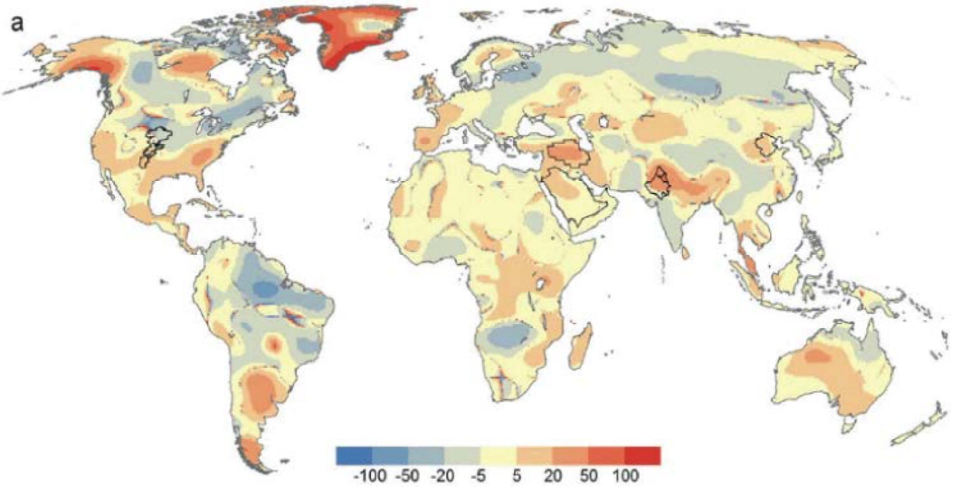

Fig. 2: Change in water storage 2003 to 2009 as observed by GRACE (average of 3 interpretations) given in [6] (Units mm/yr, blue increase, red decrease of storage)

available, groundwater is allowed to recharge, in order to be able to take over at times, when surface water is not available. Over-abstraction of groundwater translates to falling groundwater tables or piezometric heads. With falling groundwater levels the energy cost of pumping increases. Larger declines of groundwater levels reduce the transmissivity of an aquifer and thus its yield, which may have the consequence that the time for pumping up a required amount of irrigation water with existing wells will be considerably prolonged [7]. The first aquifer in the world, which has seen large numbers of farmers turn away from groundwater irrigation for economic reasons, is the Ogallala aquifer in Texas, US. Its development shows a scenario how economic forces could eventually regulate overpumping [8]. However, before economic forces lead to a new equilibrium, many other negative consequences of overpumping arise. Falling groundwater levels lead to drying up of groundwater fed stream, lakes and wetlands. Pressure drop in clay layers prone to settling, leads to land subsidence, a phenomenon seen worldwide, with Mexico City being an iconic case. While the concerns about water quantity are usually in the focus of the sustainability discussion, the deterioration of groundwater quality due to overpumping is possibly the

Fig. 3: Map of China with locations of the 3 illustrative cases

even more serious long term threat. In coastal aquifers overpumping leads to sea water intrusion, but also inland large abstractions cause mobilization of saline water contained in underlying or overlying strata.

Current Situation in China: No comprehensive study of China's groundwater resources has been published yet. We therefore take 3 regions for illustrative purposes. These are the North China plain, the Shiyanghe river basin and the Heihe river basin. Their geographic positions are shown in Fig. 3.

In the past 40 years the aquifers in the semi-arid North China plain have been severely over-exploited. In some places water tables dropped continuously at a speed of 2 meters per year. The natural flow system, in which water is recharged from the mountains and in the plain and discharged towards the sea, has been reversed in both the lower and the shallow aquifer layers due to the formation of deep cones of depression in heavily exploited areas [9, 10].

The overexploitation is primarily a consequence of the intensification of agriculture in an effort to feed a growing population. While the natural precipitation in the North China plain of 500 to 600 mm/a is sufficient to support one grain crop per year under average rainfall conditions, the double cropping of mainly winter wheat and summer maize (with a combined evapotranspiration of over 1000 mm/a) can only be sustained by the depletion of groundwater resources. The situation has been aggravated by the fact that annual precipitation has decreased by 14% over the last 5 decades. The North China plain contributes 40% of China's grain production including two thirds of total wheat output [11]. A conflict between China's self-sufficiency in grain and sustainable agricultural production is apparent, which is hard to solve unless the nation changes its food security policy. The South North Water Transfer will provide additional water, but - due to its high price - exclusively to households and industry, replacing their groundwater abstraction. This is by far insufficient to bring the aquifer back to balance between recharge and abstraction. There is hardly any other option but changing the cropping system. As rainfall is concentrated in summer, winter wheat is responsible for most of the groundwater overpumping and reduction of this crop seems to be the most efficient demand management measure.

Minqin County is located in the Shiyanghe river basin (Gansu province). It is the first region where a strict groundwater control regime was put into practice in China. The problems started with the building of an upstream dam and irrigation canals in the 60s. Upstream consumptive use of water resources led to unreliable water supply in the downstream communities such as Minqin. As a consequence farmers started to use groundwater in the 70s and with the advent of generally available electricity expanded groundwater use rapidly. Severe overpumping resulted in streams and terminal wetlands falling dry. Despite declining water levels farmers continued to plant high water demanding crops. Salinity was the only criterion for crop choice and wheat could not cope with the salinity. Desertification was widespread. A comprehensive study was carried out between 2005 and 2010 with the purpose of investigating "Replicable integrated water resources management (IWRM) approaches and methods for implementation of the Water Law that respond to stakeholder and beneficiary demands" [12]. After 2005 two main regulation measures were effectively implemented. A total of 3000 wells were closed down between 2007 and 2010, which left 4000 operating wells in Minqin. The well-owning farm groups were offered compensation for the closure of their wells, the sum depending on the year of construction. A water quota of 415 m^3 per Mu (1/15th of a hectare) was set. IC card systems were installed on wells to get pumping under control. The solution was brought about by a combination of the crisis plus some bold measures to reduce pumping. The region is one of the few examples in China, where over-pumping was basically stopped. The reduction of farmland was the key for the solution. The political pressure in this area was high due to the fact that the former Premier is a native of this area and being a geologist himself took a personal interest in reaching the ambitious goals.

Our study area is the Heihe River Basin (Gansu province). The arid climate in the mid-reach of the basin requires full irrigation. Main crops grown are seed maize, wheat, onions and fruit trees. Irrigation water was traditionally provided via canals from the Heihe River with groundwater being a supplementary source of irrigation water in times of low flows. Due to the expansion of irrigated perimeters the consumptive use of river water increased to a degree that the downstream flow was not sufficient to maintain the riverine forests of *populus euphratica*. The terminal lake of East Juyuanhai dried up completely in the 1990s. From 2001 the State Council imposed a minimum residual flow in the stream of 0.9 billion m^3/yr. This in turn led to more groundwater pumping and severe over-abstraction in irrigation districts at the far end of the main irrigation channels [13]. Groundwater table decline in the irrigation district of Luotuocheng is the most severe. This district was chosen as a pilot project in cooperation with the Swiss Agency for Development and Cooperation (SDC) to foster sustainable abstraction, groundwater table recovery and an increase of the region's resilience to consecutive drought years.

Legislative Background: On a national level, the legislative basis for water resources management in China is the 2002 Water Law in combination with the State Council Decree No. 460. Regionally, provincial regulations complement the national legislation. In 2012 the State Council approved the plan of implementing the "Strictest Water Resources Management System", which promotes water consumption control, water use efficiency improvement and water pollution control strategies. In Gansu province there are supporting regulations such as the "Measures and Rules of Gansu Province for Implementing the Strictest Water Resources Management"(2011) and "Measures of Gansu Province for Administration of Water Abstraction Licensing and Water Resource Fee Collection" (2010, amended in 2014). The key element of the regulations is the implementation of a system of permit based water withdrawal and volume based resource fee collection. In the spirit of Integrated Water Resources Management (IWRM), both surface water and groundwater are jointly considered. The total amount of approved water withdrawal in a river basin is limited. According to the document it should on average not exceed the sustainably exploitable water resources in the river basin.

Despite restrictive regulation, implementation of sustainable use in the field is still insufficient. In many places permits exist but allocation volumes are still issued based on estimates of crop type, area and norms irrespective of the basin's capacity. Water quotas are set rather high in Heihe mid-reach (700 m^3/Mu, equivalent to 1000 mm of irrigation water depth). Due to the lack of metering facilities, in most places resource fees can only be collected according to cropping area instead of differentially priced actual consumption. In addition, the expansion of irrigated perimeters has inevitably prevented any progress in curbing the overuse of the resource. It is obvious that under these circumstances monitoring the amounts of groundwater extracted by the large number of small-scale permit holders is already difficult, not to speak of controlling them.

Current Development: Current developments in China clearly suggest that the problem of drought resilience in the face of climate change and resource overuse is increasingly prioritized on decision-makers agenda. Strong efforts are being made to improve the monitoring of both groundwater level and abstraction in order to enhance quantitative assessment of the available resources. Monitoring is the basis for enforcing abstraction limitations and will at the same time help to better understand what quotas are sustainable. A way of control chosen in an increasing number of regions in China is an IC-card system. Pumps can only be operated with a swipe card containing a prepaid amount of water. Prepayment guarantees 100% cost recovery. The irrigation district recharges the cards and keeps book on how much water has been sold for a particular well. By controlling the amount issued to a card the water authority can in principle control the amount of water pumped at any well equipped with the system (Fig. 4).

Fig. 4: Well equipped with IC system (Photo Tobias Siegfried)

Qingxu County, Shanxi Province is an example where the swipe card system worked well and where 70% of farmers were content with it. The volume of groundwater consumed decreased steadily from 59 million m^3 in 2004 to 35 million m^3 five years later. Groundwater levels recovered by 1.6 to 4.8 m in a year [14]. In other places the results were less impressive. In Minqin County mentioned above, a review team of the International Water Management Institute in Colombo studied 3 villages and reported that only very few of the IC card systems were still working [15]. They also reported that the system did not reduce water use as the farmers were not refused a recharge of the IC-card when they needed more water. It is clear that the system is only one component in the chain of control, the other important ingredient for success being an efficient and determined water administration. In our region in the Heihe basin some villages are already fully equipped with IC card systems. Luotuocheng is only partially equipped (40 wells out of 670), but will be fully equipped in the near future. Experience with the first generation of automatic water meters was negative. Mechanical meters were not robust enough and easily tampered with. The second generation relies on measurement of electric energy used and is much more reliable. Measuring the electric energy is not sufficient to determine the amount of water pumped. The proportionality constant between the two quantities has to be established through a pumping test, which has to be repeated annually. Due to the variability of transmissivity and the depth to water table of the aquifer, the volume of water pumped with the same amount of energy can easily vary from well to well by a factor of 10. For reasons of fairness a cubic meter of water should in principle have the same price for everybody. On the other hand, accounting for energy only would make the water in places with large depth to groundwater automatically more expensive than in places with shallow groundwater table and thus lead to the desired effect of pumping less where the cones of depression are deepest. In that sense setting a water price via the electricity fee could be fulfilling the purpose of abstraction control even without metering the volumes. Of course this assumes that the price elasticity of water is already high.

The determination of sustainable quota is difficult when no long term data are available or when the crucial figure for sustainability, the amount of recharge to an aquifer, is not known to any accuracy. In a move to implement the “Strictest Water Resources Management System” the Ministry of Water Resources set the maximal usable water quotas on a national level and distributed it in a top-down approach to provinces, municipalities, counties, townships and water user associations for different sectors. It is obvious that on the local level these figures cannot be used without substantial corrections through studies taking into account local characteristics e.g. of aquifers, ecological water needs etc. Besides a long-term average allocation, annual abstraction plans and dry period allotment schemes are necessary for sufficient flexibility to adapt to year-to-year variability.

Permit holders are in principle required to keep records of water use, to submit annual abstraction summaries and to comply with abstraction plans. As the installation of measurement devices requires capital and knowledge, they will have to be installed by the local water authorities. Financing of the systems is feasible by imposing a “water metering fee” proportional to volume of water pumped. Of course initial seed funds for hardware installation provided by the local administration or institutions such as the World Bank or ADB would be necessary to start the system. The water metering fees could then be set at a level sufficient for serving the loan as well as maintenance, repair and renewal of the system.

Drought Relief Capacity and Value of Storage: One of the most prominent purposes of water resources management is closing the hydrologic deficit by storing water in times of excess and releasing it in times of need. Surface reservoirs offer simple controllability and water flow is gravity driven without any further energy requirement. Evaporative losses may be high for shallow reservoirs in the plain while they are low for reservoirs in the mountains. However, except for the biggest dams in the world, surface reservoirs only allow to buffer supply and demand within a year. Aquifers on the other hand, often offer much larger storage volumes and allow to buffer discrepancies between supply and demand over a prolonged period of several years. Assuming that a well infrastructure cannot be changed (e.g. by deepening wells) there is a physical limit to drawdown given by the limitation in yield. So every meter of water level above that limit is useful storage which can be mobilized in times of need. The decision on how big this storage has to be depends on the drought period one wants to bridge or insure against. Climate change may aggravate droughts while at the same time reducing other water storages such as storage in snow packs. That water storage has an economic value is seen from the fact that groundwater storage and recovery (ASR) schemes in the Southwestern United States ([16]) are financially viable and beneficial for their owners. On a larger scale this means that naturally stored groundwater that can be retrieved in times of need should be even more beneficial to the larger community living on top of their own storage device. One could envisage a coupling of drought insurance with storage management [17]. Discipline in abstraction and fulfillment of water level targets could be rewarded by lowered insurance rates. In China, where drought insurance is subsidized by the state, the state could save on subsidies.

Problems and Ideas to Overcome Them: Three ways of aquifer management are distinguished: In the regulatory approach, rules are given top-down and enforced, in the market approach participants allocate water optimally by free trade and in the self-control approach agents organize bottom up in a participatory way taking decisions in their own hands. While there are reported cases where the market approach has increased efficiency of water use considerably, so far only the regulatory approach has in some cases been able to stop groundwater table decline. The Chinese water administration is organized in a top down approach, which is an absolute must in surface water irrigation systems depending on central reservoirs and their coordinated operation. Contrary to surface water irrigation systems, groundwater does in principle not require any administrative structures for its abstraction, however to prevent the "tragedy of the commons" some top down steering from a water administration is obviously necessary. Water user associations (WUAs) for groundwater have been established in China. So far their influence is small. They provide guidance to well operators who supply larger groups of farmers with irrigation services against payment. Potentially this group of people could be a major instrument in getting groundwater table decline under control. To rely on self-control is risky in China as water theft is common. Water meters are tampered with or destroyed in order to sabotage payment. The elements of prepayment and electricity metering help to reduce fraud. The incentive system for water suppliers is criticized by social scientists. If the salaries of a well operator, a dispatcher at a reservoir gate or even the water authority officials themselves depend on the amount of water sold by them, saving water remains an illusion. A separation of salary and amount of water sold is of paramount importance.

In many cases, overpumping of groundwater, above all in North China Plain, eventually can only be abolished if cropping systems and irrigated areas are adjusted. Changes are, however, only acceptable to farmers if they do not lead to a reduction in incomes. There are two types of vision how this could be achieved: In one variant, farmers produce crops more valuable than wheat or maize on a smaller irrigated area, possibly with water saving irrigation techniques such as drip irrigation in green houses (big plastic tents). In another variant, today's often tiny small holder farms are merged into large farms, which can be operated more economically and with more scientific input. At the same time the reduction of agents in number reduces the problem of well control. Subventions for farmers are common in China as in many other countries. Subvention of water prices does not send the right price signal to induce water saving. Subvention of food increases food waste. More intricate and less disruptive subventions are the subventions for water saving equipment or artificial recharge measures. In the Heihe basin, a substantially higher sustainability score can be reached at very small economic loss. Subventions would only have to cover this small gap. To make a farmer abandon a field, a compensation of 500 Yuan RMB per year and mu would be required. With the usual amount of 500-700 m^3/mu/yr of irrigation water that would amount to a water price of 1 Yuan or less for every m^3 saved. This number should be compared with the price of 10 Yuan/m^3 for water supplied by the South North Water Transfer project.

Vision for Optimal Control: Fig. 5 shows the vision for an optimal real time control scheme of water allocation in a basin. Piezometric heads, pumped volumes, surface water inflows and meteorology are monitored by sensors in the field. All data enter via data transmission (from sensors or data files) to a central data base. The data base is used to feed a groundwater/surface water model which coupled to an optimization routine suggests a small number of optimal or quasi-optimal allocation variants for the decision makers. The decision leads to a determination of quotas for the next season or month, depending on the number of feasible interventions in a season. The quota are charged to the IC cards and applied to the real system.

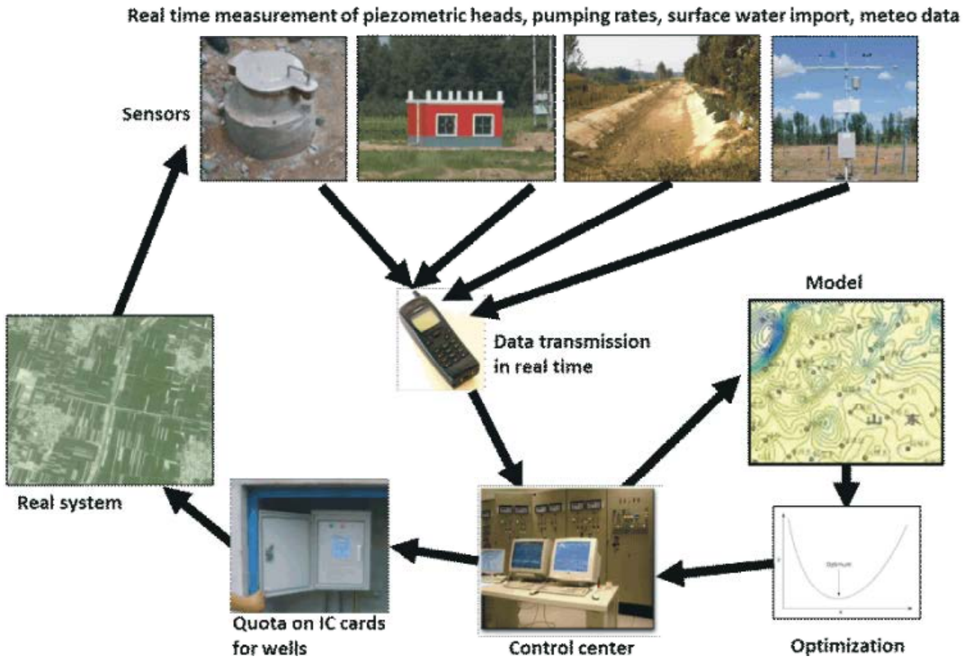

Fig. 5: Vision for optimal real time control

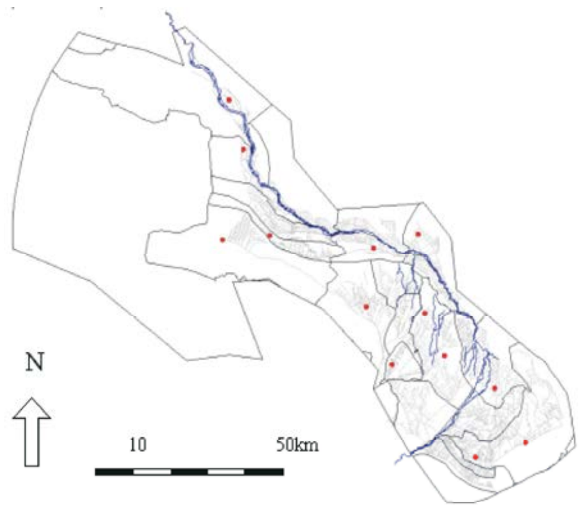

Fig. 6: Irrigation water supply system of the Heihe mid-reach consisting of surface irrigation canals and pumping wells organized in 20 irrigation districts. The red points indicate the location of the observation wells selected for the computation of the head indicator.

The measurement of the reaction of the real system to decisions in the previous control step closes the control loop. Real time measurements serve an additional purpose: By assimilating them the model stays close to reality for the next optimization step.

Case Study Example: Real-time control in the mid-reach of the Heihe River Basin was simulated to investigate the potential for improvement of the spatio-temporal allocation of irrigation water on a sub-basin-scale compared to the present practice. The real system is illustrated in Fig. 6. Conjunctive use of surface and groundwater is considered for 20 irrigation districts on a basis of yearly time-steps. For the exercise it is assumed that all flows are perfectly known in advance. Historical data were used for the optimization. Three indicators representing the impact on the three spheres of sustainability are used: The economic indicator contains the agricultural profit ((I_{profit}) taking into account groundwater pumping cost. The societal indicator stands for the groundwater level at critical points (I_{head}) and reflects the value of storage and societal resilience against droughts. The environmental indicator is the residual flow to the downstream basin maintaining the natural environment of the lower basin ($I_{resflow}$).

The three indicators are aggregated into an objective function *OF* using weights *w* such that their sensitivity is comparable:

$$OF = (1 - w_{res_{flow}} - w_{head}) \cdot I_{Profit} + w_{res_{flow}} \cdot I_{res_{flow}} + w_{head} \cdot I_{head}$$

This function is maximized for optimal allocation. The optimization routine is written in MATLAB R2013a and coupled with a 1kmx1km-grid numerical MODFLOW groundwater model (Fig. 7).

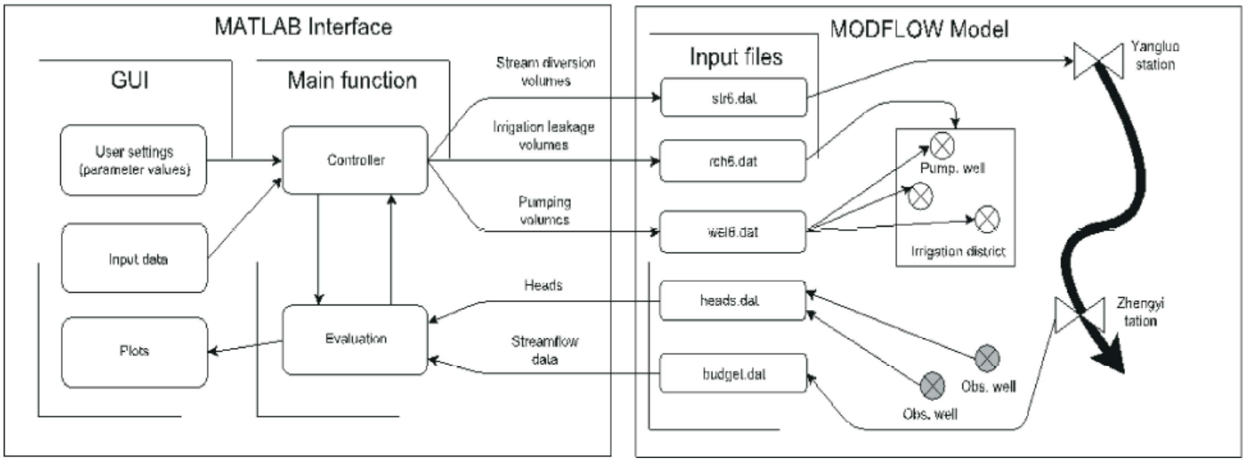

Fig. 7: Coupling of optimization module to groundwater/surface water model

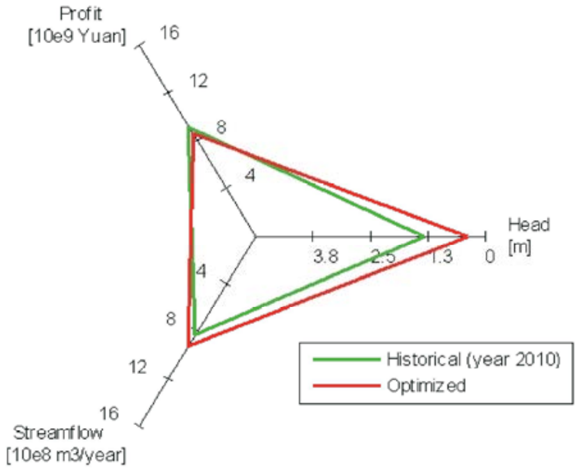

Fig. 8: Spider plot for the year 2010 comparing actual with optimal allocation.

Irrigation is implemented through the well-package, irrigation backflow through the recharge package, the streams are implemented using the stream-package and results are evaluated from the heads and budget files. Surface runoff and natural groundwater recharge can be neglected as the region has an average yearly precipitation of only 130 mm.

The outcomes produced by the optimized allocation are compared to the current allocation scheme for single years and over a period of 10 years using real upstream inflow data. The comparison for a single year (2010) is shown in the form of a spider plot (Fig. 8) and by spatial distributions of the surface and groundwater allocations (Fig. 9a and 9b). The larger the triangle in the spider plot, the better the variant. It can be seen that present allocation leaves room for improvement. For a very small loss in profit a big improvement in the two other indices can be obtained.

The results show that compared to the actual choice in 2010 the controller shifts allocation to a more surface water oriented irrigation practice particularly in districts that currently use predominantly groundwater such as Luotuocheng or Shansan. Generally we note that the controller allocates more water to the districts in the downstream while reducing water allocation to districts in the upstream or further away from the river.

This allocation allows to reduce the drawdowns and slightly augment the stream flow without substantially altering the total profit (Figure 10). The time-series simulation over 10 years using real inflow data illustrates the yearly optimized allocation (red line) as compared to applying the current allocation (of 2010) to every year. We observe that by allowing a small reduction in profit it is possible to substantially increase stream flow, particularly in times of low flow. Drawdown at the observation wells, particularly the critical one, is remarkably reduced.

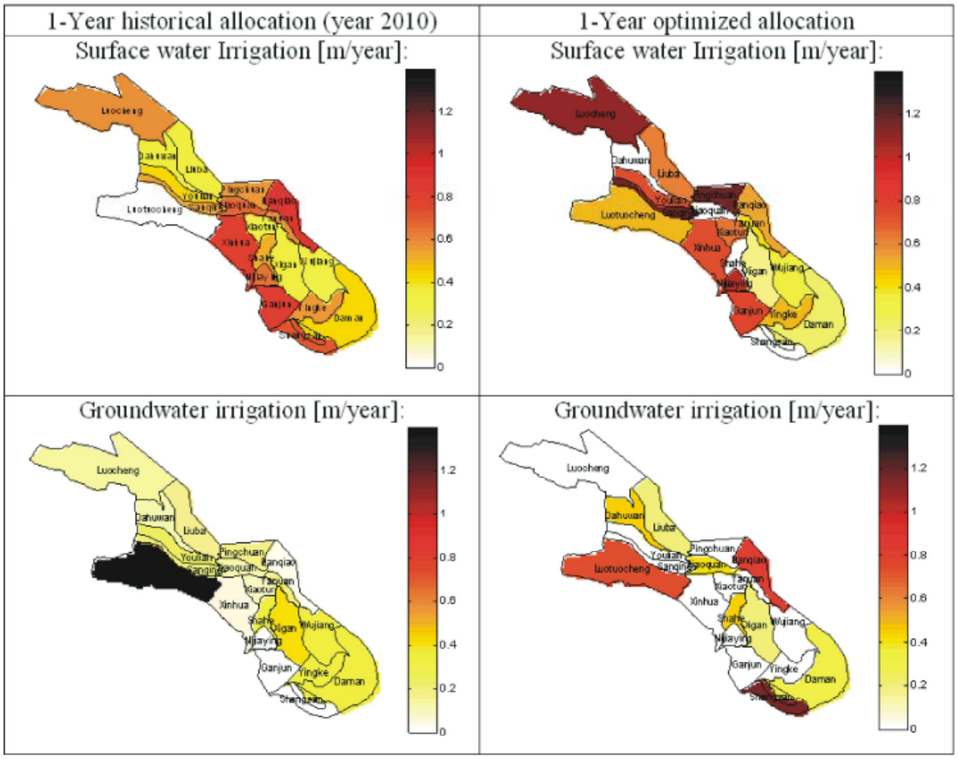

Fig. 9: Spatial allocation of surface water (a) and groundwater (b): Actual allocation (left) and optimal allocation (right)

Time series 2010 allocation rule (blue) vs. optimized allocation (red)

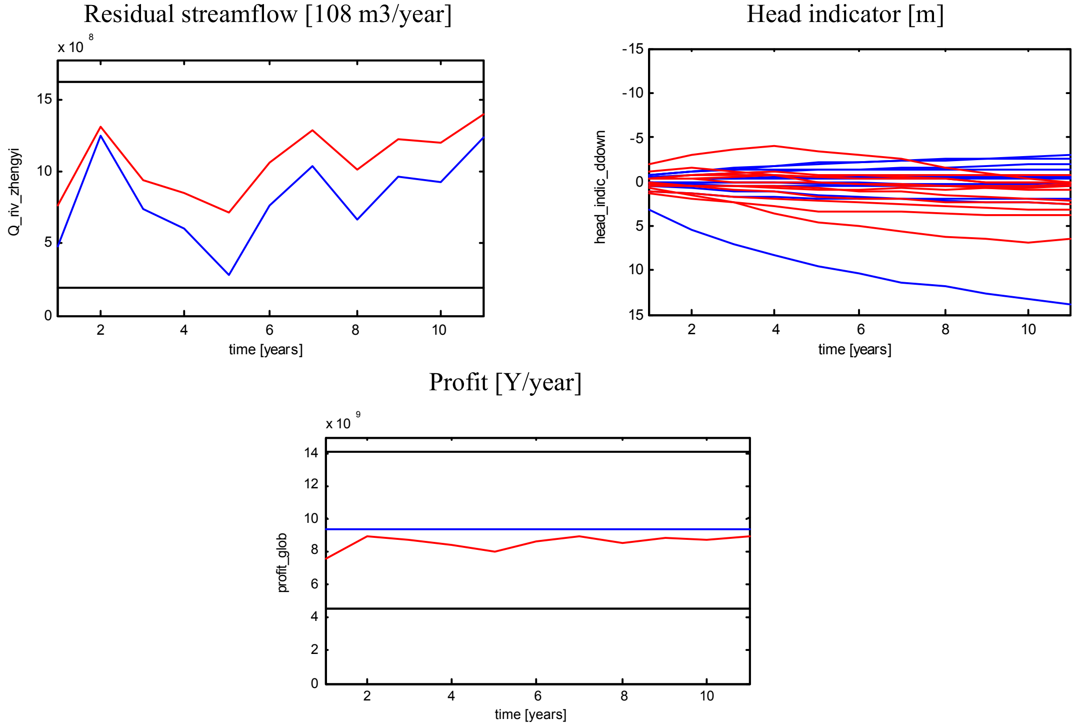

Fig. 10: Results of optimal control over a period of 10 years: Development of profits, residual flows to downstream and groundwater heads (heads shown for all control points)

CONCLUSIONS

Any overpumping of aquifers will eventually come to an end by depletion of the resource. Stopping overpumping at an earlier stage may lead to a much more desirable scenario. While irrigation demand has to be reduced, the still feasible agricultural production is much more resilient to climatic variability due to available storage.

Tools for planning optimal allocation tailored to the preferences of a region are available and functioning. The challenge is the implementation. A regulatory approach with close monitoring and sanctioning is the most natural way to go in the Chinese system. Technology for close monitoring both of groundwater levels and pumped volumes is available even in real time or close to real time. The experience gained from existing examples of implementation allows avoiding mistakes and being more efficient in a second generation approach. It must however be noted that there is "no free lunch". Improving ecological and drought risk indicators will cause some loss in income if no changes in the cropping system are made. These losses, however, seem to be acceptably small in the case of the Heihe.

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