Strategic rehabilitation of overexploited aquifers through the application of Smart Water Management: Handan pilot project in China

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Summary

Where quality is not an issue, groundwater is more reliable than surface water supply from existing surface reservoirs and irrigation canals, especially during persistent droughts. However, unlike surface reservoir releases, groundwater abstraction is neither easily monitored nor effectively controlled by local water authorities due to the large number of wells that are not fully equipped with costly registered meters.

This weakness in oversight, combined with pressures to extend cropping, has inevitably resulted in over-abstraction and severe groundwater depletion in arid and semi-arid regions in China such the North China Plain, which has become China's granary. The over-abstraction has a number of serious consequences: It decreases the amount of water stored and thus the ability of aquifers to serve as reservoirs for drought relief. It increases the amount of energy required to lift the groundwater to the surface. It harms aquatic ecosystems by reducing the amount of groundwater discharging to streams (and constituting the streams' base flow) and by drying up wetlands and springs. Finally it leads to land subsidence.

Thus, in northern China where groundwater is intensively utilized, a number of challenges have been identified, such as: increasing gap between fresh water supply and demand in mid and long term; difficulties in groundwater management due to the vast number of unregistered pumping wells with pumping rate of less than 1000m3/d (registering and monitoring all of these wells would require a significant investment); current groundwater metering and monitoring systems of low efficiency.

Confronted with the aforementioned challenges, the project presented here aims at optimizing and controlling the real-time allocation and consumption of groundwater under climate variability. The focus is placed on developing and implementing a real-time monitoring, modelling and controlling system for groundwater management to address climatic variability and to prevent groundwater depletion. The main elements of this smart water system are: (1) automatic monitoring of groundwater levels in observation wells, (2) automatic monitoring of pumping rates of wells, (3) wireless transfer of those data in real time to a control center, (4) a real time model of the aquifer assimilating the data and (5) a method to exert control over the maximum seasonal pumping volumes of wells.

The development and pilot use of the smart water system is done in a typical aquifer sub basin located in coastal Guantao County, Hebei Province, China, which is part of North China Plain. The North China Plain is the site of extremely severe groundwater depletion, exemplified by the significant groundwater level drop under sites of intensive abstraction. The project will pilot a smart water system for the sub basin, which can be scaled up to the whole basin. The implementation of the project allows a comparative approach with different climate conditions, different cropping patterns and intensities farming, and different farming communities.

1. Background and context of the project

1.1 Groundwater overexploitation in China

The vulnerability of China to the impacts of climate change is high. Together with rapid economic and population growth and urbanization, long-term climatic trends have strained China's water resources to an extent that all major river basins in the North and North-West (except for Xinjiang and Qinghai provinces in the far West) are suffering from water shortage. In the past 30 years the aquifers in the semi-arid North China plain have been severely overexploited. In some places water tables have dropped at an average of about 2 meters per year. The natural flow system, in which an aquifer is recharged from the mountains and in the plain and discharged into the sea, has been reversed in coastal areas with seawater intruding into the aquifer (Kinzelbach, 1983; Tang et al., 2007).

The overexploitation is primarily a consequence of the intensification of irrigated agriculture to feed a growing population. While the natural precipitation in the North China plain is sufficient to support one grain crop per year under average rainfall conditions, the double cropping of mainly winter wheat and maize can only be achieved through the over extraction of groundwater resources. The situation has been aggravated by a decline in average annual precipitation by 14% over the last 5 decades, that has reduced the aquifer's recharge. When real-time monitoring and modelling systems are implemented in groundwater management, the over extraction of groundwater can be controlled by reducing irrigation areas, and adjusting the cropping structure. We can grasp the information of the irrigation location with more water consumption, then by using administrative and economic means, we can guide the farmers to reduce irrigation water consumption and indirectly affect the irrigation area and water use (Kinzelbach et al., 2004).

China could function as a laboratory to investigate the implementation of smart water systems application for groundwater use in irrigation, which in future can be transferred to other arid and semi-arid countries. China, as a developing country, faces severe water issues, and despite differences in climatic and economic conditions, the infrastructure and human labor conditions implemented in its water sector approximate those in other developing countries. It is therefore an excellent testing ground for implementation of technologies and rural institutional development aiming at sustainable groundwater allocation and drought mitigation (Li et al., 2014, Yu et al., 2017a).

1.2 Project initiation

In April 2009, a MoU between the Swiss Federal Department of the Environment, Transport, Energy and Communications (DETEC), and the Ministry of Water Resources of the People's Republic of China (MWRC) was signed. Our two partners, the Swiss Agency for Development and Cooperation (SDC) and the Swiss Federal Office of Environment (FOEN) have experience in the field of climate change, water and risk prevention in China. The MWRC and SDC jointly outlined the strategic orientation of the MoU-based project towards a more programmatic approach integrating various aspects of water management and tackling the risks related to groundwater over-abstraction in view of changing climate. In April, 2014, based on the framework, MWRC and DETEC initiated a pilot research project in Hebei Province, China, which concentrates on the rehabilitation and management strategy for over-exploited aquifers under a changing climate.

1.3 Policy Framework of Groundwater Over-Exploitation

This study is primarily aimed at creating control mechanisms to address groundwater over-exploitation. This is one part of a larger effort by the Chinese government, which placed environmental protection and climate change issues, for the first time, in its 12th five-year plan for the years 2011-2015. On January 12, 2012, China's State Council published a guideline to implement water resources management in China called the "Strictest Water Resources Management System". To implement this system, the guideline sets management criteria based on "three red lines" outlined in the approved National Integrated Water Resources Plan 2010-2030 by the Ministry of Water Resources (MWR). The Three Red Lines provide year 2015, 2020 and 2030 targets for total water used, water use efficiency and water quality to guarantee the sustainable development of China. Our study focuses on the first red line, total water used. The total annual water consumption within each administrative area is strictly capped by a fixed quota. One of the greatest challenges to implementing this red line is to control groundwater exploitation. As with surface water, groundwater exploitation limits are set first at the national level, then at the province based on those quotas, and then at the municipal and county level based on the provincial quotas.

In addition, each province is to set a reasonable variation range for the groundwater level. Especially in the groundwater over-exploitation areas, water level should be strictly controlled within this range.

A further push was made in December, 2016, when MWR, along with the National Development and Reform Commission (NDRC) and the Ministry of Housing and Urban-Rural Development (MOHURD) in China, jointly launched the "The 13th five-year plan for water conservancy reform and development", which articulates that the overdraft of groundwater should be strictly controlled and over-abstracting in severe overdraft areas should be diminished by 2020. Comprehensive measures have been implemented to control groundwater overdraft in pilot regions in China including our project site Guantao, such measures include the encouragement of water saving mechanisms in different sectors, increasing the use of reclaimed water, introducing desalinated water, shutting down high water-consuming companies and modifying the cropping structure, reducing irrigation area and other measures to reduce water demand, optimizing the regional water resources allocation and groundwater exploitation layout, replacing groundwater with surface water and conserving groundwater sources.

The project is aligned with the governmental strategies of water use control mentioned above and will translate them into concrete actions. The project aims at developing practical approaches to optimize water resources management at the regional level using smart water systems, and to improve national and international knowledge on regional-scale of real-time modelling and control for water resources management so as to increase climate change adaptation capacity, especially in developing countries.

1.4 Project pilot region

The project boundary has been defined in Handan pilot region. It was agreed by both Chinese and Swiss partners that Guantao county administrative boundary would be used as the modeling boundary for the Handan pilot region. Figure 1 illustrates the location of Guantao County. The modeling efforts involved a much larger area in the North China plain, however the monitoring/controlling efforts were focused on Guantao administration boundary and the surrounding Handan East Plain area. As the aquifer(s) boundaries surpass the administrative boundary of the pilot area, groundwater level monitoring points from neighboring counties were also included in the data platform. Additional groundwater level monitoring wells were installed to better define the model boundary. Guantao is a typical agricultural county in North China Plain with many small wells, each one serving a small irrigated area. The project is designed to make Guantao county a showcase for developing the methodology of aquifer rehabilitation and capacity building for subsequent up-scaling to the North China Plain.

Figure 1. Location of Guantao county.

1.5 Overall Goal of the project

The overall goal of the study is to use a smart water system consisting of an integrated real-time monitoring, modelling and controlling system to prevent groundwater depletion and build up the local community's adaptation capacity to climate change. The combined architecture of these three systems can be seen in Figure 2. The overall goal is going to be reached by achieving four objectives, which are presented in Table 1 and elaborated on in section 4 based on the results of pilot tests.

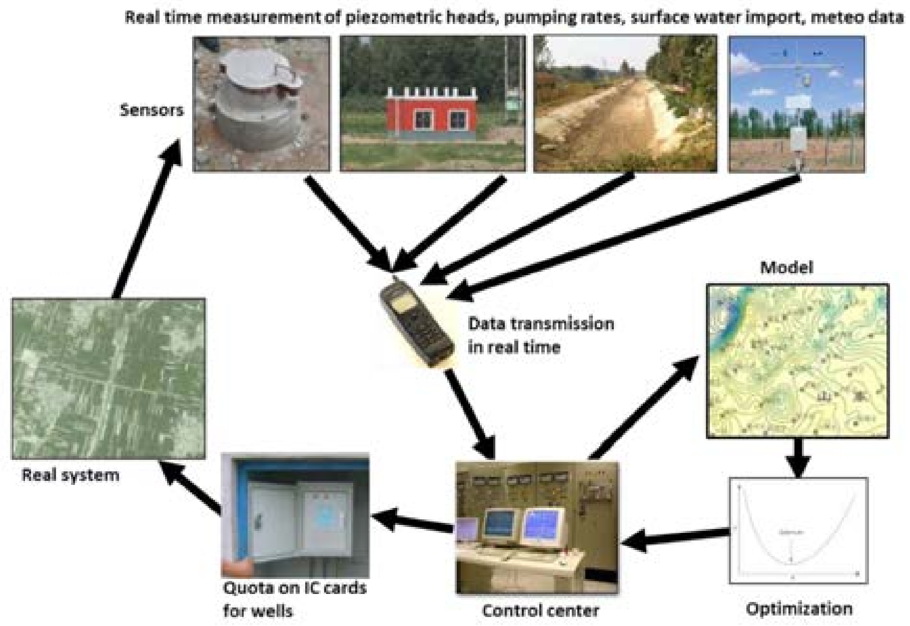


Figure 2. The Architecture of real time groundwater monitoring, modeling and controlling system.

Table 1. Four objectives of the project

Objective	Key indicators
1. Providing the data and information base for real time water allocation.	• Collection of groundwater level observation data, land use, meteorological station data, crop type, harvest and irrigation areas. • Pumping test and a complete hydrogeological report. • Real-time groundwater pumping monitoring system is developed and implemented.
2. Developing and implementing an integrated real-time monitoring, modelling and controlling system to stop or prevent groundwater depletion and build up adaptation capacity to climate change.	• Real-time groundwater model is developed and calibrated. • Overall groundwater monitoring/controlling system is implemented. • Developed a geo-strategic decision support system for abatement of groundwater over-exploitation.
3. Elaborating policy options with the stakeholders that are implemented by the local authorities.	• Control criteria and groundwater recovery strategies are established. • New regulations for groundwater pumping and water quota policies .are proposed • Functions, roles and responsibilities of each sectors are clearly attributed
4. Improving knowledge of using real-time monitoring, modelling and controlling system to stop or prevent groundwater depletion for arid regions in developing countries.	• New scientific findings of real-time groundwater monitoring and controlling published in scientific papers. • Publications regarding real-time groundwater monitoring/ modelling/controlling system • New/improved water resources management regulation/rules/methodology formulated in the project. • Other national/international partners show interest to install the system in their regions

2. Water challenge

2.1 Consequences of groundwater over-exploitation

Severe over-abstraction of aquifers has been common, especially in developing countries. It is estimated that 25 percent of the 800 km^3 pumped annually from aquifers worldwide are not renewed by recharge and thus lead to depletion of aquifers. Aquifers can store water over years with minimal loss to evaporation and are therefore particularly suited as a mitigation tool in the face of droughts, which are expected to occur more frequently under climate change. To serve this purpose they must however be allowed to recover in times of above-average rainfall. Only under strict management will aquifers be able to relieve droughts reliably.

Over-abstraction has a number of serious consequences: It decreases the amount of water stored and thus the ability of aquifers to serve as reservoirs for drought relief. It increases the amount of energy required to lift the groundwater to the surface. It decreases the yield of wells and requires the drilling of even deeper wells. It harms aquatic ecosystems by reducing the amount of groundwater discharged to streams (and constituting the streams' base flow) and by drying up wetlands and springs. Finally, over-abstraction leads to land subsidence and fissuring of the ground.

A household survey financed by the World Bank (2012) reveals that more and more Chinese farmers are investing in pumping facilities to use groundwater for irrigation because it is more reliable than surface water supply than existing reservoirs and irrigation canals, especially during persistent droughts. Yet, unlike surface reservoir releases, groundwater pumping is neither easily monitored nor effectively controlled by local water authorities due to the large number of wells involved.

2.2 Water resource endowment in Guantao county

Guantao county, located in Handan Municipality of Hebei province, has been chosen as the pilot region for the project implementation in North China Plain. Guantao features semi-arid continental climate. The long term average annual precipitation is 530 mm with an annual potential evapotranspiration of 1516 mm. Annual average temperature is 13.4°C. Total annual water consumption is 112.6 million cubic meters (Mm^3), of which agricultural irrigation consumes 98 Mm^3, industrial water use 3.6 Mm^3, domestic and other water use 11 Mm^3.

The renewable water resources in Guantao are about 62.3 Mm^3 per year, of which 57.65 Mm^3 are from groundwater while the remaining 4.65 Mm^3 is from surface water. The gap between renewable water resources available and water consumed in Guantao is about 50 Mm^3 per year, and it is served by pumping excessively the available aquifers. The over-pumping includes 27 Mm^3 per year from shallow aquifer and 23 Mm^3 per year from a deep confined aquifer. The shallow aquifer is less than 150 m in depth, with average thickness of 19.78 m, and the lithology of aquifer is fine sand, medium sand and silt. The deep aquifer, on the other hand, is porous aquifer, and the bottom of which is more than 150 m in depth, with average thickness of 49.70 m, and the lithology is mainly fine sand. The direct consequence of over-pumping is the rapid drop of groundwater table in both the shallow aquifer (from 2 m to 25 m) and the deep confined aquifer (from 30 m to 60 m) within the past 20 years. Other consequences, include the deterioration of water quality and the increasing cost associated to the pumping requirements. Finally the widespread drop of groundwater table has led to serious land subsidence.

2.3 Groundwater pumping wells in Guantao County

There are more than 6000 groundwater pump wells in Guantao County, of which 230 wells draw from deep aquifers. Most of the wells are not monitored or managed. In this pilot project, a small fraction of the irrigation wells were chosen to be operated and managed by well managers, who are responsible for irrigating the crop land covered by their respective wells (each covering about 60-80 mu, or 4-5.3 ha, serving 8-10 families). Each well is equipped with an electricity meter that allows well managers, who are village electricians, to prepay using an integrated circuit (IC) card at the beginning of every irrigation season with sufficient kWh to irrigate all the land they are responsible for. Each family pays its share of electricity cost (about 0.5 yuan/kWh, i.e. 0.08 USD/kWh) for pumping according to the electricity they use, with an additional fee (about 0.3-0.5 yuan/kWh, i.e. 0.05-0.08 USD/kWh depending on the farm land's distance from the well) charged for the service of the well manager. This system could be used as a control mechanism by enforcing an energy quota to each well.

The wells pumping from the deep confined aquifer are to be closed down, without exception, according to the Handan county government, and the process is underway. This water will be substituted for by water from the South-North Water carrier as far as household and industry are concerned and by alternative surface water resources in agriculture. This good decision was taken to protect the mining of the deep aquifer that does not receive any significant recharge and water levels drop can only be prevented from further decline by a zero abstraction policy. It should also be noted that the deep aquifer's pressure reduction is the main cause for land subsidence. For the project it means that closing down of all those deep wells has to be checked but no other action is required concerning the deep aquifer. Therefore, the scope of the project is concentrated on the rehabilitation of the shallow unconfined aquifer, which is the main source of irrigation water and prospective reservoir for drought relief. Before this project, Guantao County established a monitoring platform which could only collect short-term data, but rarely utilized the method in this project to control the withdrawal and utilization of groundwater on a real-time basis.

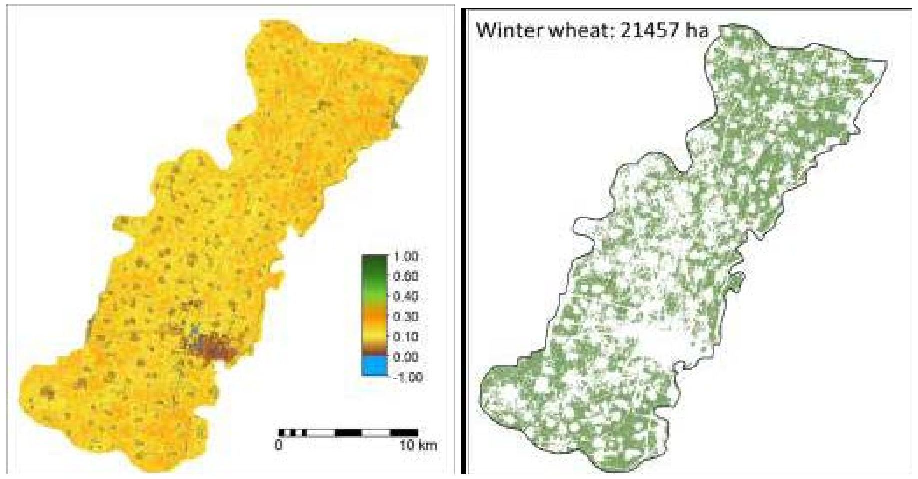
3. Smart Water Management (SWM) solution

The main purpose of the project is to develop and apply an integrated real-time monitoring, modelling and controlling system in the pilot area in China to support groundwater management under climate change conditions, including greater variability, and to restore an aquifer's ability to mitigate the effects of drought. The project intends to tackle two major issues. Firstly, to apply a system in China for improving groundwater management on the basis of monitoring, modelling and controlling groundwater abstractions. Secondly, to contribute to the global knowledge and support the south-south exchange of experience and best practices (Murphy et al., 2000; Anderson et al., 2015).

3.1 Preliminary assessment of the first phase

3.1.1 Data collection and processing

In the first phase all available data on water use, land use, cropping practices, geological structure of the aquifers, piezometric heads of shallow and deep aquifers, surface water imports, aquifer recharge and existing policies for water use and allocation was collected, and a first assessment and analysis of the collected data was made by an expert team. The data collection in this phase also included available remote sensing products of the area. Images from a Landsat 8 satellite were processed by extracting total crop area and winter wheat planting area in Guantao region (an example can be seen in Figure 3).



(a) (b)

Figure 3. (a) Normalized Difference Vegetation Index (NDVI) extracted from a Landsat 8 satellite, and (b) the extracted winter wheat planting area on December 6, 2013 for Guantao region shown in green

3.1.2 Initial assessment of groundwater monitoring system on the project site

Groundwater monitoring included groundwater level changes and groundwater pumping rates within the Guantao county. An initial assessment of the existing groundwater monitoring system and plans on how to proceed during the project implementation phase has been done.

(1) Groundwater level monitoring

In the first phase, within Guantao county there were 38 groundwater level observation wells, of which 25 were manually measured twice a year from 2006 (in spring and autumn), while the other 13 were monitored automatically with data of groundwater level and water temperature transferred directly every 12 hours to Handan Municipal Department of Water Resources and Guantao County Department of Water Resources. The locations of these automatic online wells are shown in Figure 4. There were three more automatic measuring points for groundwater level operated within the national groundwater observation network of the Ministry of Land and Resources, for which the data were provided by the Chinese project partner China Institute of Geo-Environment Monitoring (CIGEM). More groundwater observation wells were installed to define the model boundary of Guantao county in the next phase of the project since the existing wells were unable to cover the whole area of the county. The Handan Department of Water Resources had already received funding to finance 28 new online observation points, which provided real-time data for the project's data platform. Our project partner CIGEM also provided more manually measured data from observation wells through their network around the Guantao county border. These wells were equipped with automatic sensors and wireless data transfer through the project and the data was sent to the data platform. 10 sensors with wireless data transfer facilities were needed for the project to equip these wells at the county border.

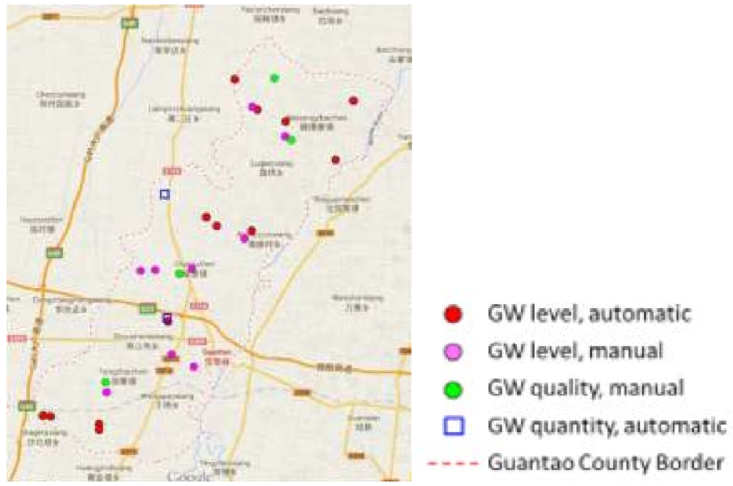


Figure 4. Available groundwater level measurement points in Guantao county in opening phase.

(2) Groundwater pumping monitoring

As monitoring systems for groundwater pumping did not yet exist in Guantao prior to this project, the volume of pumped groundwater was indirectly estimated from groundwater drawdown or irrigation practices. Generally, the pumping wells in Guantao were small in size, with some of the pumping wells sharing only one mobile pump. Installing a monitoring/controlling system for all the pumping wells in Guantao would involve a large effort and high hardware costs. However, it was discovered that monitoring the electricity consumption could be an alternative and easy way to monitor the groundwater pumping. As there are 2-3 power transformers in each village (many of which were exclusively serving irrigation), energy consumption can be monitored easily. While the electricity company also has all of the relevant consumption data on electricity use in the county, this data is not be accessible for us as each government division uses a different governmental company and there is no information sharing between them. As an alternative to acquiring the data from the electricity company, the power transformers can be equipped with an additional power meter, attached to the main cable, which can transmit power use data through General Packet Radio Service (GPRS) or Short Messaging Service (SMS). As the water levels during the pumping stages vary from well to well depending on the aquifer's local transmissivity, the energy use per cubic meter pumped is different for each well. Therefore direct water metering (either permanently using traditional water meters or short-term using electricity use to calculate water use), has to be introduced in all large wells for the efficient monitoring of water pumped from each well.

3.2 Data and information as the basis for real time water allocation

The data and information platform is crucial and fundamental in the whole process of the project, and therefore requires a lot of attention. The following section will illustrate the details of the design structure of data platform and data receiving and processing system.

3.2.1 Data platform design

A preliminary web-based data and information exchange platform has been implemented by GeoPraevent, a Swiss company providing geological and environmental solution services, and is illustrated below in have proposed a preliminary design (see Figures 5-7). The platform has the capacity to accommodate incoming real-time information from all of the existing wells in the national network, which are run the Ministry of Land Resources and the Ministry of Water

Resources of China. The design took into account that part of the observation network (the key hydrologic station) also served as a boundary condition for the real-time groundwater model, which is at the core of the control module. Suitable existing observation wells without monitoring devices were also identified and equipped with monitoring devices so they can be incorporated into these networks. New necessary observation wells were planned and sited for drilling, and were chosen according to their sensitivity in showing the reactions to interventions. Interventions such as a reduction of pumping rates or artificial recharge through unlined irrigation canals or recharge ponds presently being excavated were readily detected. The initial set of production wells to be controlled, were chosen in correspondence with the available observation wells.

The hardware for the data platform consists of 2 servers provided by General Institute of Water Resources and Hydropower Planning and Design (GIWP) of China and located at GIWP in Beijing. They had to be equipped with a backup system as well as a module for receiving GPRS input.

A separate internet connection (Wide Area Network, WAN) is connected to the firewall. Behind the firewall the data connections are divided according to their source and target. Connections are routed into the demilitarized zone (DMZ). From the DMZ zone the data can be transferred into the protected local area network (LAN) zone. The server is connected with the LAN interface for regular data processing.

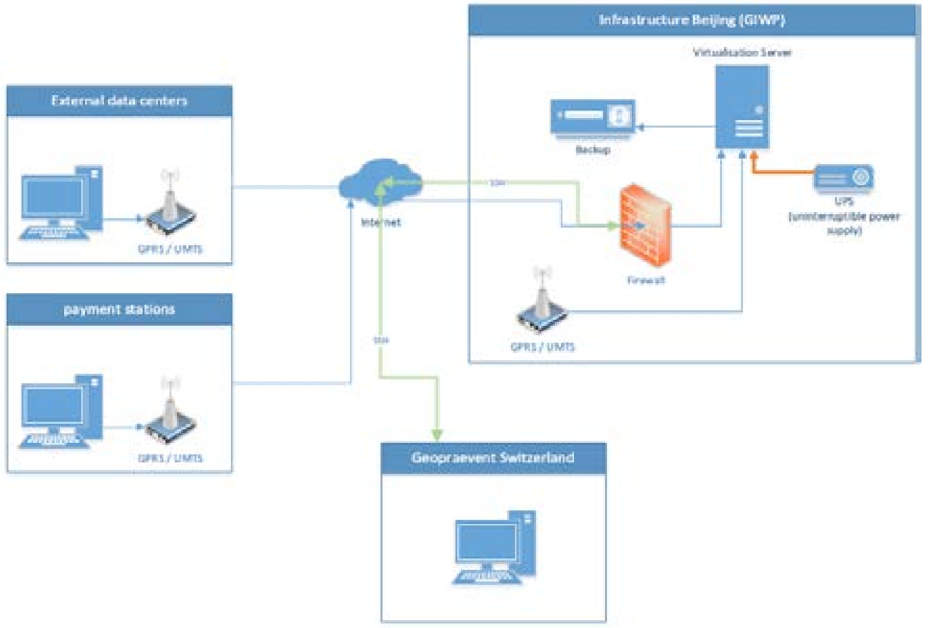


Figure 5. Illustration of infrastructure for supporting the data base platform by GeoPraevent.

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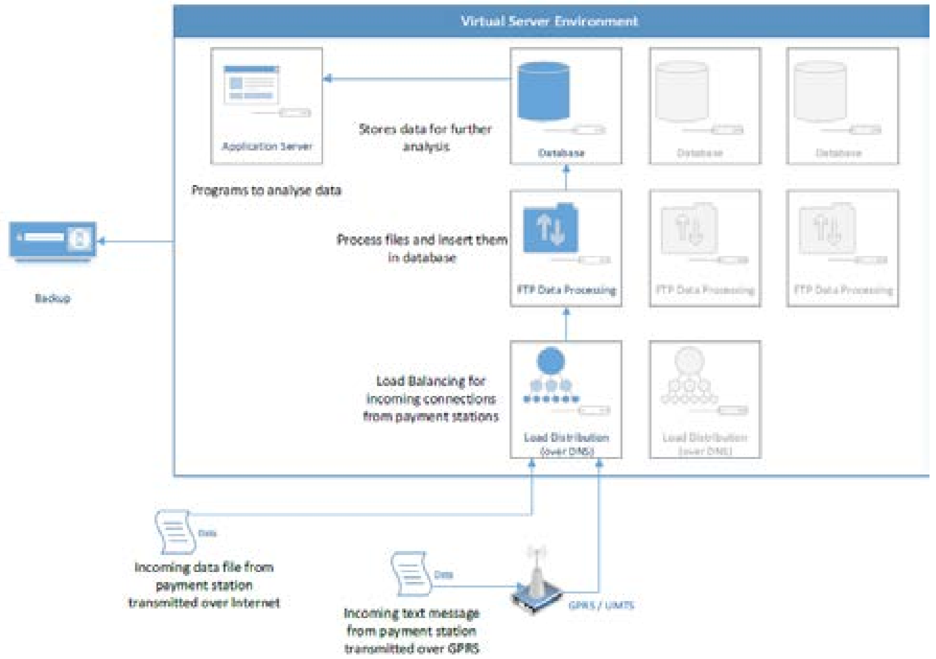

Figure 6. Data processing concept, designed by GeoPraevent.

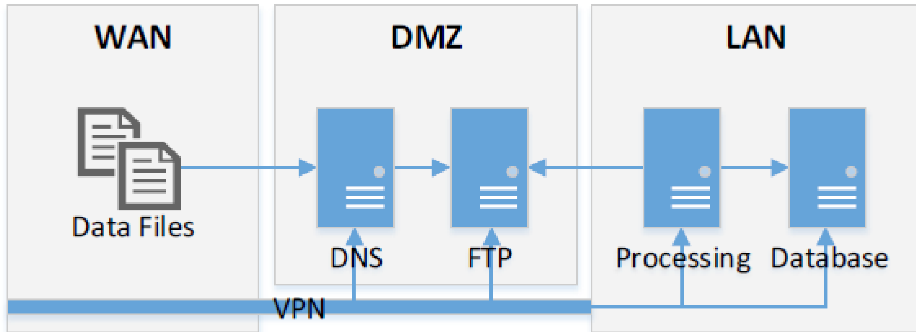

Figure 7. Security concept in Beijing for incoming data, designed by GeoPraevent.

3.2.2 Data receiving and processing system

The data server in GIWP server room in Beijing has been online since autumn, 2015. The server configuration, including firewall installation and backup settings, were designed and installed by Geopraevent experts in early 2016. The server has been configured to receive, process and visualize the dynamic real-time data from different data sources. A generic receiving unit has been built up to process the specified incoming data. After checking and discussing the sensors with Geopraevent, the correct response definition for every sensor type has been achieved.

(1) Data reception

The real-time data from the groundwater-monitoring sensors of different producers (e.g. Haisen, Hengyuan and Itron) have all been successfully received by the server. These data include the time series and the electric energy consumption at an interval of around once every 30 minutes. While some difficulties arose in the implementation of data reception from the RSA and Hengze sensors, these problems were solved in cooperation with the sensors' producers.

For example, when RSA implemented the SMS readout system on the server, they could not retrieve the data from the server due to a problem with an unstable server connection. To solve this issue, RSA proposed a back-up method, in which the SMS readout method was changed to the GPRS readout system: the data was then sent from the field directly to RSA's database via the GPRS system and then forwarded to the server in the form of a report. Similar implementation was carried out with Hengze sensors. Instead of being sent directly to the server, the data was first transmitted and saved in Hengze's database, and then the server read the data from Hengze's database. This automatic readout method has solved these issues.

The devices monitoring electricity consumption were provided by Lofty Electronics Ltd. Each device consists of an electricity meter and a data transmission unit. Real-time electricity data from the Lofty meters have also been received by the server including power, current, voltage, etc. at the frequency of around once every 2.5 minutes.

(**2) Data processing and visualization**
The database is designed to support all of the different sensor types without any special adaptation. The data visualization is presented on a web data portal (https://www.gwm-handan.cn/geoview/#/login), which users can view in real-time data after login. The locations of the sensors are shown on the satellite map of Guantao (Figure 8). By enabling the "Live" function, it shows the sensors sending data to the server in real-time as pulsing red circles.

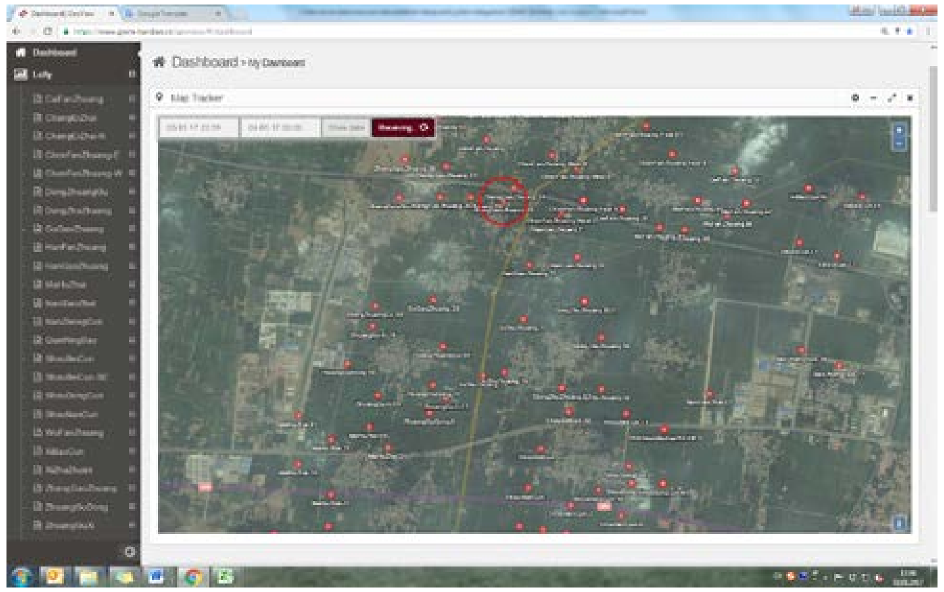

Figure 8. Screenshot of the real-time data portal based on satellite map. Users can click any red circle to view the real-time data of a sensor.

In the data portal, the list of the villages and the sensors are shown on the left of the page (see Figure 9). As an example, by selecting a specific sensor, the real-time data monitored by selected sensors can be viewed. Users can customize the results by selecting the variables listed at the bottom of the page such as 'Pumping volumes' 'Water level' and 'Pumping electricity' and view a certain period of time series by zoom-in or -out.

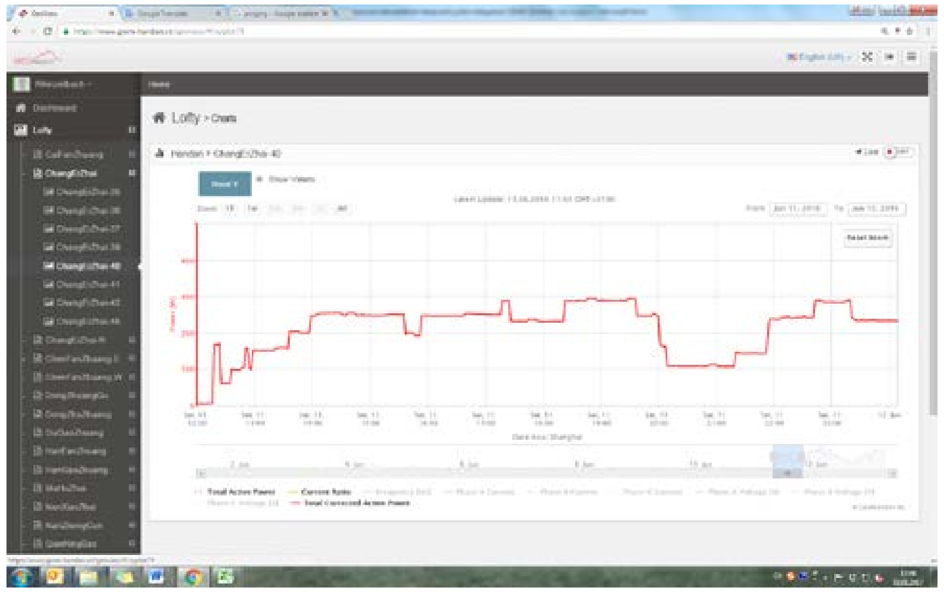

Figure 9. An example of real-time data display, received from the ChangErZhai-40 station. Users can pick any sensor and view data from a certain time period. The chart illustrates the real-time power of pumping well transformers, which reflects the current working condition of pumping wells.

3.3 Real-time monitoring system

3.3.1 Groundwater level monitoring

In Guantao, 14 new observation wells were installed and monitored in 2015/2016 by the Chinese Geological Survey (CGS), through matching funds. Similarly, 20 automatic monitoring wells were installed bythe Hebei Provincial Department of Water Resources and 29 wells including 13 automatic monitoring wells and 16 manual monitoring wells by the Handan Department of Water Resources. The map in Figure 10 indicates all locations of wells monitored in 2015 and 2016.

There are three types of data: (1) the automatically recorded data from CGS/CIGEM, (2) the automatically recorded data from Hebei province through Guantao DWR and data collected manually from (3) manual observation wells by Hebei province four times a year, in February, end of May, end of September, and end of December. In order to match the data from manual and automatic observation wells, we have to interpolate the data (using a linear interpolation on time interval) collected from the manual observation wells to estimate the values during the missing recording times. After the groundwater level data was collected, further analysis has been made, e.g. the comparison among data from different observation wells, or the trends of groundwater levels in recent years.

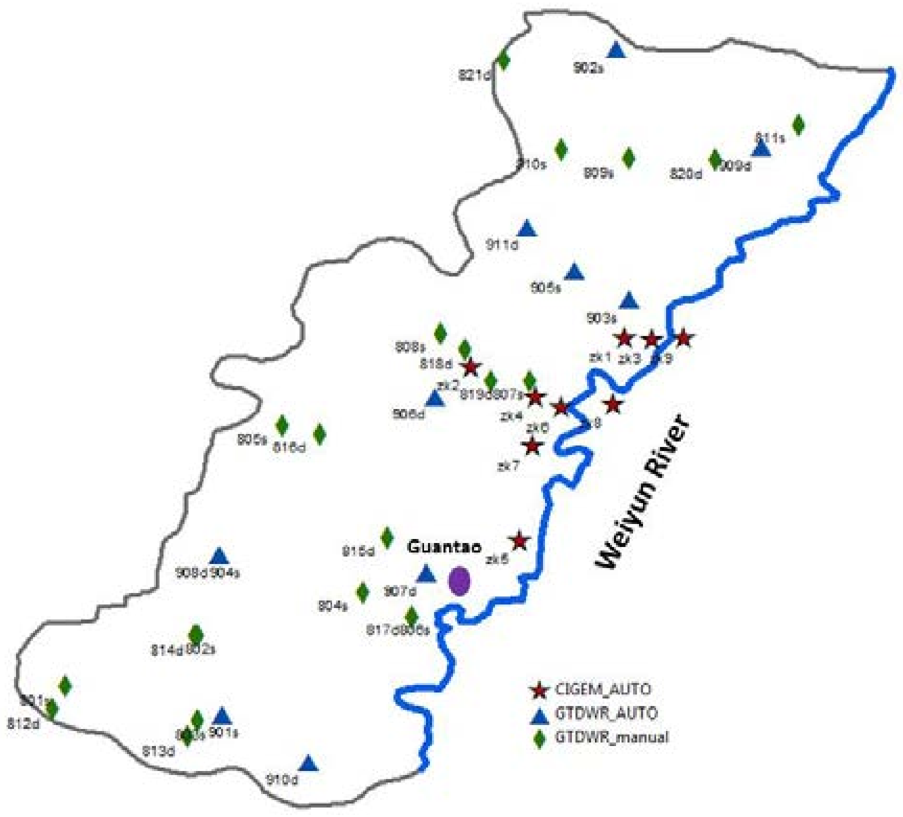

Figure 10. Location of piezometers monitored in 2015/2016 within the project area.

3.3.2 Groundwater pumping monitoring

Significant progress has been made concerning the installation and operation of the pumping monitoring systems with the efforts of the Swiss team and the local partners. All of the selected 5 pairs of the experimental flow meters from different producers have been installed or relocated in Guantao. As it is expected that that the use of sensors from different producers might result in different results while performing the conversion of electricity to water quantity, we need to experiment on each type of sensor brand. To allow the comparison on water consumption, we included a pair of sensors for each brand, with one installed at one location with water saving equipment and the other at different location without water saving equipment, respectively (in order to explore the mitigation effects of utilizing water-saving equipment on groundwater over-exploitation). Four out of five pairs of the experimental meters are in operation and have been sending data to the server. These experimental meters differ in cost, meter type and data transmission methods, which allows a comparison concerning the implementation of the different meters and techniques in practice. An overview of the meter information and current development status is summarized in Table 2.

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Table 2. Meters and current development status.

Meter (Producer)	Meter Type	Measurements	Data transmission	Price per Unit	Current development status
Haisen (Tangshan)	Mechanical flow meters (Nylon)	Flow rate, Electricity consumption, Water level	Own protocol, direct transfer to IP	4400 CNY	Installed, data received
Hengyuan (Shijiazhuang)	Ultrasonic flow meters	Flow rate, Electricity consumption, Water level	Own protocol, direct transfer to IP	12000 CNY	Installed, data received
Hengze (Qingdao)	Mechanical flow meters	Flow rate	Own software, transformation into datasheet	3000 CNY	Relocated, data received
RSA (Iran)	Electricity meters	Electricity consumption calibrated for flow	Own software, transformation into datasheet	10000 CNY	Relocated, data received
Itron (France/Suzhou)	Mechanical meters	Flow rate	Own software, transformation into datasheet	7600 CNY	Installed, data received

The locations of the installed flow meters (5 pairs) are shown below, together with the locations of 100 experimental electricity meters (from Lofty) on transformers and the locations of the wells monitored by the experimental electricity meters.

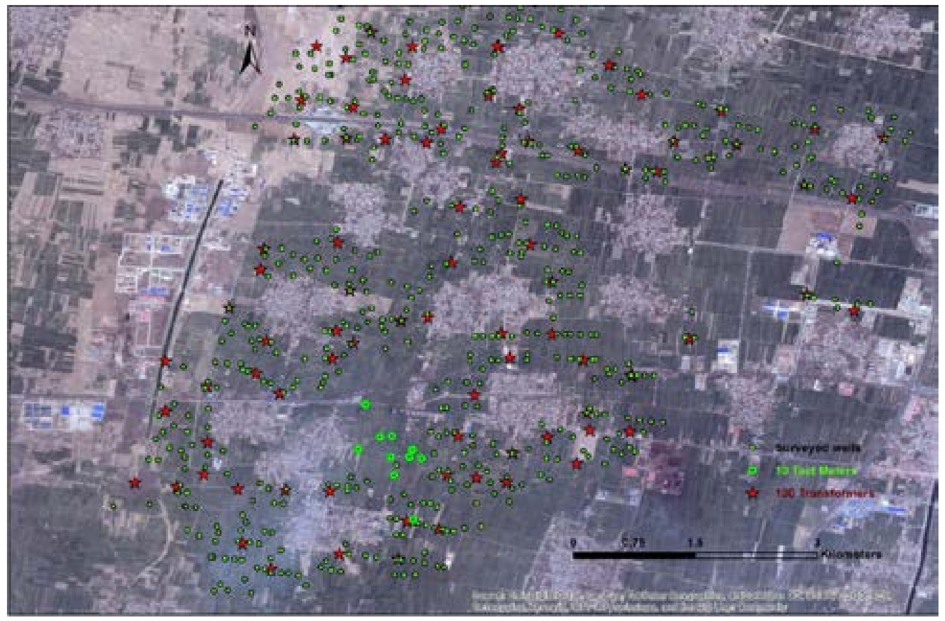

Figure 11. Locations of 10 test flow meters (green circles), 100 transformers on which the experimental electricity meters were installed (red stars), and the wells monitored by the electricity meters (green dots).

3.3.3 Pumping electricity monitoring

Essential progress has been made in monitoring pumping electricity in three respects: (1) securing the cooperation with Guantao Department of Electricity and Power Supply (DEPS) regarding electricity data sharing, (2) correctly installed and tested in the pilot region (Shoushansi District) in Guantao, and the data sent by the experimental meters have been received on the server. (3) Two sets of pumping tests were carried out in March and June 2017, respectively to establish the relation between electric energy consumption and groundwater abstraction.

To calculate the exact conversion factor, the historical data of groundwater abstraction and electricity consumption data are collected. The conversion factor, α, is defined as the electric energy consumed for a unit of water pumped. It is the key parameter to convert the electricity consumption to the volume of the groundwater pumped. Due to the uncertainty of the groundwater abstraction data, we used multiple sources. Meanwhile, as the electricity consumption data collected include the electricity used for non-agricultural purposes, we subtracted the electricity consumed for non-agricultural purposes from the data collected. The conversion factor over the region is an average of the conversion factors of the pumps across the region weighted by the volume of water pumped.

To determine the relation between the electricity consumption and the groundwater abstraction, 209 pumping tests were performed on the individual wells that are monitored by the experimental electricity meters. The results from the pumping tests show that there is a considerable variability in the values of the conversion factor (α), i.e., the electricity consumed for pumping one cubic meter, ranging from 0.2 kWh/m^3 to 0.9 kWh/m^3 (Figure 12). The corresponding pumping rates at the wells range from 10 m^3/h to 48 m^3/h. The variability of the conversion factor can be caused by various factors including the depth to the groundwater table, the hydrogeological conditions, the condition of the pumps and the accuracy of the electricity meters on the pumps. It is challenging to derive a uniform relation between the electricity consumption and the groundwater abstraction.

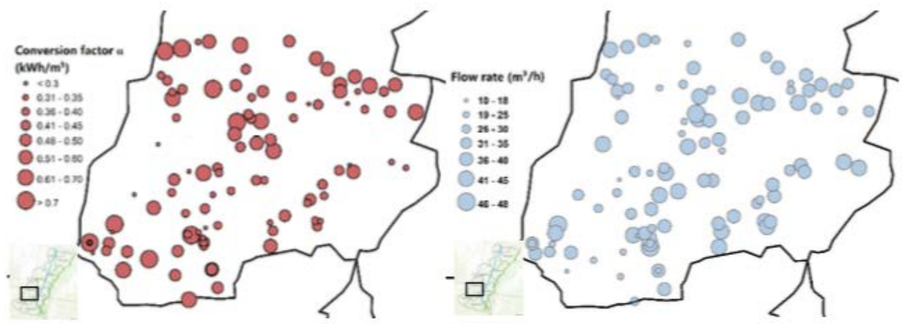

Figure 12. Spatial distribution of conversion factor (left) and measured flow rate (right).

Considering the variability of the conversion factor, regression analysis was conducted based on the pumping test and the results showed that the rated power of the pump, drawdown during pumping, irrigation type and accuracy of measurement all influence the value of conversion factors. Thus, we used the value of sample averages plus the correction based on the results from these tests as the determined conversion factor of each meter.

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3.4 Real-time modeling system

3.4.1 Water Balance modeling

To estimate the water balance of the shallow groundwater aquifer of Guantao, the input data of precipitation, groundwater abstraction, surface water runoff and the groundwater levels are required. The reliability of the model results is highly influenced by the quality of the input data. In contrast to the precipitation measurements, groundwater abstraction was not monitored in Guantao and could only be estimated based on the irrigation norm and the times of irrigation; this is considered to contribute the most to the errors in the inputs. Thus, efforts were made to improve the water balance calculation by using reconstructed groundwater abstraction data based on the historical rural electricity consumption data. Electricity records reflect the energy consumption for irrigation and thus are considered as more reliable data set than the groundwater abstraction set estimated by the water authority.

One particular issue that should be taken into account is the unreliable method of using pumping tests to determine the conversion factor α over the pilot region where the tests were being carried out. Due to the lack of information of individual pumps outside the pilot region, it is not yet practical to use the aforementioned method to calculate the annual conversion ratio over Guantao. To resolve this issue a conceptualized method was proposed in which we assume that the total amount of water pumped in a year in the whole region is lifted at once by a super pump from the shallow aquifer to the ground surface. In this scenario the electricity consumption and conversion factor can be estimated based on the energy balance of the pump. After separating shallow groundwater from deep aquifers, we can calculate the water abstraction. We can then compare this with the collected water abstraction data (estimated by Guantao department of water resources), enabling us to draw conclusions based on the data in Figure 13. It can be seen that a consistent time series of the groundwater abstraction was reconstructed from the electricity consumption for irrigation, and it agrees generally well with the abstraction reported up to 2006.

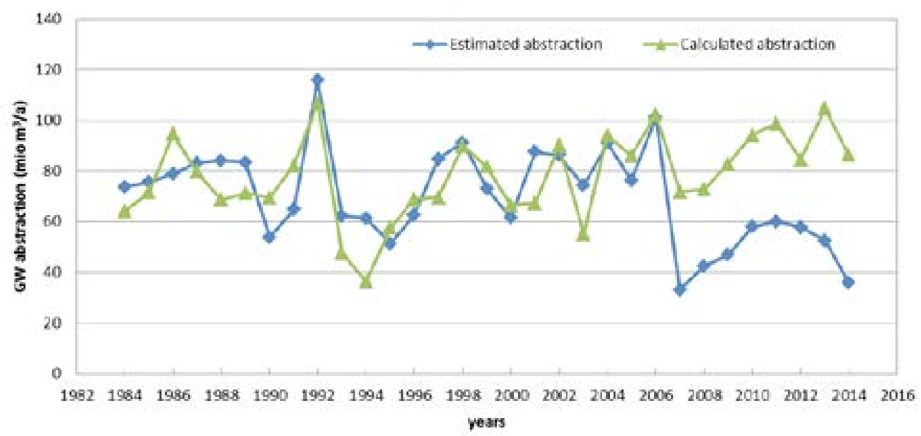

Figure 13. Shallow groundwater abstraction calculated from electricity consumption. Groundwater abstraction (million m^3/year)

To express this concept mathematically a box model of water balance was established, the water balance equation can be written as:

$$R_{pr} + R_{river} + R_{channel} + R_{backflow,channel} + V_s \cdot (1 + c) \cdot \beta - V_s = \Delta H_s \cdot \mu \cdot A$$

Where, R_{pr} is the precipitation infiltration, R_{river} is the seepage from the Weiyun River, $R_{channel}$ is the seepage from the channels, $R_{backflow,channel}$ is the irrigation backflow from the channel water, V_s is the abstracted shallow groundwater for irrigation which was reconstructed from the electricity consumption, c is the ratio between the deep water and the shallow water abstractions, β is the infiltration rate of the backflow from the groundwater irrigation, ΔH_s is the change of the depth to the water table in the shallow aquifer, μ is the porosity of the shallow aquifer and A is the area of Guantao.

From this equation, we can estimate the change of groundwater level. The calculated and observed depth to the water table and the corresponding change of storage in the shallow aquifer are shown in Figure 13. It can be seen that there is little difference between calculated and observed water depth.

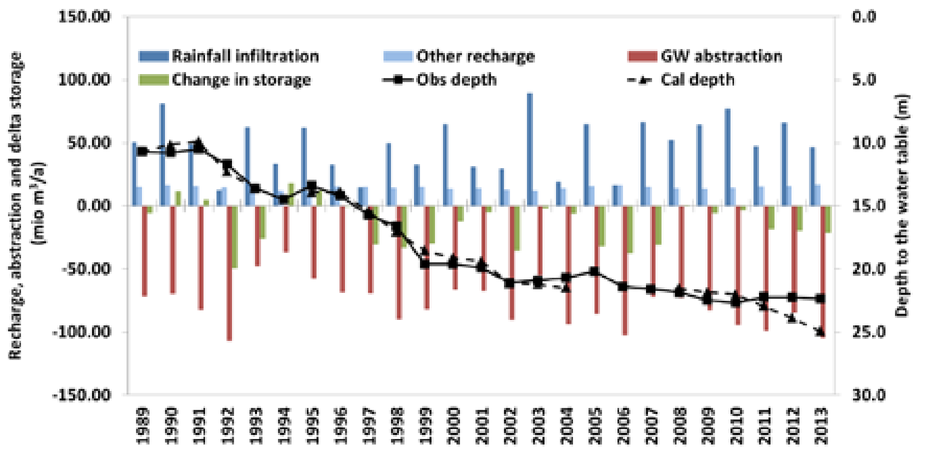

Figure 14. Calculated and observed depths to the water table (excluding jumps in the "bad years") and the corresponding change in storage (Groundwater abstraction (million m³/year))

3.4.2 Irrigation Calculator Guantao Web Implementation

An irrigation calculator has been set up by the Hydrosolutions company (a consulting company and one of our corporation companies) to compute the water requirements for crop growth considering different crops, irrigation systems and soils given the local climate. Various weather data sets (from the local meteorological station, neighbor county meteorological stations, international stations and a global station) have been taken into account to provide local climate information. The irrigation calculator was firstly implemented as a Matlab program. Input data such as the meteorological time series, crop and soil parameters can be entered into an Excel spreadsheet. When starting the main program, this information is read out and parsed into drop-down dialog boxes, from where the user can select the desired data (see Figure 15). Different fields with different selections can be added conveniently.

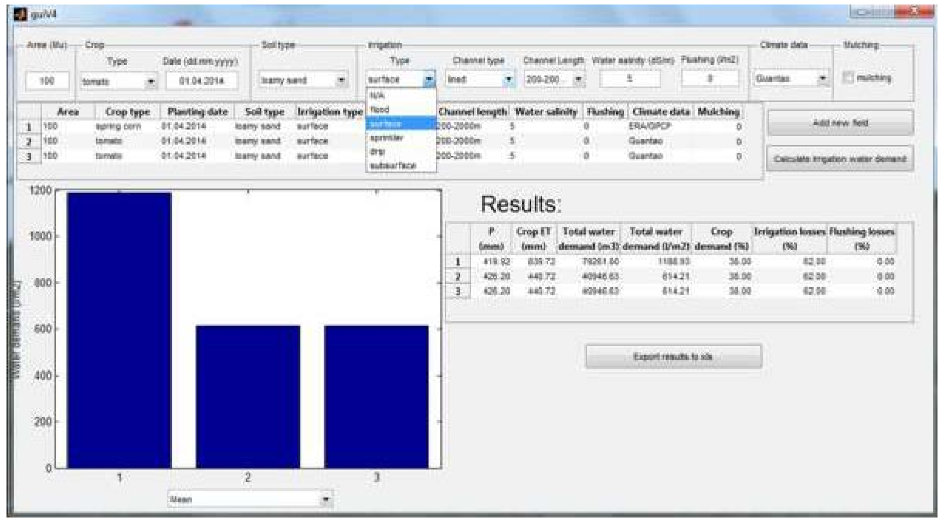

Figure 15. Screenshot of the Matlab-implementation irrigation calculator user interface.

A Hydrosolutions' Guantao Irrigation Calculator has been later implemented online and is available at: http://app.hydrosolutions.ch/IrrigationCalc-Guantao/. With this calculator, stakeholders can calculate monthly crop water demands for particular crops as a function of soil types and planting dates, given the particular long-term climate of Guantao County.

The new web-based tool uses the FAO AquaCrop web-service to calculate irrigation water requirements as a function of crop and soil types as well as data of the local climate. by using-predominantly

Monthly irrigation water demand can be calculated when navigating to the 'Irrigation Demand Calculator' tab on the page (see Figure 16) below.

Figure 16. Main elements of the irrigation water demand calculator. Panel 1: User interaction panel. Panel 2: Visual representation of monthly irrigation water demands using climate norms data for calculation. Panel 3: Advice panel on optimal cropping dates for the planting month using long-term climate norms. Panel 4: Tabular Data (also available for download, see Panel 1).

3.4.3 Real-time groundwater model development

We developed a Guantao groundwater model using a structured grid discretization. This model requires considerably less computation time, which allows it to be provided via a web Shiny-based app (Shiny is an R package[1] that makes it easy to build interactive web apps straight from R.). The model with unstructured grid also allows much faster computation of the ensembles required for the real time model. The groundwater model of Guantao is constructed using standard MODFLOW under Processing Modflow (PMWIN). The conditions of model structure, boundary, water sources and sinks, parameters, observation wells, etc. are considered in the model. The numerical model is run in two states. One is the steady state model used to calibrate the values of hydraulic conductivity and recharge ratios under constraints. The other is the transient model used to manually calibrate specific yields. We used a linear regression model between measured and modelled groundwater heads to demonstrate the effectiveness of the model, and the R^2 of the comparison between simulations and observations is around 0.8. Thus the fit to the observed data is very good considering the data situation relating to both steady state model and transient model.

3.4.4 Online toolbox of groundwater modeling

An online groundwater simulation tool has been developed by the Swiss Federal Institute of Technology Zurich (ETH) for the local authorities, which will be periodically updated and modified using monitoring data2. The goal is to facilitate the planning of water allocation for irrigation with respect to its impact on local and adjacent groundwater levels. Understanding the heterogeneous temporal and spatial response of the aquifer to anthropogenic impacts as well as its interaction with other elements of the water cycle (e.g. recharge, channel infiltration, infiltration of irrigation water etc.) presents a challenge. Our tool, based on a finite difference numerical groundwater model (MODFLOW), captures these systemic properties and allows the decision makers to assess the effect of different water allocation scenarios. The novelty concerns the fact that the model is embedded in an interactive web-interface, accessible to the users through the internet with all standard web browsers of computers, tablets or smartphones. Users can run a scenario, modify parameters and visualize the projected change in groundwater level as a consequence of their actions. The default prediction implies continuation of the status quo practices. The users can alter this practice and explore new strategies. The toolbox features include: easy online accessibility, efficient updating and maintenance, instant response and fluid interaction, customized user-friendly operation and license free software. The main window of the online toolbox can be seen in Figure 17. The contour plot on the right side of the screen shows the changes in groundwater level resulting from the simulated water allocation as compared to the current situation (initial condition). The panel on the left allows the user to choose different settings. The selected district to be worked on is highlighted by a thicker solid black line. By default, when a district is selected, the current practice values are loaded and the result shows the outcome when maintaining the status quo. Note that water levels change with time for the default values, as present practice is not in an equilibrium state. By dragging a rectangle on the map, one can zoom into a particular area. Double-clicking any location on the map allows zooming out. When clicking anywhere on the map, the plot will automatically show the drawdown over time relative to the initial heads at that specified location.

1 R is a programming language. R package is a set of functions that could be easily used in R programming.
2 The model is built based on historical data, and new current data are used to modify the data.

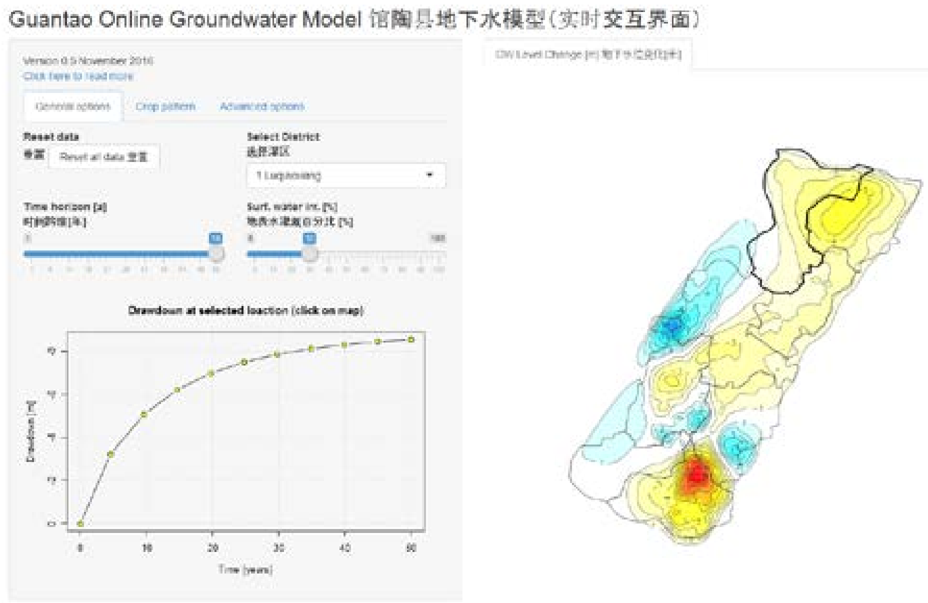

Figure 17. Main window of the online toolbox.

3.5 Management Rules and Policy Module

3.5.1 Water right and water allocation quota

The local government has set a quota of 150.5 m^3/mu (about 2250 m^3/ha) for irrigation water use. However, due to a lack of water monitoring devices, farmer's use of groundwater is actually uncontrolled and free of charge. The farmer survey conducted in March and April 2016 also asked about farmers' attitudes towards environment and groundwater management. Results show that only 3% of the farmers know of the irrigation water quota or water rights. More than 90% of the farmers noticed that the groundwater table had decreased in recent years and were worried about associated problems. About 70% of farmers support the policy of using quota/water rights to limit the quantity of irrigation water, and 60% of farmers will reduce the use of groundwater if volumetric charges of groundwater are implemented.

Hebei province government started the work of water rights verification and registration in 2015. Each farmer household will obtain a water right certificate with a valid date of three years. The water right certificate records the following information:

- Name of water user;
- Land size;
- Water rights per mu;
- Annual water rights;
- History of water rights transfer.

An implementation plan of the agricultural water pricing reform in Guantao was designed in April 2017 (referred to herein as "the plan 2017"). According to the plan 2017, three levels are defined as a basis to collect fees for agricultural water use and to reward farmers for saving water: the water right of 150.5m^3/mu, the water quota of 222m^3/mu, and the water limit of 296m^3/mu. Water used within the water right of 150.5m^3/mu costs the present base water price 0.32 CNY/m^3, above the water right an additional water fee of 0.1 CNY/m^3 is charged, and above the water limit of 296m^3/mu an additional water resources tax of 0.1 CNY/m^3 is charged (Yu et al., 2017b).

The surface water fee uses a water quota of 222 m³/mu as the starting level for charging an additional water fee. For consumption below the established water quota, only a base water fee of 13 CNY/mu/irrigation is collected, whereas above the quota an additional 20% (or more) water fee will be collected. Above the water limit of 296 m³/mu a water resources tax charge will be added. The water price structure for groundwater use is shown in Figure 18.

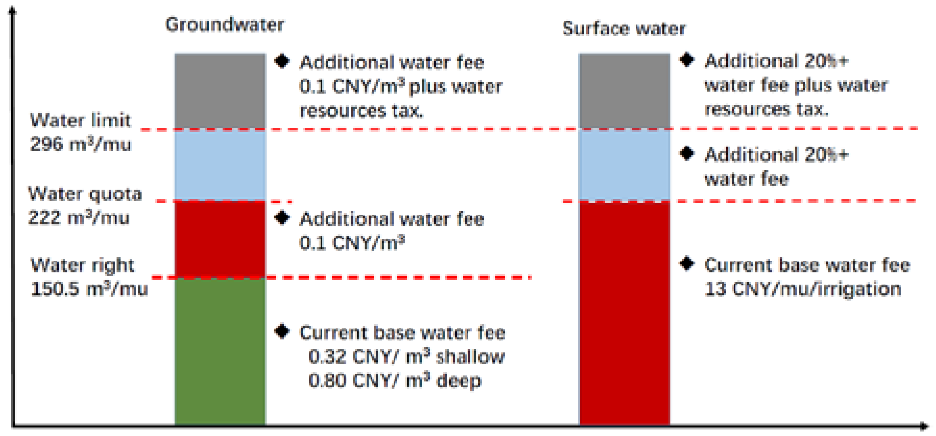

Figure 18. Comparison of irrigation water price for groundwater and for surface water in Guantao according to the plan 2017.

In the plan 2017 rewards are also proposed as incentives to encourage water-saving behavior as shown in Figure 18. Water saved within the water right can be sold to the government, traded in the market, or saved for the next year; water saved within the water quota can be rewarded by no more than 0.2 CNY/m³ for savings in grain crop irrigation, and by no more than 0.1 CNY/m³ for savings in non-grain crop irrigation; water saved at total amounts above the water quota is not rewarded.

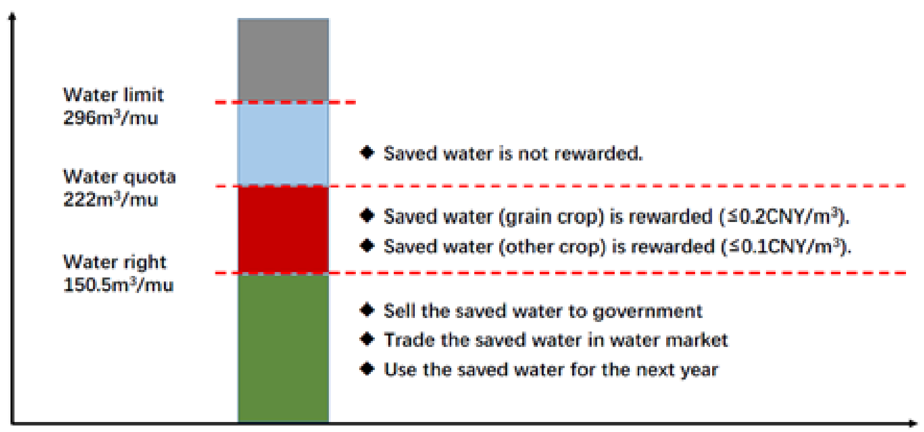

Figure 19. Irrigation water price for groundwater in Guantao from the implementation plan of the agricultural water pricing reform in Guantao.

The present rules of water right, quota and price in Guantao are still experimental and overall very complicated. For transparency and communicability, it is suggested to simplify these fee collection rules. In a pure quota system, especially in a region such as Guantao, where local rains contribute significantly to crop water supply, the violation of quota will only be apparent at the end of the season, when no more change is feasible. A base fee proportional to water use can be transparently collected together with the electricity fee. In the simplest approach,

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an effectively increased electricity fee should have the same effect as the complicated scheme proposed. This procedure does not exclude a rewarding system for farmers who stay below the sustainable quota.

3.5.2 Implementing water quota price through electricity consumption

Until now, water fee and tax have not been collected due to lack of an effective monitoring system for pumping. In March 2017 Hebei provincial DWR decided to adopt the method developed in the project. Using an average conversion factor from pumping tests of five typical wells of each county, electricity consumption is converted into groundwater water pumping volume as the base for water tax collection. In the plan 2017 for Guantao, fee and tax collection will be according to water meter readings wherever meters are installed (and function) and according to the water consumption estimated from electricity conversion everywhere else. This has given the official green light to use the electricity-water conversion method developed in project phase 1 for water fee/tax collection.

For the overall monitoring and total volume control of groundwater pumping of Guantao county, we recommended a method at transformer level for overall pumping control (see Figure 20). The fee/tax collection, however, will be at single farmer household. We proposed a fee collection structure (Figure 20), which makes use of the existing electricity fee collection system. A village electrician is responsible for paying electricity bills for every transformer in the village to the Department of Electricity and Power Supply. This bill is paid from the electricity fees collected for every single well attached to that transformer according to its electricity use. The village electrician can also be the person responsible for water fee collection according to electricity use and the proposed method of conversion. Farmers pay for their water use at the same time as they pay electricity bills. The proposal has received positive feedback from the local DWR. An additional suggestion is to include the village electrician as a key member into the village water use association. In this way they can be fully informed and updated with the newest local water policy changes concerning quota and price. This suggestion has already been included in the plan 2017.

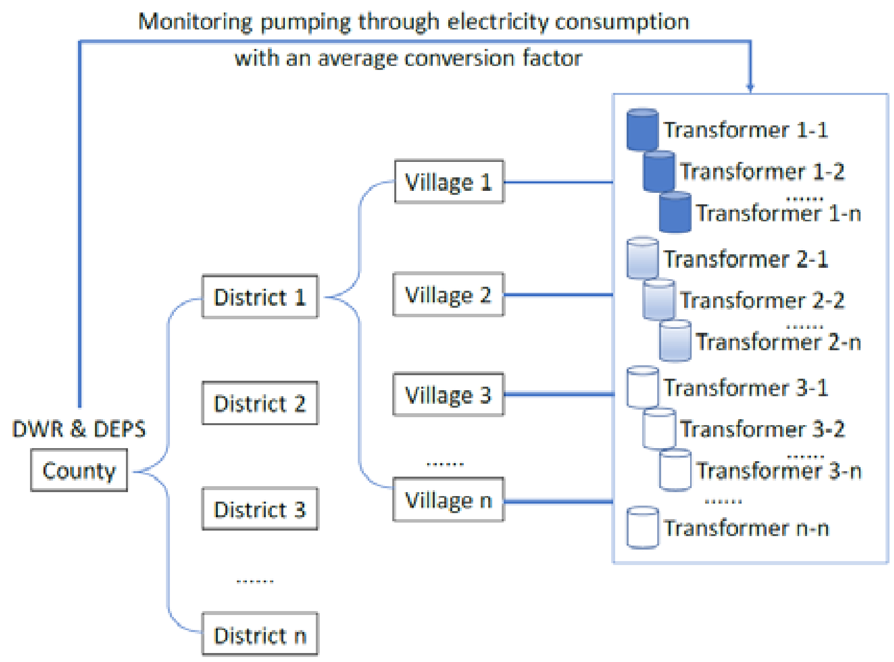

Figure 20. Illustration of county administration structure and monitoring of groundwater pumping through the electricity network.

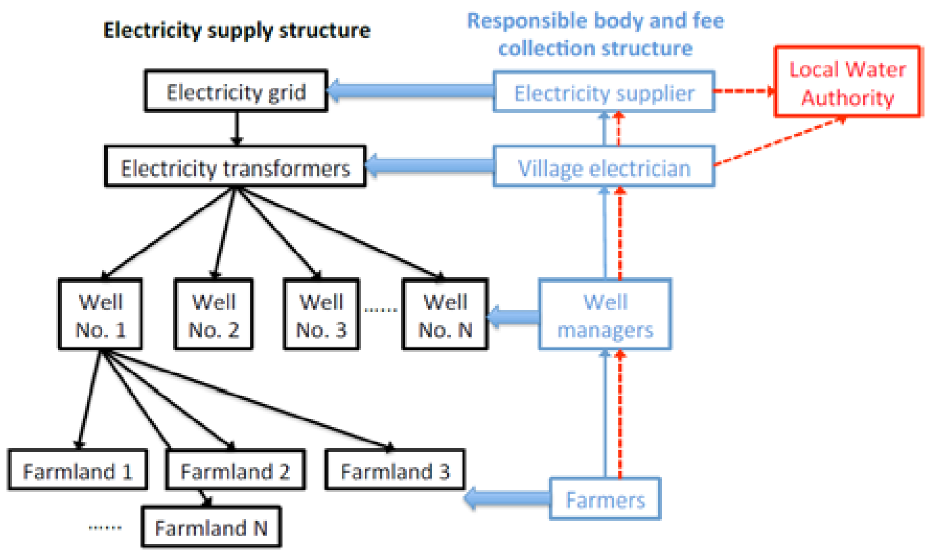

Figure 21. Proposed water fee collection structure for next phase.

4. Links to the SDGs

The Handan pilot project was conducted within a quite complex context. To some extent, the Handan pilot project serves as a pioneer for sustainable water management system building in China, as it shows the capacity for using smart technology to protect and recharge regional groundwater supplies and to introduce more sustainable water management. Groundwater over-abstraction is not caused by a single reason. Climate change, human impacts (from different sectors), poorly matched production – resources' distribution are among the many causes. All of these pose various difficulties to work to be done, which can only be overcome with an assembly of methods (e.g. water diversion construction projects, water savings projects, alternating high water consuming crops and many knowledge products reporting to the policy makers, such as water right allocation). The results gained and lessons learned within this pilot project can provide the technical support necessary to the implement these methods in other regional areas both in China and internationally. The monitoring and control methods introduced could also be up-scaled to larger areas requiring over-abstaction control. Links to several SDGs are as shown in Table 3, with descriptions below.

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Table 3. Links to the Sustainable Development Goals

Sustainable Development Goals and Targets	
SDG 2: Food security through sustainable agriculture **End hunger, achieve food security and improved nutrition and promote sustainable agriculture**	
2.3	By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment
2.4	By 2030, ensure sustainable food production systems and implement resilient agriculture practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality.
SDG 6: Clean water & sanitation **Ensure availability and sustainable management of water and sanitation for all**	
6.4	By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity
6.a	By 2030, expand international cooperation and capacity-building support to developing countries in water and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies
6.b	Support and strengthen the participation of local communities in improving water and sanitation management
SDG 11: Sustainable cities and communities **Make cities and human settlements inclusive, safe, resilient and sustainable**	
11.b	Encourage official development assistance and financial flows, including foreign investment, to States where the need is greatest, in particular least developed countries, African countries, small island developing States and landlocked developing countries, in accordance with their national plans and programmes.
SDG 12: Sustainable consumption **Ensure sustainable consumption and production patterns**	
12.2	By 2030, achieve the sustainable management and efficient use of natural resources

Links to SDG targets 2.3 and 2.4: One of important outcomes of the projects is the irrigating calculator, which is designed as a web tool to calculate the irrigation water demand of the main crops grown in the project pilot region. The total irrigation water demand of a whole region can be determined by cumulating the water demands for all crops with their respective areas. This provides a good plan for sustainable agriculture through ensuring equitable water for irrigation and makes the best use of water, so as to prevent that large arable areas may be left un-irrigated when water shortage occurs and secure agricultural productivity and farmer's income. By increasing farmers' knowledge of sustainable water management and providing better tools to allow more sustainable access to irrigation, these tools support resilient agricultural practices, sustainable food production and increased knowledge sharing for better decision-making for farmers.

Link to 6.4 and 6.A: 5 sets of water meters have been installed at the farmland with and without water saving facilities respectively, so that the effect of the water saving methods could be evaluated. This gives valuable feedback every year to the decision makers on how to adjust irrigating plans and the crop planting patterns. By increasing the farmers' awareness of water use and savings, they become able to adjust their irrigation practices to become more efficient and to use less water. The local departments of water resources are crucial in educating farmers of water saving since they have more expertise and motives.

Link to 6.B: This project is a great example of real time groundwater monitoring and its management through scenario based modeling on a pilot scale. Based on our model of using several decision support tools provides users with much easier access, such as computer, tablets and smartphones, and the irrigation calculator online tool of groundwater modeling. Training on the use of these tools has been conducted during the implementation of the project. The local technicians are now getting familiar with these technics and will definitely put them into their daily work in the future.

Link to 11.B: In addition to the informative tools and research that this project provides the government for decision making and planning for resilience to extreme weather and emergency situations, our findings also enable us to provide informed policy recommendations to the government to assist with effective and efficient policy decision for groundwater management in China. Our hope is that by sharing the results of our pilot project we can also assist other developing nations to implement smart tools and technology to address sustainable groundwater abstraction.

5. Outcome & lessons learned

5.1 Outcome

As presented in Table 1, the Handan pilot project has four fundamental objectives, and these objectives need to be fulfilled from May 2014 to December 2020. The project has been divided into two phases, and the first phase ended in March 2018. making major progress. Several outputs realized during Phase I have been illustrated in previous sections. Table 4 lists the task completion of Phase I of the project.

Table 4. Task completion in Phase I

Outcome/Outputs	Completion in Phase I
1. Providing data and information base for real-time water allocation	
1.1 Build up a central data and information exchange platform	Completed
1.2 Aquifer characterization of Guantao county	Completed
1.3 Water balance data for the chosen area in Guantao County	Completed
1.4 Groundwater table monitoring system	Completed
1.5 Real-time groundwater pumping monitoring system is developed and implemented	Completed
2. Developing and implementing an integrated real-time monitoring, modeling and controlling system to prevent groundwater depletion and build up adaptation capacity to climate change	
2.1 A water allocation tool for optimizing the choice of options to achieve a balanced groundwater reservoir is operable.	Completed
2.2 Real time groundwater model of the region is developed and calibrated	Almost completed
2.3 Overall groundwater monitoring/ controlling system is implemented	Continuing
3. Strategy options are elaborated through dialogues with the stakeholders and implemented by the local authorities.	
3.1 Control criteria and recovery strategy are established	Continuing
3.2 Strategies of optimizing surface water allocation will be elaborated and implemented in the Guantao region	Continuing
3.3 Strategies of groundwater control and recovery will be assessed, elaborated, and implemented in Guantao region	Continuing
3.4 Suggestions on legislation of conjunctive use of water resources according to water availability is proposed	Continuing
4. Improved knowledge of using real-time monitoring, modeling and controlling system to prevent groundwater depletion for arid regions in developing countries.	
4.1 Capacities and competences to operate the real-time monitoring/ controlling system are established	Continuing
4.2 Knowledge of a functional and tested real-time groundwater control system with supporting policies and strategies to be transferred to other water scarce regions in China	Continuing
4.3 Enriched experience of knowledge and technology of real time groundwater controlling transferrable to other developing countries	Continuing

5.2 Lessons learned

The project has made great progress since 2014 and achieved numerous results. However, during the project implementation we also experienced difficulties and have learned associated lessons. The following points summarize the lessons learned during the project operation. Special attention should be paid to these lessons so as to guarantee a successful continuation of the project implementation:

(1) Farmer's cooperation is important for monitoring system's installation and functional operation.

In Handan pilot region we have installed 10 sets of experimental meters of 5 different brands with two sets each, metering similar wells with and without water saving devices. All these different meters from different manufacturers were installed with much more effort than was expected in the project planning phase. Some of the meters were broken because of the careless (or intentional) removal/pulling of the power cables, and some were never operated due to farmers' refusal to use the installed water saving facilities. In summer 2016, all the experimental meters were moved to wells of which the owners/well managers were more cooperative. This problem does not only happen to our project meters, but also to the meters that have been installed with local monitoring wells. This results in delay of meaningful and reliable data to be collected.

Farmers' unwillingness to cooperate is partially motivated by their suspicion that the metering will eventually cost them additional fees. Another reason is that farmers feel that water saving facilities installed through the local water saving projects made them pay higher electricity bills for pumping the same amount of water. The successful operation of the metering system and water saving facilities will rely on farmers' cooperation. Necessary education and compensation will be necessary to maintain the farmers' cooperation on these issues. At the same time the pricing of water has to be reviewed to guarantee that farmers who use water savings do not end up paying more for a cubic meter than farmers who do not care about water saving.

(2) Integration of all the existing real-time data sent by different systems to one data platform proves to be a challenge. Our project experience could help future data integration of the local monitoring systems already installed or to be installed.
In Handan pilot region integrating 5 different varieties of pumping meters and 100 electricity meters for electrical transformers have shown quite some difficulties. The different meters from different manufacturers need different software to read the data from the signals sent to the central server at GIWP. The 100 sets of Lofty electricity meters also need their own software for reading the incoming data. For all metering companies and especially for the Iranian company, the business model is to install meters at low cost but to provide paid services for the customers afterwards. So they require sending the data to their own servers. After long discussions and negotiation between the project team and different meter manufacturers, an agreement has been reached that the manufacturers would provide the data format information, while Geopraevent provides code to read signals from different providers to extract data and saved in the database. In two cases the solution was found in giving Geopraevent access to the firm's database.

Sharing of the data from the devices installed on almost 1000 pumping wells and the 20 groundwater level monitoring wells installed by the local funds was agreed by Hebei provincial Department of Water Resources before the steering committee meeting, but the data has not been shared so far. The reason for this is that Hebei Provincial Department of Water Resources has not yet compiled all the data nor integrated them in one data platform, although it was supposed to be done by them. All the data are scattered in different softwares on different servers of various department divisions. This also shows how big a challenge it is to compile and integrate all the data from the monitoring devices installed by the local projects into one provincial system, as they are all in different formats. Our project experience could be useful to help the local authorities of data integration.

(3) The installation of electricity meters and monitoring electricity consumption needs cooperation with electricity sector
It took several months and several field visits to find out the reason why the electricity readings from the project electricity meters and the meters from the electricity department were inconsistent. The joint field investigation of the project expert team and implementation team, together with the electricity department finally found out that the electricity meters installed for the project were not properly installed. All the meters have to be re-installed. This shows the need for close cooperation with the electricity sector, not only because of their technical expertise and their ownership of the transformers, but also because only they can provide the data for the past, and even more important, in the future. Installing additional meters helps the project team to access more data directly and in real-time. However, for the scaling up of the effort in future, we urgently suggest to the water authorities to cooperate with the electricity department. Sharing their electricity data is a more cost-effective approach for groundwater abstractions monitoring than installing additional electricity meters.

(4) Importance of the calibration process
As the meters are produced by different manufacturers, various formats of output data are received, making it essential to integrate all of the monitoring data and transform them into normalized data values as quickly as possible to ensure the data is standardised.

5.3 Future plans

Phase II of the project was planned to commence in March 2018, however, the plan is still under examination for approval. In the second phase of the project, the aquifer will be managed as drought-relief storage using the real time groundwater monitoring, modelling, and control system. Different control strategies will be applied to achieve best results under different circumstances. The recovery of groundwater tables is a long-term process and can only be reached over a time span of decades.

6. Conclusion

One of the most salient problems of non-sustainable water use worldwide is the over-pumping of aquifers. A prominent example is the North China Plain aquifer system, which is heavily overexploited mainly by agricultural water use. Emptying of aquifers is more deplorable as they are the only over year storages for water available and thus capable of combating prolonged drought conditions. Extraction of groundwater by innumerable wells is not controllable. The difficulty posed by managing them is the major reason why many aquifers in the world are over-pumped. With new technology, the challenge of bringing these aquifers back to a sustainable extraction mode can be tackled.

To rehabilitate the aquifer in the North China Plain, we proposed a real-time monitoring, modeling and controlling system where in the final stage all major pumping wells can only be operated by an Integrated Circuit (IC) system carrying the quota allowed for each well. This system was tested and then adapted to and implemented in a pilot region in Guantao County of Handan Municipality in the North China Plain. The first phase of pilot project lasted from 2014 to 2018. In this phase we designed and introduced a strategy of managing resources which allows this equilibrium to be reached. In parallel, a system for monitoring and control of groundwater levels and groundwater abstraction have been built and tentatively operated putting a priority on enforcing pumping restrictions for the wells exploiting the deep aquifer. The planned goals have been realized.

The technical knowledge of controlling groundwater well fields in real-time has been developed in Switzerland. Developing a control system in the agricultural context of China, demonstrating its functionality and then transferring it to developing and transition countries has a high potential to contribute to drought mitigation and climate adaptation world-wide. This objective is in line with SDC's focus on sustainable development.

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