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Real-time Management of groundwater resource based on wireless sensor networks

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Abstract

Groundwater plays a vital role in the arid inland river basins, in which the groundwater management is critical to the sustainable development of area economy and ecology. Traditional sustainable management approaches are to analyze different scenarios subject to assumptions or to construct simulation–optimization models to obtain optimal strategy. However, groundwater system is time-varying due to exogenous inputs. In this sense, the groundwater management based on static data is relatively outdated. As part of the Heihe River Basin (HRB), which is a typical arid river basin in Northwestern China, the Daman irrigation district was selected as the study area in this paper. First, a simulation–optimization model was constructed to optimize the pumping rates of the study area according to the groundwater level constraints. Three different groundwater level constraints were assigned to explore sustainable strategies for groundwater resources. The results indicated that the simulation–optimization model was capable of identifying the optimal pumping yields and satisfy the given constraints. Second, the simulation–optimization model was integrated with wireless sensors network (WSN) technology to provide real-time features for the management. The results showed time-varying feature for the groundwater management, which was capable of updating observations, constraints, and decision variables in real time. Furthermore, a web-based platform was developed to facilitate the decision-making process. This study combined simulation and optimization model with WSN techniques and meanwhile attempted to real-time monitor and manage the scarce groundwater resource, which could be used to support the decision-making related to sustainable management.

Keywords

groundwater, management, networks, sensor, wireless, resource, real-time

Disciplines

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Article

Real-time Management of groundwater resource based on Wireless Sensors Network

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Abstract: Groundwater plays a vital role in the arid inland river basins, in which the groundwater management is critical to the sustainable development of area economy and ecology. Traditional sustainable management approaches are to analyze different scenarios subject to assumptions or to construct simulation-optimization models to obtain optimal strategy. However, groundwater system is time-varying due to exogenous inputs. In this sense, the groundwater management based on static data is relatively outdated. As part of the Heihe River Basin (HRB), which is a typical arid river basin in northwestern China, the Daman irrigation district was selected as the study area in this paper. First, a simulation-optimization model was constructed to optimize the pumping rates of the study area according to the groundwater level constraints. Three different groundwater level constraints were assigned to explore sustainable strategy for groundwater resource. The results indicated that the simulation-optimization model was capable of identifying the optimal pumping yields while satisfying the given constraints. Second, the simulation-optimization model was integrated with Wireless Sensors Network technology to provide real-time features for the management. The results showed time-varying feature for the groundwater management which was capable of updating observations, constraints and decision variables in real-time. Furthermore, a web-based platform was developed to facilitate the decision-making process. This study combined simulation and optimization model with WSN techniques and meanwhile attempted to real-time monitor and manage the scarce groundwater resource which could be used to support decision making related to sustainable management.

Keywords: Groundwater management; real-time; simulation; optimization; sustainable

1. Introduction

Freshwater is one of the precious, unique resources on the planet. It is meanwhile essential for agriculture, domestic usage, industry and environment. The rapid economic growth, population growth, urbanization and continuous expansion of human development, have aggravated water scarcity in many basins. Owing to several unique features (e.g. widespread and continuous availability, low development cost, drought reliability), groundwater has become one of the important sources of water supplies among the available water resources throughout the world in the last decades. The importance of groundwater resources increases in pace with the continuous growth of world population, which is expected to reach 11.2 billion in 2100 [1]. Therefore, it is very important to sustainably manage the groundwater resources in order to satisfy the increasing demand. However, because of the lack of policy making and supervision measures for the utilization, the over-exploitation of groundwater in many areas was serious, which may alter the flow regimes and become a threat to socio-economic development and ecological health [2]. The middle reaches of Heihe River Basin (HRB), which is located in the arid regions of northwestern China, have faced serious water problems [3]. In the last 30 years, the groundwater level declines along with the dramatically increase of agricultural pumping wells (from 3199 in 1985 to 6275 in 2005). Especially, in Daman irrigation district, the groundwater level has dropped 20m due to the unconstrained groundwater exploitation. A number of researches have tried to tackle the groundwater resources management problems by using scenario analysis [4,5]. However, to select the optimal operational procedure or policy could be extremely difficult because of the complexity of groundwater systems and relatively limited onsite studies. To address this difficulty, the groundwater simulation models are suggested to be linked with optimization techniques to obtain the best (or optimal) management strategy from many possible strategies [6]. These approaches are all based on static data which cannot reflect the real-time situations. Therefore, decisions, which are made based on these approaches, are always obsolete to some extents. On the other hand, among traditional sampling techniques related to groundwater monitoring, the most common method is grab sampling which can be conducted on-site using hand held instruments. Grab Sampling is subject to several disadvantages. First, process is labor intensive and costly. Second, the sampling interval is quite large which leads to sparse results datasets.

With the rapid development of Information and Communications Technology (ICT), Wireless sensors network (WSN) techniques have gained worldwide attention in recent years. The WSN was already recognized as part of the Earth Observing System (EOS) by most researchers. Many famous institutions in Geo-Information Science (United States Geological Survey, USGS; National Research Council, NRC; National Geo-Spatial-Intelligence Agency, NGA, et. al.) have considered WSN as an extension and important part of EOS, International Earth Observing System and Global Earth Observation System of Systems. In the field of hydrology, WSN was also an important source of observation data. In China, researches and developments of major projects and frontier fields in the “National plan for medium and long-term science and technology development (2006 ~ 2020)” have emphasized WSN as one of the most important directions. The emerging technology of WSN can be used to mitigate the aforementioned problems due to its integrity and wireless network of sensing devices. The WSN requires little maintenance after its deployment. The sampling interval can be from minutes to days. Therefore, the real-time management of groundwater system is built on top of a WSN.

In this paper, we developed a real-time groundwater management system for Daman irrigation district in the middle reaches of the HRB. The WSN techniques were used in the system in order to provide the real-time data. We also optimized the proposed highly efficient and reliable method to calculate the pumping yields of groundwater, subject to the constraints of groundwater level. A numerical model was constructed to provide objective function evaluations. A larger boundary was selected to provide the boundary conditions for Daman irrigation district. The contributions of this paper include:

1. developing a simulation-optimization model to analyze the groundwater level data;
2. designing and implementing an architecture of real-time groundwater management system to provide real-time support for the decision making.

This work is inter-disciplinary in nature. Different expertise from computer science and environmental engineering were combined. We anticipate this paper contributing to real-time sustainable management researches of groundwater resources. Findings on intelligent techniques for sensor data collection can be found in [7].

2. Related Work

A number of researches have tried to tackle the sustainable management problems of groundwater resources by using monitor systems and model simulations [8-10]. The groundwater flow and land deformation were integrated in anisotropic aquifer system. The model was applied to conduct pumping recovery tests under various conditions in order to design groundwater pumping projects for Shanghai, China [11]. Carmen et al. proposed a hydro-economic model to balance the trade-off between sustainable management of groundwater resource and the cost of overexploited aquifers in the Segura basin, Southeast Spain [12]. Huo et al. integrated the soil and water assessment tool (SWAT) for simulating the surface water and MODFLOW for simulating the groundwater in order to explore the discharge from the river under future predictions [4]. A few optimization techniques have been used for irrigation management [6,13-16]. Sadeghi-Tabas et al. proposed an attempt to link MODFLOW with the multi-algorithm genetically adaptive search method (AMALGAM) to optimize the pumping rates for the groundwater system in Iran [17]. A surrogate-based approach was developed based on the integrated surface water-groundwater modeling to optimize the percentage of surface water and groundwater in the irrigation water in order to obtain a better balance between the groundwater storage in the middle reaches of HRB and the environmental flow for the lower reaches [18]. Hamid R. Safavi and Mehrdad Falsafioun conducted a combination of a genetic algorithm optimization model and scenario analysis to develop an optimal plan for the conjunctive use of surface water and groundwater resources in Zayandehrud Basin, Iran [19]. However, these researches were based on static data which were relatively obsolete.

As recent technology advancements occur in WSNs, an ideal application - environmental monitoring is becoming feasible. Environmental sensor networks provide a powerful combination of distributed sensing capacity, real-time data visualization and analysis, and integration with adjacent networks and remote sensing data streams. Rundel et. al reviewed environmental sensor networks in ecological research [20]. Lin et. al. examined the relationship between home occupant behavior and indoor air quality by collecting both sensor-based behavior data and chemical indoor air quality measurements in smart home environments [21]. Jiang et. al. [22] developed a water environmental monitoring system based on WSN. The system was proved to auto-monitor the water temperature and pH value of environment and artificial lake. This study makes use of WSNs to monitor the environment in real-time. The WSNs was integrated with groundwater contamination transport models in a realistic simulative environment [23]. This study focused on the contaminant transport and suggested that contaminant transport models could benefit from WSNs techniques as WSNs getting mature. In this study, advances in WSNs, groundwater simulations and optimizations were integrated to sustainably manage the groundwater resources in real-time.

3. Materials and Methods

3.1. Study area

Daman irrigation district which located in the upper part of the middle reaches of HRB was selected to examine the proposed groundwater management system. Located in the northwest of China (Figure 1), the HRB is dominated by very limited (69-216 mm) precipitation but strong evaporation (1453-2351 mm). The Heihe River flows into the middle reaches through Yingluo Gorge hydrologic station which located at the southeast of the basin and flow out through Zhengyi Gorge hydrologic station which located at northwest of the basin. About 788 pumping wells had been constructed in the Daman irrigation district since the 1980s [24]. The groundwater level declined 20m in the past 20 years due the over-exploitation of groundwater. An observation well at (38.8N, 100.4E) was constructed in the Daman irrigation districts and time series data of groundwater level had been obtained from 1980s. In this work, we primarily focused on utilizing the data of Daman irrigation districts and the time period was set to year. All these well data were collected and preprocessed for the structured groundwater study via the sensor network [7,25,26]. Meanwhile, the feedback and executors, which are operating in the real fields, were also deployed by the remote sensor network. We will detail the backend system design and development in following sections.

3.2. System Design

The scheme of the real-time groundwater management system is illustrated in Figure 2. Recent achievements in hydrology tended to benefit from the development and application of sensor technology, wireless communication and information infrastructure. Six groundwater probes (HOBO water level Logger U20-001-01 and U20-001-01-Ti) were installed in the middle reaches of the Heihe River Basin (Figure 1) with the capability to record the pressure of groundwater (which could be used to obtain the groundwater level) and the temperature of groundwater. One of the probes was deployed in the study area in Daman borehole. All the sensors were connected to a data logger and the data recording interval was setting as one hour. The groundwater depth could derive from the pressure of groundwater. Together with the depth of HOBO and the elevation from differential Global Positioning System (GPS), the groundwater level was calculated. The observed data relayed to the database via General Packet Radio Service (GPRS). The groundwater level was used by simulation-optimization model to generate optimal water usage scheme in order to support the decision makings. The decisions would have positive or negative effects on the groundwater resources which could be later observed by the probes. As we were building this real-time management system of groundwater as our first attempt, the time interval was set to one year. The observed data by HOBO was averaged to the system time interval.

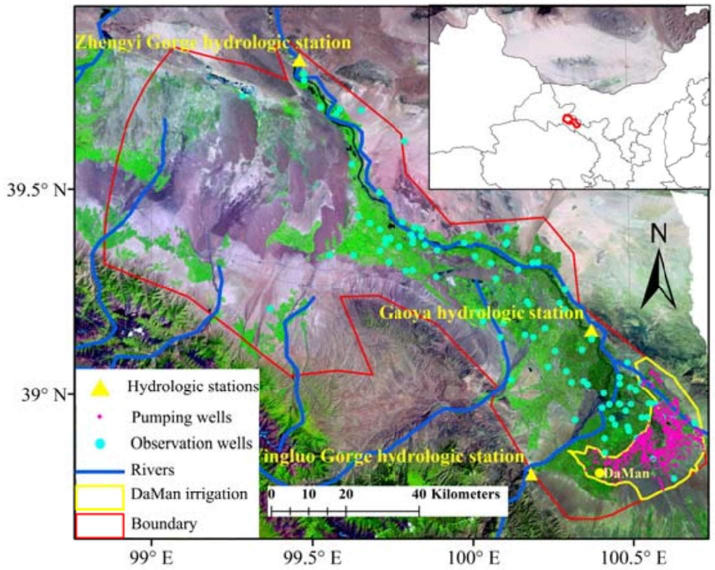


Figure 1. Location and map of the middle reaches of the Heihe River Basin and Daman irrigation district

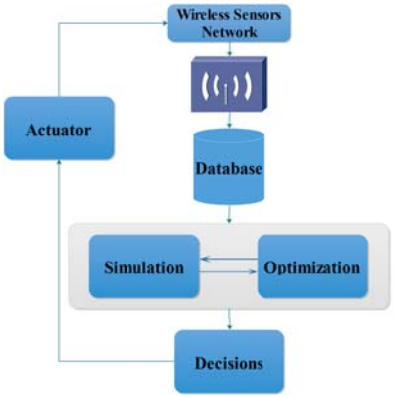


Figure 2. Scheme of real-time groundwater management system

3.3. Simplex Method

The groundwater management problem was formulated by three components: an objective function, a set of decision variables and constraints. The optimization problem is defined as to maximize or minimize the objective function which is usually stated in terms of decision variables subject to the specified constraints. In this study, the optimization problem was to identify the maximum groundwater pumping rates (decision variables) in Daman irrigation district (objective function) subject to specified groundwater level (constraints) at Daman borehole. In other words, the objective function was to maximize:

$$\begin{aligned} &\mathrm{Z} = C^{T}X \\ \text{Subject to,}\quad &\mathrm{AX} \leq \mathrm{B} \\ &\mathrm{LB} \leq \mathrm{X} \leq \mathrm{UB} \end{aligned} \tag{1}$$

Where Z was the pumping yields in Daman irrigation district; $C^T = (c_1, c_2, \ldots, c_n)^T$ represented the weights of the decision variables which were all set to 1 in this study; the superscript T stands for vector transpose; X was the pumping rates; A represented the vector of response coefficients which were calculated from the Response Matrix method in following section; $B = (b1, b2, \ldots, bp)^T$ was the vector of groundwater level constrains; LB and UB were the lower bound and upper bound of the pumping rates.

3.4. Response Matrix Method

Due to the large computational cost of the numerical model, the response matrix method was applied to transform the groundwater management problem into an optimization function approximately. The response matrix method was briefly summarized as follows, please referred to [27] for detailed description.

The idea of the response matrix is to approximate the relations between the decision variables and the constraints which are originally described in the numerical model by physical equations. Suppose the groundwater level is a function of a set of pumping rates.

$$H_{i,j,k,t} = H_{i,j,k,t}(Qw) \tag{2}$$

Where Qw represents the vector of all withdrawal and/or injection rates in Daman irrigation district; H is the groundwater level; (i, j, k) represents a location in the three-dimensional aquifer system; and t is time.

A first-order Taylor series expansion can be applied to approximate the groundwater level at the constraint location:

$$H_{i,j,k,t}(Qw) = H^{0}_{i,j,k,t}(Qw^{0}) + \sum_{n=1}^{N} \frac{\partial H_{i,j,k,t}}{\partial Qw_n}(Qw^{0})(Qw_n - Qw_n^{0}) \tag{3}$$

Where H^0 and Qw^0 represent the base (initial) condition of groundwater level and pumping rates; $\frac{\partial H_{i,j,k,t}}{\partial Qw_n}$ are the response coefficients; n is the number of decision variables.

The response coefficients are approximated as:

$$\frac{\partial H_{i,j,k,t}}{\partial Qw_n} \approx \frac{\Delta H_{i,j,k,t}}{\Delta Qw_n} = \frac{H_{i,j,k,t}(Qw_{\Delta n}) - H^{0}_{i,j,k,t}(Qw^{0})}{\Delta Qw_n} \tag{4}$$

Where ΔQw_n is the perturbation for the n-th decision variable; $Qw_{\triangle n}$ represent the pumping rates after perturbation.

3.5. Numerical Groundwater Flow Model

In this study, the response coefficients were calculated from a three-dimensional groundwater model which was constructed by MODFLOW. For detailed information about MODFLOW, please refer to [28]. Several physical processes were identified as principal processes in the study area (shown in Table 1).

Table 1. Packages used in the establishment of the groundwater model.

Physical processes	MODFLOW Packages
Irrigation and precipitation	RCH[28]
Evapotranspiration	EVT[28]
Groundwater exploitation	Well[28]

River	STR[29]
Boundary influx	Well[28]

3.6. Data Collection

The management system was conducted from 1986 to 2012 with yearly stress period due to the availability of data. Landsat TM/ETM+ images in 1986 [30], 2000 [31], and 2007 [32] were processed to obtain the cultivated area. Groundwater levels from 42 monitoring wells (Figure 1), annual runoff at Yingluo, Gaoya, and Zhengyi hydrologic stations, irrigation and groundwater exploitation data were used and obtained from the WestDC [33].

4. **Results**

4.1. Calibration

The groundwater simulation was conducted from 1986 to 2012 with yearly stress periods. The parameters of the middle reaches of the HRB were calibrated. The calibration of the model was accomplished by a combination procedure of the parameter estimation code PEST [34] and trial-and-error method. Eight sub-zones of hydraulic conductivities were identified based on the hydrogeological map [35] and adjusted (shown in Figure 3). The observed and simulated groundwater level at all the observation wells in the middle reaches of the HRB during the calibration period indicated a reasonable match. The calculated and observed streamflow hydrographs at Gaoya and Zhengyi Gorge hydrologic stations basically had similar trends, with the calculated streamflow being in good agreement with the observed ones over a yearly time step. The calculated groundwater levels and streamflow during the simulation periods could be referred to [27].

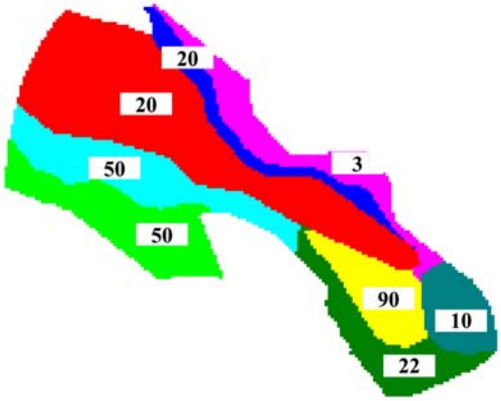


Figure 3. The sub-zonation and values of hydraulic conductivities

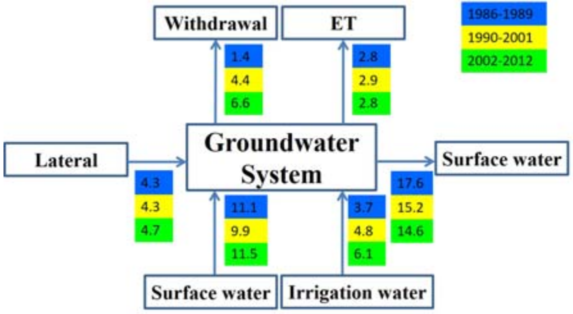


Figure 4. Water balance of the middle reaches of the HRB

The groundwater pumping data, irrigation data and cultivated areas obtained from WestDC [33] were divided into three periods (1986 ~ 1989, 1990 ~ 2001, and 2002 ~ 2012). Therefore, the water balance for the middle reaches of the HRB was analyzed corresponding to the three periods (Figure 4). Figure 4 indicated that the main groundwater recharge source of the study area was the leakage from the Heihe River which accounted for about 50% of the total recharge amount. Other important sources of groundwater recharge were the irrigation backflow and the lateral inflow from the mountain area which accounted for about 27% and 21%, respectively. The principal sink term of the groundwater was the drainage from the groundwater to the river which accounted for about 80%, 67%, and 60% of the total amount in different periods. The difference between periods represented the groundwater dynamics, which is mainly due to the different groundwater exploitations in different periods. In addition, the figure also indicated that the groundwater system was under negative water balance in almost 30 years.

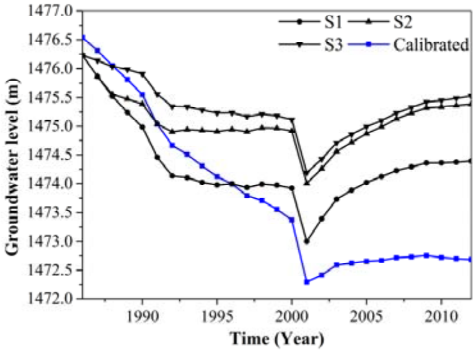


Figure 5. Comparison of the optimized groundwater levels for S1, S2, and S3 and the base condition (the calibrated groundwater level) at Daman observation well

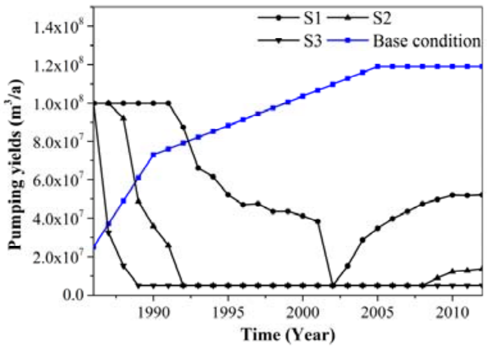


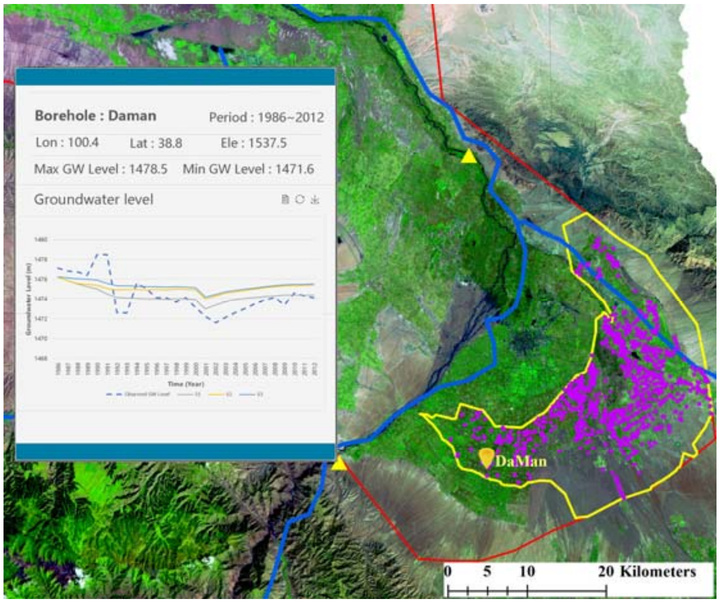
Figure 6. Comparison of the optimized pumping yields for S1, S2, and S3 and the base condition (the pumping yields from the collected data) of Daman irrigation district

4.2. Optimization

The calibration results indicated the serious shortage and decreasing trend of the groundwater resources in the study area. Therefore, a test case for groundwater management was conducted and analyzed in this section. In our system, the optimization problem was to maximize the total groundwater pumping yields in Daman irrigation district subjected to the groundwater level constraints at Daman observation borehole. Several groundwater level constraints with 1474 m, 1475 m, and 1476 m were applied (hereafter referred as S1, S2, and S3, respectively). By analyzing the historical data, the LB and UB of the pumping yields in all scenarios were set to be $0.05 \times 10^8 m^3/a$, and $1.0 \times 10^8 m^3/a$ respectively. In most researches, offline data was used to sustainably manage the groundwater resources. However, the groundwater level was observed incessantly. A WSN with HOBO water level Logger U20-001-01 was deployed to measure and record the continuous groundwater level. A real-time system was implemented to manage the groundwater resources by combining the incessantly real-time observation and optimization. The data from 1986 to 2012 was used to simulate the real-time data by inputting the simulation/optimization model each time step. During each time step, the groundwater level was calculated by simulating groundwater system. The decision variables (pumping rates) were used to adjust the simulated groundwater level to the constraints. The optimized groundwater levels were shown in Figure 5 to indicate a reasonable control based on the constraints. The pumping yields, which were optimized in three different scenarios with different groundwater level constraints, was shown in Figure 6. The average pumping yields for S1, S2, and S3 were ~ $0.57\times10^8 m^3/a$, ~$0.2\times10^8 m^3/a$, and ~$0.1\times10^8 m^3/a$, respectively. The annual amount of surface water diverted from the Heihe River was around $1.36\times10^8 m^3/a$ which was used to sustain a cultivated area of about $3.29\times10^8 m^2$ according to the data collected by WestDC [33]. We assume that, the climate condition remains an average level with usual runoff and lateral flow from the upper reaches. Under this assumption, the total cultivated area, which could be supported by the limited water resources in Daman irrigation district, could be calculated with the consideration of the optimal irrigation water demand (on average ~570 mm expressed in water depth) [36]. Therefore, the cultivated area, which could be sustained by the available water resources in S1, S2, and S3, were ~$3.38\times10^8 m^2$, ~$2.73\times10^8 m^2$, and ~$2.56\times10^8 m^2$ respectively. However, according to the current irrigation techniques, the average total irrigation water in Daman irrigation district was 601 mm expressed in water depth [36] which meant ~$0.22\times10^8 m^2$, ~$2.3\times10^8 m^2$, and ~$0.2\times10^8 m^2$ of cultivated area could be supported.

4.3. Real-time Management of groundwater resources

The real-time management of groundwater resources was accomplished by integrating WSN techniques, simulation process and optimization modelling. The simulation process was prepared before the optimization and real-time management using the offline data to calibrate and verify. The real-time data from WSN was used to optimize the groundwater level by adjusting the pumping rates. The management system was updated when new groundwater level observations and pumping data became available. The decision makers could manage the groundwater resources based on the real-time optimization to obtain better decisions. Furthermore, the real-time management system was integrated into a web-based platform (shown in Figure 7), which facilitate the decision makers. The platform emphasized the study area and the location of the borehole. By clicking the (yellow) label for the borehole, detail information was displayed. The observed groundwater level (dashed line in Figure 7) was plotted based on the in-situ observation stored in the database which measured and transferred by the WSN. The groundwater resource was optimized based on different groundwater level constraints and displayed in the chart (solid line in Figure 7). The optimized curves could offer rational results of the decision on groundwater level constraints. The observed groundwater level was an indicator of the management effects. Therefore, the decision makers could make decisions at every time step based on the real-time observations and optimizations.



Borehole : Daman Period : 1986~2012

Lon : 100.4 Lat : 38.8 Ele : 1537.5

Max GW Level : 1478.5 Min GW Level : 1471.6

Figure 7. Real-time monitoring and management of groundwater resources.

5. Conclusions

In this study, a real-time management system of groundwater resource was designed and developed based on WSN techniques. This system was preliminarily deployed in the middle reaches of the Heihe River Basin (HRB) to help solving the groundwater depletion problem. Daman irrigation in the middle reaches of the HRB was selected as the pilot region. The management system contained a correlated simulation-optimization model, which offered the optimal decision variables subject to constraints. With the facility of WSN techniques, a real-time management system was implemented to provide accurate decision support. Reasonable results were obtained by appropriately defining the initial/boundary conditions and calibrating the parameters. The simulated results revealed that Daman irrigation district were experiencing dramatically groundwater level drawdown with 20m in the past three decades. The optimization part employed in this simplex method was proved to be effective, while controlling the groundwater level from drawdown. Under the normal water resources condition, the cultivated area for different scenarios, which could be sustained by the available water resources, was calculated. Furthermore, the real-time management system was integrated into a web-based platform to ease the decision makers' work. In our future direction, we will deploy more wireless sensors and further expand the concept of real-time management to the whole basin with the consideration of surface water to regulate water resources in a basin scale.

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Author Contributions: Qingguo Zhou and Chong Chen initialized the research idea and developed the models with contributions from Huaming Chen, Gaofeng Zhang and Rui Zhou collected the data. Yingnan Yan helped the implementation and tested the whole system. The manuscript was accomplished by Chong Chen and Huaming Chen with Jun Shen providing reviews and comments. All the authors were engaged in the final manuscript preparation and agreed to the publication of this paper.

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