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

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

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 In this sense, the groundwater management based on static data is relatively outdated.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

Engineering | Science and Technology Studies

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1 Article

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

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16 management is critical to the sustainable development of area economy and ecology. Traditional
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18 to construct simulation-optimization models to obtain optimal strategy. However, groundwater
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20 based on static data is relatively outdated. As part of the Heihe River Basin (HRB), which is a
21 typical arid river basin in northwestern China, the Daman irrigation district was selected as the
22 study area in this paper. First, a simulation-optimization model was constructed to optimize the
23 pumping rates of the study area according to the groundwater level constraints. Three different
24 groundwater level constraints were assigned to explore sustainable strategy for groundwater
25 resource. The results indicated that the simulation-optimization model was capable of identifying
26 the optimal pumping yields while satisfying the given constraints. Second, the
27 simulation-optimization model was integrated with Wireless Sensors Network technology to
28 provide real-time features for the management. The results showed time-varying feature for the
29 groundwater management which was capable of updating observations, constraints and decision
30 variables in real-time. Furthermore, a web-based platform was developed to facilitate the
31 decision-making process. This study combined simulation and optimization model with WSN
32 techniques and meanwhile attempted to real-time monitor and manage the scarce groundwater
33 resource which could be used to support decision making related to sustainable management.

34 **Keywords:** Groundwater management; real-time; simulation; optimization; sustainable
35

36 **1. Introduction**

37 Freshwater is one of the precious, unique resources on the planet. It is meanwhile essential for
38 agriculture, domestic usage, industry and environment. The rapid economic growth, population
39 growth, urbanization and continuous expansion of human development, have aggravated water
40 scarcity in many basins. Owing to several unique features (e.g. widespread and continuous
41 availability, low development cost, drought reliability), groundwater has become one of the
42 important sources of water supplies among the available water resources throughout the world in
43 the last decades. The importance of groundwater resources increases in pace with the continuous
44 growth of world population, which is expected to reach 11.2 billion in 2100 [1]. Therefore, it is very
45 important to sustainably manage the groundwater resources in order to satisfy the increasing

46 demand. However, because of the lack of policy making and supervision measures for the
47 utilization, the over-exploitation of groundwater in many areas was serious, which may alter the
48 flow regimes and become a threat to socio-economic development and ecological health [2]. The
49 middle reaches of Heihe River Basin (HRB), which is located in the arid regions of northwestern
50 China, have faced serious water problems [3]. In the last 30 years, the groundwater level declines
51 along with the dramatically increase of agricultural pumping wells (from 3199 in 1985 to 6275 in
52 2005). Especially, in Daman irrigation district, the groundwater level has dropped 20m due to the
53 unconstrained groundwater exploitation. A number of researches have tried to tackle the
54 groundwater resources management problems by using scenario analysis [4,5]. However, to select
55 the optimal operational procedure or policy could be extremely difficult because of the complexity
56 of groundwater systems and relatively limited onsite studies. To address this difficulty, the
57 groundwater simulation models are suggested to be linked with optimization techniques to obtain
58 the best (or optimal) management strategy from many possible strategies [6]. These approaches are
59 all based on static data which cannot reflect the real-time situations. Therefore, decisions, which are
60 made based on these approaches, are always obsolete to some extents. On the other hand, among
61 traditional sampling techniques related to groundwater monitoring, the most common method is
62 grab sampling which can be conducted on-site using hand held instruments. Grab Sampling is
63 subject to several disadvantages. First, process is labor intensive and costly. Second, the sampling
64 interval is quite large which leads to sparse results datasets.

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

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

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

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

93 **2. Related Work**

94 A number of researches have tried to tackle the sustainable management problems of
95 groundwater resources by using monitor systems and model simulations [8-10]. The groundwater
96 flow and land deformation were integrated in anisotropic aquifer system. The model was applied to

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

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

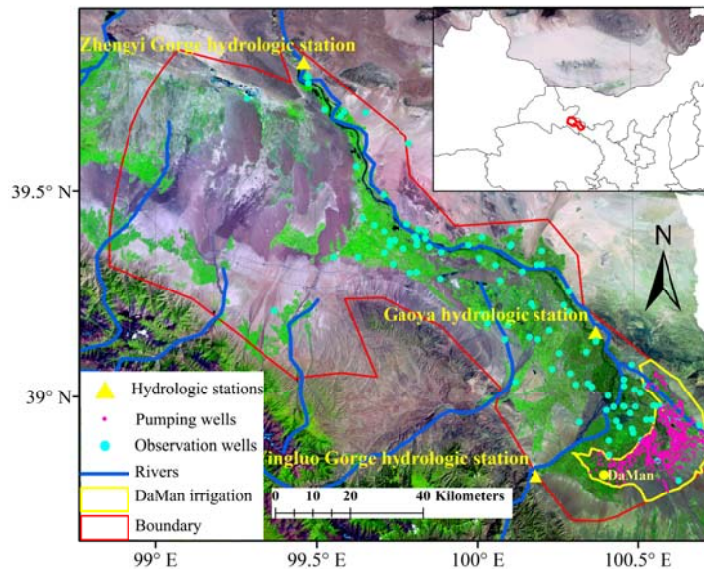
129 **3. Materials and Methods**

130 *3.1. Study area*

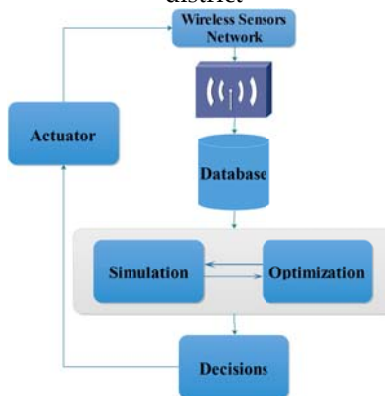
131 Daman irrigation district which located in the upper part of the middle reaches of HRB was
132 selected to examine the proposed groundwater management system. Located in the northwest of
133 China (Figure 1), the HRB is dominated by very limited (69-216 mm) precipitation but strong
134 evaporation (1453-2351 mm). The Heihe River flows into the middle reaches through Yingluo Gorge
135 hydrologic station which located at the southeast of the basin and flow out through Zhengyi Gorge
136 hydrologic station which located at northwest of the basin. About 788 pumping wells had been
137 constructed in the Daman irrigation district since the 1980s [24]. The groundwater level declined
138 20m in the past 20 years due the over-exploitation of groundwater. An observation well at (38.8N,
139 100.4E) was constructed in the Daman irrigation districts and time series data of groundwater level
140 had been obtained from 1980s. In this work, we primarily focused on utilizing the data of Daman
141 irrigation districts and the time period was set to year. All these well data were collected and
142 preprocessed for the structured groundwater study via the sensor network [7,25,26]. Meanwhile, the
143 feedback and executors, which are operating in the real fields, were also deployed by the remote
144 sensor network. We will detail the backend system design and development in following sections.

145 *3.2. System Design*

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



163
 165 Figure 1. Location and map of the middle reaches of the Heihe River Basin and Daman irrigation
 166 district



166
 167 Figure 2. Scheme of real-time groundwater management system

168 3.3. Simplex Method

160 The groundwater management problem was formulated by three components: an objective
 161 function, a set of decision variables and constraints. The optimization problem is defined as to

170 maximize or minimize the objective function which is usually stated in terms of decision variables
 171 subject to the specified constraints. In this study, the optimization problem was to identify the
 172 maximum groundwater pumping rates (decision variables) in Daman irrigation district (objective
 173 function) subject to specified groundwater level (constraints) at Daman borehole. In other words,
 174 the objective function was to maximize:

$$175 \quad \quad \quad Z = C^T X$$

$$176 \quad \quad \quad \text{Subject to, } AX \leq B \quad (1)$$

$$177 \quad \quad \quad LB \leq X \leq UB$$

178 Where Z was the pumping yields in Daman irrigation district; $C^T = (c_1, c_2, \dots, c_n)^T$ represented
 179 the weights of the decision variables which were all set to 1 in this study; the superscript T stands
 180 for vector transpose; X was the pumping rates; A represented the vector of response coefficients
 181 which were calculated from the Response Matrix method in following section; $B = (b_1, b_2, \dots, b_p)^T$
 182 was the vector of groundwater level constrains; LB and UB were the lower bound and upper bound
 183 of the pumping rates.

184 3.4. Response Matrix Method

185 Due to the large computational cost of the numerical model, the response matrix method was
 186 applied to transform the groundwater management problem into an optimization function
 187 approximately. The response matrix method was briefly summarized as follows, please referred to
 188 [27] for detailed description.

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

$$192 \quad \quad \quad H_{i,j,k,t} = H_{i,j,k,t}(Qw) \quad (2)$$

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

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

$$198 \quad \quad \quad H_{i,j,k,t}(Qw) = H_{i,j,k,t}^0(Qw^0) + \sum_{n=1}^N \frac{\partial H_{i,j,k,t}}{\partial Qw_n}(Qw^0)(Qw_n - Qw_n^0) \quad (3)$$

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

201 The response coefficients are approximated as:

$$202 \quad \quad \quad \frac{\partial H_{i,j,k,t}}{\partial Qw_n} \approx \frac{\Delta H_{i,j,k,t}}{\Delta Qw_n} = \frac{H_{i,j,k,t}(Qw_{\Delta n}) - H_{i,j,k,t}^0(Qw^0)}{\Delta Qw_n} \quad (4)$$

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

205 3.5. Numerical Groundwater Flow Model

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

210 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]

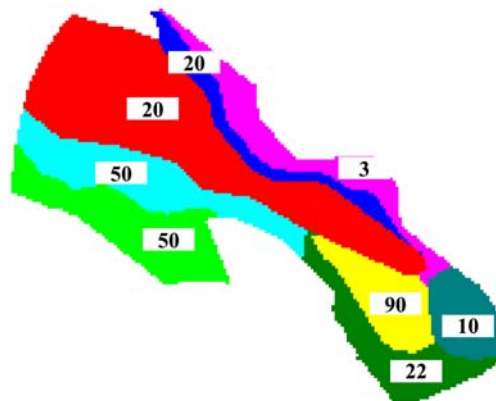
211 3.6. Data Collection

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

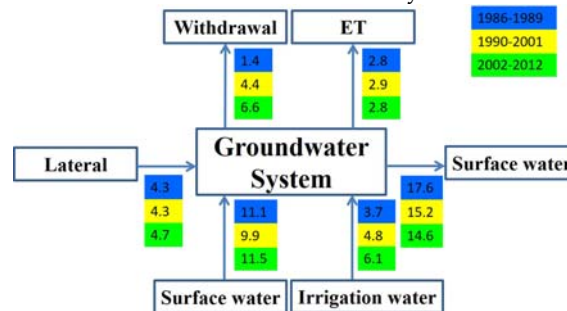
217 4. Results

218 4.1. Calibration

219 The groundwater simulation was conducted from 1986 to 2012 with yearly stress periods. The
 220 parameters of the middle reaches of the HRB were calibrated. The calibration of the model was
 221 accomplished by a combination procedure of the parameter estimation code PEST [34] and
 222 trial-and-error method. Eight sub-zones of hydraulic conductivities were identified based on the
 223 hydrogeological map [35] and adjusted (shown in Figure 3). The observed and simulated
 224 groundwater level at all the observation wells in the middle reaches of the HRB during the
 225 calibration period indicated a reasonable match. The calculated and observed streamflow
 226 hydrographs at Gaoya and Zhengyi Gorge hydrologic stations basically had similar trends, with the
 227 calculated streamflow being in good agreement with the observed ones over a yearly time step. The
 228 calculated groundwater levels and streamflow during the simulation periods could be referred to
 229 [27].



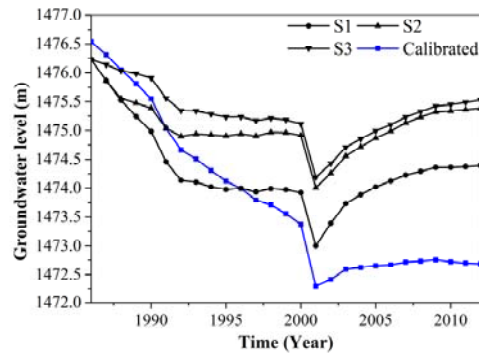
230 Figure 3. The sub-zonation and values of hydraulic conductivities



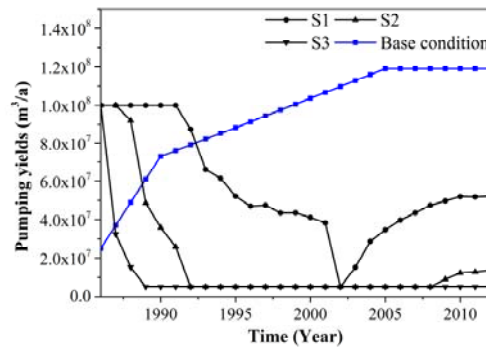
231 Figure 4. Water balance of the middle reaches of the HRB

232 The groundwater pumping data, irrigation data and cultivated areas obtained from WestDC
 233 [33] were divided into three periods (1986 ~ 1989, 1990 ~ 2001, and 2002 ~ 2012). Therefore, the water
 234 balance for the middle reaches of the HRB was analyzed corresponding to the three periods (Figure
 235 4). Figure 4 indicated that the main groundwater recharge source of the study area was the leakage
 236
 237

238 from the Heihe River which accounted for about 50% of the total recharge amount. Other important
 239 sources of groundwater recharge were the irrigation backflow and the lateral inflow from the
 240 mountain area which accounted for about 27% and 21%, respectively. The principal sink term of the
 241 groundwater was the drainage from the groundwater to the river which accounted for about 80%,
 242 67%, and 60% of the total amount in different periods. The difference between periods represented
 243 the groundwater dynamics, which is mainly due to the different groundwater exploitations in
 244 different periods. In addition, the figure also indicated that the groundwater system was under
 245 negative water balance in almost 30 years.



246
 247 Figure 5. Comparison of the optimized groundwater levels for S1, S2, and S3 and the base condition
 248 (the calibrated groundwater level) at Daman observation well



249
 250 Figure 6. Comparison of the optimized pumping yields for S1, S2, and S3 and the base condition
 251 (the pumping yields from the collected data) of Daman irrigation district

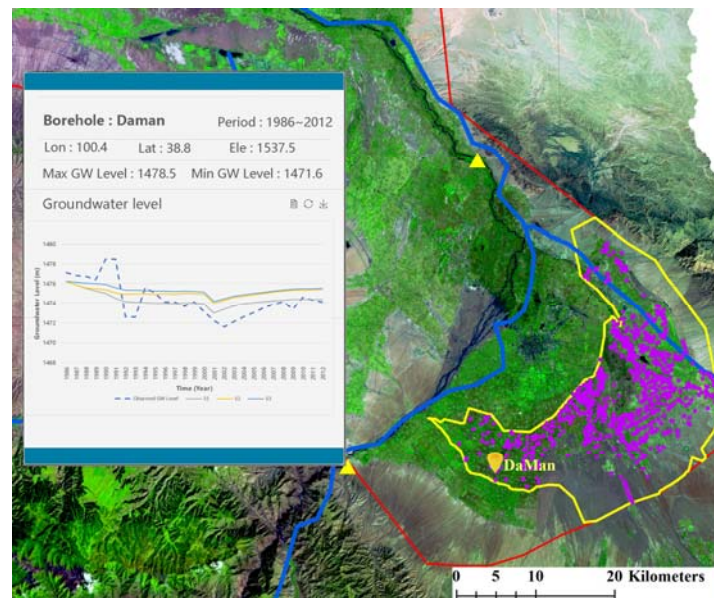
252 4.2. Optimization

253 The calibration results indicated the serious shortage and decreasing trend of the groundwater
 254 resources in the study area. Therefore, a test case for groundwater management was conducted and
 255 analyzed in this section. In our system, the optimization problem was to maximize the total
 256 groundwater pumping yields in Daman irrigation district subjected to the groundwater level
 257 constraints at Daman observation borehole. Several groundwater level constraints with 1474 m,
 258 1475 m, and 1476 m were applied (hereafter referred as S1, S2, and S3, respectively). By analyzing
 259 the historical data, the LB and UB of the pumping yields in all scenarios were set to be $0.05 \times$
 260 $10^8 \text{ m}^3/\text{a}$, and $1.0 \times 10^8 \text{ m}^3/\text{a}$ respectively. In most researches, offline data was used to sustainably
 261 manage the groundwater resources. However, the groundwater level was observed incessantly. A
 262 WSN with HOBO water level Logger U20-001-01 was deployed to measure and record the
 263 continuous groundwater level. A real-time system was implemented to manage the groundwater
 264 resources by combining the incessantly real-time observation and optimization. The data from 1986
 265 to 2012 was used to simulate the real-time data by inputting the simulation/optimization model
 266 each time step. During each time step, the groundwater level was calculated by simulating
 267 groundwater system. The decision variables (pumping rates) were used to adjust the simulated

268 groundwater level to the constraints. The optimized groundwater levels were shown in Figure 5 to
 269 indicate a reasonable control based on the constraints. The pumping yields, which were optimized
 270 in three different scenarios with different groundwater level constraints, was shown in Figure 6.
 271 The average pumping yields for S1, S2, and S3 were $\sim 0.57 \times 10^8 \text{m}^3/\text{a}$, $\sim 0.2 \times 10^8 \text{m}^3/\text{a}$, and $\sim 0.1 \times$
 272 $10^8 \text{m}^3/\text{a}$, respectively. The annual amount of surface water diverted from the Heihe River was
 273 around $1.36 \times 10^8 \text{m}^3/\text{a}$ which was used to sustain a cultivated area of about $3.29 \times 10^8 \text{m}^2$ according to
 274 the data collected by WestDC [33]. We assume that, the climate condition remains an average level
 275 with usual runoff and lateral flow from the upper reaches. Under this assumption, the total
 276 cultivated area, which could be supported by the limited water resources in Daman irrigation
 277 district, could be calculated with the consideration of the optimal irrigation water demand (on
 278 average ~ 570 mm expressed in water depth) [36]. Therefore, the cultivated area, which could be
 279 sustained by the available water resources in S1, S2, and S3, were $\sim 3.38 \times 10^8 \text{m}^2$, $\sim 2.73 \times 10^8 \text{m}^2$, and
 280 $\sim 2.56 \times 10^8 \text{m}^2$ respectively. However, according to the current irrigation techniques, the average
 281 total irrigation water in Daman irrigation district was 601 mm expressed in water depth [36] which
 282 meant $\sim 0.22 \times 10^8 \text{m}^2$, $\sim 2.3 \times 10^8 \text{m}^2$, and $\sim 0.2 \times 10^8 \text{m}^2$ of cultivated area could be supported.

283 4.3. Real-time Management of groundwater resources

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



302
303

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

304 5. Conclusions

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

322

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