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Web-based decision support system for canal irrigation management

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ABSTRACT

Irrigation plays an important role in agricultural production. In this paper, a Web-based irrigation decision support system (WIDSS) is designed for canal irrigation management in large irrigated districts. WIDSS has many functions including data acquisition and detection, real-time irrigation forecast, dynamic water allocation decision and irrigation information management. It uses technical methods to reduce the need for users' specialized knowledge and can also take users' managerial experience into account. As the system is developed by the Browser/Server model, it is possible to make full use of the Internet resources and to facilitate users at any place with access to the Internet. Two years' application in the Zhanghe Irrigation System (Central China) indicates that the proposed WIDSS can achieve promising performance for canal irrigation.

1. Introduction

China is facing severe water scarcity while the demand keeps increasing and distribution of water resources is spatially and seasonally uneven. Although the total fresh water volume in China is large in absolute value, ranking sixth in the world, the per capita water resource is only 25% of the world average. In the past 10 years (2006–2015), the Chinese average total water consumption was 601.4 billion m^3, 62.5% of which is agricultural water consumption ("China Statistical Yearbook-2015," 2015). Therefore, conserving water in agriculture is important for both water and food security for China.

With urbanization and enhanced living standards, the amount of water used for domestic and industrial purposes has also increased (Peng, 2011). Increasing the efficiency of water use in irrigation practice is important for ensuring the sustainable development of agriculture. However, the lack of practical methods of irrigation management results in substantial waste of irrigation water and labour. Surface irrigation using canals is the main method of water application in paddy rice irrigation systems in Southern China. Owing to the constraints of canal water delivery capacity, irrigation often has to be rotated, and it usually takes several days to complete one round in a large irrigation system. Uncertainty of rainfall and difficulty of monitoring overall field water availability complicate the irrigation practice. Unexpected rainfall and underestimated actual field water availability will lead to the wastage of labour, water, and energy.

An irrigation decision support system is a platform developed for irrigation water management. It can improve irrigation efficiency and reduce labour inputs in daily irrigation management with a few added engineering services. Furthermore, adopting the latest technology in agricultural practice is also meaningful. The influence of rainfall uncertainty on irrigation decisions can be improved with the help of weather forecast information (Gowing and Ejieji, 2001). Daily reference evapotranspiration (ET_0) prediction using the public weather forecast information can be adopted for real-time water allocation and irrigation management (Cai et al., 2007, 2009; Luo et al., 2014). Weather forecast information can be produced by many public websites. In China, Weather China (www.weather.com.cn) can provide weather forecast data including weather type, wind scale, and maximum and minimum air temperatures. These data are provided daily for many cities in China for up to 15 days ahead, which is sufficient for a real-time irrigation scheduling trial. The decision to initiate irrigation should consider knowledge of true field water availability (soil moisture and ponding water) in the whole area. The practice of utilizing sensors and their networks is a positive step for agriculture (Abbasi et al., 2014). Distributed in-field sensor-based irrigation systems offer a potential solution to support site-specific irrigation management that allows producers to maximize their productivity while saving water (Kim et al., 2008; Kim and Evans, 2009). However, the integration of distributed in-field sensors, software design, data interface, and communication can be challenging.

Many irrigation decision support systems have been developed with different emphases in the past 20 years. Scheme irrigation management information system (SIMIS) was developed in 1993 to assist managers in their daily tasks (Mateos et al., 2002). Pl@nteInfo® was developed on the Internet to provide personalised advice to farmers and advisers in real time based on information across platforms (Jensen et al., 2000).

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Table 1
Project data requirement description.

	Items	Data acquisition approach					Refresh rate		
		Local managers	Experiments	Field survey	Sensors	Internet	Hourly	Daily	Yearly[a]
1. Meteorological data	1.1 Weather station data	√						√	
	1.2 Weather forecast data					√		√	
2. Engineering information	2.1 In-field monitoring station locations and codes			√					√
	2.2 Canal length & default rotational irrigation group	√							√
	2.3 Canal net irrigation area & conveyance losses	√		√					√
3. Crop and soil characteristics	3.1 Crop distribution details	√		√					√
	3.2 Crop water demand calendar & crop coefficient	√	√						√
	3.3 Soil distribution and corresponding infiltration data	√	√	√					√
4. Real-time data	4.1 In-field monitoring data				√		√	√	

[a] The data only need a yearly check. Updates will only be needed in cases with construction activity or a change in farmers' cultivation techniques.

However, it is more suitable as an information management system, as the decision support model needs further development. WISE was created as a tool based on daily water balance that users can operate without professional aid and can also apply their own expertise (Leib et al., 2001). It introduced a feasible framework to develop this type of model further. AQUAMAN used the FAO-56 guidelines and the APSIM peanut model to assist with irrigation management for peanuts and showed good performance in improving irrigation water use efficiency (Keating et al., 2003; Chauhan et al., 2013). Thysen and Detlefsen (2006) developed an entirely Web-based system in terms of input of farm and field data, automatic supply of weather data, and advice consulting. The system had 322 active users in 2004 and 490 in 2005. Fernandez and Trolinger (2007) fully discussed the structure of a Web-based decision system and offered a simple online system for crop managers. Flores et al. (2010) developed a dynamic decision support system (DDSS) called INNOVA RIEGO based on the formulation and integration of three components: a dynamic-relational data base, an administrator model, and a graphical user interface. It was applied in an orange orchard and assisted the decision-making process effectively. A risk-based online decision support system for the operation and management of agricultural water was developed to support the preliminary step of irrigation water decision-making, aiming at evaluating the water delivery performance of irrigation canals (Hong et al., 2015). Different systems have diverse emphases for the given objectives and physical conditions. Constant research on the irrigation decision support system makes the structure more explicit and the function more diverse. However, researches seldom consider using the platform to integrate automatic data acquisition, complicated computing process encapsulation, and input and output (IO) graphical display. Managers only need to follow an operation process, perform confirmations, and make decisions. A more intellectualized decision support system should reduce the workload of the user and simplify comprehension for operation.

The different systems listed above contain both online systems and stand-alone PC programmes. As the Internet technology advances, it is important to provide up-to-date website building technologies and excavate useful information for a more scientific and user-friendly irrigation decision system. This paper presents a Web-based decision support system for canal irrigation management (WIDSS). The WIDSS model is based on water balance approach for both lowland paddy and upland crops. Considering a basic database for different crops' water demands in the whole growth stages and irrigation system engineering information, the WIDSS can make efficient decisions for water allocation with the help of real-time, in-field moisture detection and weather forecast. This system uses technical methods to reduce requirements of a user's specialized knowledge and can also take a user's managerial experience into account. As the system is developed by the Browser/Server model, it is possible to make full use of the Internet resources and to facilitate users at any place with access to the Internet. Two years' application in the Zhanghe Irrigation System (Central China) indicates that the proposed WIDSS can achieve promising performance for surface irrigation.

2. System design

The WIDSS is based on a stand-alone PC programme, available since 2003 (Cai et al., 2003). The early version was developed in VisualBasical6.0, which must be installed on the computer. The Internet version (WIDSS) has experienced several modifications and upgrades, mainly focusing on aspects of the inputs and developing platform. Input data updates automatically from in-field monitoring stations, the database of the meteorological station, and the public weather forecast website. This makes the operation easier and more intelligible. A Web-based version provides in-field data displayed with geographic information, makes upgrades more convenient, and allows users to easily access the system at any place with Internet access.

2.1. Data requirement

The project data are organized into four main categories related to meteorological data, engineering information, crop and soil characteristics, and real-time data (see Table 1).

Weather station data can be divided into historical data and recent data. Meteorological data from the past 30 years can been obtained from irrigation experiment station located in the catchment, and are used for model parameter calibration and validation. Recent data can be acquired from the administration's server. Weather forecast data come from Weather China (www.weather.com.cn). This public weather forecast data can be obtained automatically through a regular expression match using the PHP language in the server.

Engineering information data will not change frequently, which contains in-field monitoring station locations and codes, canal length, default rotational irrigation group, canal net irrigation area and conveyance losses. It comes from detailed design reports and operating experience of canals and monitoring stations. Crop and soil characteristics data depend on field investigation and experiments. A great deal of preliminary work (field investigation and experiment, material collection) is required before the software development.

These data are stored in the system in advance or will be obtained by the server automatically to reduce the workload of users and simplify use. The basic data that do not change frequently, such as engineering information data, crop and soil characteristics data, and historical meteorological data, will be stored in the system as default in advance. However, data that need to be updated frequently will be captured by the Web server automatically. It provides real-time in-field data and weather forecast data. Task Scheduler (a system tool in windows operating system) is used to execute some batch scripts written on the server to realize data obtain and update automatically.

2.2. Objectives and architectural design

Attention to the end user's requirement is imperative when planning a decision support system (Fernandez and Trolinger, 2007). WIDSS is developed for irrigation system managers. In simple terms, it will provide managers with a better understanding of the overall field water availability truth and determine canal operating details 10 days ahead if irrigation is needed. To ensure a user-friendly environment and relatively transparent decision-making process, the developer must address the visible complexity of the decision support system. The overall goals for developing WIDSS include the following:

- To provide the irrigation system manager with field truth knowledge to assist in making more practical irrigation decisions.
- To systemize and visualize irrigation system information with up-to-date website development technology for practical advice.
- To carry out research on the possibilities of using Internet resources and real-time data to help irrigation systems achieve better performance.
- To fully understand the demand of irrigation system managers and build a user-friendly, Web-based, decision support system.

The WIDSS, including data acquisition terminals, Web server, client browser and communication system, is built by Browser/Server architecture (see Figs. 1 and 2). The Web server is developed by PHP; the client browser page is written using HTML/CSS/JavaScript; and the data exchange uses Ajax technology. Data acquisition terminals are designed to measure paddy water level, soil water content in dry land, pond water level, groundwater level, and canal water level. A Web server is responsible for collecting meteorological data, weather forecast data, real-time in-field data, and managers' feedback data. Water allocation decisions are made in the Web server. The client browser is responsible for friendly display, interacting with managers, and collecting managers' irrigation intentions. The communication system includes the Internet and the GPRS network used by monitoring stations.

2.3. Development of the irrigation decision model

The irrigation decision model development mainly contains two parts: the real-time irrigation forecast module and the water delivery scheduling module. The real-time irrigation forecast module predicts the irrigation quota (irrigation amount per m^2) and irrigation date based on the fresh data, if irrigation is needed in the coming 10 days. The water delivery scheduling module focuses on canal water delivery details.

2.3.1. Real-time irrigation forecast module

Real-time irrigation forecasting emphasizes correct estimation of field water availability and mastering the latest weather forecast data. Each prediction is based on the revised initial state, and then uses the short-term weather forecast data to predict the irrigation date and irrigation quota. This process is shown in Fig. 3 and discussed in the following section.

2.3.1.1. Initial field water availability amendment. The real-time, in-field monitoring stations are settled in the catchment comprehensive considering the terrain, physiognomy, climate, soil, and other conditions. Amendments based on the real-time monitoring data at the beginning of every decision process are needed. As the system is highly reliant on the accuracy of input data, the user should have a basic judgement of data exception. The system will perform a preliminary inspection of the in-field monitoring data and weather data and provide a list. The system will run only after the user's confirmation.

2.3.1.2. Evapotranspiration prediction. Evapotranspiration prediction is based on prediction of reference crop evapotranspiration, crop coefficient, and soil water correction coefficient.

$$ET_{ci} = K_{ci} \cdot K_{si} \cdot ET_{oi}, \tag{1}$$

where ET_{ci} is the actual evapotranspiration (mm/d) on day i; ET_{oi} is reference crop evapotranspiration (mm/d) on day i; K_{ci} is crop coefficient and K_{si} is soil water stress coefficient on day i, dimensionless.

Mao (1994) analysed the changes of multiple sites' daily reference crop evapotranspiration over time, and created the 'index model' for daily reference crop evapotranspiration forecasting. Li and Cui (1996) developed a real-time forecasting model of irrigation water requirement of paddy fields based on the 'index model'. Luo et al. (2006) proposed a 'Fourier series model' based on Mao's research, with high forecasting precision and easier programming.

Daily ET_o can be estimated from Eq. (2):

$$ET_{ot} = \varphi_t \cdot \left\{ \overline{ET_0} + \sum_{i=1}^{n} \left[a_i \cos\left(\frac{2\pi it}{365}\right) + b_i \sin\left(\frac{2\pi it}{365}\right) \right] \right\}, \tag{2}$$

where φ_t is the weather type factor on day t obtained from the ratios of actual ET_o under clear, cloudy, overcast and rainy weather conditions to the long-term mean values on the same day (see Table 2); $\overline{ET_0}$ is daily average reference crop evapotranspiration of years (mm/d); t is Julian day number, t = 1, 2, 3, …, 365; and a_i, b_i are constants.

2.3.1.3. Water balance simulation. Field daily water balance simulation will begin after the correction of initial field water availability. The evapotranspiration data and precipitation data are forecast value. The water balance simulation sets the soil layer above the root zone as a closed system. The inputs include precipitation, irrigation, lateral recharge, and groundwater recharge. The outputs include crop evapotranspiration, surface runoff, lateral seepage, and deep percolation. At any time, the total amount of water in the system should be balanced. It can be expressed as:

$$W_{i-1} + P_i + I_i + V_i + K_i - (ET_{ci} + R_{oi} + Q_i + G_i + W_i) = 0, \tag{3}$$

where W_{i-1} *and* W_i are total water storage on day i-1 and i respectively; P_i is precipitation on day i; I_i is irrigation amount on day i; V_i is lateral recharge on day i; K_i is groundwater recharge on day i; R_{oi} is surface runoff on day i; Q_i is lateral seepage on day i; and G_i is deep percolation on day i. The units of the above variables are in mm.

If we suppose the lateral recharge and lateral seepage of soil are equal, soil water flow does not occur in the horizontal direction of the soil layer. Therefore, Eq. (3) can be simplified as:

$$P_{ei} = P_i - R_{oi} = \alpha P_i \tag{4}$$

$$W_{i-1} + P_{ei} + I_i + K_i - (ET_{ci} + G_i + W_i) = 0 \tag{5}$$

$$K = ET \cdot e^{-\sigma H_0}, \tag{6}$$

where P_{ei} is effective precipitation on day i, mm. α is the infiltration coefficient, which relates to factors such as rainfall, rainfall intensity, rainfall duration, soil properties, land cover, and terrain. K is groundwater recharge, mm. It is related to groundwater depth, soil texture, crop water requirement. σ is a dimensionless empirical coefficient. H_0 is groundwater depth, m.

For a paddy field, we consider the later seepage and deep percolation together as seepage in this research.

$$h_{i+1} = h_i - ET_{ci} - S_i + P_i + I_i - D_i, \tag{7}$$

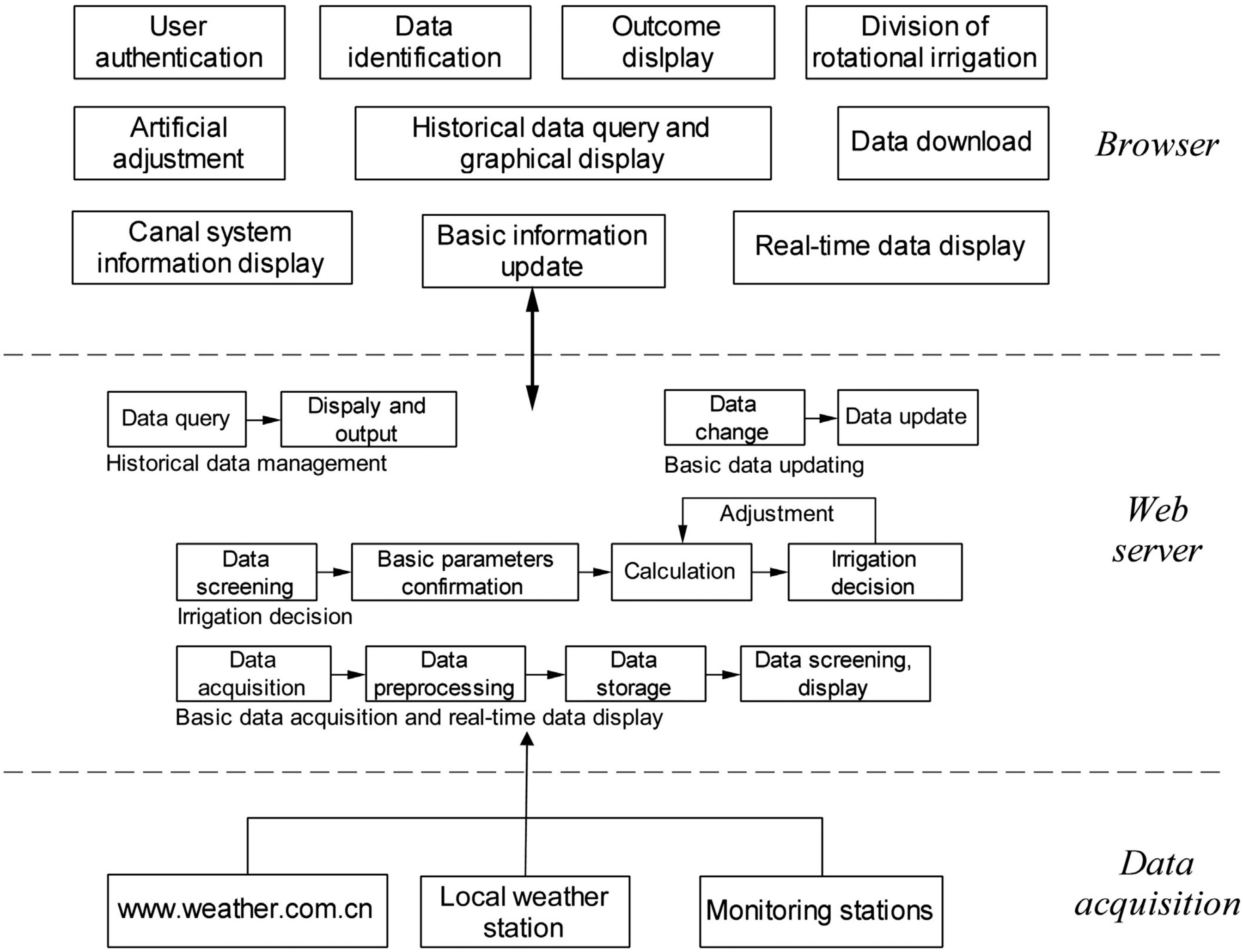

Fig. 1. Schematic of Web-based irrigation decision support system.

where h_i, and h_{i+1} are water level on day i and $i+1$, respectively; S_i is seepage on day i; and D_i is paddy drainage on day i. Units of the above variables are in mm.

2.3.1.4. Irrigation date and quota forecasting. Irrigation date is determined by the field water availability. When the paddy water level or soil moisture content in dry land decreases to the limited standard of current crop growth stage set in advance, the irrigation decision is made according to the weather forecast.

For paddy fields, the irrigation plan provides three water levels (maximum, minimum, and ponding) for different growth periods. If paddy water level is over the ponding water level, then drainage is needed. If paddy water level is less than the minimum water level, then irrigation is set at the maximum water level.

Irrigation quota is determined by the difference between minimum and maximum soil moisture (paddy water level) in each stage of crop growth. According to the characteristics of crop growth, suitable soil moistures (paddy water level) are set at different stages of the crop growth period. If the user wants to change the irrigation schedule of one crop, they can adjust the default critical values.

For dry crop, the irrigation quota can be calculated as:

$$m_j = (\theta_{\max} - \theta_{\min})H \tag{8}$$

For paddy, the irrigation quota can be calculated as:

$$m_j = h_{\max} - h_{\min}, \tag{9}$$

where m_j is irrigation quota, mm; $\theta_{\max}$, $\theta_{\min}$ are appropriate maximum limit and minimum limit of root zone soil moisture in a dry crop's growth period,%; H is root depth of dry crops, mm; $h_{\max}$, $h_{\min}$ are appropriate maximum limit and minimum limit of paddy water level, mm.

2.3.1.5. Irrigation water demand forecast. The net irrigation water demand is calculated for each canal.

$$m_{s,j} = \sum_{i=1}^{M} \frac{A_i}{A_j} m_i \tag{10}$$

$$W_{net,j} = m_{s,j} \cdot A_j \tag{11}$$

$$W_{gross} = \sum_{j=1}^{N} \frac{\left(\frac{W_{net,j}}{\eta_{f,j}} - L_j\right)}{\eta_{c,j}}, \tag{12}$$

where $m_{s,j}$ is the synthesized irrigation quota of the crops planted in the controlled irrigation area of canal j, mm; A_i and m_i are the planted area and irrigation quota of crop i in the controlled irrigation area of canal j respectively; A_j is the total area of the controlled irrigation area of canal j, m^2; $W_{net,j}$ is net irrigation water demand in the controlled irrigation area of canal j; L_j is the local water supply amount of the controlled irrigation area of canal j, m^3; $\eta_{f,j}$ is the field water use coefficient in the controlled irrigation area of canal j; and $\eta_{c,j}$ is the water delivery coefficient of canal j. W_{gross} is gross irrigation water demand of the irrigation system, m^3.

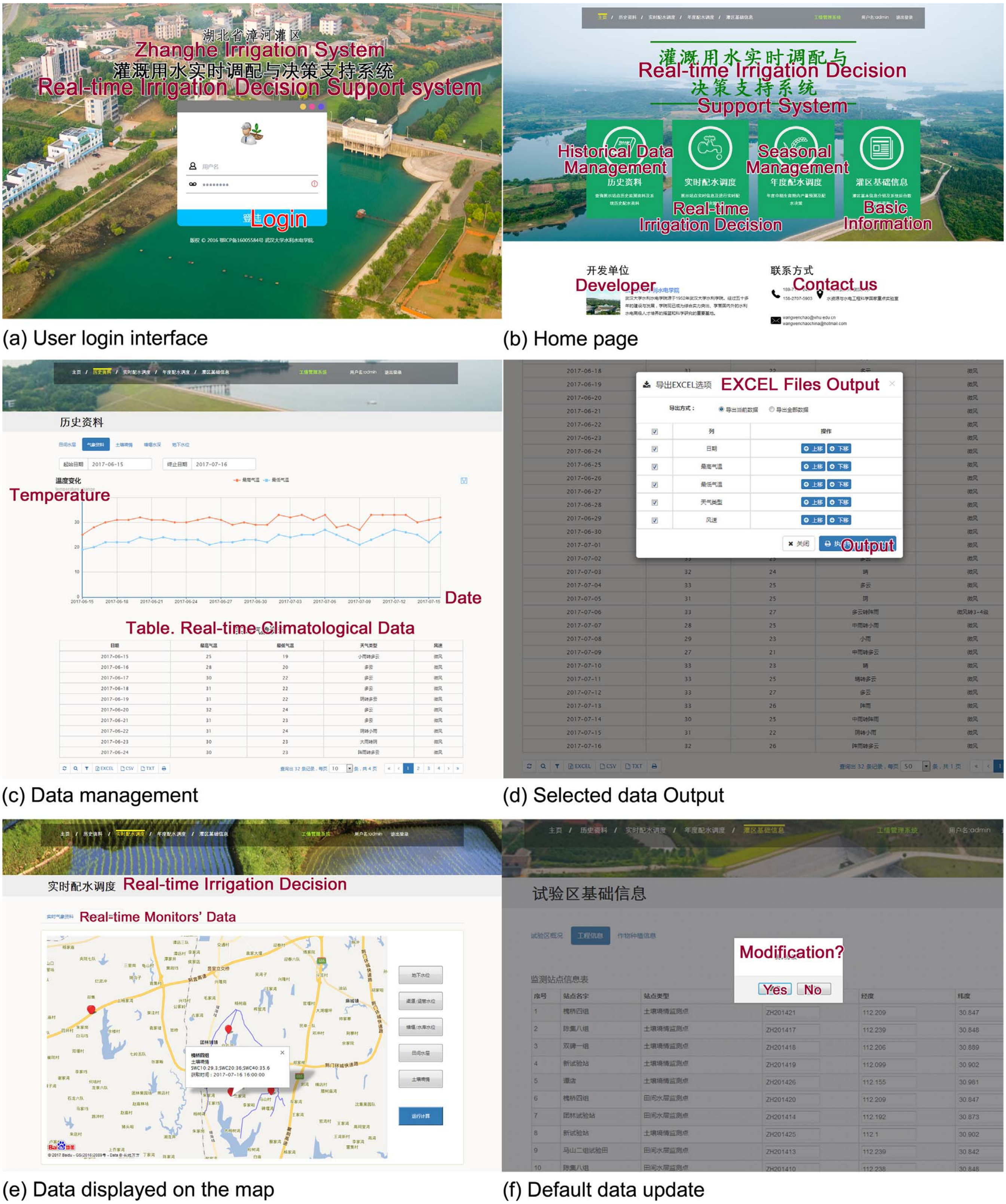

Fig. 2. Screenshots of WIDSS.

2.3.2. *Water delivery scheduling module*

Real-time irrigation forecasting is a necessary condition to develop a dynamic irrigation operation plan. However, an accurately predicted irrigation date and irrigation quota cannot always guarantee timely and appropriate irrigation. The water delivery scheduling module works for an irrigation system operation plan after the gross irrigation water demand is confirmed. Accurate irrigation time (start time, end time) and flow rate of each canal is provided for practical application. The main steps are as follows.

Rotational irrigation group adjustment. Logical rotational irrigation

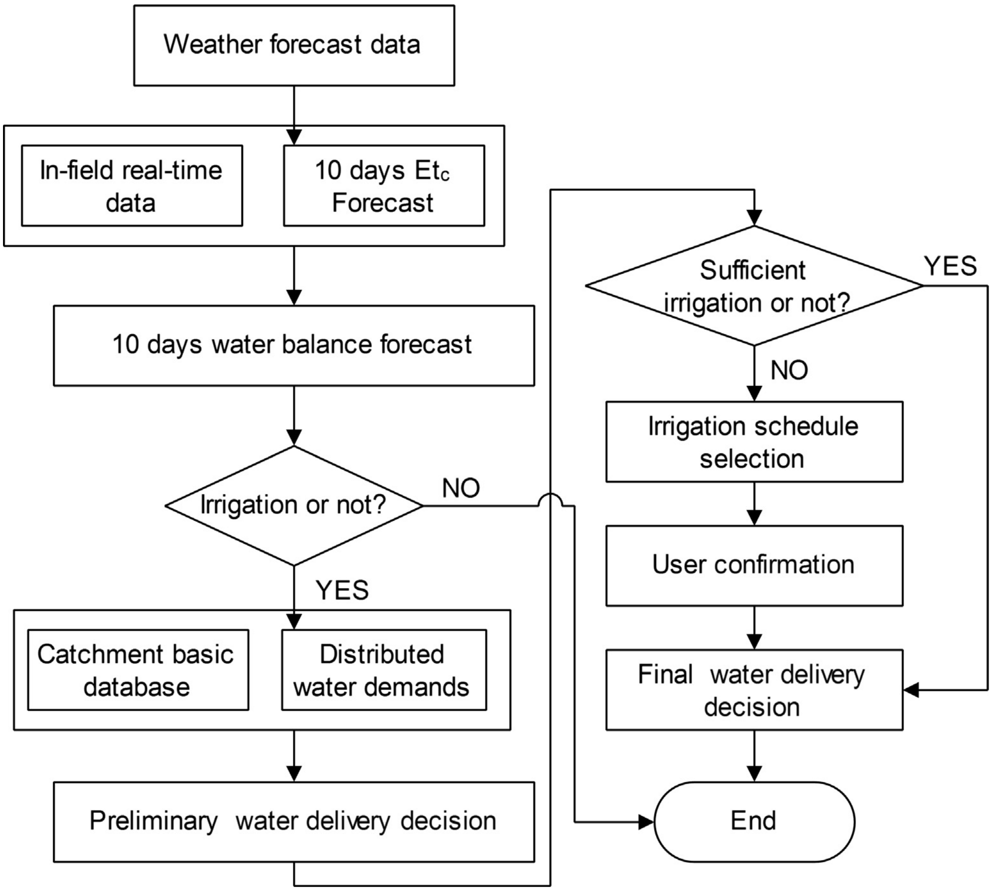

Fig. 3. Flow diagram of the WIDSS.

Table 2
Values of weather type factor.

Month	Term[b]	Weather			
		Clear	Cloudy	Overcast	Rainy
Apr	1	1.54	1.28	0.92	0.79
	2	1.49	1.28	0.95	0.74
	3	1.47	1.24	0.92	0.74
May	1	1.49	1.23	0.88	0.70
	2	1.51	1.22	1.00	0.72
	3	1.51	1.30	0.91	0.75
June	1	1.51	1.27	0.94	0.72
	2	1.48	1.23	0.90	0.68
	3	1.49	1.23	0.89	0.69
July	1	1.52	1.23	0.88	0.64
	2	1.53	1.21	0.86	0.66
	3	1.33	1.10	0.77	0.59
Aug	1	1.33	1.08	0.79	0.58
	2	1.37	1.12	0.81	0.60
	3	1.39	1.14	0.85	0.64
Sept	1	1.45	1.12	0.82	0.67
	2	1.39	1.17	0.86	0.67
	3	1.38	1.18	0.86	0.69
Oct	1	1.40	1.12	0.93	0.75
	2	1.46	1.21	0.92	0.80
	3	1.31	1.04	0.89	0.81

[b] 1,2, and 3 refer to the first, second, and the third 10-d terms in a month respectively.

group is an important factor in successful irrigation application. It should consider the actual canal system layout, canal operation status, crop cultivation truth and soil difference. A default (frequently-used) rotational irrigation group is saved in the system, so users can revise it and calculate it again for comparison.

Irrigation time. Irrigation duration is calculated from gross irrigation water demand and canal water deliver capacity. However, it is only a guide for irrigation practice and cannot be applied to practical application directly. Irrigation duration should consider the maintenance of canals, crop types and their growth stages and labour limits. Irrigation start time should be coordinated with the water delivery demand situation of canals in the same irrigation group.

Irrigation flow rate. Irrigation flow rate is calculated from irrigation time. It should be in the range of $0.4Q_{design}$ to $1.2Q_{design}$ (Q_{design} is canal design flow rate).

3. System application

3.1. Study area

The system area is a catchment called Yangshudang (YSD) in the Zhanghe Irrigation System (ZIS). It has been studied since April 2015. The ZIS is located at Hubei Province in Central China, North of the Yangtze River and has a total area of 5540 km^2. The ZIS serves one of the most important sources of commodity grain in Hubei Province, which has irrigated area of 1600 km^2. A general main canal, five main canals, and a large number of branch canals with a total length of more than 7000 km comprise the surface irrigation system of ZIS (Dong, 2008). YSD is a relatively closed catchment in ZIS, with an area of 42.7 km^2 (see Fig. 4). The catchment is a segment insulated by Yangshudang reservoir, the Third Main Canal and its first branch canal. The average annual rainfall is around 960 mm and mean annual temperature is 16.9 °C. The main crops are rice in summer and wheat/rapeseed in winter and they occupy more than 80% of the cultivable land and 69.5% of the total area (Wang and Cui, 2013). Summer season (May–September) is the main irrigation supply period during which rice

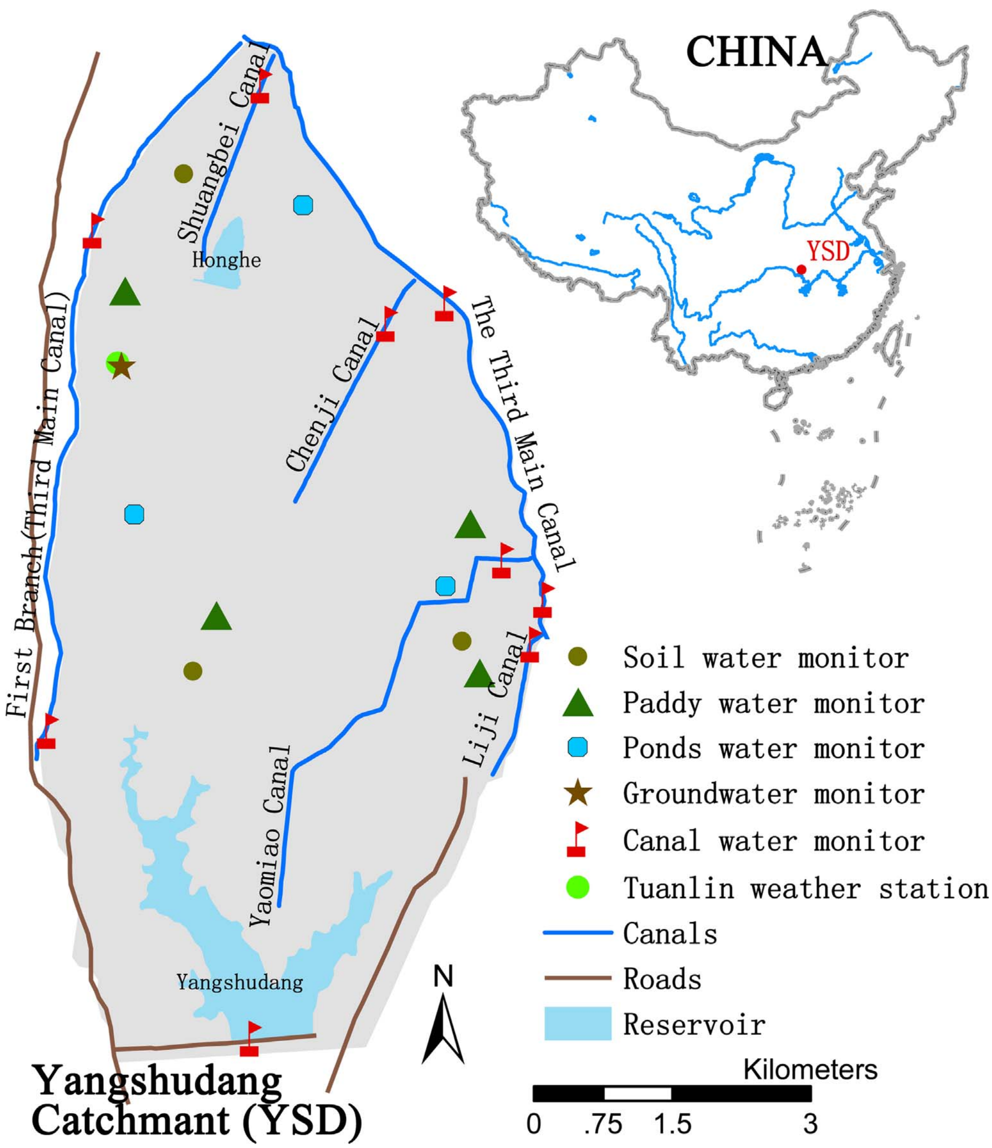

Fig. 4. Location of Yangshudang catchment (YSD).

Fig. 5. Real-time In-field monitoring station examples: left, soil moisture monitor; right, canal water level monitor.

Table 3
Irrigation decision on 21 June 2014.

Main canal name	Branch canal name	Irrigation quato (mm)	Total water supply (m^3)	Start time	End time	Irrigation time (h)	Flux (m^3/s)
The third main canal (TC)	Chenji canal	56	188926	12–06-2014 08:00:00	14–06-2014 12:28:00	52.47	1
	Yaomiao canal	50	134704	12–06-2014 08:00:00	13–06-2014 21:25:00	37.42	1
	Liji canal	50	110887	12–06-2014 08:00:00	13–06-2014 14:48:00	30.8	1
	Branch culvert of the TC	56	101729	12–06-2014 08:00:00	14–06-2014 16:30:00	56.5	0.5
First branch of third main canal (FBoTC)	Branch of the FBoTC	56	411898	13–06-2014 08:00:00	15–06-2014 17:12:00	57.2	2
	Tuanlin canal	56	281561	13–06-2014 08:00:00	15–06-2014 12:08:00	52.13	1.5
	Shuangbei canal	56	292472	13–06-2014 08:00:00	15–06-2014 14:09:00	54.15	0.5
	Yapu canal	55	211733	13–06-2014 08:00:00	14–06-2014 13:24:00	29.4	2
	Branch culvert of the FBoTC	55	162904	13–06-2014 08:00:00	15–06-2014 05:15:00	45.25	1

is growing, imposing pressure on the canal supply system.

3.2. Real-time in-field monitoring stations

Twenty in-field monitoring stations have been constructed in this research, including three soil moisture monitors, four paddy water level monitors, three pond water table monitors, one groundwater table monitors, and nine canal water level monitors (see Fig. 4). Every monitoring station integrates an independent power supply system, in-field sensor, and a data terminal. The power supply system uses batteries powered by solar power panel and the data terminal accounts for data collection, storage, and transmission (Wu et al., 2015). This station uses a GPRS wireless communication network as the data transmission channel. It will provide hourly, real-time, in-field data to support irrigation decisions (see Fig. 5).

3.3. System implementation and results

Ease of operation is an important original intention of WIDSS. Basic data have been stored in the server's database. Therefore, only data related to crop growth need to be updated before operation. It contains crop planting distribution, a growth stage calendar and water requirement range for every planted crop.

System development, debugging, and installation were completed at the beginning of 2014. System validation also began at the beginning of 2014, when public weather forecast data were first collected. The performance comparison can only be done when canal irrigation has occurred. In this study, the comparison between actual irrigation implementation and the WIDSS simulation output occurs in 2014. As 80% of the cultivable land is planted with rice and its water requirement is larger than other dry crops, the following analysis of the WIDSS outcome will focus on the growth period of rice (the 21st of May to the 10th of September).

Considering the system operation time interval is 10 days and the middle-season rice growth takes around 100 days, 11 irrigation decisions have been made from the 21st of May to the 1st of September. Three of them (the 1st of June, the 11th of June, and the 21st of July) show the need for irrigation.

Irrigation at the beginning of June occurs during rice's vegetative stage. Tillering begins around then, and the continuous high temperature and lack of rainfall makes irrigation necessary. All the canals start irrigation at 8:00 am on the 3rd of June.

On the 11th of June, the weather indicates no rainfall in the coming 10 days. Additionally, there were very few rain days prior to the last irrigation. To prevent the paddy from drought under the heavy daily water consumption, irrigation is necessary. The third main canal and its branch canals (except the first branch of the third main canal) start irrigation at 8:00 am on the 12th of June. The first branch of the third main canal and its branches begin irrigation at 8:00 am on the 13th of June.

The last irrigation decision made by WIDSS occurred at the end of July. This is the beginning of the ripening stage, and the next 10 days will be sunny or cloudy according to the weather forecast. As rainfall is relatively abundant before the 21st of July, the initial water level in the paddy is high. However, to avoid paddy drought in this critical period and make full use of canal irrigation, WIDSS recommended irrigation of the catchment at the end of July. All the canals begin irrigation at 8:00 am on the 28th of July. The operation details according to the sheet given by WIDSS are shown in Table 3.

The water level changing process in the selected paddy is shown in Fig. 6. It started from the transplanting stage because the water requirement from this time to harvesting is uncertain and may be urgent. The water level in the selected paddy is 30 mm during transplanting, which represents the normal condition. Irrigation took place three times during the 2014 paddy growth period: twice in the vegetative stage and another in the ripening stage. Drainage occurs three times at

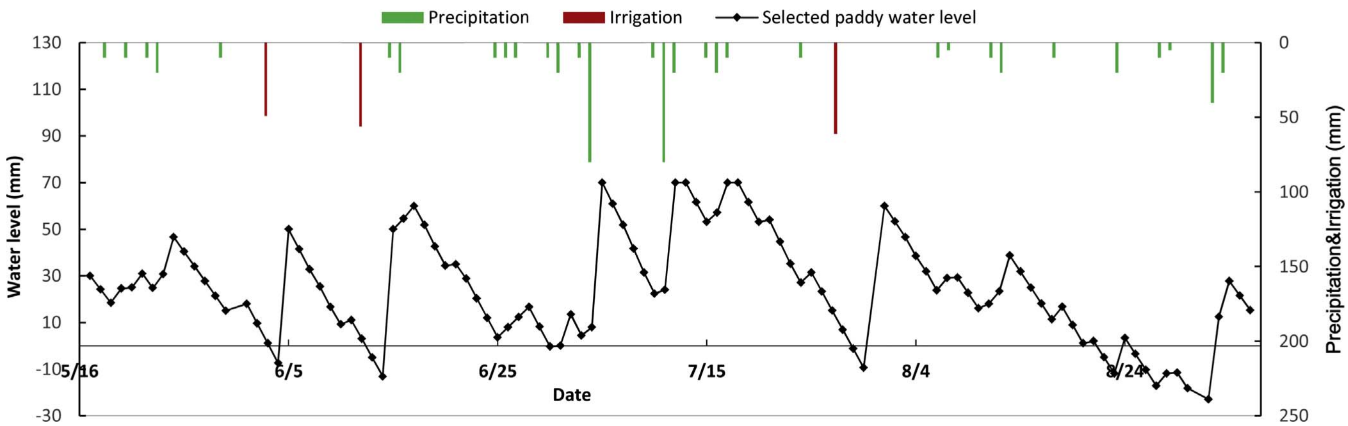

Fig. 6. Selected paddy water level changing process.

Table 4
Simulation results of WIDSS.

Analog result	Middle-season rice
Plant area [km^2]	30.75
Irrigation times	3
Total irrigation amount [10^4 m^3]	554.18
Corresponding actual irrigation amount [10^4 m^3]	652.96
Water savings [10^4 m^3]	98.78
Reduction [%]	15.13

the beginning of July because of the concentrated rainfall, which led to some water wastage.

At the same time in 2014, during the growth period of middle season rice, this catchment supplied water twice and the total irrigation amount was 652.96 m^3. The first irrigation occurred from the 26th of May to the 21st of June and the second one happened from the 29th of July to the 18th of August. The above situation is consistent with the WIDSS decision. However, each irrigation maintained small flow over a long time in actual practice due to the low estimation of water required. This also causes the wastage of water. The WIDSS simulation result is 554.18 m^3, and the corresponding amount of total irrigation decreases by 15.13% (see Table 4).

4. Discussion

In this study, a Web-based irrigation decision support system (WIDSS) was proposed. The system uses public weather forecast and real-time in-field sensors to help predict irrigation schedules. It showed the practicability of developing an online irrigation decision platform.

Stable, real-time, in-field data and uploaded weather forecast data inform errorless irrigation decisions. Monitoring station construction is a foundation of WIDSS's implementation. Their data reflect how much water exists in the selected catchment. Distribution should consider both field water availability truth and variability of topography. Sufficient field investigation is needed, as it can reduce the number of sensors required, to a degree. Different measuring targets should set different time intervals. For example, the paddy water level, canal water level, and dry land soil moisture should have hourly data. For groundwater level and pond water level, daily data are sufficient. Weather forecast data are used to calculate how much water will be needed in the future. Considerable research has focused on evapotranspiration forecasting with the help of weather forecasts; thus, the prediction model is essentially mature for practice. The ET_0 forecasting model introduced in Section 2.3.1.2 is examined for its forecast accuracy in the same simulation period (see Fig. 7); the mean absolute error (MAE) is 0.51 mm and the root mean square error (RMSE) is 0.69 mm. The accuracy can meet the requirement of the system. With technology development, weather forecast precision has improved, large potential exists for more detailed weather forecast data available for public use.

To ease managers' workload, inputs of WIDSS are mainly made via automatic upload. The basic information about the irrigation system that will not change frequently is set as a default value in the database, and an individual page is developed to display and update this data. These designs make the system more intelligent for managers. Reducing system operating steps can reduce the specialized skills required to understand the system. However, on one hand, users must make basic judgements of the input data and outcomes based on their experience

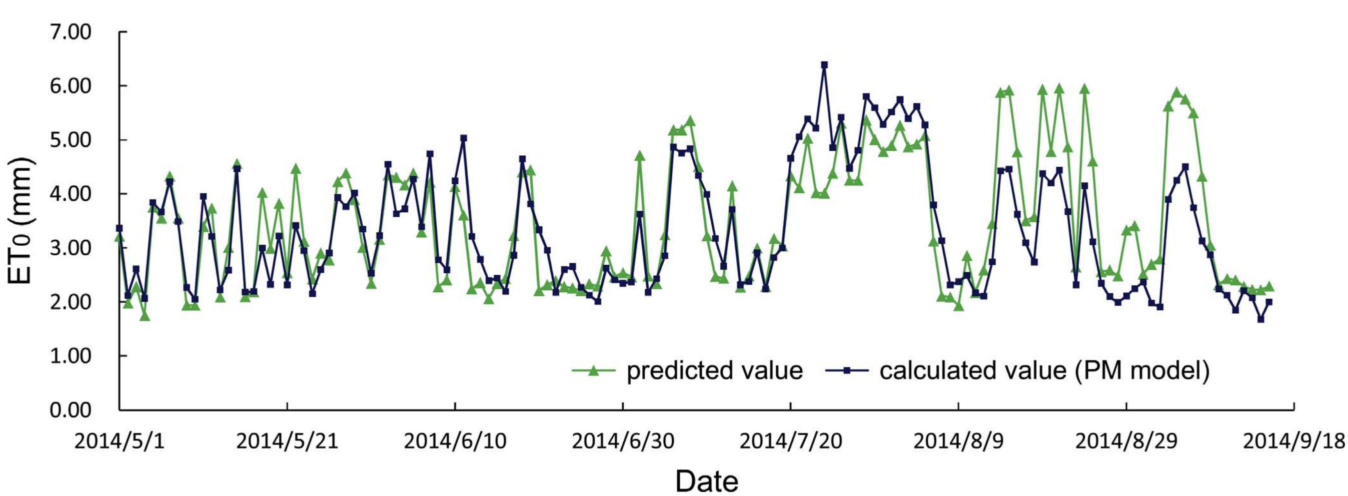

Fig. 7. Comparative values of the daily reference evapotranspiration.

because the system is closed and highly dependent on inputs. On the other hand, this system developing process relies on abundant field survey and communication and it requires that the developer has a good knowledge of water resource management. To a degree, the WIDSS has sacrificed universal applicability and transplantability for better performance at the specific location.

Adopting the Browser/Server architecture to build the system as a Web application provides many advantages in realising the design functions and providing friendly system display. Browser-based applications can operate on computer or smartphone where the Internet exists, if the website developing process has considered the layout difference between computer and smartphone. This design requires no installed application; only a Web browser is required. The update can also be very convenient, because developers can just revise the programme on the Web server. A Web server will account for 24-h collection of real-time in-field data and updated weather forecast data. The Browser/Server programme is built on the browser and has more vivid and friendly ways to communicate with users. It can reduce the difficulty of understanding the system and requirement of specialized skills. However, designing and creating Web pages based on the Browser/Server architecture consumes more time and slower development will be costlier.

Highly precise irrigation forecasting cannot always guarantee efficient and timely water delivery. A system should also consider the prioritization of different crops' water demands, different conditions of canals, and the proximity of water resources to make the irrigation schedule easy to operate and benefit farmers equally. Canal water delivery does not always follow clear and precise rules. Therefore, it is important to assign reasonable rotational irrigation to consider irrigation system reality. Field experiments and onsite investigations are essential for system design. As system developers and users are not the same, they should communicate throughout the entire developing process. It is important to understand users' requirements and take full advantage of their managerial experience.

5. Conclusions

This paper discussed the structure, design, objectives, development, and application of WIDSS. The developing process is integrated with in-field sensor construction, software programming, data interface, and communication design. Browser/Server development architecture is adopted to realise automatic data acquisition, complicated computing process encapsulation, and input and output (IO) graphical display.

The application in YSD showed the practicability of the system. It will determine when irrigation is needed, how much water is required, and offer guidance on canal operation. The system can change the current irrigation situation (keeping small flow for a long time) and effectively save water in Southern China. However, the system still needs further research on (1) response of yield decrease corresponding to insufficient irrigation, (2) monitoring station construction site selection problems, and (3) irrigation risk assessment and system universality improvement.

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References

Abbasi, A.Z., Islam, N., Shaikh, Z.A., 2014. A review of wireless sensors and networks' applications in agriculture. Comput. Stand. Interf. 36, 263–270.
Cai, X., Cui, Y., Song, Z., Wang, L., Wu, L., 2003. Study on real-time irrigation forecasting in doushan irrigation scheme. J. Irrigat. Drain. 22, 33–36 (in Chinese, with English abstract).
Cai, J., Liu, Y., Lei, T., Pereira, L.S., 2007. Estimating reference evapotranspiration with the FAO Penman-Monteith equation using daily weather forecast messages. Agric. For. Meteorol. 145, 22–35.
Cai, J., Liu, Y., Xu, D., Paredes, P., Pereira, L., 2009. Simulation of the soil water balance of wheat using daily weather forecast messages to estimate the reference evapotranspiration. Hydrol. Earth Syst. Sci. 13, 1045–1059.
Chauhan, Y.S., Wright, G.C., Holzworth, D., Rachaputi, R.C., Payero, J.O., 2013. AQUAMAN: a web-based decision support system for irrigation scheduling in peanuts. Irrig. Sci. 31, 271–283.
China Statistical Yearbook-2015, 2015. From National Bureau of Statistics of China.
Dong, B., 2008. Study on environmental implication of water saving irrigation in Zhanghe Irrigation System. Wuhan University (Available at http://spm-water-ap.net/wc/modules/news/) (accessed 15 July 2010), 142, 224.
Fernandez, C.J., Trolinger, T.N., 2007. Development of a web-based decision support system for crop managers. Agron. J. 99, 730–737.
Flores, C.I., Holzapfel, E.A., Lagos, O., 2010. A dynamic decision support system for farm water management in surface irrigation: model development and application. Chilean J. Agricult. Res. 70, 278–286.
Gowing, J., Ejieji, C., 2001. Real-time scheduling of supplemental irrigation for potatoes using a decision model and short-term weather forecasts. Agric. Water Manage. 47, 137–153.
Hong, E.M., Choi, J.Y., Nam, W.H., Kim, J.T., 2015. Decision support system for the real-time operation and management of an agricultural water supply. Irrigat. Drain. 65, 197–209.
Jensen, A.L., Boll, P.S., Thysen, I., Pathak, B.K., 2000. Pl@nteInfo®—a web-based system for personalised decision support in crop management. Comput. Electron. Agricult. 25, 271–293.
Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267/288.
Kim, Y., Evans, R.G., Iversen, W.M., 2008. Remote sensing and control of an irrigation system using a distributed wireless sensor network. IEEE Trans. Instrum. Measur. 57, 1379–1387.
Kim, Y., Evans, R., 2009. Software design for wireless sensor-based site-specific irrigation. Comput. Electr. Agricult. 66, 159–165.
Leib, B.G., Elliott, T.V., Matthews, G., 2001. WISE: a web-linked and producer oriented program for irrigation scheduling. Comput. Electr. Agricult. 33, 1–6.
Li, Y., Cui, Y., 1996. Real-time forecasting of irrigation water requirements of paddy fields. Agric. Water Manage. 31, 185–193.
Luo, Y., Chang, X., Peng, S., Khan, S., Wang, W., Zheng, Q., Cai, X., 2014. Short-term forecasting of daily reference evapotranspiration using the Hargreaves-Samani model and temperature forecasts. Agric. Water Manage. 136, 42–51.
Luo, Y., Cui, Y., Cai, X., 2006. A Fourier series model for forecasting reference crop evapotranspiration. Eng. J. Wuhan Univ. 38, 45–47 (in Chinese, with English abstract).
Mao, Z., 1994. Forecast of crop evapotranspiration. ICID Bull. 43, 23–36.
Mateos, L., Lopez-Cortijo, I., Sagardoy, J.A., 2002. SIMIS: the FAO decision support system for irrigation scheme management. Agric. Water Manage. 56, 193–206.
Peng, S., 2011. Water resources strategy and agricultural development in China. J. Exp. Bot. 62, 1709–1713.
Thysen, I., Detlefsen, N.K., 2006. Online decision support for irrigation for farmers. Agric. Water Manage. 86, 269–276.
Wang, J., Cui, Y., 2013. Water saving potential based on ET control and drainage reuse. J. Irrigat. Drain. 32, 1–5 (in Chinese, with English abstract).
Wu, Z., Tazvinga, H., Xia, X., 2015. Demand side management of photovoltaic-battery hybrid system. Appl. Energy 148, 294–304.