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A Decision Support System for irrigation water allocation along the middle reaches of the Heihe River Basin, Northwest China

Yingchun Ge, Xin Li*, Chunlin Huang, Zhuotong Nan

Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, China

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A B S T R A C T

To improve the water resource management of the inland river basins of northwestern China, a Decision Support System (DSS) is developed to provide an operative computer platform for decision makers. The DSS is designed according to actual water resource management problems and is seamlessly integrated into a user-friendly interface implemented in the Visual C# programming language. The DSS comprises an information management system that performs data collection, verification, management, and visualization, and models estimated crop water demand and water allocation for different levels of water use units. The objective of this study is to aid in the decision-making process related to water allocation scheme planning and implementation and to aid real-time responses to changes in water supply, allowing a new water allocation scheme to be developed based on the actual relationship between the supply and demand for water. The system is tested to allocate water to different levels of water use units as a standard decision support tool by means of the actual total available water from rivers, reservoirs, and groundwater. More than 60 water decision makers use the system at more than 40 locations along the middle reaches of the Heihe River Basin.

1. Introduction

Water crises around the world frequently occur because of global climate change and the increasing intensity of human activity. The main reason for water crises is the lack of sustainable methods of water resource management (UNESCO, 2006). Many international organizations, including the Global Water Partnership (GWP), the International Network of Basin Organizations (INBO), the European Parliament, and the International Center for Integrated Water Resource Management (ICIWaRM), have made considerable efforts to improve water resource management efficiency. A Decision Support System (DSS) is an efficient tool that is often used to address water resources management problems.

DSS, which is management in origin, can solve semi-structured and un-structured problems that cannot normally be expressed in unambiguous formulas (Little, 1970; Anthony et al., 1971). The underlying premise of DSS has been applied to water resources decision-making processes since the early 1970s (Hashemi and Decker, 1969; Andersen et al., 1971; Cleary et al., 1973; Kumar and Khepar, 1980; Fedra, 1984), even though the DSS concept was not proposed until later. Guariso et al. (1985) developed the first Water Resource Management Decision Support System (WRMDSS) and applied it to Lake Como in northern Italy. Since then, many successful WRMDSSs have been developed, including WaterWare (Jamieson and Fedra, 1996a,b; Fedra and Jamieson, 1996), RiverWare (Zagona et al., 2001), L-THIA (Engel et al., 2003), mDSS (Mysiak et al., 2005), E2 (Argent et al., 2009), and other DSSs (David et al., 2012; Rowan et al., 2012). DSS has also proven to be a useful and widely applied tool in environment (McIntosh et al., 2011; Panagopoulos et al., 2012), policy support (Delden et al., 2011), and urban water management (Aulinas et al., 2011; Gualtieri, 2011).

WRMDSSs have been developed in China to address water resource problems, including water allocation (Chen et al., 2008), water use management for agriculture (Xu et al., 2003; Niu and Quan, 2009), and water supply management (Liu, 2000). The development of WRMDSS was prompted by two factors. One factor is that the ability of DSS to address semi- or un-structured problems is gradually increasing because of the integration of optimization methods (Azamathulla et al., 2008; Efendigil et al., 2008; Azamathulla et al., 2009), physical models (Mysiak et al., 2005; Zagona et al., 2001), geographical information systems (GISs) (Crossland et al., 1995; Liu, 2004; Qi and Altinakar, 2011), remote sensing (RS) (Jones and Barnes, 2000; Cai et al., 2006; Michel et al.,

* Corresponding author. 320# Donggang West Road, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, Gansu Province, China. Tel.: +86 931 4967249; fax: +86 931 4967250.
E-mail address: lixin@lzb.ac.cn (X. Li).

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2012), expert systems (ESs), and other technologies. GIS has ushered in a revolution in the development of distributed modeling. GIS has been widely applied to support the parameterization of many distributed models (Jamieson and Fedra, 1996a,b; Koutsoyiannis et al., 2003; Maia and Silva, 2009) due to its advantages in the analysis and visualization of spatial data. The other factor driving the development of WRMDSS is that each component of the water cycle with a higher spatial and shorter time resolution can be accurately calculated by means of the physical processes in the water cycle, which have been clearly described and simulated by scientists. In addition, the keys to developing a successful WRMDSS lie in fully understanding real water resources management problems and dealing with the relationship among the applicability, maneuverability, and flexibility of systems (Mysiak et al., 2005; Argent et al., 2009).

Water resource management, however, is increasingly influenced by climate change and human activities (Arnell, 1998; Christensen and Lettenmaier, 2007). Climate change is an exogenous process related to runoff and precipitation, which cannot be affected by decision makers, managers or farms. Climate change can cause more extreme hydrological events (e.g., flood, drought) and create greater uncertainty in water resource management. The impacts of human activities (e.g., hydraulic engineering, crop structure, and water allocation among multi-level sectors) on water resource management are subjective and can be prioritized by policy makers based on the information available to them. It may be difficult for decision makers or managers to devise a water allocation scheme for a particular region within a particular period without up-to-date information due to the considerable extent of human activities.

This paper, therefore, introduces a methodology for allocating water based on water requirements and equity to help multi-level decision makers manage water resources in a DSS while fully accounting for the effects of human activities (e.g., hydraulic engineering and crop structure). The methodology is incorporated into DSS for water allocation along the middle reaches of the Heihe River Basin in northwestern China. This DSS integrates GIS, Internet, relational database (SQLServer), software engineering, and visualization techniques to provide a flexible, user-friendly, and applicable information system. The DSS also incorporates models that are used to calculate the components related to solving water resource management problems.

The next section introduces the background and the user's requirements. Section 3 describes the system design and implementation. The components and models combined in the system and their application will be introduced in Sections 4 and 5, respectively. The last section discusses the benefits and shortcomings of the WRMDSS.

2. Background

2.1. A brief description of the water resource management context

As a representative inland river, the Heihe River Basin of northwestern China, crossing Qinghai province, Gansu province, and the Inner Mongolia Autonomous Region, is separated into upper, middle, and lower reach areas and has a surface area of approximately 14.3×10^4 km^2. The inflow of the middle and lower reaches is measured by the Yingluo Gorge and Zhengyi Gorge hydrology stations, respectively. The Heihe River, with a length of 821 km, originates from the Qilian Mountains, and the end of Juyan Lake. The mean annual runoff of the Heihe River is approximately 1.588×10^9 m^3 (Yingluo Gorge hydrological station, from 1945 to 2010). In the middle reaches, where 95% of the population and 88.7% of the economy contributing to the Heihe River Basin (Sun, 2002) is concentrated, agriculture is the dominant activity, with 84% of the total available water resource volume consumed by irrigation. The mean annual precipitation is only 120 mm. However, the mean annual potential evaporation is approximately 1410 mm. With the goal of maximum economic benefit, the agricultural water consumption has gradually increased, and groundwater has been excessively exploited due to the lack of sufficient surface water, which has caused numerous ecological and environmental problems. Thus, water management for agriculture plays an important role in water resource management.

In addition, there are 33 main irrigation districts located in 6 counties (Shandan, Minle, Ganzhou, Linze, Gaotai, and Sunan) in the middle reaches (Fig. 1). The water authority is decentralized into irrigation districts, counties, and cities which have formed multi-level sectors of coordination management for water resources. Different levels of water authority sectors work on different water resource management problems (e.g., field water distribution for water management sectors of irrigation districts, water allocation between irrigation districts for water management sectors of counties, water allocation between counties for water management sectors of municipalities), and low-level sectors are governed by high-level sectors. Accordingly, the factors impacting water resource management problems are different among the multiple levels and sectors. At present, each water management sector develops a water policy or a water allocation scheme to maximize the economic benefit according to only limited statistical information and little coordination with other sectors. Thus, it is difficult to reach a water allocation equilibrium among all water management sectors.

An investigation of existing WRMDSSs shows that a general WRMDSS can be applied to some regions; however, it is not presently implemented in the Heihe River Basin. It is difficult to apply WRMDSSs in the Heihe River Basin for the following reasons:

(1) Water resource management problems exhibit large differences between regions or countries due to the impacts of geological conditions, water policies, economic development, and the complex relationships among water management sectors. In economically developed countries or regions, there are high-quality hydraulic infrastructures, flow, and water quality monitoring systems, and efficient water-saving technologies. Water resource management problems focus on how to optimize drip irrigation, spray irrigation, and sprinklers to allocate water at small spatial scales (Pedras et al., 2009) and how to control the emission of pollutants and their migration to protect water quality and aquatic ecosystems (Monte et al., 2009). At the middle reaches of the Heihe River Basin, however, flood irrigation is the common system, and water allocation for different levels of water use units, rather than water quality problems, is a the priority for decision makers.

(2) Decision makers play an important role in water resource management. They may subjectively use different methods to address the same water resource management problem because of the impact of culture, water policies, and the cognitive ability to solve problems. How one makes a decision largely depends on one's culture and personality (e.g., hierarchist, individualist, egalitarian, and fatalist) (Douglas, 1982), which are internal causes, as well as one's cognitive ability. Water policies are external causes for decision makers and are influenced by government, climate change, and economic development.

(3) The development of DSSs requires cohesion among diverse members of a group to address complex problems. Water resource managers, decision makers, scientists, and system developers are included in the group. When these group