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Operational performance improvements in irrigation canals to overcome groundwater overexploitation

S. Mehdy Hashemy Shahdany[a,*], Alireza Firoozfar[b], J.M. Maestre[c], Iman Mallakpour[d], Saleh Taghvaeian[e], Poolad Karimi[f]

[a] Irrigation and Drainage Engineering Department, Aburaihan Campus, University of Tehran, Pakdasht, Iran
[b] HDR, 601 Union St. Suite 700, Seattle, WA, 98101, USA
[c] Department of Systems and Automation Engineering, University of Seville, Seville, Spain
[d] Department of Civil and Environmental Engineering, University of California, Irvine, CA, 92697, USA
[e] Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater, OK, USA
[f] Water Science & Engineering Department, IHE Delft Institute for Water Education, The Netherlands

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ABSTRACT

Groundwater overexploitation due to unsustainable agricultural development is a widespread problem in irrigation districts relying on conjunctive use of surface and groundwater resources. Nearly 90% of global groundwater supported irrigated areas have conjunctive use of both surface and groundwater. A major driver behind the use of groundwater in these regions, in addition to surface water scarcity, is the poor operational performance of the irrigation schemes. The lack of reliability of water deliveries at farm gates forces farmers to increasingly turn to groundwater. Therefore, they intensively extract water and continuously deteriorate groundwater aquifers. This case study investigates the potential impact of improved water distribution and delivery through implementing canal automation techniques. These techniques can enhance the reliability of irrigation deliveries to the endpoint, resulting in reduction of groundwater extraction and associated benefits in decreasing energy consumption and CO_2 emissions. The current study focuses on six main irrigation districts located in the Zayandeh-Rud River Basin (ZRB) in central Iran, where a total area of 200,000 ha is irrigated using surface water in conjunction with groundwater. To improve the performance of the irrigation networks for each of these districts, three operational model alternatives, including fully automated systems, were considered. Each of these models was designed and run for each of the six districts separately. The results showed a reduction of operational water losses in the range of 15% –25% depending on the implemented operational model. These potential water savings are then available to be used in the agricultural sector and can result in a reduction in groundwater extraction of up to 300 Million Cubic Meters (MCM). The associated reduction in energy consumption and carbon emission was about 450 GWh and 57,500 t each year, respectively. The results of this study can be employed in designing a centralized configuration of automated systems that enable water managers to reduce pressure on groundwater resources.

1. Introduction

Providing a reliable source of water for irrigation districts is a major concern, especially in regions with frequent water shortage periods. To remedy the situation a wide range of solutions have been prescribed and sometimes implemented in whole or in part. The solutions offered range from short-term supply-oriented measures such as interbasin water transfer projects (Madani and Mariño, 2009), desalinization (Ghaffour et al., 2013), conjunctive use of surface and groundwater resources (Singh, 2014), construction of reservoirs (Zhuo et al., 2017), and mid-term and long-term demand management strategies (i.e. converting to pressurized irrigation techniques (García et al., 2017), increasing water use efficiency in irrigated agriculture (Taghvaeian and Neale, 2011), and change of cropping pattern (Inas et al., 2017)).

Within these solutions, the simultaneous use of surface and groundwater resources, also known as the conjunctive use, has become the preliminary action to overcome water deficiencies and improve the environmental impacts of most irrigation districts (Liu et al., 2013; Singh, 2014). Nearly 90% of global groundwater supported irrigated areas have conjunctive use of surface and groundwater (Thenkabail

* Corresponding author.
E-mail addresses: mehdi.hashemy@ut.ac.ir (S.M. Hashemy Shahdany), AliReza.Firoozfar@hdrinc.com (A. Firoozfar), pepemaestre@us.es (J.M. Maestre), imallakp@uci.edu (I. Mallakpour), saleh.taghvaeian@okstate.edu (S. Taghvaeian), p.karimi@un-ihe.org (P. Karimi).

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et al., 2009). According to a global irrigation map, 41% of the total area is irrigated by conjunctive use, with less than 15% surface water contribution (Siebert et al., 2010). Groundwater remains as the ultimate source of irrigation, due to the unreliable performance of the surface water distribution systems in arid and semi-arid areas (Burt, 2013; Singh, 2014). For instance, the Middle East, with 36.6%, and Southern and East Asia, with 37%, include the highest total irrigated area as a percentage of cultivated land. However, the value of consumptive groundwater use for irrigation, as a percentage of internally produced groundwater, is 43.3% for dry regions of the Middle East, while the value is 12.7% for East Asia, indicating a significant pressure on groundwater resources for arid areas subject to over-extraction and even the exploitation of fossil groundwater (Siebert et al., 2010).

Substantial investments have been made in canal networks to allocate surface water through farms in the arid and semi-arid regions. However, reliable water distribution has not been attained due to poor canal operation (Burt, 2013). Moreover, traditional canal operation methods are not capable of dealing with multiple objectives. These objectives include equitable water distribution between the upstream and downstream users in drought periods (Clemmens, 2012); water storing strategies (using inline or offline reservoirs) during the water shortages (Hashemy et al., 2013b); and implementing local water markets to incentivise stakeholders to increase profits by saving water and performing efficient operation based on the economic value of water (Hashemy Shahdany et al., 2017). Negative outcomes are resulting from poor operational management throughout the irrigation districts, and this is shifting the dependency of farmers from surface water to the groundwater resources (Karimi et al., 2012). Additionally, it must be noted that supply-oriented measures, despite being popular short-term solutions, are of no benefit in the longer term because there is an underlying issue of physical water scarcity (Rijsberman, 2006). Such short-term solutions often only postpone the problem at the cost of increasing its magnitude later since they increase the use of water (Pittock et al., 2009). For this reason, modernization, rehabilitation, and renovation of irrigation districts, including farm-scale and off-farm water management, need to be focused on long-term demand management. To achieve this objective, operational management strategies need to be upgraded from traditional unreliable methods (i.e., manual operation by ditch-riders and employing the hydro-mechanical control structures) to modern canal operational methods.

Previous studies have shown that automatic operational services can provide consistent and reliable water delivery to water users, from those located at the most upstream laterals to all the end users of the main canal, due to increases in the reliable performance of the systems (Clemmens, 2012; Guan et al., 2011; Hashemy Shahdany et al., 2015). An intelligent operation of the canals, provided by optimal control systems, can significantly reduce the operational water losses within the canals, and consequently, lead to significant water saving.

Canal system automation requires implementing advanced real-time control algorithms to deal with the sophisticated interactions between control objectives and the water saving operational strategy. In this study, two configurations of decentralized (PI) and centralized control (Model Predictive Control (MPC)) are designed and tested. In addition, the impacts of performance improvements on reducing operational water losses are thoroughly investigated.

Application of decentralized PI control systems has been investigated in different irrigation canals (Burt, 1999; Hashemy et al., 2013a; van Overloop et al., 2005; Wahlin and Clemmens, 2006). Successful experiences with the first generation of automatic water level regulators encouraged the authorities to upgrade their operational strategies. MPC (Camacho and Bordons, 2004), which has been widely applied in the studies related to canal automation (Maestre and Negenborn, 2014; van Overloop et al., 2010; Zafra-Cabeza et al., 2011), has shown promising performance, since it combines feedback control on measured water levels at different locations along the canal with feedforward control to deal with predictable disturbances, and optimal control to provide the highly intelligent operational performance of the canal network (Camacho and Bordons, 2004).

This article hypothesizes that improved canal operational management through automation techniques can improve the surface water distribution system, and reduce operational water losses, groundwater exploitation, energy consumption and CO_2 emissions throughout the six irrigation districts. Accordingly, the main objectives of this article can be summarized as follows:

- To assess the capability of canal automation techniques to distribute surface water adequately and equitably within the main canals of the study area.
- To examine the potential reductions in groundwater exploitation, energy consumption, and CO_2 emission as a result of improving surface water distribution with the automation of irrigation canals.

Finally, the present study uses the Zayandeh-Rud River Basin, a subbasin of the Central Plateau Basin (CPB) in the central part of Iran with six main irrigation network districts, as a benchmark.

2. Overview of the study area

2.1. Study area description

Zayandeh-Rud River Basin (ZRB) is located in the central part of Iran, on the east side of the Zagros Mountains in the Esfahan Province. The Zayanderud River is one of the major rivers in the central part of Iran extending from west to east and draining into the Gave-khuni swamp (Fig. 1). The ZRB has a total area of 41,524 km^2 and is characterized by a semi-arid climate with a range of 50–1500 mm of annual precipitation (125 mm is the annual average), and 1500 mm of annual evapotranspiration. For this basin, the primary source of water is snowmelt which peaks during spring (Bhadra et al., 2010). An overview diagram of the ZRB water budget in the 2011–2012 water year, consisting of water resources and total demands according to official data records (IDE, 2015) is presented in Fig. 2. Irresponsible water management has led to an unsustainable condition where there is a 460 Million Cubic Meters (MCM) annual overexploitation from the groundwater sources. Surface water sources also face a similar situation, although to a lesser extent, in which the annual over-diversion of the surface water has led to a 16.4 MCM deficit in the water budget.

Currently, there are six irrigation districts (ID) within the basin, and basic information regarding these, including infrastructure, operation and groundwater extraction is given in Table 1. According to Table 1, the total amount of groundwater extraction throughout the 28116 number of tube-wells within the six IDs, in the 2015–2016 water year, was about 1232 MCM (IDE, 2015). In addition, Fig. 3 shows the growth in tube-well installations in the ZRB, which are classified as deep (deeper than 90 m), semi-deep (60–90 m) and shallow (less than 60 m). Fig. 3 shows that the number of tube-wells has increased by two to four times in all of the irrigation districts, with the exception of ID No. 3, during the last decade.

All six IDs in ZRB receive enough surface water from the Zayandeh-Rud River (based on the available information in the local water authority's database) to meet their demand during years with normal precipitation (IDE, 2015). However, due to poor irrigation efficiency (between 32.1 and 42.1% (Abbasi et al., 2017; IDE, 2015), farmers are forced to extract groundwater continually to meet the crop demand. Poor operational management and unreliable water distribution within the irrigation canal networks are sources of distrust for the farmers and even the local authorities. As a consequence, the districts are shifting towards groundwater-oriented networks instead of improving the operational performance of conveyance and delivery systems.