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A geo-informatics approach for estimating water resources management components and their interrelationships

Umar Waqas Liaqat[a,b], Usman Khalid Awan[c], Matthew Francis McCabe[b], Minha Choi[d,*]

[a] Department of Civil and Environmental Engineering, College of Engineering, Hanyang University, Seoul 133-791, Republic of Korea
[b] Water Desalination and Reuse Center, Division of Biological and Environmental Sciences and Engineering, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia
[c] International Center for Agricultural Research in the Dry Areas (ICARDA), Cairo, Egypt
[d] Water Resources and Remote Sensing Laboratory, Department of Water Resources, Graduate School of Water Resources, Sungkyunkwan University, Suwon 440-746, Republic of Korea

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ABSTRACT

A remote sensing based geo-informatics approach was developed to estimate water resources management (WRM) components across a large irrigation scheme in the Indus Basin of Pakistan. The approach provides a generalized framework for estimating a range of key water management variables and provides a management tool for the sustainable operation of similar schemes globally. A focus on the use of satellite data allowed for the quantification of relationships across a range of spatial and temporal scales. Variables including actual and crop evapotranspiration, net and gross irrigation, net and gross groundwater use, groundwater recharge, net groundwater recharge, were estimated and then their interrelationships explored across the Hakra Canal command area. Spatially distributed remotely sensed estimates of actual evapotranspiration (ET_a) rates were determined using the Surface Energy Balance System (SEBS) model and evaluated against ground-based evaporation calculated from the advection-aridity method. Analysis of ET_a simulations across two cropping season, referred to as *Kharif* and *Rabi*, yielded Pearson correlation (R) values of 0.69 and 0.84, Nash-Sutcliffe criterion (NSE) of 0.28 and 0.63, percentage bias of −3.85% and 10.6% and root mean squared error (RMSE) of 10.6 mm and 12.21 mm for each season, respectively. For the period of study between 2008 and 2014, it was estimated that an average of 0.63 mm day^{-1} water was supplied through canal irrigation against a crop water demand of 3.81 mm day^{-1}. Approximately 1.86 mm day^{-1} groundwater abstraction was estimated in the region, which contributed to fulfil the gap between crop water demand and canal water supply. Importantly, the combined canal, groundwater and rainfall sources of water only met 70% of the crop water requirements. As such, the difference between recharge and discharge showed that groundwater depletion was around −115 mm year^{-1} during the six year study period. Analysis indicated that monthly changes in ET_a were strongly correlated (R = 0.94) with groundwater abstraction and rainfall, with the strength of this relationship significantly ($p < 0.01$ and 0.05) impacted by cropping seasons and land use practices. Similarly, the net groundwater recharge showed a good positive correlation (R) of 0.72 with rainfall during *Kharif*, and a correlation of 0.75 with canal irrigation during *Rabi*, at a significance level of $p < 0.01$. Overall, the results provide insight into the interrelationships between key WRM components and the variation of these through time, offering information to improve the management and strategic planning of available water resources in this region.

1. Introduction

Agriculture is one of the mainstays of Pakistan's economy, contributing more than 25% to the nation's GDP and employing almost half of the adult population (Bhatti et al., 2009; Yu et al., 2013). The sustainability of agriculture is almost wholly dependent on irrigation water supplies, provided via one of the world's largest irrigation networks. However, despite considerable capital expen-

* Corresponding author at: Department of Water Resources, Graduate School of Water Resources, Sungkyunkwan University, 2066 Seobu-ro, Jangan-gu, Suwon Gyeonggi-do, 440-746, Republic of Korea.
E-mail addresses: umar.liaqat@kaust.edu.sa (U.W. Liaqat), mhchoi@skku.edu (M. Choi).

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diture on the maintenance and operation of this system, it is ranked as one of the most mismanaged irrigation systems in the world (Yu et al., 2013). Mismanagement has contributed to a range of problems including land and environmental degradation, waterlogging and salinity, inequitable distribution of water, and social and institutional conflicts (Laghari et al., 2012). Sustained increases in population growth coupled with competing agricultural water users across the Indus Basin of Pakistan dictates the need to implement improved water management practices in the region (Ahmad et al., 2009; Kirby et al., 2016).

Clearly, the strategic management of available water resources is of paramount importance in understanding and predicting the hydrological behavior of this complex system (Awan et al., 2016; Cheema et al., 2014). To do this requires the identification and estimation of strategic water resources management (WRM) components across both time and space domains. Such detailed monitoring of WRM components can be used as a screening tool towards sustainable use of basin scale water resources (Hertzog et al., 2014) in an optimal way for socio-economic development. This can be achieved by implementing a geo-informatics approach, which integrates key remote sensing derived hydrological variables, auxiliary ground measurements and geo-statistics as an information source to a Geographic Information System (GIS) for analytical assessment. A combined data modelling and geo-informatics approach provides an intelligent spatial hydrological analysis that helps in describing the variation and uncertainties in WRM components associated with atmospheric, surface and subsurface water fluxes (Ahmad et al., 2005).

The lack of spatio-temporal observation data in many arid and semi-arid environments hampers the quantification of WRM components (Becker, 2006; Brunner et al., 2007). One means to address the lack of spatially distributed information is through the use of satellite remote sensing techniques, which can provide spatially continuous datasets of a number of variables (Boegh et al., 2009; Campos et al., 2013; Milewski et al., 2009). For instance, there is an extensive history of using remote sensing data for the estimation of hydrological components such as evapotranspiration (ET) (Ershadi et al., 2014; Liaqat and Choi, 2015; McCabe et al., 2005), which serves as a critical variable in the characterization of groundwater systems (Becker, 2006).

Groundwater is considered as a prime water resource in arid and semi-arid regions with the potential to bridge the gap between crop evapotranspiration (ET_c) and effective rainfall or surface water supplies (Chowdary et al., 2008; Mastrocicco et al., 2010). Declining, or even stable surface irrigation water availability, is putting greater pressure on farmers to supplement water supplies with groundwater in order to meet the needs of growing populations and increasing food demands (De Vries and Simmers, 2002). Such adjustments have resulted in dramatic drops in regional groundwater tables by approximately 1–3 m year^{-1}, as observed in various geographical settings of South and East Asia (Kinzelbach et al., 2003; Kirby et al., 2015; Yang et al., 2015). Groundwater abstraction in the irrigated Indus Basin of Pakistan range between 30 and 60% of total crop water requirements (Sarwar and Eggers, 2006; Scott and Shah, 2004), largely as a consequence of an unreliable water supply from surface irrigation (Cheema et al., 2014). For these reasons, the reliable quantification of net and gross groundwater use in space and time is critically important to develop sound groundwater management policy for sustainable exploitation.

Net groundwater recharge represents one of the most challenging components of WRM due to difficulties with its direct measurement (Anuraga et al., 2006; Castaño et al., 2010; Crosbie et al., 2015). Several approaches exist to quantify groundwater recharge, all with their own advantages and limitations (Scanlon et al., 2002). The conceptually simple water balance approach has gained considerable attention due to its simplicity and reliable estimation by use of remote sensing observations (Szilagyi et al., 2011). A number of previous studies have used this method for the determination of spatio-temporal groundwater recharge in the United States, Europe and Africa (Huang et al., 2013; Műnch et al., 2013; Szilagyi and Jozsa, 2013; Szilágyi et al., 2012) by only considering the difference in precipitation and ET. Such studies tend to ignore changes in soil moisture and surface irrigation supplies, which could lead to significant errors in net groundwater recharge estimation due to extreme variability in irrigation contributions from rivers or canals. Errors and variability associated with remotely sensed ET in heterogeneous environments with poor spatial density of needed meteorological measurements also presents as a potential source of uncertainty (Ershadi et al., 2013a; Liou and Kar, 2014).

The present study focuses on the estimation of various WRM components, as well as their interrelationships, over the Hakra Canal command area in eastern Pakistan during the period of April 2008 to March 2014. The specific components that are estimated include the actual evapotranspiration (ET_a), crop evapotranspiration (ET_c), net and gross irrigation, net and gross ground water use, recharge, net recharge, and rainfall. In addition to quantifying their spatial and temporal behavior, identifying correlation between WRM components allows for an analysis of the impact of intervention strategies on these statistical relationships to be determined. Furthermore, improved knowledge of these interrelationships will provide a mechanism through which plausible ranges of water resources allocations within the irrigation scheme can be determined and assessed (Awan et al., 2013; Cheema et al., 2014).

2. Study area

The Hakra canal command encompasses an area of approximately 0.2 Mha and has an arid to semi-arid climate that is representative of a typical irrigation area of the Indus basin. The region is situated in the southeast of the Punjab province of Pakistan (Fig. 1) with its mapping extent between latitude 29.05° to 29.95° north and longitude 72.26° to 73.40° east. Surface topography in the irrigation scheme gradually decreases from 176 m above mean sea level in the upper north of the basin to less than 125 m above mean sea level towards the south-west (Shafeeque et al., 2016). The Hakra irrigation scheme is comprised of 17 major irrigation distributaries that historically delivered water through several minor canals and direct water courses (Fig. 1a). The groundwater table in the study region ranges between 1 and 25 m (Shafeeque et al., 2016), while depth to groundwater (DTGW) is being monitored on a seasonal basis through eleven distributed observation wells, as depicted in Fig. 1a. Rainfall is insufficient to meet the crop water requirements of the region, which forces farmers to use canal water, ground water or a combination of both to support their consumptive needs. However, even with these additional sources, it is generally insufficient to meet the crop water requirements.

There are several social and institutional conflicts on access to canal water, as it is much cheaper when compared with groundwater extraction. To resolve these issues and to determine an equitable distribution of canal water, the irrigation system is being managed via public-private partnerships. Although farmer representatives are involved in the local irrigation scheme, with an aim to achieve equity and to improve cost recovery, the equitable management of irrigation waters remains challenging (Awan et al., 2016). Erratic surface water deliveries enhances (and encourages) the use of pumped groundwater to achieve a certain agriculture production level.

The study area is broadly classified as agricultural land, and has a number of major crops including rice, cotton, fodder, millet, gram, rapeseed and wheat, which are grown in rotation, depend-