Science of the Total Environment 635 (2018) 725–740

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Future irrigation expansion outweigh groundwater recharge gains from climate change in semi-arid India

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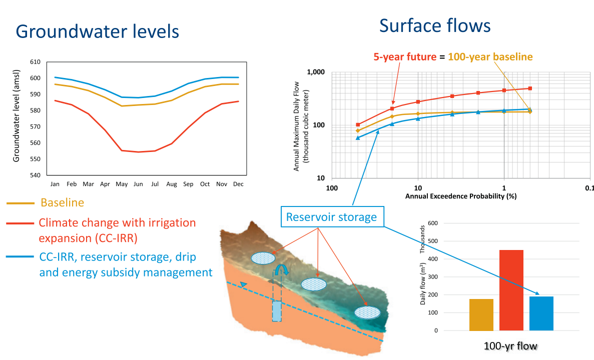
HIGHLIGHTS

- Predicted increase in future rainfall increased groundwater recharge.
- Future irrigation expansion negated the positive groundwater recharge effects.
- Increased well drying under changed climate with irrigation expansion
- Increased frequency of extreme flow events (e.g., flooding) in the future
- Energy subsidy reforms needed to fund water storage and drip irrigation

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 31 October 2017
Received in revised form 4 April 2018
Accepted 5 April 2018
Available online xxxx

Keywords:
Crystalline aquifer
Demand and supply management
Energy policy
Flooding
Uncertainty
Well drying

ABSTRACT

Simultaneous effects of future climate and irrigation intensification on surface and groundwater systems are not well understood. Efforts are needed to understand the future groundwater availability and associated surface flows under business-as-usual management to formulate policy changes to improve water sustainability. We combine measurements with integrated modeling (MIKE SHE/MIKE11) to evaluate the effects of future climate (2040–2069), with and without irrigation expansion, on water levels and flows in an agricultural watershed in low-storage crystalline aquifer region of south India. Demand and supply management changes, including improved efficiency of irrigation water as well as energy uses, were evaluated. Increased future rainfall (7–43%, from 5 Global Climate Models) with no further expansion of irrigation wells increased the groundwater recharge (10–55%); however, most of the recharge moved out of watershed as increased baseflow (17–154%) with a small increase in net recharge (+0.2 mm/year). When increased rainfall was considered with projected increase in irrigation withdrawals, both hydrologic extremes of well drying and flooding were predicted. A 100-year flow event was predicted to be a 5-year event in the future. If irrigation expansion follows the historical trends, earlier and more frequent well drying, a source of farmers' distress in India, was predicted to worsen in the future despite the recharge gains from increased rainfall. Storage and use of excess flows, improved irrigation efficiency with flood to drip conversion in 25% of irrigated area, and reduced energy subsidy (free electricity for 3.5 h compared to 7 h/day; $1 billion savings) provided sufficient water savings to support future expansion in irrigated areas while mitigating well drying as well as flooding. Reductions in energy subsidy to fund the implementation

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https://doi.org/10.1016/j.scitotenv.2018.04.130
0048-9697/

of economically desirable (high benefit-cost ratio) demand (drip irrigation) and supply (water capture and storage) management was recommended to achieve a sustainable food-water-energy nexus in semi-arid regions.

1. Introduction

Changes in temperature, precipitation and other climatic variables during 20th century (Donat et al., 2013; McVicar et al., 2012; Mishra et al., 2015; Wild, 2009; Willett et al., 2008) have altered the surface and groundwater systems globally (Stocker et al., 2013). Future changes in the climate are likely to affect surface flows (Vano et al., 2015; Van Vliet et al., 2013), groundwater recharge (Crosbie et al., 2013; Doll, 2009) and water availability in many parts of the world. At the same time, increased food demand due to demographic, cultural and socio-economic changes is likely to increase the future water demands (Sauer et al., 2010; Vörösmarty et al., 2000). For example, in India, under the "business-as-usual" scenario, 40% increase in groundwater withdrawals has been predicted for 2050 compared to the base year 2000 (Amarasinghe et al., 2007). The "business as usual" scenario in Amarasinghe et al. (2007) was based on the recent trends in population and agriculture growth and assumes rather optimistic future economic growth with increasing per capita food and water consumption. Climate change will occur simultaneously with these societal changes; therefore, climate change impact and adaptation studies must also consider changing land and water demands (Holman et al., 2012; Woldeamlak et al., 2007). Depending on the direction of change (e.g. increased or decreased rainfall), future climate may either support the increased water demands or further worsen the water availability.

Globally, groundwater provides drinking water to >50% of population (≈3.5 billion, Connor, 2015) and supports 40% of irrigated areas (Siebert et al., 2010). Groundwater supply is even more critical for arid and semi-arid regions (e.g. western United States and most of India). For example, in India, groundwater provides drinking water supply to one billion people (World Bank, 2010), supports 65% of irrigated agriculture (Siebert et al., 2010), and contributes 9% to the gross domestic product (Sharda et al., 2006). However, lack of data and uncertainties related to the complex and slow response of groundwater systems to changing climatic conditions have limited the evaluation of climate change effects on groundwater (Field et al., 2014; Zektser and Dzyuba, 2015). Furthermore, climate change impact studies using hydrologic modeling have not considered future changes in groundwater demand due to irrigation expansion related to demographic, societal and land use changes (Beigi and Tsai, 2015; Crosbie et al., 2013; Goderniaux et al., 2009; Scibek and Allen, 2006).

India is the largest groundwater user (250 billion m^3/year) (AQUASTAT, 2010) in the world and contributes to >25% of global annual withdrawals (World Bank, 2010). Increased climatic variability in the future (e.g. more frequent droughts) may further promote the groundwater use as a potential adaptation measure (Scott, 2013; Taylor et al., 2013). Many of the semi-arid regions, including the Indo-Gangetic plain and crystalline aquifers in central and south India, are already experiencing groundwater depletion and other environmental problems (Palanisami et al., 2008; Panda and Wahr, 2016; Rodell et al., 2009; Sishodia et al., 2016). Increased groundwater demands due to climatic and societal changes coupled with limited rainfall and adaptation capacity (Mertz et al., 2009) may worsen the groundwater supply in the crystalline aquifer region of central and south India (Sishodia et al., 2017). In the past, well drying, crop losses and increasing debts (e.g. loan financed for well installation) due to recurring droughts have caused many farmers in this region to commit suicide (Mohanty and Shroff, 2004; Rao and Suri, 2006). Many of the farmers resorted to well deepening or installation of deeper drilled wells to cope up with the declining groundwater levels in this region. Current regulations do not permit new well drilling in areas designated as over exploited, however the regulations are seldom followed due to lack of coordination between government agencies (Sishodia et al., 2016). Considering limited storage capacity of the shallow crystalline aquifers (Dewandel et al., 2006), management and policy changes targeted towards increasing the irrigation efficiency will be needed to support the projected expansion in irrigated area.

A few studies have been conducted in India to evaluate the effects of climate change and irrigation on groundwater recharge and availability (Ferrant et al., 2014; Sekhar et al., 2013; Surinaidu et al., 2013); however, simultaneous expansion in irrigation have not been considered to evaluate the combined effects on surface and groundwater flows and levels. For example, Ferrant et al. (2014) used the SWAT model (Gassman et al., 2007) to predict the effects of climate change on groundwater use and availability for a crystalline aquifer catchment (area = 983 km^2) in south India; however, they did not account for future changes in groundwater demand driven by changing demographic or socio-economic conditions. As opposed to focusing on either surface water or groundwater (Surinaidu et al., 2013), for basin-scale water availability assessments surface water and groundwater must be treated as an integrated system. Both surface water and groundwater play a critical role in providing water supply for agriculture, industrial, domestic sectors in India (Thatte, 2017) and the world. Evaluation of the combined effects of future climate and irrigation expansion on surface and groundwater system, followed by hydrologic and economic assessment of management and policy changes have not been conducted in India. Future changes in surface and groundwater flows brought by changed climate and irrigation are likely to influence existing management and government policies to mitigate the adverse effects on water availability (Sivapalan, 2015). In this study, we use an integrated hydrologic model to predict the effects of changes in future climate, irrigation, management and policy on surface and groundwater availability for a representative agricultural watershed in semi-arid south India. Specific objectives were to: 1) evaluate the effects of future climate, with and without irrigation expansion, on groundwater recharge, levels and surface flows and 2) evaluate the hydrologic and economic impacts of management and policy changes under changed future climate and irrigation demand to improve water sustainability.

2. Materials and methods

2.1. Study site

Integrated hydrologic models usually require extensive long-term weather, land use, irrigation, surface flows, soils, hydrogeology, and groundwater levels data, which are rarely available for Indian watersheds (Adamowski et al., 2012). International Crops Research Institute for Semi-Arid Tropics (ICRISAT) has one such well-studied watershed in south India where additional hydrologic and land use data were collected for this study. The study site, Kothapally watershed, is located at 17° 22′N latitude 78° 07′E longitude in the semi-arid Telangana state of south India (Fig. 1). The watershed elevation ranges from 600 to 640 m above mean sea level. The watershed (320 ha) is a part of the Musi river sub-basin which is a tributary of the Krishna River. Average annual rainfall (2000–2012) is 840 mm, 85% of which is received during the monsoon season (June–October). Rainfall exhibits high inter annual variability, for example annual rainfall varied from 571 mm in 2002 to 1352 mm in 2008. Surface flow in streams is mostly limited to the monsoon season. The maximum temperature climbs to 44 °C during summer (April–May) and minimum temperature dips to 6 °C in winter (November–February). Crops in the region are mainly grown during