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Uncertainty based assessment of dynamic freshwater scarcity in semi-arid watersheds of Alberta, Canada

Monireh Faramarzi[a,*], Karim C. Abbaspour[b], W.L. (Vic) Adamowicz[c], Wei Lu[c], Jon Fennell[d], Alexander J.B. Zehnder[e], Greg G. Goss[f]

[a] *Department of Earth and Atmospheric Sciences, Faculty of Science, University of Alberta, Alberta, Canada*
[b] *Eawag, Swiss Federal Institute of Aquatic Science and Technology, Duebendorf, Switzerland*
[c] *Department of Resource Economics and Environmental Sociology, University of Alberta, Alberta, Canada*
[d] *Department of Renewable Resources, University of Alberta, Integrated Sustainability Consultants Ltd., Alberta, Canada*
[e] *Nanyang Technological University (NTU), Sustainable Earth Office, Singapore 637459, Singapore*
[f] *Department of Biological Sciences, Faculty of Science, University of Alberta, Alberta, Canada*

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ABSTRACT

Study region: Alberta, Canada.
Study focus: The security of freshwater supplies is a growing concern worldwide. Understanding dynamics of water supply and demand is the key for sustainable planning and management of watersheds. Here we analyzed the uncertainties in water supply of Alberta by building an agro-hydrological model, which accounts for major hydrological features, geo-spatial heterogeneity, and conflicts over water-food-energy resources. We examined the cumulative effects of natural features (e.g., potholes, glaciers, climate, soil, vegetation), anthropogenic factors (e.g., dams, irrigation, industrial development), environmental flow requirements (EFR), and calibration schemes on water scarcity in the dynamics of blue and green water resources, and groundwater recharge.
New hydrological insights for the region: Natural hydrologic features of the region create a unique hydrological system, which must be accurately represented in the model for reliable estimates of water supply at high spatial and temporal resolution. Accounting for EFR, increases the number of months of water scarcity and the population exposed. Severe blue water scarcity in spring and summer months was found to be due to irrigated agriculture, while in winter months it was mostly due to the demands of petroleum or other industries. We found over exploitation of the groundwater in southern subbasins and concluded that more detailed analysis on groundwater flow and connectivity is required. Our study provides a general and unified approach for similar analyses in other jurisdictions around the world.

1. Introduction

Understanding temporal and spatial dynamics of water scarcity is key for sustainability of freshwater supplies. Economic expansion, population growth, extended environmental concerns, and climate change are increasing surface water scarcity and depleting groundwater resources threatening the sustainability of the natural ecosystem and human activities (Beek

* Corresponding author.
E-mail address: monireh.faramarzi@ualberta.ca (M. Faramarzi).

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et al., 2011; Doll, 2009; Famiglietti, 2014; Mwangi et al., 2016; Oki and Kanae, 2006). Global organizations and national governments have announced water stress as the largest global risk and the main reason for regional insecurity (Intelligence Community Assessment (ICA), 2012; World Economic Forum, 2015). To manage limited water resources, development plans have been shifted from a sector specific focus to a broader scale through integrated measures (UNEP, 2011). The studies on integrated water resources management have mostly been concerned with sustainability issues aiming to understand the balance between supply and demand components (Alcamo et al., 2007; Richey et al., 2015). The water-food-energy nexus is considered as an emerging concept that advocates sustainable management of the water-food-energy system in concert with environmental protection (Vlotman and Ballard, 2014). Within the context of water and food sustainability, the majority of research studies have focused on understanding the role of a virtual water trade strategy and agricultural water management in alleviating groundwater and surface water scarcity at the global (Allan, 1997; Chapagain et al., 2006; Lenzen et al., 2013; Yang et al., 2006), regional (Zeitoun et al., 2010), and national (Faramarzi et al., 2010a; Talozi et al., 2015) scales. To determine levels of sustainable water use, and to warrant balance between water supply and demand, it is critical to understand the spatial and temporal dynamics of water scarcity and the hydrologic system with its associated physical processes.

Water scarcity analysis is useful to understand the balance between water supply and water demand (Hoekstra et al., 2012) that helps to manage human interaction with natural systems. Different approaches have been developed to assess water stress worldwide. These are: i) the per-capita water availability indicator (Falkenmark et al., 1989), ii) the critical ratio indicator (Alcamo et al., 2003), iii) the International Water Management Institute (IWMI) indicator (Seckler et al., 1998), and iv) the water poverty index (Sullivan et al., 2003). Given the widespread use of these indicators, their accuracy depends on the accuracy of the water supply and demand assessments. Here we refer to some shortcomings in the assessment of water supply and demand terms that has resulted in an inaccurate representation of the water scarcity in large-scale studies:

1.1. Water supply

Given that water is a dynamic and complex factor whose availability and variability of supply depends on both natural features and human factors (Richey et al., 2015), it is essential to utilize hydrological models as tools to systematically assess water availability and scarcity. Global hydrological models have been applied to simulate dynamic water resources at national, river basin, and recently at 0.5° grid resolutions (Alcamo et al., 2003; Beek et al., 2011; Feketa and Vorosmarty 2002; Oki and Kanae 2006). They have also been used to estimate surface and groundwater scarcity at high spatial and monthly temporal resolution (e.g., Beek et al., 2011; Richey et al., 2015; Wada et al., 2011). Although most models provide critical information at the global scale, often they are prone to poor representation of the actual physical processes at the local level where most of the decisions around water management are being made. High-resolution global studies often suffer from data scarcity and model complexity when dealing with the model building, calibration, and validation processes (Clark et al., 2015; Nazemi and Wheater, 2015; Wheater and Gober, 2013). Abovementioned global models often are only calibrated and validated against long-term annual discharges; hence providing a poor temporal resolution. Often they are modified using a correction factor to offset the errors in the temporal and spatial patterns, resulting in an inconsistent water balance. The most sophisticated studies have been validated using time series data of a few hydrometric stations on outlets of large river basins. In addition, most of the large-scale studies use globally reconstructed climate data without qualifying their hydrological responses at a regional level. Overlooking these details, negatively affects simulation of the hydrological processes at a high grid resolution, thereby reducing reliability at the local level.

The regional and river basin studies on water scarcity analysis have utilized more locally representative data for hydrologic model setup and calibration (e.g., Graveline et al., 2014; He and Hogue, 2012; Neverre et al., 2016). However, simulation of distributed physical processes are often simplified, and time-variant representation of the spatial patterns are compromised by ignoring an adequate calibration and validation of the models in studies of water supply and water scarcity at the regional level (Beck and Bernauer, 2011; Gain and Giupponi 2015; Sušnik et al., 2012).

1.2. Water demand

Previous studies used national water withdrawal statistics that are often static values representing water use of an entire country (Vörösmarty et al., 2000). The main drawback with withdrawal statistics is their poor spatial and temporal resolution, as well as ignoring of the return flow to the hydrological system, which becomes available for use in downstream watersheds (Kijne et al., 2003). Disregarding such important characteristics results in overestimation of water scarcity. More recent global scale studies assumed agriculture as the major water consumer, and utilized water balance models to account for dynamic water use of agricultural crops. However, to validate their model results they averaged their grid based model outputs to the national scale data and compared this with the available national average statistics (Mekonnen and Hoekstra, 2010) resulting in a poor representation of the actual water use over time and space. In addition, for sustainable management of the watersheds, there is an increasing interest to assess EFR to ensure health of aquatic ecosystem and the river's biodiversity (Vörösmarty et al., 2010). Recent studies used a simplistic approach and assumed 80% of total water availability for EFR, which does not change with river flow regime (Hoekstra et al., 2012). Limited studies used a monthly approach to account for river regime for the EFR to maintain various levels of habitat quality in the rivers (Liu et al., 2016; Tennant, 1976).