Water Consumption Impact under Climate and Population Scenarios

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ABSTRACT

Population growth and climate change have significantly altered water regimes. The challenge of managing water for increasingly populous and consumption under climatic uncertainties calls for a comprehensive framework of analysis that incorporates environmental and socioeconomic factors. This study aims to measure the potential water use impact under different scenarios associated with the change of climate and population using Minnesota as a studied case. A water use impact indicator was employed for quantifying the interaction between water demand and supply at a watershed level. A stochastic modeling framework coupling system dynamic models with geographic information system was adopted to accommodate the analysis. The simulation process enables us to understand the magnitude of climate and anthropogenic water use which on affecting water use impact potential under each defined scenario. The results indicate that population change is a more powerful force than climate in changing state-level water use impact. However, the temporal water use impact dynamics are primarily regulated by climate. Water management must take a four-dimension strategy integrating climate, population, time, and location into account in sustaining future water resources.

1. Introduction

Climate, population, and energy demands are among the most critical drivers affect long term water sustainability [1, 2], which can be manifested differently on a regional context [3]. Regional climate plays a key role in water supply, whereas population, agricultural and energy production of a region influence the region's water demands. These drivers are not independent from each other: climate conditions change the water consumption behavior, and economic activities can also alter climate patterns [4-6]. Understanding the complex interactions between climate, population, economic activities and water supply and demand is a key to sustainable water management policy. Other than the increase of water appropriation driven by anthropogenic activities, climate is often found as an important factor for determining water availability and its uncertainty [2, 7-10]. The impact of climate change on water availability has gained significant attention since the 1990s. Most studies came to a similar conclusion that (1) climate change's impact on water availability and water regimes vary region by region, and (2) climate change will generally elevate the risk of future economic growth [2, 10-14]. While all these prior studies focused on incorporating climate scenarios into hydrological models, which largely excluded the mutual relationship between socio-economic factors and natural hydro systems. Therefore, in order to verify the effects of climate change on water resources, both water availability and withdrawal should be integrated. In this study, we aimed to develop a framework integrating water withdrawal, availability, and impact assessment in a watershed resolution to cover an entire state boundary. A system dynamic framework integrating climate, environmental, social, and technical variables was proposed in this study to examine local water balance and water use impact in responding to climate and demographic scenarios by year 2030. To complete the simulation and gain insights of future water resource management implications, the state of Minnesota in the U.S. was selected as the study case (Fig. 1).

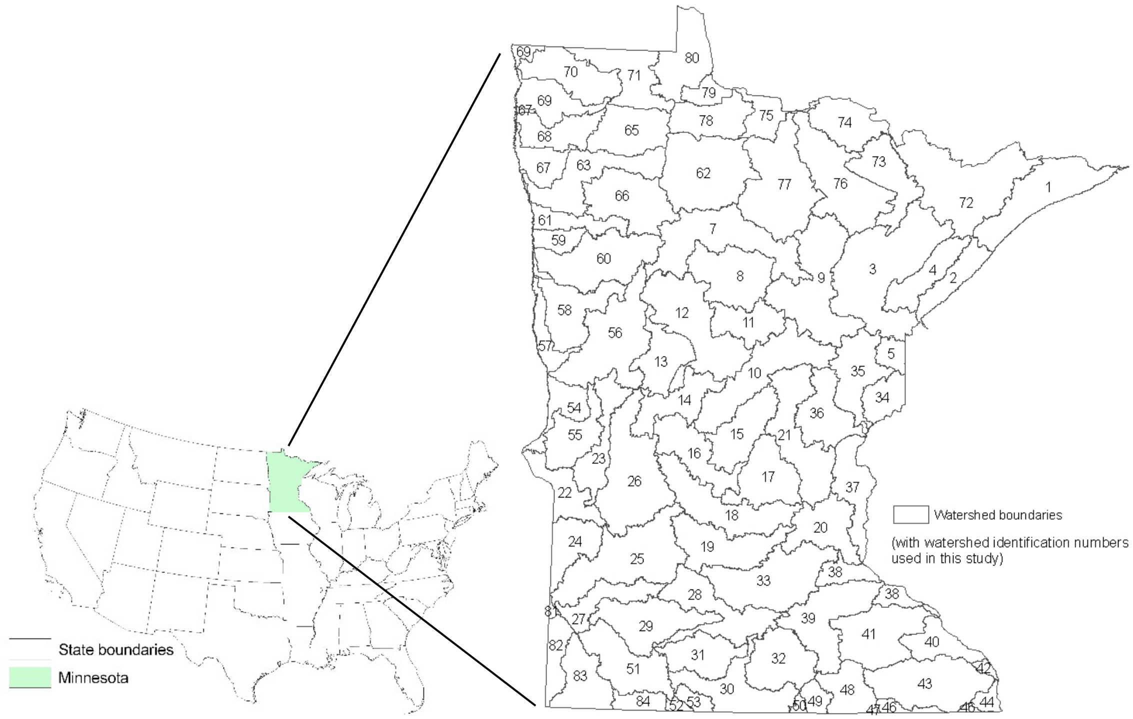

Fig. 1 Geographical location of Minnesota in relation of the U.S. and its watershed boundaries.

2. Methods

Water use impact modeling
The concept of sustainable water security tightly links domestic, agriculture, industry of anthropogenic sphere and ecosystem needs together [15]. The proposed study adopted a model first published in 2009 which aimed to translate water consumption into quantified environmental impacts [16]. To estimate the ecological impacts associated with water consumption, the indicator of an ecologically degraded area ΔEQ ($m^2 \cdot yr$) was applied to quantify the magnitude of impact and can be calculated as

$$\Delta EQ = NPP_{wl} \times \frac{WC_T}{P} = CF_{EQ} \times WC_T$$

where CF_{EQ} is the ecological damage factor which represents the land area size required to compensate appropriating per unit of consumptive water during a period of time. Local CF_{EQ} is equivalent to the fraction of water-limited net primary production (NPP_{wl}) to local annual precipitation (P, m year^{-1}). The spatially explicit NPP_{wl} is a dimensionless characterization factor which represents the local ecological vulnerability caused by water shortage. The NPP_{wl}

factor was firstly published in 2008 and can be derived from the fraction of net primary production reduction induced by the lack of water [17]. The concept of quantifying water use impact can be illustrated as in Fig. 2. Therefore, the value of NPP_{wl} / P is spatially explicit and can serve as the factor to convert consumptive water (WC_T, m^3) into ecological impact. The higher CF_{EQ} value, or NPP_{wl} / P ratio, indicates the more severe impact on local terrestrial ecosystems caused by per volume of water consumption. The model can be used to quantify water use impact, and helps to determine water-use sensitive area in terms of CF_{EQ}. In this study, the number of "extreme days" in a year within each watershed was computed for probability analysis purposes. The term "extreme days" in this study was defined as the days in a year which have impact value greater than the 80 percentile of mean daily ΔEQ in a given watershed. The distribution of extreme days in a watershed under different scenarios was then recorded for subsequent analysis.

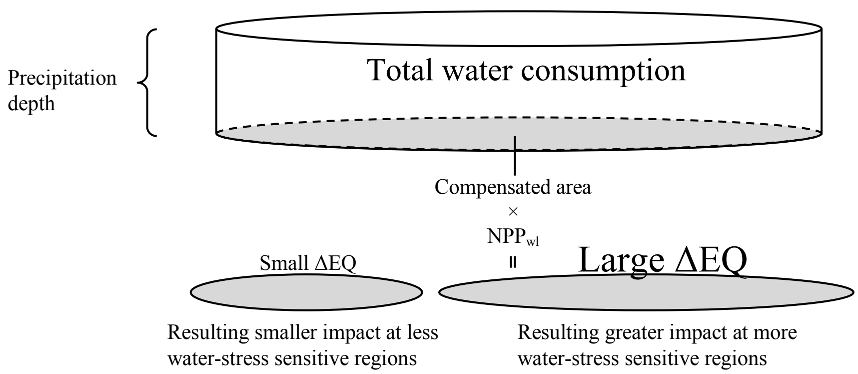

Fig. 2. Conceptual diagram illustrating the water impact assessment using NPP_{wl} as a characterization factor.

Water stock and flow

In supporting the calculation of water use impact, a system dynamic model accommodating the simulation of water stock and flow fluctuation (Fig. 3) under different scenarios was employed [18]. The water stocks are stored in four compartments including the top soil (S_{soil} l, mm), snow pack (S_{snow}, mm), aquifers (S_{gw}, mm), and surface water bodies (S_{sw}, mm) such as streams and lakes. All the compartments are linked by numerous flows primarily including precipitation (P, mm/day), surface runoff (Q, mm/day), runoff from upper watershed and flow out to down-stream watershed (Q_I, Q_O, mm/day), snow melt (F_m, mm/day), evaporation (EP, mm/day) or evapotranspiration (ET, mm/day), return flow from groundwater to streams or baseflow (F_b, mm/day), groundwater recharge (F_{sw}, mm/day), and anthropogenic withdrawal from surface water sources or groundwater (WU_{sw}, WU_{gw}, mm/day). Each watershed is treated as an independent system, and the only relationship between different watersheds is the stream flow connection. We assume there is no cross-boundary water delivery due to the lack of data.

In this study, water withdrawal is defined as the water volume extracted from either surface water bodies or aquifers disregard its fate. Notably, irrigated water (IRG, mm) is extracted from surface or ground water sources (IRG_{sw} and IRG_{gw}) and then applied onto the soil stock, which should be treated differently from other types of water withdrawal. The other types of water withdrawals are assumed to be evaporated during usage or to return to surface water stocks within the same day of extraction if the quality is not degraded. To account for the net water loss from anthropogenic extraction, water consumption is computed and defined as the amount of water lost from the system through evaporation, undeterminable fate, or due to expected quality degradation after extraction. Thus, the amount of water which does not return to its origin of extraction is considered as consumptive. Therefore, water withdrawn from groundwater is assumed as consumptive or $WC_{gw} = WU_{gw}$. In contrast, surface water withdrawn volume is proportionally classified as consumptive based on a designated ratio (r_{cw}) by water use category or $WC_{sw} = r_{cw} \times WU_{sw}$. The model is built to simulate water balance on a daily basis for long-term scenario analysis, therefore, it is not to be used for detailing single flood routing. Mathematically, the water stock can be computed using a simple mass balance method. Thus, water stock of a compartment at time t (S_t) can be presented as a result of its previous state (S_{t-1}) plus the difference between inflows (I) and outflows (O), or $S_t = S_{t-1} + I - O$. The dynamics of each compartment and its associated flows are described in the following sections.

Data sources and Scenarios

All the required input data were grouped in three categories: climate, demographic, and land cover. All data were derived from public-assessable datasets managed by National Climate Data Center of NOAA, US Geological Survey, US Census Bureau, National Agricultural Statistics Service of US Department of Agriculture, and Minnesota Department of Natural Resources [19-25]. To generate climate scenarios, data were downloaded from an exogenous source. The tool was developed by U.S. Bureau of Reclamation Technical Service Center, Santa Clara University, and Lawrence Livermore National Laboratory [26]. Various global climate models are available for selection and the one tagged as CCSM3 developed by the US National Center for Atmospheric Research was used. The projected climate change under extreme (A2), mid-level (A1B), and low (B1) green-house gas emission pathways were then generated, and the precipitation and temperature data were acquired accordingly. Population scenario was developed based on official projections published by Minnesota State Demographic Center [27]. Four designated scenarios were analyzed in this study including the 2000 baseline (2000BL), the 2030 business-as-usual (2030BAU), the 2030 climate change (2030CS), the 2030 population change (2030PS), and the 2030 extreme scenario combining both population and climate change effects (2030CPex). Each group of data were stored and managed as GIS map layers. In order to reach a consistent spatial resolution of watershed among each map layer, datasets which were not formatted in watershed scale would be further transformed by using area weighting or inverse distance weighting function in ArcGIS® tool.

3. Results and Discussion

Model Performance and Validation

To better present the results with a concise fashion while keeping ample details, watersheds were aggregated into nine regions using the climate-division boundaries defined by NOAA. All the results presented as divisional averages in the following section were area-weighted, unless otherwise specified. For comparison purpose, the climate simulation was compared with monthly historical data, whereas water withdrawal can only be plotted against annual historical records due to the lack of availability in monitored data. As for testing the spatial and temporal accuracy of hydrological module in this study, simulated annual stream flow was plotted against historical average on a watershed basis, and simulated state-wide average monthly stream flow was compared with state-level historical data as well. Simulated results agree with the selected historical data well in all aspects of climate, water withdrawal and stream flow. The synthetic precipitation and temperature variables fit well with the historical annual records (Fig. 4). The accuracy of the selected parameters from both hydrological and water withdrawal modules also fall in acceptable ranges (Fig. 5 and 6). These positive outcomes provide sufficient confidence in the performance of the model framework.

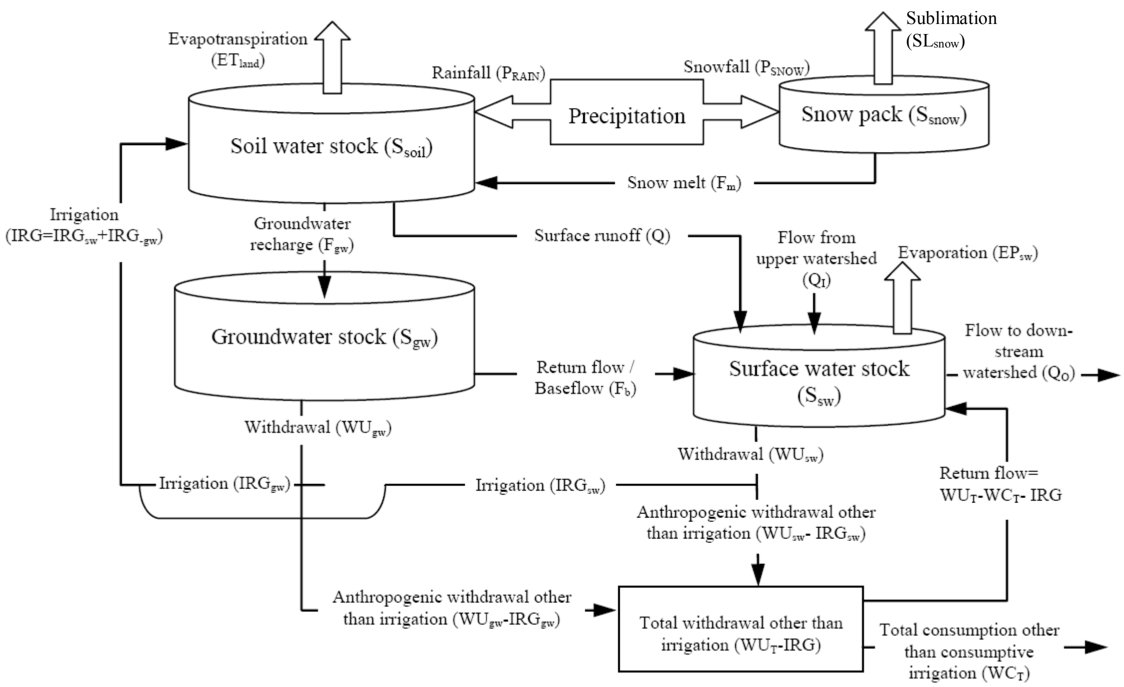

Fig. 3. Diagram of the model framework used in the study. The same structure is applied on each watershed in Minnesota.

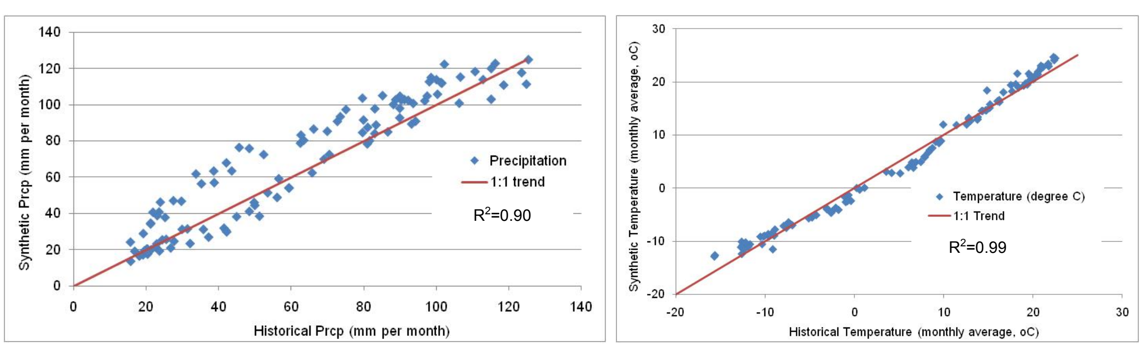

Fig. 4. Synthetic precipitation and temperature of each division fitted well with monthly climate records derived from NOAA.

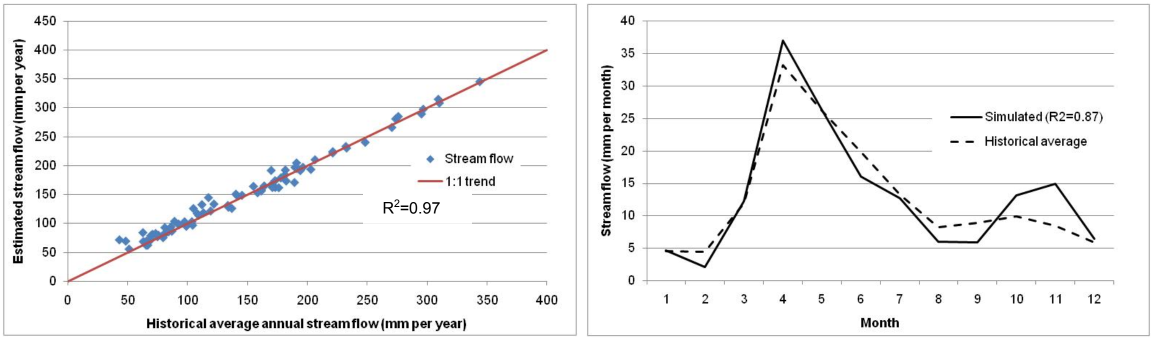

Fig. 5. Simulated stream flow fits well with historical records (1970s – 2000) on both spatial (left) and temporal (right) aspects.

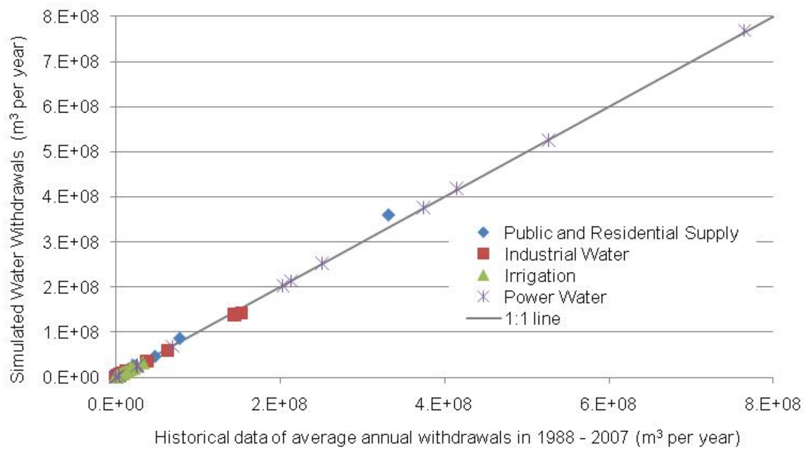

Fig. 6. Simulated water withdrawal results plotted against historical water withdrawal records. The results indicated substaintial goodness-of-fit.

Spatial and temporal trends of water use impact

Geographically, Division 5, 6, and 8 resulted in 58% of state total annual water use impact followed by Division 3 and 9, whereas the rest of divisions accounted for less than 14% of that. High impact was observed during summer time (June to August) accounting for 43% of annual total impact, whereas low impact most likely occurred in winter time (December to February) accounting for 14% of annual total impact. Both fall and spring were attributable for 23% and 21% of annual total water impact, respectively. The seasonal gradient maps also showed clear transition of increasing water use impact around central Minnesota sprawling toward the upper region from winter to summer (Fig. 7). Notably, though Division 4 was among the lower-impact group on an annual basis, water impact in this division during summer time may temporally surpass Division 3 and 9 which had higher annual water use impact. Geographically, Division 4 and 5 appeared to have sharp increases of water use impact during summer due to substantial seasonal consumption from the irrigation and power generation.

Change of water use impact under different scenarios

This study examined water use impact change driven by population (2030PS), climate change (2030CS), and their joint effects (2030CPex). The intention was to illustrate the magnitude of a target parameter under these designated scenarios departing from its averaged status under the 2000BL scenario. However, in order to distinguish the effects caused solely by population, climate, or combined, simulated results under each 2030 scenario were then compared with that from business-as-usual scenario (2030BAU) in the same year. The results provide strong evidence that population is a more influential driver than climate in altering local and seasonal water use impact. In general, the 2030PS scenario would cause the highest impact, followed by 2030CPex, 2030BAU, and 2030CS in descending order. Population can significantly cause the leap of water use impact departing from both 2000BL and 2030BAU scenarios, whereas the impact may be offset by the intervention of climate change. However, the temporal and spatial variances of water use impact under different scenarios may vary significantly (Fig. 8).

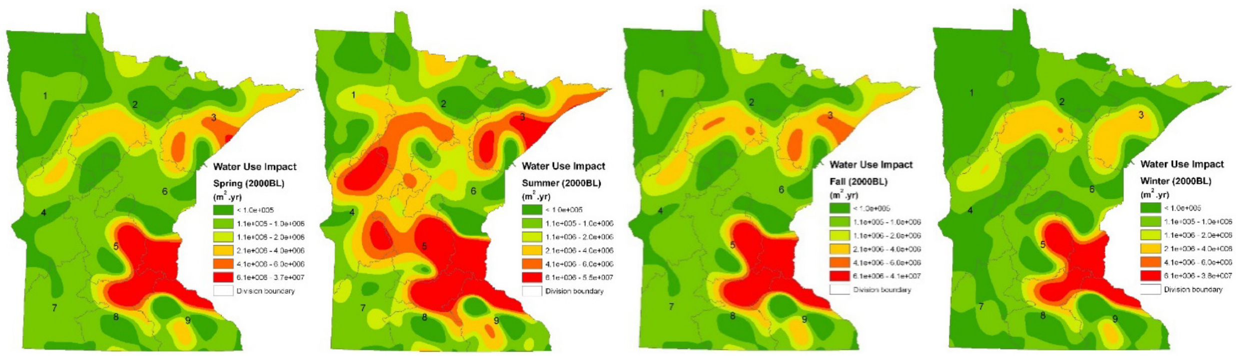

Fig. 7. Seasonal and geographical dynamics of water use impact in Minnesota.

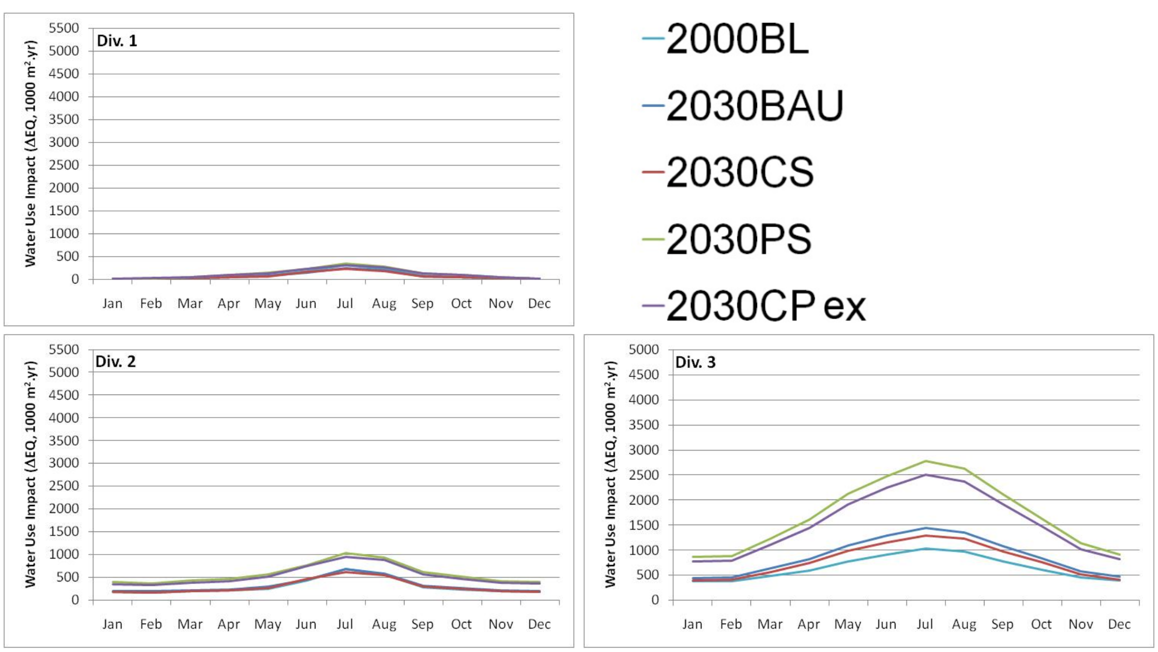

Fig. 8. Water use impact by division by month under different scenarios (continue).

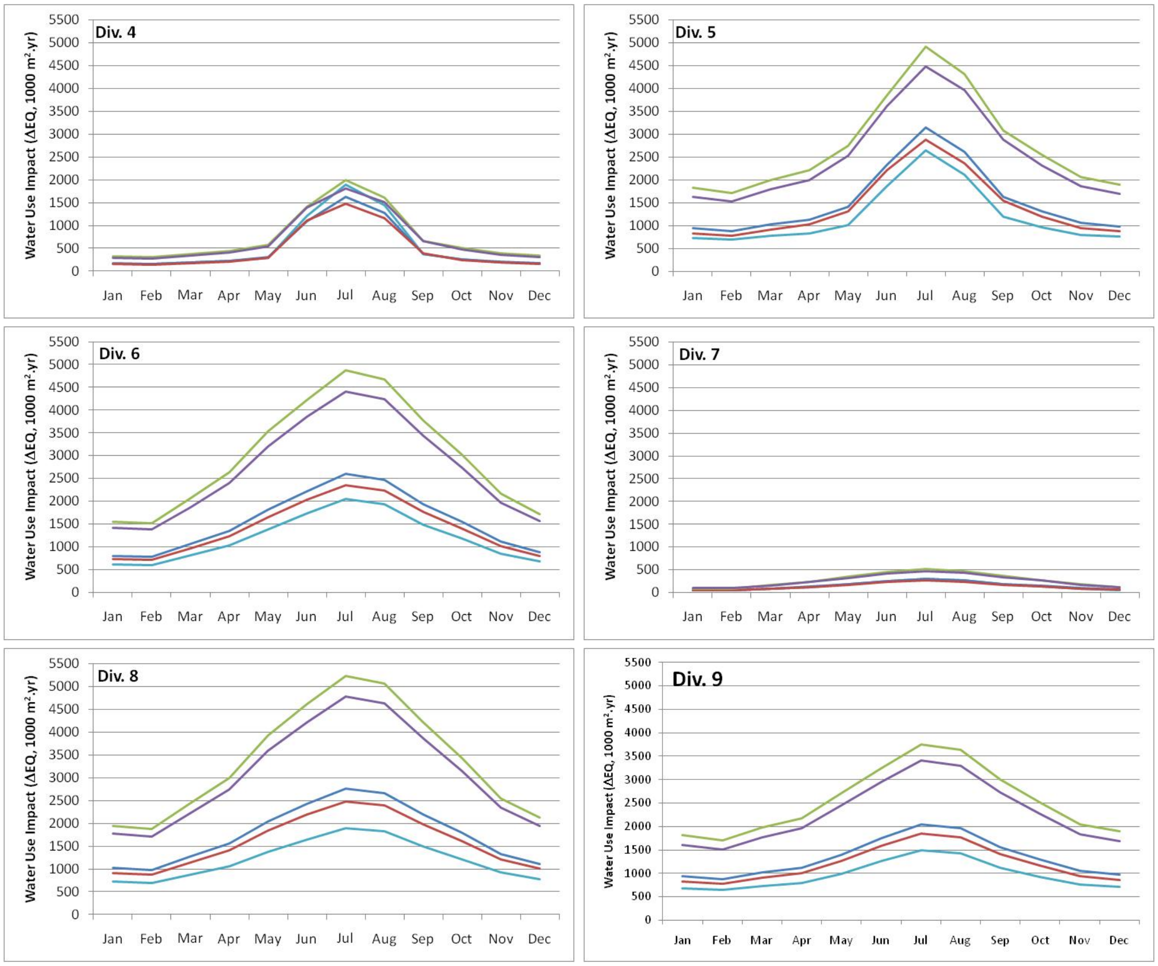

Fig. 8. Water use impact by division by month under different scenarios.

4. Management implications

The spatially and temporally uneven distribution of water withdrawals and supplies elevates the concerns and challenges to water resources authorities. Previous studies estimated that 30% of the world population is under severe water stress, which may increase approximately over 40% from 2000 to 2025 under the Intergovernmental Panel on Climate Change's scenarios. The fraction of population experiencing water stress is very likely to continuously amplify with an averaged 2% annual increase rate from 2000 to 2050, and shows little sign of declining [14, 28]. In order to better picture future water sustainability, studies often suggest that certain criteria should be incorporated, including a future water scarcity and water consumption scenario and regional differences in environmental and social characteristics [29-31]. Many water use schemes are the integrated results of population and climate change. For example, climate change can affect water withdrawals through cooling, heating, or watering. Thus, the seasonal flux of water use is especially anticipated from power generation, domestic use, and agricultural sectors boosted by air conditioning and crop growing. While climate change has taken over the spotlight, a recent report states anthropogenic activities should be recognized as a more important driver altering water resources than climate [32]. A study also warns that anthropogenic extraction of water resources can significantly affect the quality of ecosystem and environmental balances whether or not it is in a water-scarce region [33].

Like many other states in the U.S., Minnesota responds to climate and socioeconomic driving forces differently, and its complex of water withdrawals and consequential impacts must be examined from a systematic aspect. Our results agree with previous studies stating Minnesota would likely experience an increase of average annual precipitation and runoff [14]. However, from a temporal aspect, as our system model indicates that available water is more likely to increase only in spring, this pattern may consequentially reduce seasonal river water levels leading to an increase in water withdrawal from accessible groundwater sources, thereby changing the water regime by altering the absorbing processes in the soil [34].

Due to the significant momentum of anthropogenic water withdrawals in increasing water use impact, the temporal and spatial patterns shown in our study highlight the importance to take water saving measurements during summer and fall in watersheds where agriculture, population, and energy facilities are supported. As the results reveal the influence of climate in shaping temporal dynamics of water use impact associated with the probability of severe water stress and drought events, water authorities must integrate water allocation and storage infrastructure and practices with seasonable buffering features. Giving the complexity of water cycles, our study demonstrates an innovated framework taking climate and socioeconomic factors into account with reasonable temporal and spatial resolution for quantifying the dynamics of water demand and supply in responding to different scenarios. The framework can be easily implemented in the water management in determining the most cost-effective strategy to target water sustainable practices in the best timing and at the prioritized areas. Though many regions in the U.S, like Minnesota, have been benefited from rich water resources, it is important to realize we may have less time than what we used to envision in conducting water protection practices. The timeline for taking actions to ensure future water sustainability must be reframed within next decade.

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