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Sensitivity of future U.S. Water shortages to socioeconomic and climate drivers: a case study in Georgia using an integrated human-earth system modeling framework

Michael J. Scott[1] · Don S. Daly[1] · Mohamad I. Hejazi[2] · G. Page Kyle[2] · Lu Liu[2] · Haewon C. McJeon[2] · Anupriya Mundra[2] · Pralit L. Patel[2] · Jennie S. Rice[1] · Nathalie Voisin[3]

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Abstract One of the most important interactions between humans and climate is in the demand and supply of water. Humans withdraw, use, and consume water and return waste water to the environment for a variety of socioeconomic purposes, including domestic, commercial, and industrial use, production of energy resources and cooling thermal-electric power plants, and growing food, fiber, and chemical feed stocks for human consumption. Uncertainties in the future human demand for water interact with future impacts of climatic change on water supplies to impinge on water management decisions at the international, national, regional, and local level, but until recently tools were not available to assess the uncertainties surrounding these decisions. This paper demonstrates the use of a multi-model framework in a structured sensitivity analysis to project and quantify the sensitivity of future deficits in surface water in the context of climate and socioeconomic change for all U.S. states and sub-basins. The framework treats all sources of water demand and supply consistently from the world to local level. The paper illustrates the capabilities of the framework with sample results for a river sub-basin in the U.S. state of Georgia.

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✉ Nathalie Voisin
Nathalie.Voisin@pnnl.gov

[1] Pacific Northwest National Laboratory, Richland, WA, USA

[2] Joint Global Change Research Institute, Pacific Northwest National Laboratory/University of Maryland, College Park, MD, USA

[3] Pacific Northwest National Laboratory, Battelle Seattle Research Center, 1100 Dexter Avenue N, Suite 400, Seattle, WA 98109, USA

1 Introduction

Socioeconomic change and climate change both are expected to increase society's future demand for water, while climate change also is expected to make future water supply less certain. This paper presents an analysis of future water demand and supply uncertainties with a structured integrated model sensitivity analysis of the demand and supply of water. This paper uses the Platform for Integrated Modeling and Analysis (PRIMA), a flexible modeling system for analyzing the regional consequences of climate change with an integrated human-earth systems framework (Kraucunas et al. 2015). The framework contains an integrated assessment model capable of calculating end-use demand for water, energy and land at the state level within the United States, downscaling routines to estimate these water demands on a monthly basis and on a 1/8th degree grid, a regional climate model, hydrology and river routing models, and a water management model that integrates water supply and demand to manage surface water flow on the 1/8th degree grid and reservoir operations at the sub-basin level.

The literature contains a long list of studies going back at least three decades with models that projected future water supplies for regions of the world from downscaled climate forecasts with corresponding forecasted human populations or water demands and sometimes, potential deficits or other measurements of system performance. Examples are shown below, with selected additional references listed in section S.1 of the online Supplemental Material (ESM_1.pdf). Much of the work has focused on the consequences of climate change for water supply. It has used geographically gridded temperature, precipitation, and (sometimes) water runoff from global-scale general circulation models to drive hydrologic and water management models to estimate climate change impacts on surface water availability. This has been done worldwide for individual basins and catchments (e.g., Tanaka et al. 2006; Paton et al. 2013,), for multiple river basins (e.g., Lettenmaier et al. 1999; Haddeland et al. 2014) or for larger areas such as multi-country regions (e.g., Gosling and Arnell 2013).

Recent model improvements estimate climate change impacts on groundwater supplies (e.g., Portmann et al. 2013), and incorporate both supply and demand (e.g., Haddeland et al. 2014). Following the needs of national and international climate assessments, it has included work on multiple climate scenarios with perturbed physics of individual models (Harris et al. 2013), multiple techniques to combine results from multiple general circulation models (e.g., Gosling and Arnell 2013; Haddeland et al. 2014), and has explored a variety of means for downscaling climate information with statistical techniques (Foti et al. 2014) and dynamical regional climate models (Voisin et al. 2013b). Several recent global studies have compared water supply uncertainties due to choices of GCM models and climate scenarios, socioeconomic growth scenarios, and use of different types of land surface and hydrologic models through projects such as WATERMIP (Haddeland et al. 2011) and ISI-MIP (Warszawski et al. 2014). Some have assessed the relative importance of various contributors to water supply uncertainty for individual basins (e.g., Chen et al. 2011, 2013, 2015), and the strengths and weaknesses of both statistical and dynamical downscaling methods (Fowler et al. 2007; Gutmann et al. 2014; Mearns et al. 2012, 2013). Recent studies have dealt with uncertainty in earth system models, including impacts of uncertain climate on both demand and supply uncertainties (e.g., Foti et al. 2014; Haddeland et al. 2014). Haddeland et al. (2014) and Nazemi and Wheater (2015a, 2015b) summarize many of the more recent large-scale comprehensive water demand–supply studies, and remaining issues, which include continued divergence among climate model projections (especially at small scale), divergence in the results of downscaling methods, differences in methods and results among land surface and global hydrologic models, appropriate spatial and temporal scales, and limited reliable data on several issues including groundwater and its connections to surface water.

The current study is a large scale sensitivity evaluation of the PRIMA integrated model system, not an applied policy study. For water demand PRIMA uses a version of the GCAM-USA integrated assessment model to estimate the economic and technical uncertainties of human demand for water at a state scale, which it systematically allocates to local gridded scale (see supplement material). PRIMA uses the Community Earth System Model (CESM) as its global circulation model (GCM) and a regional earth system model (RESM) to dynamically downscale regional climate and water supply estimates (Kraucunas et al. 2015). The initial PRIMA analyses include two RCPs (RCP8.5 and RCP4.5) and one global circulation model (CCSM4). RCP8.5 is used in this paper.

This study explicitly focuses on the sensitivity of the integrated models to uncertainty in water demand and water supply. Because we use only one GCM, one downscaling approach, and one land surface hydrology model, we artificially bound the uncertainty in water supply and water demand as explained below in the experimental approach, rather than using the differences in simulations between RCP4.5 and RCP8.5, for now. This approach isolates the sensitivity of the integrated water management framework (i.e. GCAM demand and MOSART-WM water management) from the uncertainty in GCMs, downscaling and hydrology models. The study allows for realistic interannual geographic and temporal variability of water supply and water demand. Although the entire United States was modeled at the state and sub-basin level, the empirical results reported relate to the state of Georgia (within the U.S. Geological Survey's South Atlantic Gulf Basin), and to the Flint River drainage in the southwestern part of that state in particular, illustrating its applicability in a limited area. For additional historical/institutional information on the Flint River, including other studies of the Apalachicola-Chattahoochee-Flint (ACF) basin, of which it is a part, see Section S.2 in the Supplemental Material.

In the following sections, this paper presents the analysis methods and modeling framework, the input assumptions, sensitivity analysis results, a discussion, and conclusions.

2 Methods

This research employs a structured sensitivity analysis. This approach was selected because it provides a more efficient means to identify the future potential range in magnitude of water shortages and the driving uncertainties compared to conducting a full stochastic simulation across all the variables in the multi-model framework. Such a simulation not only would require significant data development for potentially irrelevant variables, it would also require large computing resources. Instead, by using a structured sensitivity analysis, only reference, high, and low values need to be developed for each variable, and a fractional factorial approach is used to develop deterministic sensitivity ranges with a relatively small number of simulations. Note that the low and high experiments are artificially designed in order to bound the two ends of the probability distributions. Subsequent studies could then develop approaches to derive the full probability distributions to the isolated key variables resulting from the sensitivity analysis, greatly reducing the dimensionality and cost of the stochastic analysis. This approach is consistent with standard sensitivity analysis methods employed in the decision sciences literature (Lempert et al. 1996; Groves et al. 2008; Morgan et al.

2009; Means III et al. 2010), but here the methods are applied to a new class of high resolution, integrated modeling frameworks.

Figure 1 is a diagram of the integrated modeling framework used for this research. This framework is a subset of the larger PRIMA platform (Kraucunas et al. 2015) selected to address potential water shortages. The GCAM-USA integrated assessment model[1] determines water demands from multiple sectors on an annual basis and at the state level in the U.S. (Liu et al. 2015). The simulated water demands have been calibrated with respect to USGS observed water demand (Kenny et al. 2009) as shown in Voisin et al. (2013b). The GCAM-USA water demand results are downscaled to a daily time step and to a 1/8th degree spatial resolution using a range of sector-specific, high-resolution datasets to be consistent with the geography of water supply within the U.S. (Voisin et al. 2013b; Hejazi et al. 2014, 2015). This step relies on national gridded information, on population, irrigation, livestock densities, and locations of electric power plants. GCAM's land use component clears markets for crops and other land uses and allocates cropland between dry land and irrigated agriculture within the agroeconomic zone (AEZ) level and grids the result. The temporal downscaling step relies on climate information along with cropping seasons and the irrigation patterns for each crop. Electricity water demand was spatially downscaled from the state to the grid level using locations of power plants, their generation capacity, generation type, cooling technology and fuel type. This estimated demand at a 0.5° grid on a monthly basis. The 0.5° monthly GCAM demand was uniformly downscaled to 1/8th degree daily resolution to match with the resolution in the supply analysis. Water supply is simulated by a dynamically downscaled regional earth system model (RESM) (Leung et al. 2006; Ke et al. 2012; Gao et al. 2014) coupled to a land surface model (Community Land Surface Model 4 or CLM) (Lawrence et al. 2011), and a river routing model (Model for Scale Adaptive River Transport or MOSART) (Li, et al. 2013). In contrast to statistical downscaling methods, use of a regional earth system model makes direct use of regional atmospheric physics and local geographic features such as elevation and water bodies, land surface processes to compute and allocate local runoff. Projected regulated stream flows and water deficits are determined by a water resource management model (WM) (Voisin et al. 2013a) that regulates natural flows using standardized reservoir rules and the downscaled water demands from GCAM-USA. WM is fully coupled to the routing model MOSART (Li et al. 2013) which hydrodynamically transports the managed water through the river channels. The MOSART-WM model is forced by runoff and base flow simulated by CLM and water demand from GCAM.

This coupled framework has been documented and previously validated and applied to the SRES and Representative Concentration Pathways RCP8.5 and RCP4.5 developed for the climate community (Voisin et al. 2013b; Hejazi et al. 2015). The multi-regional water demand capability in PRIMA previously has been used to evaluate the impact of future world and regional water demands for regional water scarcity under a wide set of socioeconomic scenarios (Hejazi et al. 2014). In addition, the full PRIMA water demand and supply modeling capability has been used to identify subnational water deficit "hot spots" under socioeconomic scenarios matched to concentration pathways RCP8.5 and RCP4.5, in order to evaluate the regional impacts of climate mitigation on water deficits within the United States, including the

[1] http://wiki.umd.edu/gcam/index.php/Main_Page. GCAM-USA used in this study is based on the global version of GCAM 3.1. The USA region of GCAM has been extended to model the energy and water systems at the 50-state level (Liu et al. 2015; Hejazi et al. 2014).

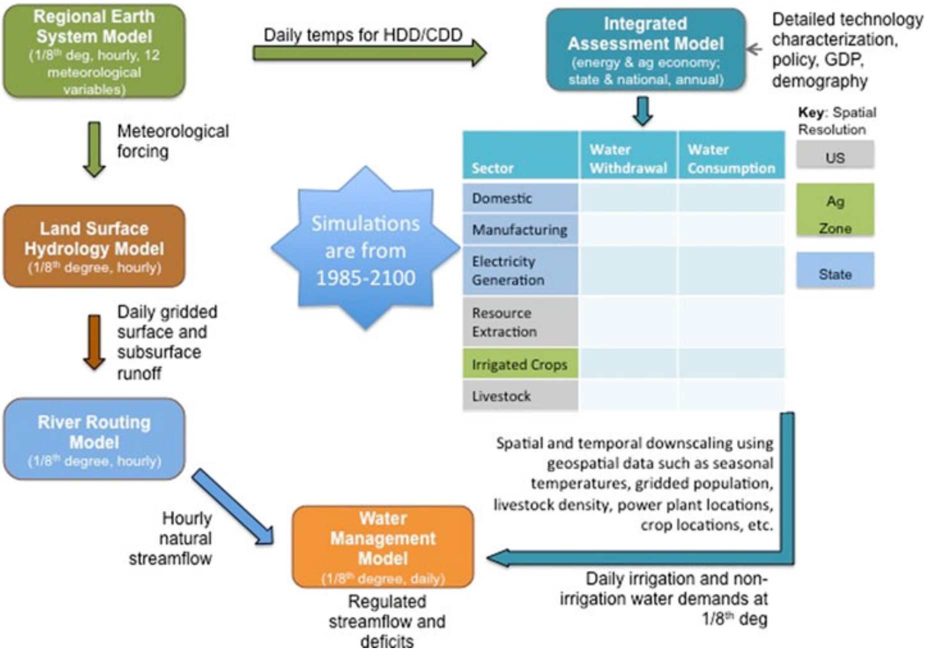

Fig. 1 The Platform for Regional Integrated Modeling and Analysis (PRIMA) models used in this study and information flows between them

ACF Basin (Hejazi et al. 2015). The one-way coupling in this paper does not attempt to rerun GCAM-USA to reconcile any water deficits identified by CLM-MOSART-WM. However, the integrated modeling approach captures the energy-water interactions at regional and national scales and can improve understanding of the key drivers that govern those interactions (Voisin et al. 2015).

The research presented in this paper focuses on the sensitivity in future water shortages as projected by this framework under the RCP8.5 scenario, which the U.S. National Climate Assessment describes as roughly a continuation of the current path of emissions increases (Walsh et al. 2014) (commonly referred to as a business as usual scenario). The PRIMA modeling system produces consistent water demand and surface water supply for the entire United States on a daily basis on a 1/8th degree (approximately 12 km) grid for 2005–2100 and then realistically manages forecasted available surface water to minimize water deficits in each grid cell and calculates water deficits in each sub-basin. However, for tractability and clarity this paper demonstrates potential local impacts by highlighting results in the Flint River sub-basin for the period 2040–2059. The scenarios for the range in natural flow inputs to WM were based on the high and low scenario of simulated natural flow, described next, during the period 2040–2059 by the CLM-MOSART model under RCP8.5 temperature and precipitation projections.

3 Sensitivity scenarios for water demand and natural flows

This section first describes the results of the process to develop sensitivity scenarios of demand and then discusses the results for natural flows.

3.1 Water demand sensitivity

An uncertainty analysis was performed for each water demand sectors. The coefficients for domestic water use included price and income elasticities, a technology improvement rate, and a water use efficiency. The other five end use sectors had water use coefficients in m^3 per unit of physical output. Manufacturing had one use coefficient for the sector; primary energy, one for each of five fuels; livestock, one for each of six types of animals; electricity generation, one for each of 29 generation fuel/technology/cooling combinations and one for cooling shares; and agriculture, one use coefficient for each of 13 crops, and an overall irrigation efficiency factor. Each of those variables is associated with reference, minimum and maximum coefficients drawn from the literature (see Section S.3 of the Supplemental Material). These variables were grouped into eight groups ("factors") that were varied together. GCAM-USA was then used to generate water demand scenarios for the 21st century using combinations of high, low, and reference water demand parameter values. An exhaustive set of possible combinations would have resulted in 6,561 GCAM downscaled model runs, but we used a fractional factorial design that required only 2,187 runs and still identified the combinations of parameter values that would bound the highest and lowest water demand (Montgomery 2012). We then had only to downscale the highest, lowest, and reference cases for the sensitivity analysis.

Additional details are shown in section S.3 of the online Supplemental Material, which also contains graphs showing the distribution of water demand scenarios for each end use prior to downscaling.

3.2 Natural flow sensitivity

The high and low water supply scenarios were developed based on the simulated interannual variability between 2040 and 2059 using simulated results for two stream gauges, near the mouths of the Flint River at Bainbridge, GA and Chattahoochee River at Columbus, GA, respectively, chosen due to their locations and the availability of USGS gauging stations.[2] The simulated Flint River flow at Bainbridge is used in this paper as the reference case. Much of the uncertainty in the supply results from uncertainty in future precipitation, which can vary spatially over short distances, masking more fundamental changes. To create the high and low scenarios, the simulated flow for both gauges was uniformly aggregated into one 2040–2059 annual natural flow time series, reducing some of the "noise" between the two sub-basins.

Downscaled average annual natural flow in the Flint sub-basin was projected to increase 13 % between the historical period (1985–2005) and 2040–2059 period in the reference case scenario, which includes RCP8.5 climate change, a finding at odds with some other studies (Georgakakos et al. 2014). However, this 13 % change of average surface water supply in the reference scenario due to climate change was less than its interannual variability. The highest water year between 2040 and 2059 had a natural flow 1.74 times the 2040–2059 average while the lowest water year had a natural flow 0.43 times the average. To comprehensively characterize climate-driven water supply uncertainties, an analysis of uncertainties in water supply and demand would have required that the RCP8.5 scenario be run through several GCMs, with several different downscaling methods, then several hydrologic models and

[2] The trend can vary substantially from one climate scenario to another and one hydrology model to another, which we do not address here.

possibly different water management models (Warszawski et al. 2014; Chen et al. 2015). However, project time and resources did not permit more than a single end-to- end run of the RESM community regional climate model used for dynamically downscaling climate information for the United States. Instead, the highest and lowest water years between 2040 and 2059 from the RESM-MOSART models were used to rescale the reference scenario to obtain some insight into supply sensitivity. The high and low 2040–2059 runoff scenarios corresponding to the 2040–2059 runoff and base flow from the hydrology model for the Flint River sub-basin were shifted upward by a factor of 1.74 and downward by a factor of 0.43 to create high and low supply scenarios for the water management model. The supply sensitivities were assessed in terms of averages. In order to capture the uncertainties in the long term, mean unmet demand, the sequencing of events needs to be maintained. A different sequencing and/ or inter-annual variability would need further evaluation of implied changes in reservoir operations and associated uncertainties, which is out of the scope of the paper. We therefore assume stationarity in inter-annual variability in these scenarios that allows us to isolate and bound effects on flow, water supply and deficit due to changes in the long term mean only. It implies that we do not assess the effects of shifts in higher-order moments of base flow and runoff. However, given the time horizon out to 2059, just shifting the long-term mean still provides valuable insights in this context by also changing the intensities of the high/low flows.

3.3 Combined demand and supply sensitivity

The sensitivity analysis discussed in sections 2 and 3 produced downscaled reference, high, and low demand and supply scenarios for water consumption in the Flint River sub-basin. The demand scenarios were matched with the supply scenarios to produce three combined cases that were simulated with WM: both demand and supply at their reference values, low demand paired with high supply (least likely for water deficits) and high demand paired with low supply (most likely for water deficits). To determine the source of impacts, we also ran reference demand with high and low supply and reference supply with high and low demand (9 cases total).

4 Results

The overall sensitivity is evaluated as differences between the future cases with respect to the difference between the reference future case and the historical period. We assess in this section the boundaries of the sensitivity, i.e., the overall range. The 9 cases are evaluated in the supplemental material in order to further capture the non linearity of the sensitivity.

Figure 2 illustrates that in the Flint River sub-basin (see irregular outline in all panels), unmet (surface water) demand exists even in the historical period. Except in years of serious drought, this unmet demand is served with groundwater (Environmental Protection Division EPD 2006). The main groundwater resources in the basin are hydrologically connected to surface water, so heavy groundwater use can significantly reduce surface water flows. In years with severe drought, ground irrigation water rights are purchased temporarily at voluntary auction by the State of Georgia from farmers, and the land fallowed. This happened in 2001 and 2002 (Wright et al. 2012). With demand projected to increase from both irrigation and other uses, the level and geographic extent of the unmet demand increases with the RCP 8.5

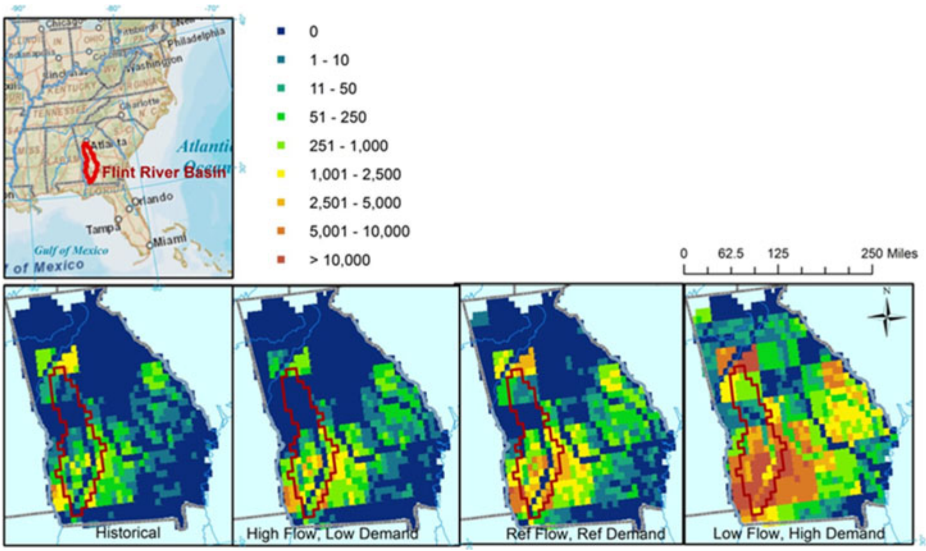

Fig. 2 Average unmet annual water demand, historical and projected for 2040–2059 (m^3 per day)

climate in the Flint River sub-basin and begins to spread to other basins in the reference scenario. In the reference scenario, average unmet demand in the Flint River sub-basin in 2040–2059, is 0.058 km^3 per year, 0.047 km^3 (427 %) more than in the 1985–2004 historical period (0.011 km^3 per year) (Table 1). Under the most favorable conditions (low demand-high supply) unmet demand is 0.031 km^3 per year (−53 %) less than in the reference case (0.058 km^3 per year), but still is 0.016 km^3 per year (145 %) larger than in the historical period. Under the least favorable conditions (low demand-high supply), unmet demand is 0.324 km^3, 0.266 km^3 per year (459 %) more than in the reference case, and 0.313 km^3 per year (2,870 %) larger than in the historical period.

The gridded representation differs from typical single-basin water operations model representations; however, it facilitates the integration with large scale hydrological modeling. Each 1/8th degree grid cell is associated with a demand, which was uniformly downscaled from a 0.5 degree spatial resolution. Each 1/8th degree grid cell is also associated with water supply coming from the 1/8th degree hydrological simulation. If the local supply in a grid cell is not enough, and the grid cell is within reach of a reservoir (downstream and within reasonable distance to the river – see Voisin et al. 2013a for the criteria) then the supply can be complemented by diversion from reservoir releases. The uncertainty in the spatial representation of the demand and the interactions of grid cells with reservoirs have been the subject of discussions in previous literature, including the most recent Nazemi and Wheater (2015a, 2015b). The problem is difficult to solve generically in large-scale models. For the most accurate and operational estimates of the supply deficit, local models should be used and should include groundwater use and recharge. However, despite the uncertainties, our analysis of the U.S. identified the Flint River sub-basin as a water-sensitive location, and this has been confirmed by others, as shown in section S.2 in the Supplemental Material. Although the analysis did not include any additional uncertainty resulting from different climate models or different downscaling routines, the results still constitute a very broad range of consistently-derived potential unmet

Table 1 Components of and changes in natural flow, water demand, and unmet demand (deficit) in the Flint River sub-basin of Georgia, historical period (1985–2004), and in 2040–2059 under RCP 8.5 climate change

Variables Changing	Values for Total Water Demand and Natural Flows					Effect of Highest-Lowest Difference		
	Historical value (1985–2004)	Reference value, 2040–2059	Lowest value, 2040–2059	Highest value, 2040–2059	Highest-lowest difference	Total deficit (unmet demand)	Irrigation deficit	Non-irrigation deficit
Absolute value (km^3 per year)								
Natural Flows Only	5.875	7.030	3.015	12.222	9.207	0.102*	0.096*	0.005*
Total Demand Only	0.316	0.646	0.602	1.050	0.448	0.108*	0.100*	0.008*
Deficit, Value	0.011	0.058	0.027	0.324	0.297	0.058	0.056	0.002
Percent Deficit Value	3.5	9.0	4.6	30.8	26.2	9.0	10.0	2.6
High Flow and Low Demand Together, Value						0.027	0.027	0.000
Low Flow and High Demand Together, Value						0.324	0.306	0.018
Difference, Low Flow and High Demand-High Flow and Low Demand						0.297*	0.279*	0.018*
Percent of 2040–2059 reference value:								
Natural Flows Only	84	100	43	174	131	174*	172*	216*
Total Demand Only	49	100	93	163	70	185*	178*	356*
Difference, Low Flow and High Demand- High Flow and Low Demand						512*	498*	900*
Sensitivity of deficit: percent change in deficit per 1 % change in:								
Natural Flows Only						−1.33*	−1.32*	−1.65*
Total Demand Only						2.67*	1.22*	15.73*

*Variables marked with an asterisk in the last three columns are changes. For example, 0.102 km^3 in the first row is the change in average water deficit resulting from changing natural flow alone from its lowest value (3.015) to its highest value (12.222) in 2040–2059. The unmarked values in those columns are levels. For example, 10.0 in the fourth row of the table is the percent irrigation water deficit in the reference case and 0.306 is the value, in km^3 of the irrigation water deficit in Low Flow and High Demand case demands which could be useful in identifying causes of potential future water shortages and in screening potential ways to reduce shortages.

Table 1 shows the impact of future water demand and supply changes in the Flint River basin with RCP 8.5 climate. Unmet demand is affected by climate, reservoir operations, and location and type of water consuming operations. Row 1 in Table 1 shows total natural flow, the projected annual amount of water flowing past the gauging station at Bainbridge in the absence of reservoirs; the rest of the rows are stated in terms of annual consumption, which equals withdrawals minus returned flows. Additional detail is provided in Table S.2 in Section S.4 of the Supplemental Material. Withdrawals are typically 2–3 times consumptive use, depending on the type of use and region. Met demand is the amount of consumptive use in Table 1 that can be met by available surface water, given the type and location of demand—so it depends on the type, location, and level of demand. Total consumptive water demand increases by a factor of slightly less than two to over three times historical values by mid-century (second line of Table 1), with most of the increase due to irrigation demand. However, row 1 of Table 1 shows that natural flow is more variable, ranging from 0.5 to 2.1 times historical flow. In row 4 of Table 1, unmet demand increases from 3.5 % historically to 9.0 % in the reference case, ranging from a low of 4.6 % to a high of 30.8 %.

The biggest quantitative range in Table 1 is in natural flow, due to RCP8.5 and to interannual variability of flow. The difference from 1985 to 2004 to 2040–2059 in average natural flow in the reference case is an increase of 1.155 km^3 per year, while demand increases by 0.333 km^3 per year. The difference between the lowest and highest case in average water demand is 0.448 km^3 per year (row 2), while the difference in average natural flow from the lowest to highest case is 9.207 km^3 per year (row 1). This is without any uncertainty that might result from additional greenhouse gas emission scenarios, climate models, land surface hydrology models, or downscaling schemes.

However, Table 1 also shows that change in natural flow is a less sensitive determinant of unmet demand (shortages) than is change in demand. Table 1 demonstrates for both the absolute and percentage changes in the water deficit that uncertain demand by itself is a bigger driver than uncertain flow by itself. In row 2, the range in total unmet demand due to changes in demand alone is about 0.108 km^3 per year, but row 1 shows only 0.102 km^3 per year due to variability in natural flows alone, even though the change in natural flows is over 20 times as large. The sensitivity calculations in Table 1 (last two rows) show that the water deficit is more than twice as sensitive to variation in demand as to variation in flow.

The key driver of the trend in the worsening water deficit situation in the Flint River sub-basin in the RCP 8.5 scenario is irrigation demand. Despite a projected increase in natural flow by mid-century in the reference case, not all of that water is actually available at the time and locations where the demand increases.

Finally, it is also obvious from Table 1 that the non-irrigation sector is most sensitive to changes in demand (last row); however, the consumptive water use over the Flint River Basin is mostly for irrigation and the changes in irrigation demand dominate the absolute total (row 2, last three columns). In order for supply to be useful, it must match demand both temporally and geographically.

Lettenmaier et al. (1999), Georgakakos et al. (2010), and Lownsbery (2014) also have estimated climate change impacts on water in the ACF Basin. Additional details are available in Section S.2 of the Supplemental Material.

5 Discussion

The results in the previous section permit some tentative observations regarding future water deficit sensitivity with climate change at the local level. First, even though there is significant difference between the highest and lowest demand scenarios, future consumptive demand for water increases in all cases. The largest component of demand in the Flint River sub-basin is irrigation demand, which may increase with overall warmer temperatures and longer growing seasons, but also is driven by additional demand for agricultural products of all types due to significant increases in world population and per capita income. Second, even very large changes in surface water flows have comparatively little impact on unmet demand. That could be because much of irrigation demand actually is met with groundwater or because delivery systems have limited capability of responding to variability in supply. Third, the results are sensitive to the variable of interest, consumptive demand. Had the variable of interest been annual withdrawals, minimum stream flow, or something else, the sensitivities might have been very different, especially across sectors. Although irrigation currently accounts for over 76 % of all consumptive water demand in the Flint River sub-basin, it accounts for only about 14 % of withdrawals. This is the subject of a separate paper in preparation.

One advantage of conducting a geographical multi-model sensitivity analysis is that it allows the analyst to evaluate the location and extent of risk associated with policy prescriptions not knowable by running demand and supply scenarios independently or at more aggregated levels. For example, the maps in Figure S.2 shows the water deficits spread in both location and intensity over time as demand rises and natural flow is reduced. In this framework changes in unmet demand do not have a single cause but are influenced by the independent geographical patterns and intensities of changes in both supply and demand (Voisin et al. 2015). The concentration of irrigated agriculture demand in the lower Flint sub-basin and nearby areas is evident. Figure S.3 in the Supplemental Material shows the changes can be geographically complex.

The results in Table 1 show that future water vulnerability in Georgia may be more affected by changes in demand than interannual variability in natural flow, even though natural flow itself is more variable. We interpret the difference as a result of differences in temporal resolution in the two analyses; we take into consideration the seasonal variation in the supply availability and demand pattern. The high demand scenario in the third column of Table 1 is a fairly extreme case since all of the variables contributing to water demand were simultaneously set at the values found in the literature that would maximize water demand. The model could also be used to investigate more likely cases, to explore alternative technology scenarios, and to see how much demand reduction prevents how much of the projected water deficits. It can also be used to see how that reduced deficits vary both geographically and by demand and supply scenario.

6 Conclusions

This paper has demonstrated regional integrated modeling of water supply and demand sensitivity at a very local scale while maintaining gridded results and simultaneous and consistent impacts for every basin in the United States, leaving rich possibilities for screening, comparing, and prioritizing adaptive actions that would have the greatest impact in the greatest number of localities.

The multi-model sensitivity analysis incorporates and evaluates two sources of sensitivity, quantitatively demonstrating a wide range of shortages and identifying some of the key drivers for possible future policy action. For example, future follow-up studies could consider the potential cost-effectiveness of technological “fixes” or other actions to limit the growth in irrigation consumptive demand as a way to combat unmet demand. Or they could evaluate the cost-effectiveness of technological “fixes” in the energy sector to limit the withdrawal of water to protect in-stream flows. Such studies could also include additional supply options such as additional storage.

An obvious additional question concerns the impact on water shortages of climate mitigation policies. The PRIMA model suite currently has been run to assess the impact on water supply and demand of an RCP 4.5 climate with consistent reference national and international energy/land use/water scenarios to identify the impacts of mitigation on water demand and supply (Hejazi et al. 2015). Future plans include running the PRIMA suite using the procedures in this paper to see the degree to which water demand and supply impacts identified in this paper can be controlled by climate mitigation. Risk may not be reduced by mitigation. For example, mitigation actions that involve high levels of biofuel production may exacerbate water shortages even if RCP 4.5 climate is “cooler” and “wetter” (Hejazi et al. 2014, 2015). Structured sensitivity analysis such as the one in this paper could evaluate the geographic extent and severity of that risk and of actions to offset it.

This study also has some limitations that could significantly change the risks of water shortages reported in this paper. While we believe that the high and low demand cases represent reasonable extreme estimates of water demand given the RCP 8.5 scenario, the climate-driven water supply aspects apply to one climate model, represent only interannual variation around a reference case (and do not include groundwater). That interannual variation has a range from 43 to 174 % of the reference flow, and from 51 to 208 % of the historical average flow; it thus spans a significant supply uncertainty and proved useful in identifying sources of water deficit risks and in demonstrating the multi-model sensitivity assessment capabilities of the PRIMA framework. The analysis bounds the probability distribution but without an associated risk, or probability of occurrence. This paper did not address water supply risks inherent in either inaccuracies or differences between climate models; nor did it address demand and supply risks in very different climate scenarios, limiting its direct policy relevance. Precipitation and runoff are climate results that have some of the lowest inter-model agreements, especially at the local level. Accordingly, at some point it would be critical to incorporate other estimates of climate change from other climate models to develop a more robust range of supply forecasts.

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