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A REVIEW OF THE UNITED STATES' PAST AND PROJECTED WATER USE[1]

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ABSTRACT: Good information and data on water demands are needed to perform good analyses, yet collecting and compiling spatially and temporally consistent water demand data are challenges. The objective of our work was to understand the limitations associated with water-use estimates and projections. We performed a comprehensive literature review of national and regional United States (U.S.) water-use estimates and projections. We explored trends in past regional projections of freshwater withdrawals and compared these values to regional estimates of freshwater withdrawals made by the U.S. Geological Survey. Our results suggest a suite of limitations exist that have the potential for influencing analyses aiming to extract explanatory variables from the data or using the data to make projections and forecasts. As we explored regional projections, we paid special attention to the two largest water demand-side sectors — thermoelectric energy and irrigation — and found thermoelectric projections are more spread out than irrigation projections. All data related to water use have limitations, and there is no alternative to making the best use that we can of the available data; our article provides a comprehensive review of these limitations so that water managers can be more informed.

(KEY TERMS: water resources management: planning; water use; water allocation; water-use projections; water-use trends.)

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INTRODUCTION

Water demand is becoming increasingly important to quantify. Recent drought events in the United States (U.S.) (Campana *et al.*, 2012; http://droughtmonitor.unl.edu) have suggested that developed countries with substantial infrastructure are not immune to the risks of increased water demand and compromised water supply. From a national perspective, the U.S. has plenty of water to meet demands, but looking at water resources at such a large scale is simplistic — water demand and supply are space and time specific. To develop and assess strategies adequately, we need to understand how limitations in available data affect projections of future water use and the details of how water use has unfolded at regional levels.

Good information and data are needed to perform good analyses, but what exactly does this mean? All

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data related to water use have limitations, and there is no alternative to making the best use that we can of the available data. Collecting and compiling spatially and temporally consistent data have been a challenge. Water-demand data, compared to water-supply data (i.e., hydrological data), are poorly measured, are not reported publicly, or are collected differently across regions (Gleick, 2003; Gleick *et al.*, 2005; Goldstein *et al.*, 2008; Averyt *et al.*, 2011). When data are not available, analysts typically must calculate informed estimates as best they can. Few researchers have examined national or regional historical water-use estimates or future water-use assessments in part because these data are not comprehensive (Osborn *et al.*, 1986).

How can looking at historical water-use estimates and future water-use assessments inform water management? The U.S. Geological Survey (USGS) water-use database is one of the best in the world, representing more than a 50-year time-series of historical water-use estimates (National Research Council, 2002). The time series of data is not totally consistent internally; however, as the methods of data collection, the spatial aggregation levels, and the categories of water use reported have changed over the years. Nevertheless, these limitations do not preclude using the data to understand general water-use trends. Limitations do arise when using historical water-use estimates to inform future water-use assessments, in part because assumptions about future conditions may not be realistic. The few studies that have taken up a review of future water-use assessments found that, over the long term, actual events often failed to mimic the scenarios used to derive future water-use estimates (Osborn *et al.*, 1986; Brown, 2000; Christian-Smith *et al.*, 2012). These studies are either dated (Osborn *et al.* 1986) or their review focuses on national water use (Brown, 2000; Christian-Smith *et al.*, 2012); consequently, there are not many details on how water-use estimates and projections have unfolded at regional levels.

The objective of our work was twofold. First, we explored factors that influence analyses aiming to extract explanatory variables from USGS water-use studies. To do this, we performed a comprehensive literature review of national and regional U.S. water-use estimates and projections. Second, we explored trends in past regional projections of freshwater withdrawals and compared these values to regional estimates of freshwater withdrawals made by the USGS. We paid special attention to the two largest water demand-side sectors: thermoelectric energy and irrigation.

METHODS

National Water-Use Literature Review

Water-use data for the U.S. were available from a variety of sources (MacKichan, 1951; Picton, 1952; MacKichan, 1957; Senate Select Committee on National Water Resources, 1960, 1961; Wollman, 1960; MacKichan and Kammerer, 1961; Murray, 1968; Water Resources Council, 1968, 1978; Wollman and Bonem, 1971; Murray and Reeves, 1972; National Water Commission, 1973; Murray and Reeves, 1977; Viessman and DeMoncoda, 1980; Solley *et al.*, 1983, 1987, 1988, 1993, 1998; Guldin, 1989; Brown, 1999 [technical assessment]; Brown, 2000 [peer-reviewed paper]; Hutson *et al.*, 2004; Roy *et al.*, 2005, 2012; Dziegielewski and Kiefer, 2006; Kenny *et al.*, 2009; Brown *et al.*, 2013). We reviewed these sources, identifying water type (fresh or saline), water use (withdrawal or consumptive), spatial scope (contiguous, continental, or territorial U.S.), study type (projections or estimates), and temporal scope.

We created time series from our literature review on national water withdrawal projections and compared them with national water-use estimates from the USGS, which are available every five years from 1950 to 2005. Estimates from 1900 to 1950 were from Picton (1952); unfortunately, limited methodological information was provided so it is unclear how these estimates were made. We looked at offstream water use — water withdrawn or diverted for public supply, industry, irrigation, livestock, thermoelectric power generation, and other uses. This is in contrast to instream uses (e.g., hydropower) or consumptive uses (i.e., water withdrawn that is evaporated, transpired, or otherwise removed from the immediate surface environment). Instream and consumptive water use was not included in this analysis because few studies project or forecast consumptive use, and the USGS discontinued data collection on consumptive use in their 2000 report (Hutson *et al.*, 2004). Water-use data were divided into fresh or fresh and saline water categories; literature that does not differentiate between fresh and saline was categorized as “unknown.”

Regional Freshwater Withdrawals

We used four projection datasets (Water Resources Council, 1968, 1978; Guldin, 1989; Brown, 2000) to explore regional variations in freshwater withdrawal projections for 2000 compared to the USGS 2000 freshwater withdrawal estimates (Hutson *et al.*, 2004). These four datasets were chosen because they use comparable, disaggregated spatial resolutions — Water Resource Regions (WRRs). The New England and Mid Atlantic regions were combined for this analysis because Water Resources Council (1968) does not differentiate between the two regions. We picked the year 2000 because it was the most recent year for which there was a portfolio of projections and USGS estimates; only two reports projected 2010 water use and the 2010 USGS water-use estimates were not available at the time of our analysis. USGS water-use data were available at the county and state level for 2000, but not at the WRR scale. We used USGS county-level water-use data for 2000 and a WRR shapefile (http://water.usgs.gov/GIS/dsdl/huc250k_shp.zip) to aggregate county data to the regional level using ArcMap.

We calculated rough variation bounds — which we refer to as envelopes hereafter — of most likely water use in 2000. Plots of regional water use over the 1950-2000 period show report-to-report fluctuations; to account for these fluctuations, we assumed that the uncertainty in estimated water use was associated with the time-series variability. We found the standard deviation of the residuals from a linear trend in each WRR's time series of USGS estimates (1950-2000). A linear trend was a reasonable conceptual model for our envelopes because the noise around the linear trend was random about the *x*-axis. The envelopes were calculated using plus or minus two standard deviation bands around the point estimate for 2000. This process was used for total water withdrawals, thermoelectric freshwater withdrawals, and irrigation freshwater withdrawals. The irrigation and thermoelectric sectors represent the largest water-use categories in the U.S. These two sectors combined represent 50 to 90% of total water withdrawals for all WRRs except one.

RESULTS

National Water-Use Literature Review

Changes in USGS data collection methods, definitions of water-use categories, and spatial scales have the potential for influencing analyses aiming to extract explanatory variables from the data or using the data to make projections and forecasts (Table 1). In part because of these limitations, few studies making projections of future water use in the U.S. included analyses for both fresh and saline water or both withdrawal and consumptive use (Table 2).

Prior to 1980, U.S. water-use estimates were increasing over time (Figure 1). In 1985, there was a

TABLE 1. Factors Influencing Analyses Aiming to Extract Explanatory Variables from the USGS Water-Use Studies.

	Limitations	Implications
Data collection constraints	Data are available in five-year increments starting in 1950	Variability of water use in years between reports is unknown
	USGS does not have regulatory or management responsibilities and does not collect its own water-use data; primary sources of information are water-use measurements and estimates from state and local agencies	Quality assurance is a key part in preparing reports, but data are collected from different sources and personnel introducing random errors
	Census data may not be available in years that align with the water-use report; some states may use data from plus or minus three years around the report year depending on the category	Some states correct for the temporal misalignment among the various categories, but an additional assumption of smooth interannual change is needed
	National Water-use Information Program established in 1978 standardized data compilation practices, units, and category definition	Reports prior to the 1980s may be subject to differences in data collection and estimates across counties and sectors
Category constraints	1950 report combines thermoelectric and industrial uses, 1950-1955 rural category includes rural domestic and livestock, and pre-1985 commercial, mining, and aquaculture categories are included in the other industrial category	Difficult to compare some individual categories over the full time series
	2000-present reports do not include consumptive use	Distinction between withdrawal and consumptive use is important, especially when examining thermoelectric and irrigation trends
Spatial constraints	1950-present reports provide data at the state level	Full time series, but lower spatial resolution
	1985-present reports provide data at the county level and provide data in digital form; 1955-1995 reports provide data at the water resource region level	Shorter time series, but higher spatial resolution

TABLE 2. Information about U.S. Water-Use Studies.

	Water Type		Water Use		Study Area			Study Type and Range	
Literature Cited	**Fresh**	**Saline**	**Withdrawal**	**Consumption**	**Contiguous U.S.**	**U.S.**	**U.S. + territories**	**Estimates**	**Projection/ Forecast Year(s)**
USGS[1] (http://water.usgs.gov/watuse/)	X	X	X	X[8]			X[7]	Every five years, 1950-2005	
Picton (1952)	-[9]	-[9]	-[9]	-[9]	-[9]	-[9]	-[9]	Every 10 years, 1900-1950	
Senate Select Committee on National Water Resources (1961)	X		X	X	X				1980, 2000
Water Resources Council (1968)	X	X	X	X			X		1980, 2000, 2020
Wollman and Bonem (1971)[2]	X		X		X				1980, 2000, 2020
National Water Commission (1973)[3]	-[9]	-[9]	X	X			X		2020
Water Resources Council (1978)[1]	X	X	X	X			X		1985, 2000
Viessman and DeMoncoda (1980)	-[9]	-[9]	X	X		X			2000
Guldin (1989)	X		X	X			X		Every 10 years, 2010-2040
Brown (2000)[4]	X		X		X				Every 10 years, 2010-2040
Dziegielewski *et al.* (2003)[5]	X	X	X				X		2040
Roy *et al.* (2005)[6]	X		X		X				2025
Roy *et al.* (2012)	X		X		X				2030, 2050
Brown *et al.* (2013)[7]	X		X		X				Every 10 years, 2010-2090

[1]Fresh and fresh + saline withdrawal estimates or scenarios plotted in Figure 1.
[2]Low, high, and revised withdrawal scenarios plotted in Figure 1.
[3]Low and high withdrawal scenarios plotted in Figure 1.
[4]Brown (2000) is the peer-reviewed article that matches with the Brown (1999) report.
[5]Fresh + saline scenario plotted in Figure 1.
[6]Business as usual and improves efficiency scenarios plotted in Figure 1.
[7]High and low projections of water use under scenarios of climatic change plotted in Figure 1.
[8]See Table 1 for discontinuities with data collection.
[9]Information not specified clearly enough to make inference.

noticeable decrease in water-use estimates and, since then, the estimates have been increasing only slightly. Given that some projections used extrapolations of prior estimates of water use, we considered those made prior to 1985 and those made afterwards as indicated by publication year (Table 2, Figure 1). Most projection studies provided values for 1980, 2000, and 2020, providing a basis for comparison in those years. The range of projections made for 1980, 2000, and 2020 in studies prior to 1985 was 230 to 560 billion gallons per day (BGD) (0.87-2.1 billion cubic meters per day [BCM]), 260-890 BGD (0.98-3.4 BCM), and 430-2300 BGD (1.6-8.7 BCM), respectively; many of these projections for future water use at the national scale were gross overestimates relative to the USGS estimates (Figure 1A). Conversely, the range of estimates for post-1985 studies was much narrower (Figure 1B).

Regional Freshwater Withdrawals

The Water Resources Council (1968) projection was much larger than the other projections on the national scale (Figure 2A); this trend continues at the regional level (Figures 2C-2E).

The USGS estimates of freshwater withdrawals at the WRR scale showed variability across the years of

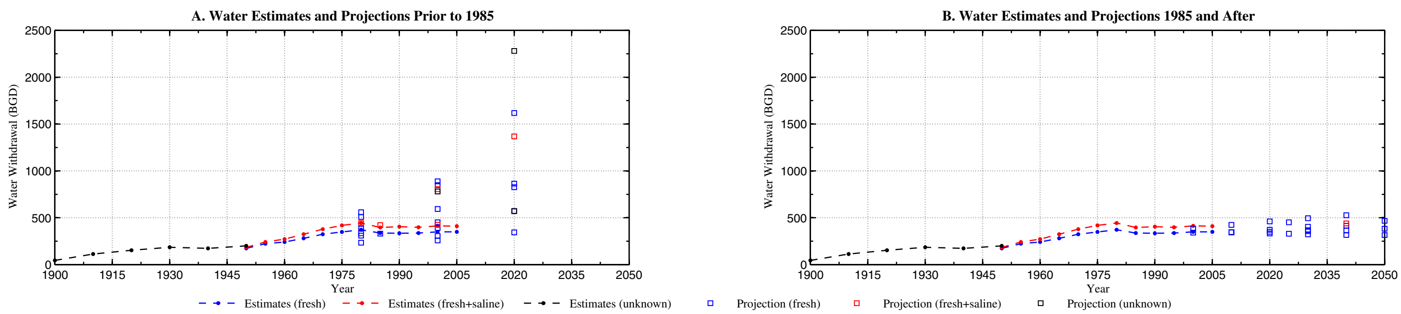

FIGURE 1. (A) Water Estimates (1900-2005) and Projections Published Prior to 1985. (B) Water estimates (1900-2005) and projections published in 1985 and after. Fresh- and saline water withdrawal estimates for the contiguous U.S. are plotted as dots; lines connect the dots to show the general trend over the time series. Fresh- and saline water withdrawal projections are presented as markers: blue for freshwater, red for the combination of fresh- and saline water, or black for values with unknown water type. See Table 2 for reference information and variations in data across references. There are more projections shown on the graphs than there are cited references in Table 2. Some references have multiple scenarios; refer to the footnotes in Table 2.

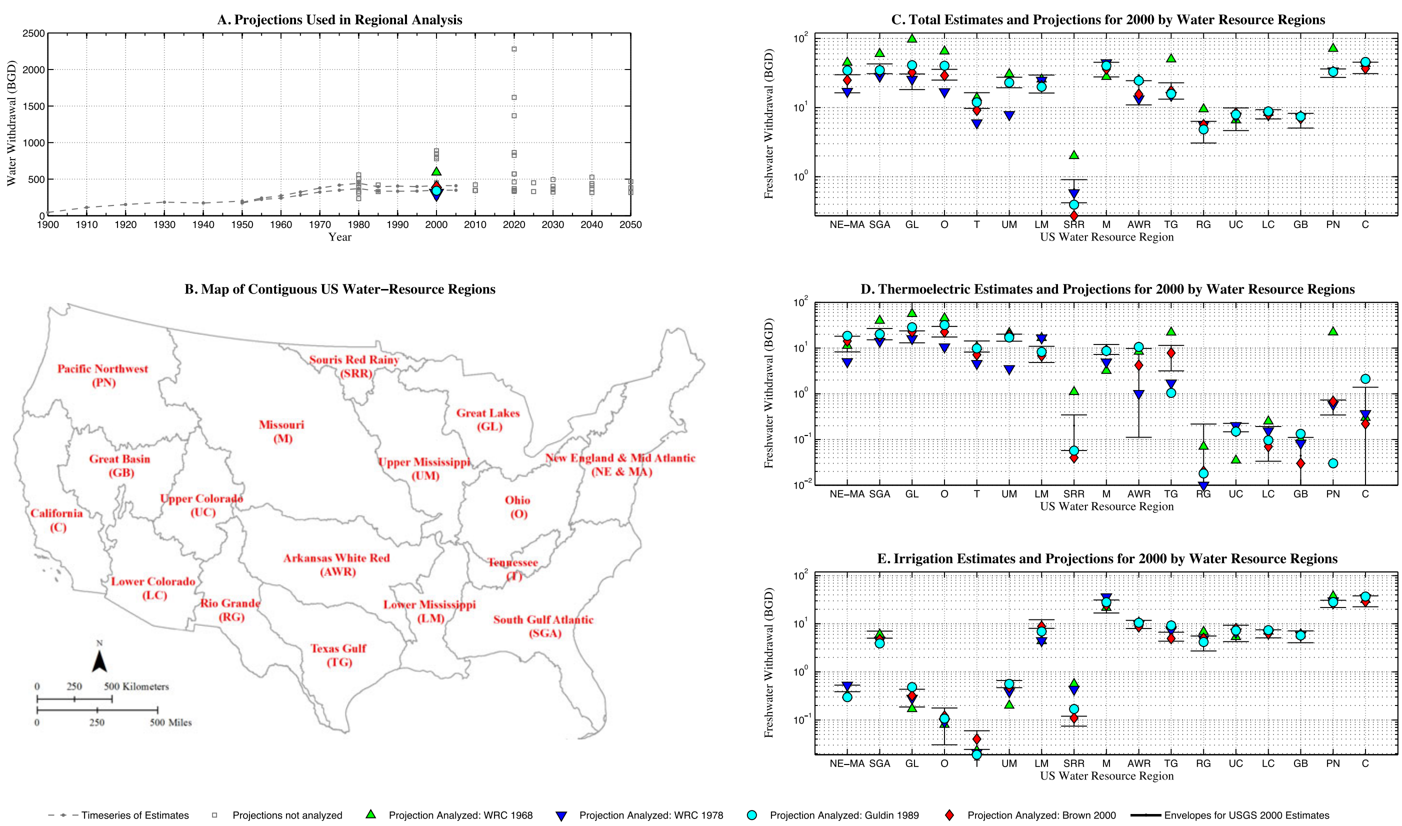

FIGURE 2. Regional Water-Use Analysis. (A) USGS water withdrawal estimates and withdrawal projections showing projections used for water-resource regional analysis. (B) Map of contiguous U.S. water-resource regions with abbreviations. (C) Water-resource region analysis: USGS total withdrawal estimates with standard deviation envelopes from detrended time series and total freshwater withdrawal projections by Water Resources Council (1968, 1978), Guldin (1989), and Brown (2000) for 2000. (D) Water-resource region analysis: USGS thermoelectric withdrawal estimates with standard deviation envelopes from detrended time series and thermoelectric freshwater withdrawal projections by Water Resources Council (1968, 1978), Guldin (1989), and Brown (2000) for 2000. (E) Water-resource region analysis: USGS irrigation withdrawal estimates with standard deviation envelopes from detrended time series and irrigation freshwater withdrawal projections by Water Resources Council (1968, 1978), Guldin (1989), and Brown (2000) for 2000.

the surveys (Figures 2C-2E, see envelopes). On the WRR level, the Water Resources Council (1968) study was not largely consistent with the other projections and is the largest of the total and thermoelectric freshwater withdrawal projections more often than not (Figures 2C and 2D).

Patterns for thermoelectric and irrigation withdrawals reflect the larger importance of the former in the east and of the latter in the west (Figures 2D and 2E). Thermoelectric withdrawal envelopes are larger than irrigation withdrawal envelopes and thermoelectric projections are more spread out than irrigation projections.

DISCUSSION

Limitations: Data and Projections

The USGS has continually improved and refined their estimation procedures, a laudable overall strategy. Nevertheless, the nature of the USGS water-use estimates imposes four significant limitations (out of the eight in Table 1) with respect to making projections of future water use. (1) The change in method for aggregating data made in the 1985 report introduces some uncertainty in the interpretation of trends; the abrupt drop in total water use from 1980 to 1985 may be a partial result of overestimation prior to the adoption of the new aggregation method (Solley *et al.*, 1988; Brown, 1999), but no estimate of the size of this potential effect has been made. (2) Changes in categories of water use reported, especially pre- and post-1985, mean that some aggregation must be carried out when using the full time series of estimates to inform projections. For example, Brown (2000) used the coarser pre-1985 categories in making projections. (3) In 2000, the USGS ceased making estimates of consumptive use of water because of budget constraints and the recognition that the estimates of consumption were not highly reliable (Bredehoeft, 2013). The distinction between withdrawal and consumptive use is valuable especially when managing thermoelectric demands; wet-recirculating systems consume up to twice the amount of water as once-through facilities (Macknick *et al.*, 2011). (4) Finally, some of the USGS estimates are not based on primary data; some categories and states use ancillary data plus coefficients. For example, most estimates of irrigation water use from irrigated acreage are based on crop irrigation requirements. These are not stable, but vary with type of crop and climatic conditions, which are taken into account with methods such as Blaney-Criddle or Penman-Monteith. At a fundamental level, "...only to the extent that the assumed relations were accurately specified do the USGS data provide a basis for describing the relations of past use to factors affecting that use and for projecting future water use" (Brown, 2000).

Limitations also must be recognized in making comparisons of projections of water withdrawals with USGS estimates. Projections can be made using many methods, ranging from a detailed economic-hydrological analysis through various levels of extrapolation of factors that affect water withdrawals. Furthermore, assumptions about future changes in factors can be made with the intention of capturing a best guess and thereby making an actual forecast of an expected future or can be made with the intention of laying out one or more "what if" scenarios to illustrate the implications for water use under the scenarios regardless of any expectation that a given scenario is likely to play out. Guldin (1989) frames the issue as follows: "[the projections] portray what might occur if factors determining water resource management and use continue unchanged." National Water Commission (1973) takes the "what if" scenario one step further. Suggesting that it is too difficult to make best estimates because of the myriad of variables driving water use, National Water Commission (1973) presents alternative futures: "...the nation should not be bound by any particular projection or forecast of the future. Rather, the problems of meeting future water requirements should be investigated in terms of a range of possible outcomes, or alternative futures."

Regardless, a projection of a factor that turns out to be badly at odds with actual events can have a major impact on water withdrawal projections. For example, the first report by the Water Resources Council (1968) projected a U.S. population of 337 million in 2000 and 468 million in 2020 in the conterminous U.S. This can be compared with the 2010 U.S. census that reported a total population of 309 million and a 2012 projection made on the basis of that census of 334 million in 2020 (http://www.census.gov/population/projections/). In the second assessment by the Water Resources Council (1978), it was recognized that the population projection in the early study was too high and also that the assumption that efficiency of water use would not improve was wrong. Because these assumptions were changed for the later report, the Water Resources Council (1978) projections are much lower than the Water Resources Council (1968) projections, actually being somewhat lower for 2020 than those for more recent projections (Brown, 2000).

Not all of the studies from which we drew projections are clear about the intent of the study or about the details of the methods used in making projections. New studies should define the intentions of their future water-use estimates explicitly. Borrowing terminology from the climate literature (IPCC DDC, 2013), a projection is a description of the future if certain assumed conditions were to prevail. Forecasts are projections with high confidence levels; that is, the underlying assumptions are assumed to be representative of actual events in the future. Projections and forecasts provide very different information to stakeholders. The differences between these definitions are subtle but important when thinking about the future of water use given the state of present knowledge (National Research Council, 1999).

Regional Freshwater Withdrawal

Looking over the time series of USGS total withdrawal estimates at the WRR scale, fluctuations are apparent in the data. Comparisons of regional water-use projections with the regional USGS estimates for 2000 were complicated by the fact that the USGS estimates are collected every five years. These data point estimates can be affected by variables outside those included typically in projections. Gradual shifts in resource use tend to be influenced by population and behavioral changes, which tend to be included in projections, but year-to-year variations are influenced by weather, changes in estimation methods, economic activity, construction and retirement of once-through systems, and urgent technological mandates. In recognition that USGS estimates implicitly reflect such external variability, we constructed envelopes about each WRR's estimate for the year 2000. By constructing envelopes about each WRR's estimate for the year 2000, we got an idea of these fluctuations and how the fluctuations differ by WRR and sector: uncertainty in estimated water use in 2000 is associated with its time-series variability. If withdrawal estimates are fairly constant or changing at a nearly linear rate, the envelopes will be small, but if withdrawal estimates show large fluctuations — or a fuzzy trend — the envelopes will be larger.

Looking over Figure 2, we see that the Water Resources Council (1968) study is not consistent largely with the national USGS estimate nor most regional USGS estimates. There are several regions where the total water withdrawal inconsistency appears to be driven by thermoelectric withdrawal projections. For regions where the discrepancies between the Water Resources Council (1968) projections and USGS estimates are not likely linked to overestimates in thermoelectric withdrawal projections, discrepancies could be linked to overestimates in other withdrawal categories. For instance, Water Resources Council (1968) overestimates public supply and domestic water use at the national level, as well as in some WRRs. Total water withdrawal estimates and irrigation water withdrawal estimates fluctuate, but the most significant year-to-year variations come from western WRRs thermoelectric withdrawals. Water Resources Council (1968) overshoots its regional projections for both total and thermoelectric freshwater withdrawals more often than any other study, and this is likely the result of three assumptions: the extrapolation of early water-use trends, the notion of a stronger dependence on nuclear-fueled plants in the future, and the assumption that future plants would use once-through cooling. Furthermore, the letter of transmission from Water Resources Council (1968) suggests that the report was intent in warning readers about water resource limits: "These are some of the stark warnings that nature's abundance cannot be taken for granted." Freshwater thermoelectric withdrawals projections by the Water Resources Council (1978), on the other hand, tend to be the lowest of the four studies; this is likely the result of the assumption that technology would become more water efficient — a reaction to environmental legislation and regulation in the 1970s.

For the most part, irrigation freshwater withdrawal projections tend to fit within the USGS envelope of estimates. Because of the steady increase in water withdrawals over the time series, it is not surprising that irrigation withdrawal projections by Guldin (1989) and Brown (2000) fall within or close to the USGS estimate envelopes; both studies take similar approaches by extrapolating USGS trends and other demographic information. Nevertheless, in most regions Guldin (1989) projects higher water use than Brown (2000). Guldin's (1989) values "are intended to suggest future demands if water resource management continues as it has from 1960 to 1987," whereas Brown (2000) takes into account per capita efficiency gains that occur in the 1990s (Brown, 2000). Using our conceptual model of "the envelope," the goodness of projections should be evaluated in comparison to the uncertainty of the historical data the projections are based upon. That is, a rough projection from fuzzy historical data may be thought of as reasonable if it falls within a large envelope, just as a projection from consistent historical data is thought of as reasonable if it falls within a small envelope.

The Need for Water-Use Estimates, Projections, and Forecasts

With so many data limitations facing stakeholders, why should they continue to collect water-use data? Despite the limitations in acquiring and interpreting water use data and in making useful future projections, data are important for stakeholders at all levels of management and planning. Water is a critical resource in sustaining political, social, environmental, and economic security. This observation is not new. The first report of the Water Resources Council stated: "Data on the use of water resources are quite inadequate and place a severe limitation on comprehensive planning, the National Assessment, and other planning and policy activities that require reliable inventories of present uses and projections of future uses." As drought events intensify water scarcity and anthropogenic disturbances increase the complexity of both the spatial and temporal components, spatio-temporally comprehensive and consistent water-use data will become a major asset in maintaining economic growth, providing reliable energy, sustaining ecosystem services, and meeting food production demands (World Water Assessment Programme, 2012). To meet future data and analysis needs, the USGS has established the National Water Census, a "program on national water availability and use that develops new water accounting tools and assesses water availability at the regional and national scales … designed to build decision support capacity for water management agencies and other natural resource managers" (http://water.usgs.gov/watercensus/).

Water-use managers are beginning to get the attention of the wide array of stakeholders that will need to cooperate to address the bottleneck in data compilation. For instance, the Western States Water Council is working with the Western Governors' Association, the U.S. Department of Energy and the National Labs, and the Western Federal Agency Support Team to create a data collection framework for western states and maintain a detailed water-use database (http://www.westernstateswater.org/wade/). And, the USGS has made significant steps in streamlining guidelines for the collection and estimation of data in their semi-decadal reports (Hutson, 2007). Despite the limitations inherent in the USGS historical water-use data, researchers who have used the data have provided useful information regarding high-level trends and drivers of water use (Dziegielewski *et al.*, 2002; Dziegielewski and Kiefer, 2006).

Considering the results of our work — the limited accuracy of past projections and forecasts when looking into the future, especially over decadal time scales — why should stakeholders care about projections and forecasts of water use? Water planners project and forecast water use for many reasons. Short-term outlooks allow managers to adjust system operations, set water rates, and evaluate how well supplies are meeting demands (Pacific Institute and Alliance for Water Efficiency, 2013). In the long term, projections and forecasts provide information needed to plan new water-supply infrastructure so that water supply meets demands or to implement behavioral change programs so that demands do not overshoot capacity (Pacific Institute and Alliance for Water Efficiency, 2013). Projecting and forecasting water use also alerts managers to potential future competition among water-withdrawal sectors, giving them time to explore economic, regulatory, or educational options that could provide solutions to water problems. U.S. trends are not always reflective of state and local water supply and demand situations, so projections and forecasts at finer scales are critical moving forward.

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