Climate Services 2–3 (2016) 30–40

Contents lists available at ScienceDirect

Climate Services

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

Co-producing actionable science for water utilities

Jason Vogel [a,*], Elizabeth McNie [b], David Behar [c]

[a] Abt Associates, 1881 9th Street, Suite 201, Boulder, CO 80302, USA
[b] Western Water Assessment and Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, 1333 Grandview Ave., Boulder, CO 80309, USA
[c] San Francisco Public Utilities Commission, 525 Golden Gate Avenue, 10th Floor, San Francisco, CA 94102, USA

ARTICLE INFO

Article history:
Received 14 February 2016
Received in revised form 1 June 2016
Accepted 15 June 2016
Available online 7 July 2016

Keywords:
Actionable science
Co-production
Climate model information
Water resources management
Vulnerability assessment

ABSTRACT

This article explores the efforts of four water utilities to co-produce actionable science by forging partnerships with scientific institutions to explore integrating climate considerations into their specific management context. The experiences of these four utilities and their scientific partners, as part of the Piloting Utility Modeling Applications project of the Water Utility Climate Alliance, provide a wealth of empirical evidence to illustrate some of the core concepts formulated to explain how to produce usable information and how to link research to decision making. Through these four case studies of co-production, we identify three findings that bridge principles and practice: each utility engaged in contextualizing research; in building and leveraging knowledge networks; and in embracing an entrepreneurial approach to their research agenda. In several instances, unanticipated but innovative assessment techniques were developed by science partners in collaboration with water utilities to fit the utility's specific needs. The paper concludes by discussing some of the hard realities of co-production illustrated by these cases that should be kept in mind by people contemplating similar projects.

Practical implications of ''co-producing actionable science for water utilities''

In this article we explore the efforts of the Water Utility Climate Alliance (WUCA) to co-produce actionable science through their Piloting Utility Modeling Applications (PUMA) project. The PUMA project was motivated by a desire to collaborate with climate scientists to generate an applied research agenda, to experiment with the practice of co-production, to generate actionable science, and to learn lessons about the state of climate services in the United States. Through this project, four water utilities forged partnerships with scientific institutions with a climate service history and mission to explore how to integrate climate considerations into their specific management context.

Each water utility engaged in a ''chain-of-models'' exercise to better understand how climate changes might affect their water systems. The chain-of-models refers to the sequence of models used to apply climate change information to water utility decision making. The sequence of models includes (1) the generation of climate projections by general circulation models (GCMs), (2) the downscaling of GCM data to spatial and temporal scales usable by hydrologic models, (3) the use of hydrologic models to translate GCM variables (e.g., temperature, precipitation, solar radiation) into variables used by water utilities (e.g., runoff, river flow, reservoir level), and (4) the use of these climate altered hydrologies in water utility operations models (e.g., reservoirs operations, transmission and distribution, demand forecasting). By running climate projections thorough this chain-of-models, the impacts of projected climate changes can be understood and water utilities can consider taking adaptation action to prepare for or mitigate those potential impacts.

At the same time, each PUMA utility began their pilot project with certain ''bottom up'' questions that zeroed in on the relationships between key meteorological phenomena and the core functionalities of their water systems. In all cases, the identification of these linkages early in their partnership with science partners drove or altered the nature of the pilot project.

* Corresponding author.
E-mail addresses: jason_vogel@abtassoc.com (J. Vogel), mcnie@colorado.edu (E. McNie), DBehar@sfwater.org (D. Behar).

http://dx.doi.org/10.1016/j.cliser.2016.06.003
2405-8807/

This paper focuses on three key outcomes of the PUMA project: (1) the importance of characterizing and understanding context, (2) the construction and leveraging of knowledge networks, and (3) the need for an entrepreneurial approach to producing actionable science.

(1) The importance of characterizing and understanding context – i.e., the unique and important features of each utility's drinking water system – arose in the shaping of research questions, in the treatment of extreme events, in considering local hydrometeorology, and in making outputs from GCMs relevant for water utilities. First, the overarching goal of the PUMA project was the same across all four participating utilities, namely to ''identify state-of-the-art modeling tools and techniques that can be used by water utilities to assess potential climate change impacts on their systems and watersheds.'' However the four utilities engaged in dramatically different research projects, focused on different potential climate impacts, different hydrometeorological variables, and even different steps in the chain-of-models exercise. Second, evaluation of precipitation-related events was the primary concern of two utilities, which both found were poorly represented among existing climate projection tools. Their response was to innovate new tools, in collaboration with their scientific partners, that better utilized existing projections to shed light on their specific areas of concern. Third, the contextualization of local hydrometeorology was critical because of the importance of a solid understanding of baseline hydrometeorology in the use of climate change data. Finally, the utilities also contextualized GCM outputs to meet their specific needs within the chain-of-models exercise, including by developing new downscaling methodologies to better capture climate variables of local interest.
(2) The importance of the construction and leveraging of knowledge networks arose in all four utility projects. The development of active partnerships with scientists at sometimes multiple institutions helped facilitate the development of actionable science in a co-production environment. In addition, while all four utilities forged knowledge networks with scientific partners, two of the utilities specifically cited developing staff capacity and expertise as a primary motivation for engaging in their project (though all four certainly achieved this result). To achieve these goals, interactions between utility and scientific partners were often carefully designed to occur early and often, and to include substantive and meaningful discussion of project progress toward identified goals. Most of these knowledge networks persist beyond the period reported in this paper and form the foundation for on-going work at each of the four utilities.
(3) The importance of the need for an entrepreneurial approach to producing actionable science was perhaps the most surprising finding of this work. The conventional paradigm might assume that the scientists played the innovation role and the utilities were passive recipients of such advances in knowledge. In reality, we saw the utilities themselves drive innovation in several circumstances. When the state of the practice for downscaling or hydrologic modeling did not produce actionable information for utilities, the utilities did not give up, but instead redoubled their efforts and worked with their scientific partners to innovate new methodologies to resolve their particular problems and allow climate projections to be useful in their utility context. For example, two of the utilities developed new downscaling methodologies for different purposes. One developed a variation on the ''delta method'' to better understand how the extreme events of greatest concern operationally might change over time. The other developed a new statistical downscaling technique which did a better job than off-the-shelf statistical downscaling tools of replicating the spatial and temporal distribution of rainfall, the key driver of local water supply. In another example, one utility worked with their science partners to bias-correct a widely accepted hydrologic dataset in order to better capture orographic effects important in its local watershed and to better reflect the instrumental record.

Overall, the four projects profiled in this article provide useful case studies in the successful co-production of actionable science for climate services. These cases deserve to be studied to identify lessons that can be applied in other locations and contexts. There are also some hard realities to co-production that these cases illustrate that should be kept in mind by people contemplating such an exercise.

1. Introduction

Climate variability and change impact the provision of hydrologic services, including both water supply and water quality, and needs to be considered in the planning, management and operations of water utilities (IPCC, 2014; Groves et al., 2008). In order to adapt to, and plan for, climate variability and change, water managers need actionable and useful climate science. Useful information will help clarify options, expand alternatives, and improve outcomes to management decisions (Pielke, 2007). Too often, however, scientists produce too much of the wrong kind of information, not enough of the right kind of information, or fail to deliver useful information in a timely manner (McNie, 2007). According to Kundzewicz and Stakhiv (2010, p. 1085), ''the current suite of climate models were not developed to provide the level of accuracy required for adaptation-type analysis" – and yet these models are today a primary source of information sought and used by decision-makers. Climate services are needed to improve the linkage between state-of-the-art climate information, generally from the peer reviewed literature, and users' information needs as they seek to build resilience and develop adaptive capacity to climate variability and change (Vaughan and Dessai, 2014).

Water utilities have been at the forefront of adapting to climate change since at least 1997, when the American Water Works Association, an international nonprofit scientific and educational society dedicated to the improvement of drinking water quality and supply, issued a statement expressing the need for water utilities to begin planning for the consequences of climate change (AWWA, 1997). Since that time, individual water utilities (e.g., EBMUD, 2009; NYCDEP, 2008; Palmer, 2007; Palmer and Hahn, 2002), water research foundations (e.g., Miller and Yates, 2006; Stratus Consulting and MWH Global, 2009; Woodbury et al., 2012), and water utility collaboratives like WUCA (e.g., Barsugli et al., 2009; Means et al., 2010) have pursued a serious agenda of understanding the implications of climate change for water resources that has generated a sizable body of work.

These efforts have culminated most recently in a research effort by the Water Utility Climate Alliance (WUCA)[1] explicitly aimed at

[1] WUCA is a coalition of ten of the United States' largest water providers that provides leadership in assessing and adapting to the potential effects of climate change through collaborative action, and seeks to enhance the usefulness of climate science for the adaptation community and improve water management decision-making in the face of climate uncertainty. See www.wucaonline.org.

exploring the co-production of scientific information that is useful for water utilities planning for climate change (Vogel et al., 2015). According to the final report of this research effort, "'co-productio n'...is intended to convey the idea that science in service of adaptation is not a one-way street, but a collaborative venture between scientists and decision-makers in which the needs and skills of each come into play throughout that collaboration" (Vogel et al., 2015). The authors continue, "Co-production requires an iterative, collaborative process across the borders between science and policy that draws upon the unique needs, experience, and even the limitations of each party, providing the strongest possible underpinning for societal action in response to the consequences of climate change" (Vogel et al., 2015). Effective co-production of information can lead to the development of new forecast products and models to address "real world problems" (Feldman and Ingram, 2010).

The four utilities that participated in the WUCA research experiment in co-production did so specifically to develop what they call "actionable science." WUCA members first presented a definition of actionable science at a 2009 U.S. Environmental Protection Agency adaptation conference (Behar, 2009). Subsequently, the term actionable science (or "actionable information" or "actionable knowledge" or "actionable climate science") has been embraced by the U.S. Army Corps of Engineers (USACE, 2012), a federal agency consortium called the Climate Change and Water Working Group (CCAWWG; Raff et al., 2013),[2] the U.S. Global Change Research Program (USGCRP, 2012), the Global Framework for Climate Services (WMO, 2011), the *President's Climate Action Plan* (Executive Office of the President, 2013) and Executive Orders 13653 (EO 13653, 2013) and 13690 (EO 13690, 2015). The term actionable science was most recently defined by the Advisory Committee on Climate Change and Natural Resource Science (ACCCNRS), appointed to advise the Secretary of the Interior, as follows:

> Actionable science provides data, analyses, projections, or tools that can support decisions regarding the management of the risks and impacts of climate change. It is ideally co-produced by scientists and decision makers and creates rigorous and accessible products to meet the needs of stakeholders.
>
> [(ACCCNRS, 2015)]

Definitions of climate services, in turn, can vary, alternately referencing products and processes. The American Meteorology Society says climate services are "scientifically based information and products that enhance users' knowledge and understanding about the impacts of climate on their decisions and actions. These services are made most effective through collaboration between providers and users" (AMS, 2015). The World Meteorological Organization adds that climate services require strong partnerships between providers and users (WMO, 2015). Vaughan and Dessai (2014, p. 588) describe climate services as the provision of "timely, tailored information and knowledge to decision makers...[and are seen] as an important part of improving our capacity to manage climate-related risk". Therefore, unlike climate information in general, most agree that climate services consists of both information content and a procedural dimension by which the knowledge is co-produced to provide information for decision support. Climate services should "engage decision makers, researchers, and others to ensure that products are relevant [and] uncertainties are explicit..." (Moss et al., 2013, p. 697). This paper reviews the experience of four water utilities to explore the procedural dimension of climate services, which we describe as the co-production of actionable science.

[2] CCAWWG members include the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, the U.S. Geological Survey, the Federal Emergency Management Agency, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Environmental Protection Agency.

The U.S. Department of the Interior's Advisory Committee published a "how-to guide" for the co-production of actionable science targeted at climate service providers seeking guidance on best practices (Beier et al., 2015). This guide, produced as an appendix to the ACCCNRS's full report and also as a stand-alone document, posited five guiding principles for co-producing actionable science in the climate services arena:

1. Actionable science is most reliably co-produced by scientists and decision makers or resource managers working in concert.
2. Start with a decision that needs to be made.
3. Give priority to processes and outcomes over stand-alone products.
4. Build connections across disciplines and organizations, and among scientists, decision makers, and other stakeholders.
5. Evaluate co-production products, processes, and the actionability of the science produced by projects.

2. Challenges in producing actionable science for climate services

Actionable science has three characteristics. First, it is salient, and context sensitive, reflecting the unique conditions and constraints of the problem in question (Cash et al., 2002). Second, it is credible, in that it was produced and vetted according to accepted standards of excellence and practice, including but not limited to peer-reviewed publications (Cash et al., 2002). And third, it must be legitimate in that the intended users of the information must believe that the information was produced without political suasion or bias. Legitimacy is grounded in the development and maintenance of relationships based on mutual trust and respect (Cash et al., 2002; McNie, 2007). Each of these three qualities needs to exist simultaneously and increasing one does not overcome shortcomings in another quality (Cash et al., 2002). Another dimension of actionable or usable science is that it is iterative, where engagement between producers and users of information must occur early, often, and throughout the duration of the project (Beier et al., 2015; Lemos and Morehouse, 2005) in what has been called a "symbiotic" relationship (Asrar et al., 2013).

Producing actionable science in a climate services environment is difficult to do for many reasons. Integrating climate information into planning processes is difficult because decision makers do not always know what information is best suited to inform their particular problem (Briley et al., 2015). Reconciling the supply of useful climate information with user demands is difficult to do, and often users do not get the information they need to address their unique problem (Moss et al., 2013; Sarewitz and Pielke, 2007). Despite efforts to improve the linkages between supply and demand, gaps between producers and users persist (Bierbaum et al., 2013; Kirchhoff et al., 2013; Vaughan and Dessai, 2014). Poor communication is another challenge in effectively linking climate information with user demands. Traditionally, communication between scientists and users has been one-directional, flowing from scientist to user (McNie, 2007). This "linear model" of science policy and the belief that usable information flows in just one direction has come under great scrutiny in the past 30 years (Kirchhoff et al., 2013). The linear model has frequently been found to fail because it does not connect the research process or its products to the needs of decision makers (McNie, 2008; Sarewitz and Pielke, 2007). A technical, but also cultural issue is that information that scientists produce is often at a temporal or spatial scale that makes it unusable for decision-makers (Asrar et al., 2013; Vaughan and Dessai, 2014). This tension is often accompanied by a corollary set of troubles caused by difficulties in communicating and understanding the uncertainties inherent in any climate projection exercise. And finally, culturally in particular, scientists and decision makers live in very different worlds, with differences in career incentives and promotional conditions, in approaches to problem solving, and, most significantly, in terms of the decisions they make. These differences have certainly exacerbated the mismatch between the supply and demand of actionable scientific information (McNie, 2007).

Approaches to successful co-production, therefore, increasingly point to the importance of processes that link scientists and users together in a shared environment of knowledge production (Beier et al., 2015; Dilling and Lemos, 2011) requiring the bi-directional flow of information in which users help to shape research problems and agendas (Moss et al., 2013). Co-production requires a foundation of strong relationships between scientists and users that is based on mutual trust and respect (McNie, 2008). This is a two-edged sword, as the co-production process, while increasing the likelihood that useful information will be produced, is time consuming and labor intensive (Briley et al., 2015).

We see, therefore, both the opportunities and difficulties laid out in the literature. Now we turn to the empirical experience of four water utilities that engaged in WUCA's Piloting Utility Modeling Applications (PUMA) project to examine real-world experiences in climate change vulnerability assessment. We explore these experiences to enhance our understanding of the dynamic that leads to co-production of actionable science.

3. The PUMA project

To respond to the growing risks presented by climate change, WUCA undertook a project aimed at co-producing actionable climate science through close collaboration between climate experts and water utility personnel that mirrored in practice many of the theories presented above. Four water utilities conducted projects: The New York City Department of Environmental Protection (NYC-DEP), the Portland Water Bureau (PWB), Seattle Public Utilities (SPU), and Tampa Bay Water (TBW). The PUMA project was motivated by a desire to collaborate with climate scientists to generate an applied research agenda, to experiment with the practice of co-production, to generate actionable science, and to learn lessons about the state of climate services in the United States. Instead of asking climate experts what they thought utilities should do regarding climate change, the four utilities decided to forge partnerships with scientific institutions with a climate service history and mission to explore how to integrate climate considerations into their specific management context.

In order to capture the story of PUMA and evaluate its process, WUCA contracted with an external consultant, Stratus Consulting, now known as Abt Associates, who tracked progress on PUMA throughout the duration of its initial three years (Vogel et al., 2015). Data were gathered through archival research and through extensive surveys and interviews with researchers and utility personnel. Utility staff (one to four people per utility per survey/interview) and their climate scientist counterparts (one to three people per utility per survey/interview) were surveyed and subsequently interviewed three times over the course of the project. An initial survey was produced based on the objectives of the PUMA project and was common across all four utilities. Subsequent surveys were tailored to elicit information specific to the unique evolution and outcomes of each PUMA project. After each written survey, a set of follow-up interviews was conducted to elaborate on issues of interest or ambiguity.

The project used a qualitative comparative case study design (Babbie, 2004) to explore a number of research questions collectively defined by the PUMA project teams. The purpose of the project was not to develop generalizable information that applied to all water utilities, but rather to develop illustrative insights into the co-production of actionable science in a water utility environment. As such, the project used a purposeful sample (Babbie, 2004) of water utilities that were part of the PUMA project because these utilities were willing to commit resources to an exploratory effort. Furthermore, because the nature of the PUMA project evolved over its first three years as chronicled in Vogel et al. (2015), the nature of the surveys and interview questions evolved as well. In other words, this research design is not a classic test of statistical significance, but rather a systematic, but qualitative exploration of the context of four PUMA pilot projects. This research design has obvious limitations regarding replicability. Nevertheless, the findings herein can inform the development and deployment of more statistically rigorous and generalizable research projects in the future.

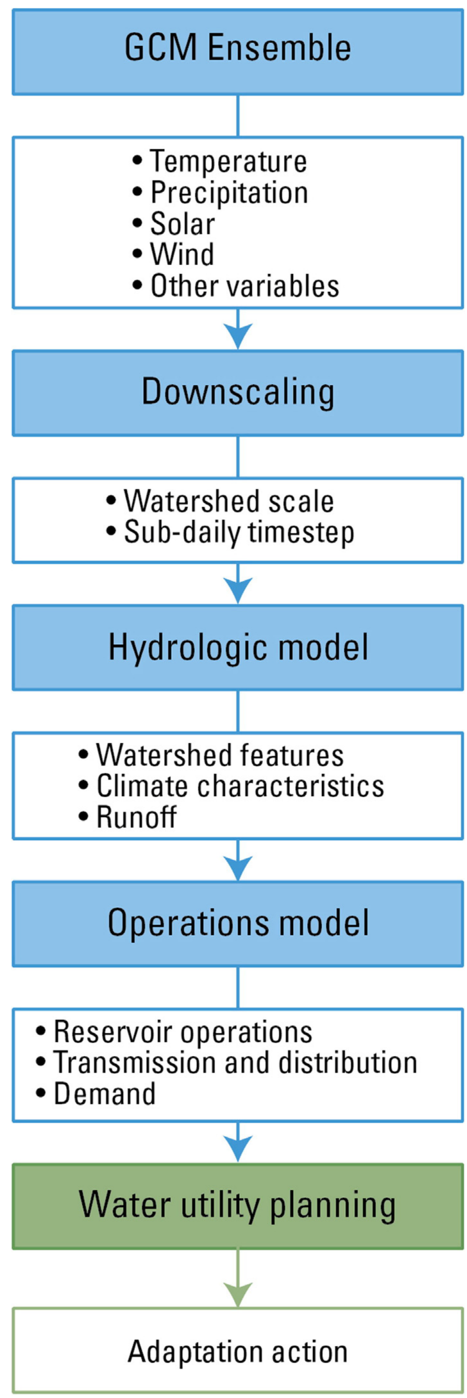

Fig. 1. Illustration of the chain-of-models concept.

All four utilities engaged in a modeling process to better understand how climate changes might affect their water systems through a "chain-of-models" exercise. The chain-of-models concept refers to the sequence of models that water resources experts use to apply climate information to a water utility context. For example, the outputs from GCMs, which are also called global climate models, become inputs into techniques for increasing the resolution of GCM data (commonly called downscaling); the resulting outputs become inputs into a hydrology model, which generates watershed runoff estimates; the outputs of the hydrology model become inputs into a system management or operations model; and the outputs of the utility system models can help define the climate change impacts on water supply, water quality, and other parameters that water utilities commonly evaluate to facilitate planning (see Fig. 1). In this way, GCM data can help identify potential climate change impacts on water system performance. For three of the utilities, this involved determining how to increase the resolution of GCM outputs and integrate them into their existing utility models; for one utility, PWB, the work focused on considering climate change in selecting and developing a hydrologic model and obtaining downscaled climate data to enable future work on climate change. See Table 1 for a brief summary of the four utilities and their PUMA projects. For more detailed case studies, see the PUMA final report (Vogel et al., 2015).

The insights gained from the PUMA project inform our understanding of the challenges and pay-offs of co-producing actionable science. This paper documents three key findings of the PUMA project: that context matters in the development of actionable science; that building and leveraging knowledge networks is crucial to making climate information useful; and that climate service providers may need to embrace an entrepreneurial approach to co-producing actionable science.

4. Bridging principles and practice – findings from the PUMA project

Here we focus on three key findings of the PUMA project: the importance of characterizing and understanding context, the construction and leveraging of knowledge networks, and the need for an entrepreneurial approach to producing actionable science.

4.1. Contextualizing research

Characterizing, describing, and understanding the importance of context is extremely important in producing useful scientific information (McNie, 2007). As mentioned earlier, one of the key tenets of producing useful information is that it be salient and context sensitive (Cash et al., 2002), thus avoiding the "loading dock" approach to knowledge production (Cash and Buizer, 2005). Of critical importance in the development of the PUMA project as a whole was to develop an overarching goal that provided adequate direction for the participating utilities while simultaneously providing enough flexibility for each to fine tune their individual research projects and agendas based on their own unique set of problems. This, in turn, made it easy to consider context in the shaping of research questions, treatment of extreme events, consideration of local hydrometeorology, and making outputs from GCMs relevant for water utilities.

4.1.1. Customizing research

The main technical goal of the PUMA project was to "...identify state-of-the art modeling tools and techniques that can be used by water utilities to assess potential climate change impacts on their systems and watersheds" (Vogel et al., 2015). While the overarching goal was to investigate how climate change affects drinking water supplies, each of the four utilities had very different research goals and objectives. NYCDEP focused on identifying possible impacts and then developing operational policies to minimize the effects of those impacts. They were particularly concerned about impacts that would affect their supply, quality, and operations, such as changes in the timing of winter run-off, reduction in winter snowpack, changes in the thermal structure of reservoirs, and an increase in the severity of extreme events. SPU developed a research project aimed at understanding the long-term effect on water availability and reliability given changing baseline conditions. They were also interested in the timing in the onset of fall rains and atmospheric rivers given the importance that these events have on water quantity and storage. PWB focused its research on a long-term evaluation of the impacts of climate change on its primary surface water supply and selecting a hydrologic model that would best fit its needs for translating GCM outputs, including temperature and precipitation, into future stream flow projections. TBW targeted its research toward climate-change data in order to increase its relevance for planning and operations. Additionally, all of the utilities were also interested in developing collaborative relationships with climate scientists.

4.1.2. Contextualizing extreme events

One way that utilities customized their research was in the investigation of the role that extreme events play in water quantity and quality regarding the utility's planning and operations. The nature of extreme events and the impact they have varies by

Table 1
Summary of the PUMA case studies.

Water utility	Number of customers	Gallons of water produced per day	Service types	Primary climate change concern	Project highlight
NYCDEP	9.2 million	1.1 billion	Drinking water supply; wastewater and storm water management	Water quality	Created a new delta-change technique to increase the resolution of GCM data called the statistically distributed (SD)-delta method, which is simple to use yet provides insight on extreme events
PWB	958,000	101 million	Drinking water supply	Shifts in hydrograph for water supply planning; water quality impacts/turbidity	Evaluated a range of hydrology models against its needs and selected a cost-effective one that can integrate climate modeling data for long-term planning purposes
SPU	1.3 million	120 million	Drinking water supply; wastewater, solid waste, and storm water management	Water availability/reliability; operational thresholds; timing/onset of fall rains; forest fire	Built internal capacity to conduct climate change impact analyses by generating climate-altered hydrology and water supply impacts assessment in-house
TBW	2.3 million	220–260 million	Drinking water supply	Changes in seasonal rainfall patterns	Developed a new downscaling method that captured the spatial-temporal relationships of rainfall that drive west-central Florida's hydrology

location and operational conditions. Characterizing extreme events is difficult to do through climate models, but was important for NYCDEP. NYCDEP was most concerned about how extreme events, usually in the form of intense rainfall and extended periods of very high heat, could lead to high turbidity in its unfiltered water supply, increased disinfection byproducts and high dissolved organic carbon. At present, GCMs cannot adequately capture quantitative changes in extreme events, for example, the potential increase in intensity of hurricanes. Most extreme events, therefore, are characterized in qualitative terms. Using qualitative terms to evaluate extreme events, however, was insufficient for the type of analysis NYCDEP sought to do, so the utility developed a new way to integrate quantitative information into models.

In order to be able to integrate quantitative values into the chain of models approach, NYCDEP developed a new delta-change downscaling technique to increase resolution of GCM data which they call the SD-delta method, a modification of the simple and widely used "delta-change" downscaling technique (see Anandhi et al., 2011b for a detailed description of this methodology). The traditional delta-change technique basically entails defining the difference between projections of a climate model (e.g., monthly precipitation values for 2050) and subtracting those from a hindcast of the same climate model (e.g., monthly precipitation values for 2000). This difference (the delta) is then added or subtracted from actual weather station data to provide a precipitation time series for a climate-altered future at that location.[3]

The SD-delta method enhances the delta-change method by allowing NYCDEP staff to gain some insight into extreme events. It does so by beginning with the source daily precipitation or temperature data for both the forecast and hindcast of climate. NYCDEP then places these daily values into bins – for example 25 bins each containing 4% of the daily values. Instead of calculating a single change factor or "delta" for each month, a separate delta is calculated for each bin for each month. This allows NYCDEP to see how the wettest 4% of days change separately from, for example, the driest 4% of days or the median 4% of days. NYCDEP applied the SD-delta method to assess the effects of projected climate change on turbidity. For example, the wettest 4% of days may lead to significant increases in precipitation and thus increased streamflow and turbidity. As shown in Fig. 2, the result was a significant increase in projected winter turbidity.

SPU used a bottom-up or threshold approach to contextualizing extreme events. Finding the right way to characterize extreme events in the context of downscaled climate projections with limited information about such extreme events, was a goal of their research. Rather than rely on standard metrics typically used in downscaling projections, such as the change in frequency of a 95th percentile event, SPU wanted to understand how climate change might affect the frequency of a hypothetical 24-h, 2-in. precipitation event, because SPU knew this threshold event would cause operational problems for the utility. High temperature extreme events, that is, multiple consecutive days over 80 °F with no precipitation, were also used as a metric of conditions that raised concerns about possible forest fires that could damage their watershed.

4.1.3. Customizing hydrometeorology

PWB was different from the other cases in that it did not have an in-house hydrologic model at the outset of the PUMA project, but needed one in order to inform its climate-impacts assessments. This allowed PWB to think through what the utility needed to do to conduct climate change impact assessments internally, without

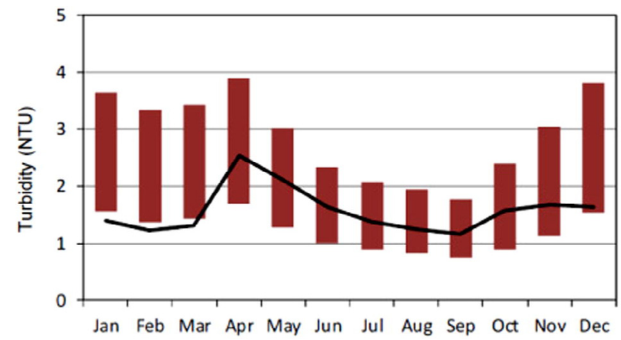

Fig. 2. Comparison of NYCDEP's mean monthly observed turbidity (black line) in Ashokan Reservoir – East Basin with range of simulated 2080–2100 turbidity from five climate change scenarios using the SD-delta method (maroon bars). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

worrying about existing processes or sunk costs in an existing utility hydrologic model. As a result, one of the major goals of the project was to identify a hydrologic model that would best fit PWB's needs for understanding its primary surface water supply (the Bull Run watershed) and which could be used to translate GCM outputs into future streamflow projections. PWB worked with researchers through the NOAA Regional Integrated Sciences and Assessments (RISA) Climate Impacts Research Consortium (CIRC), specifically the University of Washington and University of Idaho, both in person and in a workshop, to identify potential models. Eight possible hydrologic models were originally evaluated based on the following criteria:

- Non-proprietary software.
- Ability to process multiple runs through scripting.
- Ability to simulate hydrologic processes at appropriate spatial and temporal scales.
- General ease of setup and use.
- Reputation of the model and use in other Northwest climate change studies.
- Cost to the utility, including initial, setup, and operating costs.

After narrowing the choices down to three models, University of Washington researchers did further work to calibrate, validate, and compare the models by performing statistical analyses comparing simulated and actual streamflows. Following this work, PWB selected the Precipitation-Runoff Modeling System (PRMS) that was initially developed by the U.S. Geological Survey for use in hydrologic studies, many of which are related to climate change. At the final workshop, PWB personnel were trained in PRMS use and operations. The PRMS model had a good statistical fit with daily and annual flows, and the best fit with monthly flows (see Figs. 3 and 4). It also had the added benefit of ongoing technical support from the U.S. Geological Survey. Essentially, a thorough review of existing hydrology models suggested that PWB could apply a user-friendly, short run-time model in order to answer its research questions without investing in an expensive operational hydrologic model (see Chiao et al., 2013a,b for a detailed description of the hydrology model testing).

4.1.4. Customizing climate data and model outputs

In the PUMA project, GCM output, downscaling techniques, and even baseline observational datasets used to validate climate projection tools frequently needed to be customized for use in local assessments. For example, PWB and University of Washington recognized that the utility's available historical data for one

[3] This method has one well-documented drawback: the sequencing of events in future scenarios is determined by the sequencing of events in the historical record. Such replication of weather sequencing in the future is not realistic.

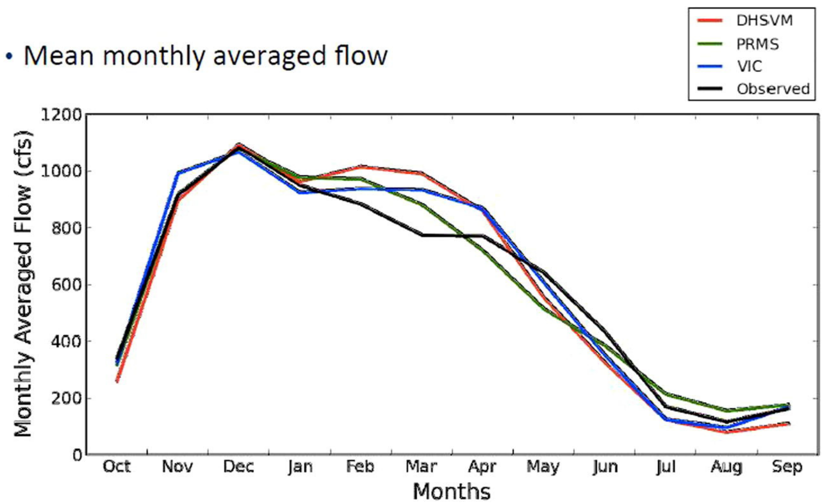

Fig. 3. Comparison of PWB's mean monthly observed streamflows with simulated streamflows from three hydrologic models. Note that DHSVM and VIC suggest higher runoff than PRMS and the observed data for the spring snowmelt-runoff months of March and April.

	Calibration Period (1976-1988)							
Model Name	Dv	Yearly NSE	Monthly NSE	Daily NSE	Daily KGE	Daily MAPE	Daily NRMSE	Daily TIE
DHSVM	-0.81%	0.95	0.88	0.70	0.68	32%	0.04	0.17
PRMS	-0.47%	0.93	0.90	0.80	0.78	38%	0.03	0.13
VIC	0.54%	0.96	0.88	0.79	0.88	34%	0.03	0.13
	Validation Period (1992-2005)							
Model Name	Dv	Yearly NSE	Monthly NSE	Daily NSE	Daily KGE	Daily MAPE	Daily NRMSE	Daily Theil
DHSVM	1.79%	0.95	0.89	0.71	0.72	32%	0.03	0.16
PRMS	2.32%	0.95	0.93	0.81	0.81	43%	0.02	0.13
VIC	3.76%	0.92	0.90	0.79	0.89	36%	0.02	0.13

Fig. 4. Error statistics of DHSVM, PRMS, and VIC in comparison to observed streamflow for the Bull Run watershed for the calibration (WY 1976–1988) and the validation periods (WY 1992–2005). Note the yearly Nash-Sutcliffe Efficiency (NSE) for PRMS validation (0.95) is equal to or better than the other models and VIC and the monthly NSE for PRMS validation (0.93) is better than the other models. We wish to acknowledge Cindy Chiao and Bart Nijssen for allowing us to publish these error statistics.

meteorological station in the watershed would not be adequate to calibrate the hydrologic models due to topographic disparities in air temperature and amount and phase of precipitation. In order to overcome this limitation, the University of Washington team recommended that PWB use a historical gridded meteorological data set (Livneh et al., 2013) to calibrate the three models' historical streamflows. However, even this gridded dataset did not fully capture the very wet micro-climate or water balance of the Bull Run watershed. To mitigate these problems, the research team had to further bias-correct the Livneh et al. dataset to ensure all three hydrologic models then were able to closely simulate observed Bull Run streamflows.

As part of its PUMA pilot, TBW sought to increase the resolution of GCM output data to better fit within the context of Florida. In order to identify and utilize the most effective model to achieve the desired resolution goals, they partnered with researchers at the University of Florida to test three different downscaling techniques (both statistical and dynamical; see Hwang and Graham, 2013; Hwang et al., 2011; Hwang et al., 2013 for detailed descriptions of the different downscaling techniques tested by TBW). Although the team members discovered that dynamical downscaling methods produced the best fit for the region's historical climate, the extreme time and computational expenses associated with it made these tools impractical and unwieldy for sustained use at TBW. Instead they chose to use statistical downscaling techniques as the basis for future analyses. Experimentation with widely available statistical downscaling databases, however, revealed that these techniques did a poor job of replicating historical spatial and temporal distribution of precipitation. These characteristics of precipitation are of utmost importance to TBW due to the nature of west-central Florida hydrology and TBW's water infrastructure. In an attempt to improve this information, TBW worked with two researchers at the University of Florida Water Institute, who developed a new downscaling technique – the bias-correction and stochastic analog (BCSA) method – that better replicates the spatial-temporal pattern of precipitation critical to TBW (see Fig. 5).

4.2. Building and leveraging knowledge networks

According to Feldman and Ingram (2010, p. 10), knowledge networks "connect people across disciplinary or occupational boundaries through various interactions". When put to use, knowledge networks can facilitate the co-production of knowledge and "provide decision support and pursue strategies that can put climate knowledge to use in better managing water" (p. 10). The utilities involved in the PUMA project actively built knowledge networks and tapped into existing networks, facilitating the development of actionable science.

SPU viewed the PUMA project not only as a way to actively pursue the best available climate-change projections but also as an

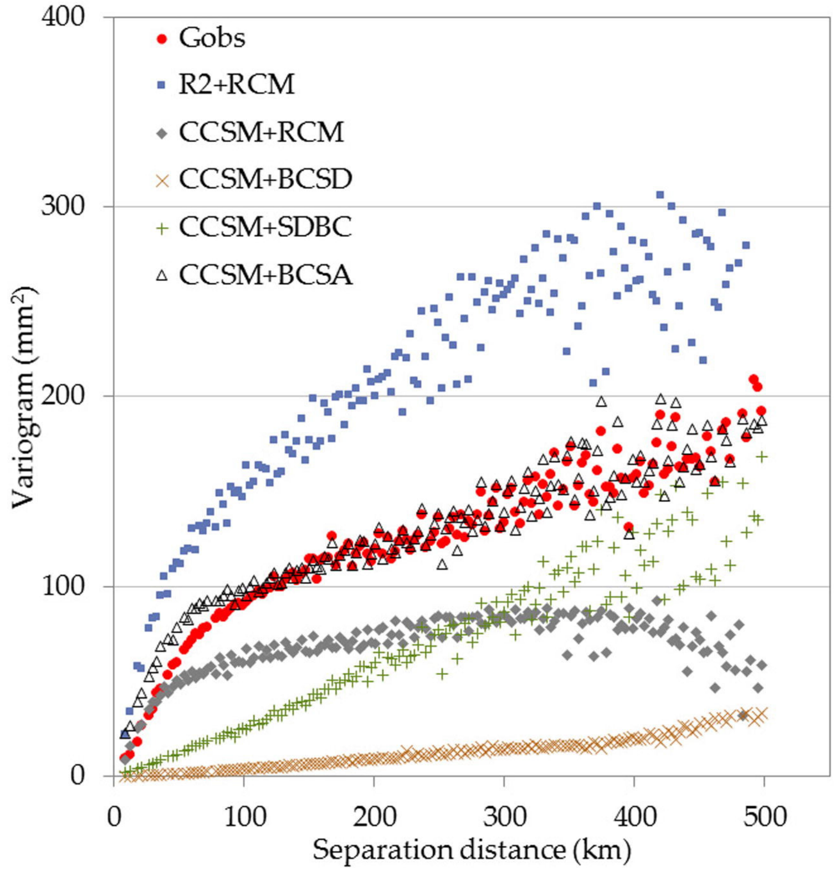

Fig. 5. Comparison of spatial variability of TBW's different downscaling methods. The variograms show the ability of TBW's different downscaling methods, dynamical downscaling (R2 + RCM, CCSM + RCM) and statistical downscaling (CCSM + BCSD, CCSM + SDBC, CCSM + BCSA), to replicate the spatial variability that exists in the observed record (red) for the wet season (June–September). The BCSA statistical downscaling method from the CCSM GCM (black triangles) co-produced in the TBW PUMA project best overlies the observed record (red circles). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

opportunity to improve its institutional capacity for conducting continued climate change research. To pursue PUMA and this longer term opportunity, SPU tapped into knowledge networks with which it had existing relationships. Specifically, SPU collaborated with CIRC, a NOAA RISA team. In past projects, SPU sought the advice of outside experts to perform hydro-climate analyses. The PUMA project gave SPU the opportunity to further develop its own in-house capabilities to do such work. It used the downscaled meteorological projections that CIRC generated to develop climate-altered hydrologies in-house as well as the subsequent water supply impact analysis. Not only did SPU tap into the existing knowledge network for guidance on how to develop their own capabilities, but it became a part of the knowledge network itself, co-producing knowledge with CIRC.

One of the goals for the PUMA project for TBW was to develop strong scientist/utility relationships in order to develop and strengthen their knowledge network. They saw the development of such a network as being not only beneficial during the short-term duration of the PUMA project but also for longer term projects and research. Efforts were made at the beginning of the project to support collaboration and ensure strong bi-directional communication between the scientists and the utility. The TBW team also forged working relationships with other science partners such as those at the Florida State University Center for Ocean-Atmospheric Prediction Studies (COAPS) for their downscaling work. Engagement between the researchers was undertaken early and occurred iteratively in an organized and intentional process throughout the duration of the project. Between their respective roles and responsibilities, the project leads from the research and utility met with each other at least every two months. TBW staff found these relationships critical in the development of innovative techniques used in the TBW pilot.

NYCDEP already had an extensive knowledge network with established partnerships with researchers at several New York universities, federal and state agencies, and a variety of consulting firms. This network is considered one of its strengths as a utility organization. Over recent years, however, NYCDEP has sought to increase its own capacity and expertise in climate-related research. Most recently, it has partnered with the City University of New York's Institute for Sustainable Cities, which hired a full-time post-doctoral scientist to work with NYCDEP directly. The program has allowed NYCDEP to maintain a broader and more continuous scope in its climate change work and provides a mechanism for technology and knowledge transfer from scientists to NYCDEP staff. Although post-doctoral scientist turnover can be problematic, NYCDEP staff judge the program as a success and as a major value-add to its climate impacts work.

While all four utilities built or expanded knowledge networks with scientific partners and thereby enhanced organizational expertise, two of the utilities specifically cited developing staff capacity as a primary motivation for engaging in their project. The active development of partnerships with scientists at sometimes multiple institutions helped facilitate both in-house staff development and the development of actionable science in a co-production environment. Interactions between utility and scientific partners were often carefully designed to occur early and often, and to include substantive and meaningful discussion of project progress toward identified goals, as well as any adjustments in project strategy that might be needed. Most of these knowledge networks persist beyond the period reported in this paper and form the foundation for on-going work at each of the four utilities.

The co-production work done by the scientific partners in each WUCA project represented innovative, perhaps even ground-breaking, work in climate services that may lead to enhanced resilience for drinking water systems. At the same time, the career objectives of the utility science partners also benefitted in many cases. Though associated with boundary organizations, each scientist had university affiliations and therefore some degree of incentive to publish in the peer review literature. Though not a primary objective of PUMA project participants, in two instances, PUMA projects did in fact produce peer review articles, including some co-authored by science partners and utility managers (Anandhi et al., 2011a,b; Hwang et al., 2011, 2013; Hwang and Graham, 2013, 2014). In this way, capacity development cut both ways, and the needs of participants "across disciplinary or occupational boundaries" were met in ways not necessarily expected at the outset of each project.

4.3. Embracing an entrepreneurial approach

The utilities involved in the PUMA project all shared one common denominator: that they were entrepreneurial in their approach to getting the work done. Rather than allowing the scientists to drive the research agenda, utilities instead collaboratively discussed decisions related to the research both with the scientists and with utility personnel most closely associated with the research. This enabled more rapid processing of information and dialogue between the researchers and utilities, thus eliminating a cumbersome bureaucracy. They were also able to be nimble, adjusting and readjusting their research agendas in response to emerging conditions, barriers and opportunities. Not only was each utility able to contextualize the research based on their own needs and priorities, but those same priorities evolved as the research was underway, creating opportunities for utilities to hone their research, or alternatively, take it in new directions. In other words, the PUMA projects began with the question in mind and not the products or the processes, enabling greater flexibility in their research environments.

For example, in response to the challenges it faced in understanding its local hydrology, TBW was forced to develop a novel and successful technique to develop actionable climate-altered hydrologic information. As discussed in Section 4.1.4 above, TBW developed the BCSA downscaling method to capture the spatial-temporal resolution of precipitation necessary to model west-central Florida hydrology.

Examples from NYCDEP highlight the importance of a willingness to support innovation in research. As mentioned previously, NYCDEP received much climate information regarding changes in extreme events in qualitative forms rather than quantitative, thus limiting their use in chain-of-models analysis which requires numeric inputs. To address this limitation, NYCDEP and its research partners developed the SD-delta method that could be used in a chain-of-models analysis as discussed in Section 4.1.2 above. By focusing on their information needs and the context of the problem they sought to inform, NYCDEP was able to invest resources that could support risk taking in their research efforts resulting in a novel way to quantify extreme events.

The conventional paradigm might assume that the scientists played the innovation role and the utilities were passive recipients of such advances in knowledge. In reality, we saw the utilities themselves drive innovation in several circumstances. When the state of the practice for downscaling or hydrologic modeling did not produce actionable information for utilities, the utilities did not give up, but instead redoubled their efforts and worked with their scientific partners to innovate new methodologies to resolve their particular problems and allow climate projections to be useful in their utility context.

5. Conclusions

While many aspects of the PUMA project provide a useful model for the co-production of actionable science, there were some bumps in the road worth exploring. First, these co-production processes took far more time than initially anticipated – this work can be time-consuming and labor intensive, as the pilot project descriptions document. The PUMA project was initially designed to be a one-year project. While the final report was written three years after the project began, none of the utilities were truly done with their research efforts, and work at each of the four profiled utilities continues.

Such temporal considerations matter for both scientists and water utilities. For scientists, allocating necessary time and resources to such a co-production project requires tradeoffs. In some cases, this may mean choosing to do research in which the promise for new discoveries and outputs that can advance one's career may be limited, although the promise for seeing knowledge used in practice may be greater. Such choices may adversely affect early career academics that are dependent on the number and quality of peer-reviewed publications for advancement.

At the same time, it is notable that the research conducted for these four PUMA utilities, which was driven by real-world problems, did not preclude new discoveries such as the development of new approaches to producing relevant climate information. The development of the SD-delta and BCSA methods, as well as the numerous peer review journal articles that emerged from the PUMA projects demonstrate the innovation driven by these four research efforts. But whether these outputs were a sufficient return on the investment put in by the respective scientists is a difficult question where the different professional incentives of scientists and water utility personnel become important.

Additionally, most of the scientific partners for each WUCA project were interested in a particular technical aspect of the utility's problem that had a definite end-point. In contrast, the utilities are more often interested in operational or management issues that evolve continuously over time and thus do not really have the kind of end-point desired by the scientific partners. This raises important questions about the durability of co-production relationships and the opportunity costs for developing such efforts should they not be continued beyond the production of initial target outputs. Additionally, this raises questions about the balance between science providing project-specific information (the scientist as consultant role) versus science exploring novel problems (the scientist as explorer role). The balance between these two roles in a co-production relationship, as well as the balance between these two roles for a particular research appointment, for federally funded science, or for science as a whole, raises difficult issues for researchers, research funding agencies, and for the nature of the modern scientific enterprise.

Lessons learned from the PUMA project largely support the broad literature relating to co-producing actionable science for climate services discussed in Sections 1 and 2. Co-producing actionable science in the four water utilities required early and ongoing interaction throughout the lifespan of the PUMA project in a process that was iterative and involved frequent and bi-directional communication (Lemos and Morehouse, 2005). This enabled researchers and utility decision makers to shape and re-shape research questions and priorities as knowledge production evolved, resulting in the production of useful climate information (Cash et al., 2002). This involved, for example, contextualizing extreme events and customizing hydrometeorological information. Climate information produced was also credible (Cash et al., 2002) because it was conducted according to accepted standards and practices and vetted by established climate-change researchers, some of which resulted in peer-reviewed publications. Information was also legitimate (Cash et al., 2002) because utility decision makers developed productive working relationships with researchers based on mutual trust and respect and therefore trusted that the information was produced free from political suasion or bias (McNie, 2007). Leveraging and building knowledge networks also facilitated the production of actionable climate science (Feldman and Ingram, 2010). Three of the utilities worked directly with RISA teams, programs funded by NOAA whose aim is to produce, and serve as test beds, for actionable climate science. The knowledge and experience of the RISAs no doubt enhanced the productivity and success of the PUMA project, and the relationships forged between utilities and the RISAs persist today.

Yet the PUMA project also revealed some shortcomings in the existing literature. Foremost, the importance of embracing an entrepreneurial approach in conducting actionable climate research is an important finding that has not previously been reported in the literature. To our knowledge, no one has yet assigned such importance to information users in driving innovation. Contrary to the conventional paradigm which envisions scientists as the innovators and the utilities as passive recipients of these innovations, we saw the utilities themselves drive scientific innovation to meet their particular needs in several circumstances. Furthermore, the co-production literature falls short in adequately characterizing organizational and institutional design, such that we understand how best to position researchers and water-utility partners within an organization in order to optimize flexibility and innovation. The experience of the PUMA utility personnel and their scientific partners suggests that this is a very important topic for future research.

Acknowledgements

The authors wish to acknowledge the PUMA project leads at each utility for their roles leading these projects and contributing to this and other publications presenting project findings: Kavita Heyn of PWB, Paul Fleming of SPU, Alison Adams of TBW, and Don Pierson of NYCDEP. We also wish to thank the anonymous reviewers of our draft manuscript for helping improve this paper.

References

ACCCNRS, 2015. Report to the Secretary of the Interior. Advisory Committee on Climate Change and Natural Resource Science. March 30. Available: <https://nccwsc.usgs.gov/sites/default/files/files/ACCCNRS_Report_2015.pdf> (accessed February 14, 2016).

AMS, 2015. American Meteorological Society Available: https://www2.ametsoc.org/ams/index.cfm/about-ams/ams-statements/archive-statements-of-the-ams/climate-services/ (accessed December 8, 2015).

Anandhi, A., Frei, A., Pradhanang, S.M., Zion, M.S., Pierson, D.C., Schneiderman, E.M., 2011a. AR4 climate model performance in simulating snow water equivalent over Catskill Mountain watersheds, New York, USA. Hydrol. Processes 25 (21), 3302–3311.

Anandhi, A., Frei, A., Pierson, D.C., Schneiderman, E.M., Zion, M.S., Lounsbury, D., Matonse, A.H., 2011b. Examination for change factor methodologies for climate change impact assessment. Water Resour. Res. 47 (W03501). http://dx.doi.org/10.1029/2010WR009104.

Asrar, G.R., Hurrell, J.W., Busalacchi, A.J., 2013. A need for "actionable" climate science and information. Bull. Am. Meteorol. Assoc.

AWWA, 1997. Climate change and water resources. Committee report of the AWWA public advisory forum. J. Am. Water Works Assoc. 89 (11), 107–110.

Babbie, E., 2004. The Practice of Social Research. Thompson Wadsworth.

Barsugli, J.J., Anderson, C., Smith, J.B., Vogel, J.M., 2009. Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change: Final Report. Water Utility Climate Alliance, San Francisco, CA. December. Available: <http://www.wucaonline.org/assets/pdf/actions_whitepaper_120909.pdf> (accessed February 14, 2016).

Behar, D., 2009. Challenges and Opportunities in Adapting to Climate Change: Perspectives on Utilities EPA-600-R-09-010. Presented to the First National Expert and Stakeholder Workshop on Water Infrastructure Sustainability and Adaptation to Climate Change. U.S. Environmental Protection Agency, Office of Water and Office of Research and Development, Washington, DC.

Beier, P., Behar, D., Hansen, L., Helbrecht, L., Arnold, J., Duke, C., Farooque, M., Frumhoff, P., Irwin, L., Sullivan, J., Williams, J., 2015. Guiding Principles and Recommended Practices for Co-Producing Actionable Science: A How-to Guide for DOI Climate Science Centers and the National Climate Change and Wildlife Science Center. Report to the Secretary of the Interior. Advisory Committee on Climate Change and Natural Resource Science, Washington, DC.

Bierbaum, R., Smith, J.B., Lee, A., Blair, M., Carter, L., Chapin III, G.S., Fleming, P., Ruffo, S., Stults, M., McNeeley, S., Wasley, E., Verduzco, L., 2013. A comprehensive review of climate adaptation in the United States: more than before, but less than needed. Mitig. Adapt. Strat. Glob. Change 18, 361–406.

Briley, L., Brown, D., Kalafatis, S.E., 2015. Overcoming barriers during the co-production of climate information for decision making. Risk Manage. Clim. http://dx.doi.org/10.1016/j.crm.2015.04.004.

Cash, D., Buizer, J., 2005. Knowledge-action Systems for Seasonal to Interannual Climate Forecasting: Summary of a Workshop Roundtable on Science and Technology for Sustainability. National Research Council.

Cash, D., Clark, W., Alcock, F., Dickson, N., Eckley, N., Jager, J., 2002. Salience, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making RWP02-046. John F. Kennedy School of Government, Harvard University, Cambridge, MA.

Chiao, T.-H.C., Nijssen, B., Lettenmaier, D.P., 2013a. PUMA Project Phase I – Hydrologic Model for the Bull Run Watershed for Climate Change Analysis (Final Report). University of Washington, Department of Civil and Environmental Engineering. December 21.

Chiao, T.-H.C., Nijssen, B., Lettenmaier, D.P., 2013b. Technical Memorandum #1 for the Portland Water Bureau PUMA Project Phase 1 – Hydrologic Model for the Bull Run Watershed for Climate Change Analysis. University of Washington, Department of Civil and Environmental Engineering. April 29.

Dilling, L., Lemos, M.C., 2011. Creating usable science: opportunities and constraints for climate knowledge use and their implications for science policy. Global Environ. Change 21, 680–689.

EBMUD, 2009. WSMP 2040: Water Supply Management Program 2040 Plan. East Bay Municipal Utility District, Oakland, CA. October.

EO 13653, 2013. Executive Order 13653 of November 1, 2013. Preparing the United States for the Impacts of Climate Change. Available: <http://www.whitehouse.gov/the-press-office/2013/11/01/executive-order-preparing-united-states-impacts-climate-change> (accessed February 14, 2016).

EO 13690, 2015. Executive Order 13690 of January 30, 2015. Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input. Available: <https://www.whitehouse.gov/the-press-office/2015/01/30/executive-order-establishing-federal-flood-risk-management-standard-and-> (accessed February 14, 2016).

Executive Office of the President, 2013. The President's Climate Action Plan. Available: <http://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf> (accessed February 14, 2016).

Feldman, D.L., Ingram, H.M., 2010. Making science useful to decision makers: climate forecasts, water management and knowledge networks. Weather Clim. Soc. 1, 9–21.

Groves, D.G., Yates, D., Tebaldi, C., 2008. Developing and applying uncertain goals climate change projections for regional water management planning. Water Resour. Res. 44, W12413.

Hwang, S., Graham, W.D., 2013. Development and comparative evaluation of a stochastic analog method to downscale daily GCM precipitation. Hydrol. Earth Syst. Sci. Discuss. 10, 2141–2181. http://dx.doi.org/10.5194/hessd-10-2141-2013.

Hwang, S., Graham, W.D., 2014. Assessment of alternative methods for statistically downscaling daily GCM precipitation outputs to simulate regional streamflow. JAWRA 1–23. http://dx.doi.org/10.1111/jawr.12154.

Hwang, S., Graham, W., Hernández, J.L., Martinez, C., Jones, J.W., Adams, A., 2011. Quantitative spatiotemporal evaluation of dynamically downscaled MM5 precipitation predictions over the Tampa Bay Region, Florida. J. Hydrometeorol. 12, 1447–1464.

Hwang, S., Graham, W., Adams, A., Guerink, J., 2013. Assessment of the utility of dynamically-downscaled regional reanalysis data to predict streamflow in west central florida using an integrated hydrologic model. Reg. Environ. Change. http://dx.doi.org/10.1007/s10113-013-0406-x.

IPCC, 2014. Climate change 2014: impacts, adaptation, and vulnerability. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1132.

Kirchhoff, C.J., Lemos, M.C., Dessai, S., 2013. Actionable knowledge for environmental decision making: broadening the usability of science. Annu. Rev. Environ. Resour. 38, 393–414.

Kundzewicz, Z.W., Stakhiv, E.Z., 2010. Are climate models "ready for prime time" in water resources management applications, or is more research needed? Hydrolo. Sci. J. 55 (7), 1085–1089.

Lemos, M.C., Morehouse, B.J., 2005. The co-production of science and policy in integrated climate assessments. Global Environ. Change 15, 57–68.

Livneh, B., Rosenberg, E.A., Lin, C., Nijssen, B., Mishra, V., Andreadis, K.M., Maurer, E. P., Lettenmaier, D.P., 2013. A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States: update and extensions. J. Clim. 26, 9384–9392. http://dx.doi.org/10.1175/JCLI-D-12-00508.1.

McNie, E.C., 2007. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. Environ. Sci. Policy 10, 17–38.

McNie, E.C., 2008. Co-Producing Useful Climate Science for Policy: Lessons From the RISA Program Monograph. University of Colorado at Boulder.

Means, E.G., Laugier, M.C., Daw, J.A., Kaatz, L., Waage, M.D., 2010. Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning. Water Utility Climate Alliance, San Francisco, CA. January. Available: <http://www.wucaonline.org/assets/pdf/actions_whitepaper_012110.pdf> (accessed February 14, 2016).

Miller, K., Yates, D., 2006. Climate Change and Water Resources: A Primer for Municipal Water Providers. AWWA Research Foundation/University Corporation for Atmospheric Research, Denver, CO/Boulder CO.

Moss, R.H., Meehl, G.A., Lemos, M.C., Smith, J.B., Arnold, J.R., Arnott, J.C., Behar, D., Brasseur, G.P., Broomell, S.B., Busalacchi, A.J., Dessai, S., Ebi, K.L., Edmonds, J.A., Furlow, J., Goddard, L., Hartmann, H.C., Hurrell, J.W., Katzenberger, J.W., Liverman, D.M., Mote, P.W., Moser, S.C., Kumar, A., Pulwarty, R.S., Seyller, E.A., Turner II, B.L., Washington, W.M., Wilbanks, T.J., 2013. Hell and high water: practice-relevant adaptation science. Science 342 (6159), 696–698.

NYCDEP, 2008. The New York City Department of Environmental Protection Climate Change Program Assessment and Action Plan: Report 1. May.

Palmer, R.N., 2007. Final Report of The Climate Change Technical Committee: Rep. of the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process, Seattle, WA.

Palmer, R.N., Hahn, M., 2002. The Impacts of Climate Change on Portland's Water Supply: An Investigation of Potential Hydrologic and Management Impacts on the Bull Run System. Portland Water Bureau. January.

Pielke Jr., R.A., 2007. The Honest Broker: Making Sense of Science in Policy and Politics. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Raff, D., Brekke, L., Werner, K., Wood, A., White, K., 2013. Short-Term Water Management Decisions: User Needs for Improved Climate, Weather, and Hydrologic Information Prepared by and for the U.S. Army Corps of Engineers, the Bureau of Reclamation, and the National Oceanic and Atmospheric Administration. January. Available: <http://www.ccawwg.us/docs/Short-Term_Water_Management_Decisions_Final_3_Jan_2013.pdf> (accessed February 14, 2016).

Sarewitz, D., Pielke Jr., R., 2007. The neglected heart of science policy: reconciling supply of and demand for climate science. Environ. Sci. Policy 10, 5–16.

Stratus Consulting and MWH Global, 2009. Implications of Climate Change for Adaptation by Wastewater and Stormwater Agencies. Water Environment Research Foundation, Alexandria, VA.

USACE, 2012. USACE 2012 Climate Change Adaptation Plan and Report. U.S. Army Corps of Engineers. June. Available: <http://www.corpsclimate.us/docs/2012_USACE_Adaptation_Plan_and_Report_23_June_2012%20final.pdf> (accessed February 14, 2016).

USGCRP, 2012. The National Global Change Research Plan 2012–2021: A Strategic Plan for the U.S. Global Change Research Program. April. Available: <http://downloads.globalchange.gov/strategic-plan/2012/usgcrp-strategic-plan-2012.pdf> (accessed February 14, 2016).

Vaughan, C., Dessai, S., 2014. Climate services for society: origins, institutional arrangements, and design elements for an evaluation framework. WIREs Clim. Change 5, 587–603.

Vogel, J.M., Smith, J.B., O'Grady, M., Flemming, P., Heyn, K., Adams, A., Pierson, D., Brooks, K., Behar, D., 2015. Actionable Science in Practice: Co-producing Climate Change Information for Water Utility Vulnerability Assessments. Prepared for the Water Utility Climate Alliance. May. Available: <http://www.wucaonline.org/assets/pdf/pubs_puma_white_paper_2015_04_27.pdf> (accessed February 14, 2016).

WMO, 2011. Climate Knowledge for Action: The Global Framework for Climate Services – Empowering the Most Vulnerable WMO-No. 1065. World Meteorological Organization, Switzerland.

WMO, 2015. Climate Services Introduction. World Meteorological Organization. <https://www.wmo.int/pages/themes/climate/climate_services.php> (accessed December 8, 2015).

Woodbury, M., Yates, D., Baldo, M., Kaatz, L., 2012. Joint Front Range Climate Change Vulnerability Study [Project #4205]. Water Research Foundation. Available: <http://www.waterrf.org/ExecutiveSummaryLibrary/4205_ProjectSummary.pdf> (accessed February 14, 2016).