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Water Quality and Extreme Events in the Face of Climate Change: Does science supply meet demand?

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Abstract
As a first line of defense on public health and safety, water resource practitioners must consider water quality in long-term climate change planning. Current policies on climate change tend to disproportionately focus on water supply and availability rather than water quality. Water quality threats from extreme events, such as drought and wildfire, are becoming more commonplace, globally affecting drinking, domestic use, food production, and ecosystem health. To begin understanding why water quality and extreme events are not prioritized, this paper asks whether published science supply is meeting managerial science demands. Science demand in this paper is defined using water quality and extreme events data from a 2015 survey of California public drinking water systems with more than 200 service connections. Science supply is defined as the subset of published literature that addresses water quality and extreme events or climate change in California. Our work benefits both researchers and decision makers by identifying appropriate fit and misfit linkages between water quality and extreme events science demand and supply.

Introduction
Research agendas and priorities are dominated by the idea that more information is better (O'Brien 2012). This linear notion of "if they knew they would do something" is continually reproduced, particularly in the fields of climate change and water resource management (Shove 2010). As a result, science and information design is primarily driven by academic research (Cash and Buizer 2005; Feldman and Ingram 2009). A major challenge of researcher-driven science is the assumption that results are reliable and useful, yet high quality science often fails to address decision makers' most important questions (Jacobs, Garfin, and Lenart 2005; Morss et al. 2005; Russell et al. 1991; Sarewitz and Pielke 2007; Tribbia and Moser 2008; National Research Council 1996, 1999a, 1999b, 2004a, 2004b).

Over the past decade, research has begun questioning the assumption that science will always be useful (Repetto 2008; O'Brien 2012; Preston, Mustelin, and Maloney 2013). Instead, studies shows that for information to be usable in decision making, it must bridge the gap between what scientists believe is useful and what is actually usable in practice (Dilling and Lemos 2011). One method for producing useful science is using the missed opportunity matrix (Figure 1). This matrix asks whether 1) relevant information is produced and 2) whether the user can benefit from it (Sarewitz and Pielke 2007). When the answer to both questions is "yes", science is considered useful. Solution-based approaches to science creation and usefulness such as the missed

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opportunity matrix and concepts like the science-policy interface and fit/misfit are becoming more pronounced in the growing body of literature on knowledge production and usability (O'Brien 2012; Iyalomhe et al. 2013; Kirchhoff, Lemos, and Engle 2013; IPCC 2014). However, research also shows that the integration of information into decision-making, particularly on climate science and water management is a slow process (Rayner, Lach, and Ingram 2005).

		Demand: Can User Benefit from Research?	
		YES	NO
Supply: Is Relevant Information Produced?	NO	Research agendas may be inappropriate.	Research agendas and use needs poorly matched; users may be disenfranchised.
	YES	Empowered users taking advantage of well-deployed research capabilities.	Unsophisticated or marginalized users, institutional constraints, or other obstacles prevent information use.

Figure 1. "Missed opportunity matrix for reconciling supply and demand" (Sarewitz and Pielke 2007).

To begin reconciling the production of water quality and climate change science with decision makers' needs, we look to Sarewitz and Pielke's concept of science "supply" and "demand" (Sarewitz and Pielke 2007). In this paper, we use California drinking water system managers' experiences as "demand" and published science on California water quality and climate change as "supply". By comparing science supply and demand we can begin identifying overlaps and gaps in the useful production of information for decision making. This paper does not attempt to answer whether published science is adequate to meet the needs of drinking water system managers. Instead it assesses the degree to which science supply and demand are similar or different. This paper assesses linkages between supply and demand of water quality and extreme event science using California's public drinking water system managers and peer-reviewed literature. This paper can help inform future research considerations by highlighting specific gaps along the science supply and demand chain.

Background

Drinking water in California

California has a Mediterranean climate with cool, wet winters and warm, dry summers. Most precipitation is during cooler months (October – April) and is highly variable geographically, ranging from less than 5 inches in southern deserts to 100 inches in northern mountains (Seasonality of Precipitation n.d.). Precipitation variability and growth demands have contributed to California's long history of disagreement over water rights and conveyance and storage systems that supply water to more than 39 million people (Hanak et al. 2011). Drinking water systems range in size from very small (0-500 people served) to very large (more than 100,000 people served) and have a variety of management structures, including private and government ownerships. California's drinking water systems are overseen by California State Water Resources Control Board's Division of Drinking Water (SWRCB). Oversight includes meeting state and federal water quality regulations. In a state with more than 7500 public drinking water systems fed by complex groundwater and surface water systems, management at multiple levels of governance can be especially difficult (California State Water Resources Control Board: Division of Drinking Water Programs 2016).

Supply of water quality science

Despite growing concerns about climate extremes and water resources, the majority of science supply focuses on water quantity instead of water quality (Delpla 2009; James 2009; Michalak 2016). While strong links between water quality and climate change exist, projections of these effects are in their infancy (Michalak 2016). Global warming will affect water quality: 1) through increased extremes such as flooding and drought; 2) because of shifts in land use towards more intensive agricultural practices; and 3) because of efforts to reduce industrial air and water discharges (Monteith et al. 2007; Delpla et al. 2011). Effects of climate extremes on water quality highlight major concerns including increased total and dissolved organic carbon, nitrates, pathogens, and total suspended solids (Delpla et al. 2009; Delpla et al. 2011; Hunter 2003; Zwolsman and van Bokhoven 2007; Van Vliet and Zwolsman 2008). Major effects of climate change on water quality are expected from droughts, increasing temperatures, more extreme storms, and flooding (Delpla et al. 2009).

Climate change and water quality

Water quality effects from climate change are likely to create challenges for drinking water systems. Treatment technologies and management costs will need to consider increased production of disinfection byproducts, pathogen fate and transport, and fate of emerging substances (Figure 2). Further complicating drinking water system management in California, there is currently no legal requirement for water utilities to prepare strategies for climate change effects on drinking water quality (Conrad 2012).

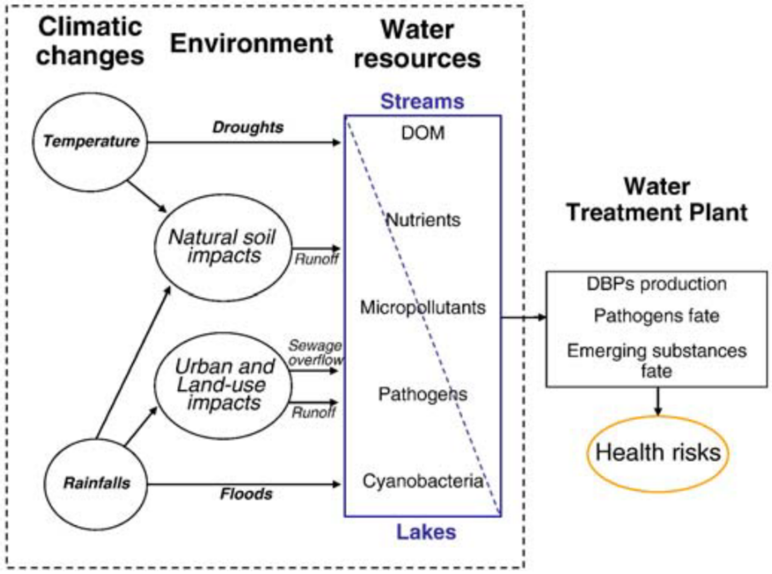

Figure 2. Potential effects of climate change (droughts and floods) on water resources and drinking water quality (Delpla et al. 2009).

Drought and increasing temperatures

A rise in surface water temperatures is projected to increase pH and decrease dissolved oxygen solubility (Prathumratana, Sthiannopkao, and Kim 2008). Increased water temperature will also influence thermal stratification, particularly during summer seasons and in shallower lakes (Bates et al. 2008, Delpla et al. 2009, Komatsu et al. 2007). Harmful algal blooms, caused by increased nutrient loading and warmer temperatures, are another concern (Hunter 2003; Arheimer et al. 2005; Wiedner et al. 2007; Jöhnk et al. 2008; Brient et al. 2009; Delpla et al. 2009; Michalak 2016). Algal blooms, cyanobacteria, and cyanotoxins can cause health issues in humans including mild skin rashes, vomiting and nausea, headaches, fevers, diarrhea, Pneumonia, and respiratory paralysis leading to death (Falconer 1996).

Warming atmospheric trends including drought are likely to cause an overall increase of nitrogen in soil and an increase in extractible organic carbon during summer and winter. These increases are projected to manifest as amplified loadings in surface water bodies subject to weather seasonality (Zhu et al. 2005). Drought impacts have already been recorded and include both increases in certain metals such as barium, selenium and nickel, and decreases in other metals like lead, chromium, mercury, and cadmium. These disparities are attributed to adsorption capacities of suspended solids (Zwolsman and van Bokhoven 2007).

Flooding and extreme storms

Greater storm intensity will increase nutrient loading to water systems. When combined with warmer air and water temperatures, nutrients cause significant algal and cyanobacteria blooms on lakes and reservoirs (Jackson et al. 2007; Komatsu, Fukushima, and Harasawa 2007). Heavy precipitation is also linked with increases in pesticide and sediment release to, and pharmaceutical and bacterial concentrations in, surface waters (Oppel et al. 2004; Bloomfield et al. 2006; Lissemore et al. 2006; Delpla et al. 2009). Flooding and more frequent storm patterns have reportedly led to groundwater contamination and disease outbreak. Over the last 50 years, half of waterborne outbreaks in the United States occurred after an extreme storm event (Curriero et al. 2001; Hunter 2003; Charron et al. 2004; Abhishek M. Pednekar et al. 2005).

Demand for water quality and climate change science

In 2016, a consortium of more than 30 scientific associations including the American Meteorological Society and the American Association for the Advancement of Science, authored a letter demanding that lawmakers place an emphasis on adapting to and mitigating climate change in order to "address unavoidable consequences for human health and safety, food security, water availability, and national security…" (Smith 2016). Much of the climate change and water quality planning inaction can be attributed to uncertainty. Climate projections and models are often made on geographic scales that are not detailed enough to suit the needs of resource managers who make daily operational decisions (Dessai and Hulme 2004). Elected officials do not want to be associated with tax increases to fund long-term climate studies and drinking water system managers would rather be in the news for redeveloping after a 'natural disaster' such as floods or droughts than for wasting money on conservation efforts, rate hikes, and water conservation rules (Rayner, Lach, and Ingram 2005).

Despite these barriers, demand for water quality and climate change science that can reduce uncertainty continues to grow. Newer literature shows that to understand the potential severity of climate change on a local scale, changes in the physical and social environments must be viewed in a real-world context (Moser 2010). Michalak argues for a retrospective assessment of past extreme events to better understand water quality and weather across different systems (2016). To support long-term planning of water quality and climate change, this paper compares the supply of California-related water quality, extreme events, and climate change science with the demands of California drinking water system managers. If we can identify current water quality threats to drinking water systems and how extreme events will trigger or worsen those threats, we can inform what climate science is needed to assist systems with adapting to climate change. First, however, we must investigate whether a disconnect exists between science supply and demand.

Methods & Materials

Survey data

In July and August 2015, a small team from the Policy Institute of Energy, Environment, and Economy at UC Davis distributed an online survey to public water systems. The goal of this survey was to gather information on water quality threats, extreme events, and climate change. The data collected through this survey represents the science demand of California drinking water managers. This survey is part of a bigger project on information needs to better prepare drinking water managers for future extreme climatic and weather events.

Distribution

The survey was sent through Qualtrics to 756 people, representing 925 public water systems that provide drinking water to more than 8 million potable connections. Utilities included in the survey were selected if they submitted annual compliance reports to the California State Water Resources Control Board (SWRCB) Drinking Water Division in 2014 and they reported at least

200 potable service connections. Surveys were addressed to the Urban Water Management Plan contact for each utility. Because Urban Water Management Plans may cover more than one utility, the number of systems included in the survey exceeds the number of participants. Survey participants held a range of management roles from general manager to water quality engineer.

Response rate

The survey response was 34.3%. A total of 259 surveys were submitted, including partial and complete surveys. For this study, partial responses are defined as answering at least one question beyond the background information. Our survey response rate is above average for online surveys of this size after the year 2000 (Sheehan 2006).

Measuring demand: survey results

Drinking water practitioner perspectives and experiences are gathered for water quality, extreme events, and climate change.

Water quality threats

Water quality threats were determined based on water source portfolios. Respondents representing drinking water systems with any surface water were shown surface water-related threats and those with any groundwater were shown groundwater-related threats. Supply portfolios were assessed with information in public water system annual reports submitted to the SWRCB and ultimately confirmed or changed by respondents during the background portion of the survey.

Surface water quality threats include:

- Eutrophication, low dissolved oxygen
- Infrastructure impairment or failure
- Nonpoint source pollution
- Point source pollution
- Salinity
- Turbidity

Groundwater quality threats include:

- Agricultural contaminants
- Naturally occurring contaminants
- Salinity
- Turbidity
- Urban contaminants

Water quality threats included in the survey were suggested by a group of four pilot survey respondents. Specific definitions for each water quality threat were not included in the survey. Respondents interpreted each threat according to their own definition. Respondents were asked to report the severity of each water quality threat. We translated each threat severity into a numeric score from 0 (not a threat) to 4 (extremely serious) for analysis. Scores are combined to determine an average severity for each water quality threat. A Chronbach's alpha test and Pearson's correlation test determined co-occurrences between water quality threats.

Extreme events
Respondents who reported current water quality threats were shown a follow-up question about extreme events. This question asked which extreme events trigger or worsen previously identified water quality threats. Respondents can report that no extreme events trigger or worsen water quality threats. For example, if a respondent reported nonpoint source pollution as a current water quality threat but not point source pollution, they were only asked whether any of the extreme event types triggered or worsened nonpoint source pollution. Extreme events included in the survey are the same for both groundwater and surface water:

- Drought
- Low flows
- Extreme storms, high flows, floods
- Landslides
- Salt water intrusion
- Increasing avg. temperatures
- High temperature episodes
- Wildfires

The combination of current water quality threats and extreme event triggers represent California drinking water system manager demands. We calculate the percentage of respondents that indicate a linkage between each water quality threat and extreme event[2]. These calculations are compared with the published science supply to identify both gaps and overlaps.

Measuring supply: published science
To understand how science supply on water quality and extreme events relates to demand from the survey results, we conducted a literature review in Scopus, an online abstract and citation database of peer-reviewed literature, about 21,500 journals. We searched journal articles, book chapters, and conference proceedings published since 2006 for terms related to specific water characteristics, system shocks, and geographic scopes (Table 1). The 2006-present timeframe is chosen because the Public Policy Institute of California's Fourth climate change assessment (AR4) was published in 2007 and most related papers were published in 2006.

[2] The denominator used was the number of respondents who reported each water quality threat and saw the extreme event question. Respondents who reported a water quality threat but closed the survey before answering questions on extreme events are not included in the denominator.

Table 1. Summary table of published water quality, extreme event, and climate change terms applied in Scopus for years 2006-present.

	Topic	Terms
Water Characteristics	Water Quantity	water quantity, “water supply”, “water availability”, “water volume”
	Water Quality	water quality, “water chemistry”
System Shocks	Extreme Events	extreme event*,"extreme weather", "hydroclimat* extreme*", "storm","flood", "high flow*", "extreme precipitation", "heavy precipitation", "heavy rain", "extreme rain","high temperature*", "heat event*", "extreme heat", "drought", "increas* average temperature*", "increas* temperature*", "low flow*", "landslide*", "salt water intrusion", “saline intrusion”, wildfire*, fire*
	Climate Change	climat* chang*, "global warming"
Geographic Scope	Global	--
	Local	California

To capture the breadth of water quality and climate change related papers, we initially searched for articles on individual water characteristics or system shocks. We then searched for combinations of water characteristics and systems shocks to compare water quality and extreme events with water quantity and extreme events (Figure 3). These searches are done with no specific geographic scope and with the geographic scope limited to California. The 142 California documents on water quality, extreme events, and climate change are manually tagged with water quality threats, extreme events, and/or climate change codes based on our developed term table (Appendix A). This term table is developed from prior knowledge and updated based on actual document content. A matrix comparing science supply of water quality characteristics and system shock linkages is developed for comparison with survey result demand.

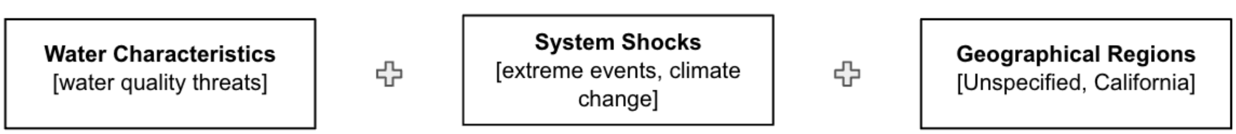

Figure 3. Conceptual diagram of water characteristics, system shocks, and geographical region components searched in published literature. The results of searches related to California are used as water quality and extreme events supply.

A Quadratic Assignment Procedure (QAP) analysis compares demand (survey results) and supply (published science) to test for correlation and significance. QAP is used to compare matrix correlations because it uses a simple permutation data structure that controls for the non-independence between network dyads. Using a resampling method similar to bootstrapping, QAP results are easy to interpret and allow us to determine whether supply and demand results are likely due to randomness.

Demand vs. supply: survey results and published science

To compare demand and supply, we developed an alignment/misalignment typology (Table 2). This table compares the percentage of survey respondents (demand) to the percentage of published articles (supply). Colors represent the level of misalignment with red symbolizing the a very high level of misfit, dark yellow symbolizing a high level of misfit, light yellow symbolizing a medium level of misfit, and green symbolizing an appropriate fit between supply and demand. Both supply and demand are considered in each level of misfit, so a ranking of "very high" could represent low demand and high supply or high demand and low supply. For example, if 10% of respondents report that wildfire triggers salinity and 90% of salinity-related articles make a connection with wildfire, the linkage of salinity and wildfire is colored red. Similarly, if 90% of respondents report that drought triggers salinity and 10% of salinity-related articles make a connection with drought, the linkage of salinity and drought is colored red.

Table 2. Alignment/misalignment typology based on fit between demand (survey results- rows) and supply (published literature- columns) where each cell's color represents the level of misfit as described. Table adapted from Treml et al. 2015.

		Published Science: Water Quality - Extreme Events Linkages			
Survey Results: Water Quality - Extreme Events Linkages		**0-25% of articles**	**26-50% of articles**	**51-75% of articles**	**76-100% of articles**
	0-25% of respondents	Appropriate	Medium level of misfit	High level of misfit	Very high level of misfit
	26-50% of respondents	Medium level of misfit	Appropriate	Medium level of misfit	High level of misfit
	51-75% of respondents	High level of misfit	Medium level of misfit	Appropriate	Medium level of misfit
	76-100% of respondents	Very high level of misfit	High level of misfit	Medium level of misfit	Appropriate

Very high level of misfit	There is a significant mismatch between survey results and published science on the water quality - extreme event linkage
High level of misfit	There is a strong mismatch between survey results and published science on the water quality - extreme event linkage
Medium level of misfit	There is a slight mismatch between survey results and published science on the water quality - extreme event linkage
Appropriate fit	There is an appropriate fit between survey results and published science on the water quality - extreme event linkage

Results

We first show raw current water quality threats and extreme events survey results. We then report the demand for water quality and extreme events science using the percentage of respondents that reported each linkage. Next, we review the results of the published science review. We begin with a general overview of literature available on water quality, water supply, extreme events, and climate change. We drill down into published literature on water quality, extreme events, and climate in California. We report the supply of water quality and extreme event science as the percentage of articles that reported each linkage. Very few articles focus on groundwater quality indicating a potential gap in science supply. Results show some appropriate fits between water quality and extreme event supply and demand. The results also highlight medium, high, and very high levels of misfit between supply and demand indicating additional gaps that may need to be addressed in future research.

Measuring demand: survey results

Survey results highlight the concern drinking water managers have about current threats to water quality. They also show a strong and clear connection of extreme events as triggers of worsening water quality threats. Both groundwater and surface water quality parameters threaten California drinking water systems indicating that climate science supply should emphasize both supply sources.

Water quality

Of the 259 participants who submitted a survey, 115 report that their supply includes at least some surface water. 185 of the 259 survey respondents report at least some groundwater in their supply. Table 3 shows the count of respondents that reported each water quality threat and the average severity score of each water quality threat. Infrastructure impairment or failure was reported in the top three threats for both surface water and groundwater. Our analyses show that all water quality threats are highly correlated and no water quality threat is more or less likely to occur with any other. This underlines the ambiguity of infrastructure impairment or failure as a water quality threat. Salinity and turbidity were the least frequently reported threats for both surface and groundwater supplies.

Table 3. Count of respondents reporting each water quality threat and the average severity score for each water quality threat.

	Water Quality Threat	# of Respondents	Average Severity Score
Surface Water (n = 115)	Eutrophication, low dissolved oxgen	72	1.78
	Infrastructure impairment or failure	82	2.21
	Nonpoint source pollution	67	1.91
	Point source pollution	70	2.03
	Salinity	67	2.03
	Turbidity	34	1.79
Groundwater (n = 185)	Agricultural contaminants	95	2.02
	Infrastructure impairment or failure	118	1.96
	Naturally occurring contaminants	130	1.93
	Salinity	56	1.71
	Turbidity	47	1.51
	Urban contaminants	85	2.11

Surface water quality threats

Of the 115 survey respondents with surface water, 97 (90%) reported at least one current water quality threat of "slightly serious" or higher severity. Infrastructure impairment is the dominant water quality threat with 82 respondents reporting it, followed by eutrophication (72) and point source pollution (70) (Table 3). About 15% of respondents report that point source pollution and nonpoint source pollution are an "unknown" threat, meaning the respondent does not know whether the water quality parameter is a current threat to their system. This indicates a need for further clarity on either 1) how point and nonpoint source pollution effect drinking water systems or 2) why managers do not know how how these pollutants effect drinking water systems.

Threat severity scores show that infrastructure impairment or failure is the top concern (2.21) followed by point source pollution (2.03), salinity (2.03), and nonpoint source pollution (1.91). Turbidity has both the fewest number of respondents reporting it as a current water quality threat and the lowest average threat severity score. Eutrophication and low dissolved oxygen has the lowest threat severity score (1.78) but was the second most frequently reported current water quality threat, perhaps indicating that eutrophication is present but under control at drinking water systems. Salinity, which has the second highest threat severity among surface water respondents, had the second lowest number of respondents reporting it as a current threat. This could indicate that either 1) surface water salinity issues are primarily coastal and most respondents represented inland systems or 2) when systems have salinity concerns, they are large.

Because of ambiguous definitions of water quality threats in the survey, we ran Chronbach's alpha and Pearson correlations to determine if "infrastructure impairment or failure" co-occurred with any other water quality threat. Our assumption was that a correlation could help explain how survey respondents were defining "infrastructure impairment or failure". The Chronbach's alpha score was 0.77. Generally, a score above 0.7 indicates that the data tested exist in only one cluster and on water quality parameter is more or less likely to occur with any other. The Pearson's correlation analysis confirmed this result. There is high correlation between all water quality threats. Therefore, the definition of "infrastructure impairment or failure" remains ambiguous.

Groundwater quality threats

Of 185 survey respondents with at least some groundwater in their supply, 160 (89%) report at least one current groundwater quality threat of at least "slight serious" severity. Natural contaminants are the dominant groundwater quality threat reported by 130 respondents, followed by infrastructure impairment or failure (118), agricultural contaminants (95), and urban contaminants (85) (Table 3). Urban and agricultural contaminants have the highest average threat severities among groundwater quality parameters (2.11 and 2.02) perhaps indicating that when drinking water systems have urban contaminant challenges they are large. Natural contaminants have a lower average threat severity (1.93) which could mean that drinking water systems are experiencing occurrences of natural contaminants but management is controlled.

Extreme events

Only 95 of the 97 respondents who report at least one surface water quality threat saw the follow-up question pertaining to extreme events (2 respondents closed the survey). All 95 respondents who saw the extreme events question reported at least one water quality threat is triggered or worsened. Drought is the most frequently mentioned extreme event with 159 incidences. Extreme storms have 144 mentions, followed by low flows (124), wildfires (98), landslides (82), high temperatures (81), increasing average temperatures (61), and salt water intrusion (23).

Of the 160 respondents reporting at least one current groundwater quality threat, 156 (98%) saw the follow-up question pertaining to extreme events (4 respondents closed the survey). Of these 156, 127 (81%) report at least one extreme event triggers or worsens groundwater quality. Again, drought is the most frequently mentioned extreme event (212), followed by extreme storms (106), low flows (71), wildfires (39), high temperatures (31), increasing average temperatures (27), salt water intrusion (27), and landslides (23).

Water quality and extreme events

When surface water quality threats and extreme events are considered together, several linkages stand out. Extreme storms and drought have the strongest surface water quality linkages among the survey respondents. 77% of surface water respondents report salinity is triggered or worsened by drought (the strongest linkage in the survey). 75% of respondents report connections between extreme storms and turbidity, 72% of respondents report a link between high temperatures and eutrophication, and 60% of respondents note a link between drought and eutrophication. Salt water intrusion had low linkages with all surface water quality threats (percentage of respondents ranges from 0% to 9%). All water quality threats except eutrophication had at least one respondent report that extreme events do not trigger or worsen surface water quality. Only 7% of respondents reported no relationship between extreme events and nonpoint source pollution (the highest no threat percentage for surface water quality). Complete results of surface water quality threats and extreme events are shown in Appendix B. These percentages represent surface water quality and extreme event science demands.

For groundwater quality, drought and extreme storms are the two major extreme events according to survey respondents. 54% of respondents note a connection between drought and turbidity, 52% of respondents report that drought triggers or worsens natural contaminants and 42% of respondents note a link between drought and urban contaminants. More than 20% of respondents report that drought triggers or worsens all groundwater quality threats. The strongest link with extreme storms is salinity (30% of respondents), followed by urban contaminants (27%), and infrastructure impairment (25%). More than 20% of respondents report that extreme events do not trigger or worsen groundwater quality threats. Complete results between groundwater quality threats and extreme events are shown in Appendix B. These percentages represent groundwater quality and extreme event science demands.

Measuring supply: published literature

Although published water quality science exists, most articles are not closely tied to extreme events and an even smaller proportion discuss climate change. Results of science supply reaffirm that water quantity is more frequently published with climate change science than water quality. These trends hold in both the general search and the California-specific search. California water quality and extreme event literature emphasizes extreme storms and flooding as well as stormwater runoff management and best management practices. The majority of California-related research applies to surface water sources.

Global scope

Table 4 summarizes the universe of published literature on water characteristics and system shocks. Since 2006, about 15,000 more articles mentioning "water quality" have been published than articles mentioning "water quantity" (Appendix A). However, when a secondary term, such as "climate change" or "extreme events" is added to the search, "water quantity" related articles (3,342 and 6,326 respectively) surpass "water quality" related articles (1,604 and 4,659 respectively). A similar trend occurs when climate change and extreme events are searched with water quantity (1,262 articles) as opposed to water quality (450 articles). These results show that the supply of water quantity, extreme events, and climate change science exceeds the supply of similarly water quality-related science.

California scope

Similar trends to the universe of water quality and extreme events literature are found in the subset of California results (Table 4). Again, articles on "water quality" by itself (692) are more prevalent than "water quantity" (595). The introduction of "climate change" or "extreme events" results in a larger number of articles on "water quantity" (102 and 191, respectively) than "water quality" (30 and 135, respectively). Additionally, the fewest number of articles result when "water quality", "climate change", and "extreme events" are combined (13 articles). These results show that climate change and extreme events science supply emphasizes water quantity connections of water quality.

Table 4. Count of published book chapters, journal articles, and conference proceedings in Scopus representing water quality, water quantity, extreme events, and climate change for 2006-present.

	Global (2006-present)	California (2006-present)
Water Quantity	34,428	595
Water Quality	49,730	692
Climate Change	113,562	1,479
+ Water Quantity	3,342	102
+ Water Quality	1,604	30
Extreme Events	497,290	3,554
+ Water Quantity	6,326	191
++ Climate Change	1,262	47
+ Water Quality	4,659	135
++ Climate Change	450	13

Demand vs. supply: survey results and published literature

Finally, we compare demand for water quality and extreme events science (survey results) with supply of water quality and extreme events science (published literature) (Appendix B). A total of 165 results from the literature search (blue cells in Table 4) represent 143 unique published documents containing California, water quality, and extreme events or climate change terms (Appendix A). Of the 143, one article was removed because its geographical scope was Baja California (Mexico). 27 articles are not tagged with water quality, extreme event, or climate change terms because they are either too vague or focused on something not relating to water quality or extreme events. The remaining 115 articles are tagged as appropriate. Percentage of publications citing each water quality threat and extreme event type in Appendix B are colored using the Alignment/misalignment typology presented in Table 2. Red represents a very high misfit, dark yellow represents a high misfit, and light yellow represents a medium misfit between water quality and extreme events science demand and supply. Green cells represent an appropriate fit between demand and supply. Uncolored cells were not compared. Results show that while science supply does fit some of California's drinking water system managers' demands, major gaps remain. QAP matrix correlation comparisons show a statistically significant positive correlation between demand supply for both surface and groundwater results.

Surface water quality

Part I of Appendix B shows surface water demand (survey) and supply (literature) results. All surface water quality threats have some appropriate fit between demand and supply. Of 48 water quality – extreme event combinations, 23 show some level of misfit. Salinity and drought have a very high misfit with 77% of survey respondents indicating a linkage, while only 12% of salinity publications indicate a linkage. Eutrophication has the largest number of misfit combinations (5 of 8) including both high misfit (drought, low flows, high temperatures) and medium misfit (extreme storms, increasing average temperatures). The majority of misfits represent larger demand (percentage of survey respondents) than supply (percentage of articles), however in some instances, the opposite is true and supply places more emphasis on water quality – extreme events linkages than demands. Both scenarios represent some level of misfit. Examples include nonpoint source pollution and extreme storms (48% of respondents indicate a linkage compared with 84% of nonpoint source publications) and salinity and extreme storms (3% of respondents reported a linkage compared with 65% of salinity-related articles). A QAP matrix analysis shows a correlation of 0.380 for $p < 0.01$ indicating a statistically significant positive correlation between surface water quality – extreme event science demand and supply.

Groundwater quality

Part II of Appendix B shows groundwater demand (survey) and supply (literature). Only 12 of 115 articles tagged for analysis made a connection between groundwater quality threats and extreme events. Every groundwater quality threats shows some level of misfit between demand and supply for at least one extreme event type. The majority of misfits represent higher demand than supply, with the exception of agricultural contaminants. Agricultural contaminants and extreme storms represent the highest level of misfit (very high) with 24% of respondents and 80% of articles citing a linkage. Of nine groundwater quality – extreme event misfits, five show 0.00% of published articles citing the specific linkages. This could signify that 1) groundwater quality is not as big a threat as surface water quality to drinking water systems or 2) that groundwater quality is not fully understood by managers or scientists. This latter point could indicate a gap in both supply and demand. A QAP matrix test shows a correlation of 0.282 for $p < 0.05$. These results show that there is a statistically significant positive correlation between groundwater quality – extreme event science demand and supply.

Discussion

Water quality threats

Overall, this study shows that drinking water system managers experience both surface water and groundwater quality threats to their systems. While infrastructure impairment has the highest average surface water threat severity, it is unclear how managers define infrastructure impairment in terms of water quality. An attempt to more clearly define infrastructure impairment or failure was unsuccessful given that all water quality threats show a high correlation with one another. This implies that drinking water system managers may see infrastructure impairment or failure as equally detrimental to all water quality, highlighting the importance of updated infrastructure. This notion is consistent with a recent federal survey that found California needs an estimated $44.5 billion to fix aging water infrastructure (U.S. Environmental Protection Agency (EPA) 2011).

Survey results also show that in some cases, managers do not know whether surface water quality threats impact their system. Nonpoint source pollution, the leading remaining cause of water degradation in the United States, has the highest percentage respondents reporting an "unknown" threat level. One explanation for its high rate of uncertainty is the difficulty of knowing exactly what is and is not nonpoint source pollution. Even the Clean Water Act provides a vague definition; "…any source of water pollution that does not meet the legal definition of a point source" (33 U.S.C. § 1251 *et seq.*). It could be that water managers are more familiar with specific nonpoint pollutants such as nitrates or sedimentation.

Groundwater quality challenges are dominated by naturally occurring contaminants. While managers reported that the majority of groundwater quality parameters are not threats, natural contaminants are the exception. This emphasis on natural contaminants could be due to groundwater overdraft from the ongoing drought in California. As the groundwater levels decrease, it is more likely that systems will see an increase in naturally occurring contaminants such as iron, manganese, and even arsenic (Wasserman et al. 2011).

Measuring demand: water quality and extreme events

Groundwater quality had above average threat scores among managers who reported them as challenges. However, almost one-fifth of respondents said groundwater quality problems are not triggered or worsened by extreme events. This indicates that 1) groundwater quality is less heavily affected by extreme events than surface water, 2) drinking water systems have a handle on groundwater quality so system shocks from extreme events have less effect on management decisions, or 3) drinking water managers have not yet experienced the effects of extreme events on groundwater quality. Of extreme events and groundwater quality linkages reported in the survey, drought is a major trigger, which is understandable considering California is currently in a multi-year drought.

The survey shows a strong relationship between drought and eutrophication which echoes the recent increase in algal blooms in California. However, drought is not the only extreme event that links strongly to eutrophication. More than 50% of respondents also linked eutrophication to low flows, increasing average temperatures, and high temperatures. These results indicate that if California continues its trend of warmer, dryer, drought years, algal blooms may continue to plague drinking water systems.

Measuring supply: published literature

Published science was categorized and tagged in the broadest sense, meaning that in reality, not all 142 documents may be useful to drinking water system managers.

Stormwater

Many articles address stormwater (testing it, capturing it, infiltrating the ground with it, designing new technologies to try to manage it). Stormwater runoff from construction is also a big theme. Upon further investigation of California over the past decade, the multitude of stormwater related documents is put into perspective. In 2005, EPA published guidance documents to educate states and municipalities on the regulation of construction runoff (U.S. Environmental Protection Agency (EPA) 2005). In addition, in 2012, Los Angeles adopted a new MS4 permit that included language and plans to conduct extensive monitoring of stormwater. Finally, in 2013, the MS4 phase II small general permit requirements went into effect (California State Water Resources Control Board 2013). Published science is often reactive towards policy creation, but not necessarily management experiences.

Groundwater

The document review highlights the lack of published science on groundwater quality. This is juxtaposed against the survey results showing that groundwater quality threat severities are high. However, the lack of linkages drawn by managers between groundwater quality and extreme events could also explain the scarcity of groundwater-related articles. While extreme events might not affect groundwater quality, a more plausible explanation for the lack of published research is that groundwater quality management has been heavily overlooked in California until recent times (Sax 2003). However, in 2014, California passed its landmark policy: the Sustainable Groundwater Management Act (SGMA). The passing of SGMA combined with severe over-pumping that is occurring in California because of the drought could increase groundwater quality related science.

Comparing demand and supply: survey results and literature

The supply of published science appears to match some of the demand from drinking water system managers. Appropriate fit of supply and demand includes point source pollution and low flows, infrastructure impairment and low flows, and turbidity and increasing average temperatures. However, many gaps highlighting medium and high misfit exist, particularly with surface water supplies. All but two water quality issues (groundwater agricultural contaminants and surface water infrastructure impairment) indicate some level of misfit between supply and demand when linked with drought. Given that California is in a multi-year drought, we expect to see an increase in drought-related papers over the next decade. However, whether this literature will address how drought may trigger or worsen specific water quality threats is unknown.

Drought, point source pollution, and infrastructure impairment

While 46% of respondents indicated that drought triggers or worsens point source pollution, 0% of published articles cited a linkage between drought and point source pollution. This major gap between demand and supply is surprising given the heavy regulation (relative to nonpoint source pollution) of point sources. Drought and infrastructure impairment or failure, however, showed an appropriate fit between supply and demand. This raises questions such as whether the stringency of point source regulations is adequate and whether oversight of point source polluters such as wastewater treatment plants, is effective.

Drought, increasing temperatures, and eutrophication

There is a large misfit between extreme events and eutrophication. More than 50% of surface water respondents linked eutrophication with drought, low flows, increasing average temperatures, and high temperatures, while less than 40% of published articles on eutrophication linked it with any of these same extreme events. This discrepancy highlights a disconnect between demand and supply. Given the recent growth in algal blooms and cyanotoxin complications facing drinking water systems in California, we expect to see an increase in related publications over the next decade. If climate projections in California lead to more frequent and prolonged droughts and heat events (as currently predicted), there is an expectation that algal blooms will continue to dominate drinking water system concerns. This could create a bigger disconnect between demand and supply of science.

Groundwater-related supply

The overall lack of groundwater quality articles precludes any sweeping discussions on related science demand and supply. While the majority of groundwater quality – extreme event linkages show appropriate fit between demand and supply, this does not mean that supply is adequate. Instead, it could highlight both a lack of supply and demand. California uses groundwater for both drinking and irrigation purposes. During the current drought, dependency on groundwater supplies increased and many basins were overdraft. Prior to passing SGMA in 2014, groundwater management occurred on a voluntary basis. This lack of emphasis and regulation placed on groundwater is one explanation for the lack of science demand and supply. Recent reports on the abundance and level of nitrates in California groundwater wells, for example, implies that research and understanding of how extreme events and climate change effect groundwater quality is crucial (Harter et al. 2012).

Limitations of the study

Published articles and survey results may not reflect actual science demand and supply for several reasons. First, because of the generalizations made in the literature review, not all documents may be useful to drinking water system managers. For example, articles about recreational water quality may remain outside drinking water system managers' scope of usefulness. Second, because we were as inclusive as possible with the literature review, documents discussing runoff were automatically tagged as nonpoint source pollution and extreme storms, whether or not the author used the specific phrasing. In these cases, science may not be addressing the exact issues that managers are reporting. Third, drinking water system managers may be underestimating the threat of water quality because they are placing more emphasis or importance on water quantity. Fourth, managers may not have yet experienced specific water quality threats being triggered or worsened by extreme events. In these cases, managerial needs and emphases placed on water quality – extreme event combinations may shift, requiring a body of adaptive literature.

Another limitation of this study is that drinking water system managers may not rely directly on published, peer-reviewed documents for their water quality and extreme events planning. In reality, drinking water managers turn to other local groups, consultants, peers, state contacts, and the federal government for information. However, even if drinking water managers are not dependent on published science directly, they depend on it indirectly through these other parties. Knowledge and information providers use published science or have at least spoken with a scientist influenced by this research. Still, it is essential that science address the needs of drinking water system managers in order to be as useful as possible.

Next Steps

Many studies could be conducted as a follow-on to this research. Topics include:

1) Work with drinking water system managers to determine information sources used when making water quality and climate change decisions. This could include a network analysis to identify key actors in the drinking water sector.
2) Conduct a similar review of government and consulting reports and documents to determine if non peer-reviewed literature better meets the needs of drinking water managers.
3) Create a map of water quality threats and severity scores to assess if different regions of California have specific priorities. This could help in targeting and focusing further published science.
4) Conduct an analysis to determine whether systems with particular water quality threats are more or less likely to be further along in the climate adaptation planning process.

Conclusion

This study provides a baseline overview of water quality threats facing California drinking water systems. Drinking water system managers report their priority surface water quality threats as eutrophication, point source, and nonpoint source pollution and major groundwater quality threats as natural contaminants, agricultural contaminants, and urban contaminants. Managers report that surface water quality poses a larger threat to drinking water systems than groundwater quality, however this may be a reflection of current California water regulations. While all extreme events reportedly trigger or worsen at least one surface or groundwater quality threat, drought is overwhelmingly the major cause of degradation. This is most likely a reflection of California's current multi-year drought. Published literature generally shows a research emphasis on water quality over water quantity. However, the opposite is true when looking at the subset of water-related documents that also discuss extreme events and climate change. Much of the published literature linking extreme events and water quality in California addresses extreme storms and flooding, a reflection of California environmental regulations and guidelines adopted over the last decade.

A comparison of water quality and extreme event science demand (survey results) and supply (published literature) shows some appropriate levels of fit, particularly with groundwater systems, but caution must be exercised given that groundwater lacked a formal management framework until the passing of the 2014 Sustainable Groundwater Management Act. Given that surface water has been much more heavily researched, it is likely that groundwater quality – extreme event linkages are largely underestimated.

High levels of misfit do exist between water quality and extreme event science demand and supply, particularly when drought effects are considered. Demand for science relating to eutrophication and algal blooms is high, yet there is very little supply of published literature that links this water quality threat to extremes. Supply of groundwater quality related research is also very low, highlighting a potential future challenge as California faces more frequent, prolonged droughts and continues to increase its dependency on groundwater as a source for irrigation and drinking water uses.

This paper highlights disconnects between water quality and extreme event science demand and supply. It underlines the focus of demand on drought-related water quality threats and underscores the importance of useful science and information that discusses linkages between extreme events, climate change, and water quality. With the creation of the Sustainable Groundwater Management Act and other water regulations and requirements that are likely to emerge over the next decade in response to increasing extremes, it is imperative that science supply be adaptive to the shifting demands of water practitioners. As California continues to face climate change, it will become even more important to reconcile science supply with demand. As a first line of defense on public health and safety, drinking water system managers must have access to the best and most relevant science available.

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Appendix A.

Water quality threats and associated terms used for tagging California-specific water quality, climate change, and extreme events literature. This body of literature acts as the supply of science.

Surface Water	
Water Quality	**Terms Included (based on what was read)**
Point Source Pollution	point source pollution, wastewater discharge, effluent
Nonpoint Source Pollution	nonpoint source pollution, runoff, stormwater
Turbidity	turbidity, total suspended solids, sedimentation, sediment loading, erosion runoff
Eutrophication	algal blooms, phytoplanktonic blooms, cyanotoxins, cyanobacteria, dissolved oxygen, biological oxygen demand
Salinity	TDS, conductivity, bromide
Infrastructure Impairment/Failure	infrastructure, treatment plants, equipment
Other	chlorine/chloride, PCBs, disinfection byproduct precursors, taste/odors, oil/grease, pH/hardness, PAHs, THMs, DBP Precursors, sulfates, calcium, cyanide, flame retardant
Bacteria	e.coli, enterococcus
Nutrients (Nitrates/Phosphates)	nitrates, phosphates, nitrogen, phosphorus, nitrite, pesticides, fertilizers, ammonia, organic carbon
Metals	aluminum, arsenic, cadmium, chromium, copper, lead, nickel, silver, selenium, iron, zinc, mercury, magnesium, potassium, silica
Groundwater	
Water Quality	**Terms Included (based on what was read)**
Urban Pollution	urban, industrial
Agricultural Pollution	agriculture
Turbidity	turbidity, total suspended solids
Natural Contaminants	
Salinity	total dissolved solids (TDS), conductivity
Infrastructure Impairment/Failure	
Other	pH, temperature, septic, dissolved oxygen
Bacteria	
Nutrients (Nitrates/Phosphates)	*carbon, nitrates*
Metals	uranium, metals

Appendix B.

Summary table containing water quality threat and extreme event linkages reported in the drinking water survey (science demand) and in Scopus publications for the years 2006-present (science supply). Data include: 1) percentage of respondents with surface water (Part I) or groundwater (Part II) supplies that reported each water quality-extreme event linkage (science demand); 2) percentage of publications citing a linkage between each water quality-extreme event (science supply); and 3) raw count of publications citing a linkage between each water quality-extreme event. Cells are colored using the alignment/misalignment typology described in Table 2 of the main paper as follows: red represents a very high level of misfit, dark yellow represents a high level of misfit, light yellow represents a medium level of misfit, and green represents an appropriate fit. Light grey cells were not compared.

Part I. Surface water

	Water Quality Threat	Extreme Event	Survey Responses (% of respondents)	Publications (% of articles)	Publications (raw count)
Surface Water Quality	Eutrophication, low dissolved oxygen	Drought	0.60	0.12	2
	Eutrophication, low dissolved oxygen	Low Flows	0.58	0.35	6
	Eutrophication, low dissolved oxygen	Extreme Storms	0.06	0.47	8
	Eutrophication, low dissolved oxygen	Landslides	0.03	0.00	0
	Eutrophication, low dissolved oxygen	Salt Water Intrusion	0.00	0.00	0
	Eutrophication, low dissolved oxygen	Increasing avg. Temps	0.52	0.35	6
	Eutrophication, low dissolved oxygen	High Temps	0.72	0.00	0
	Eutrophication, low dissolved oxygen	Wildfire	0.07	0.00	0
	Eutrophication, low dissolved oxygen	No extreme event trigger	0.00	0.18	3
	Infrastructure impairment or failure	Drought	0.25	0.11	1
	Infrastructure impairment or failure	Low Flows	0.17	0.22	2

	Infrastructure impairment or failure	Extreme Storms	0.38	0.89	8
	Infrastructure impairment or failure	Landslides	0.36	0.11	1
	Infrastructure impairment or failure	Salt Water Intrusion	0.01	0.00	0
	Infrastructure impairment or failure	Increasing avg. Temps	0.05	0.00	0
	Infrastructure impairment or failure	High Temps	0.06	0.00	0
	Infrastructure impairment or failure	Wildfire	0.30	0.11	1
	Infrastructure impairment or failure	No extreme event trigger	0.06	0.00	0
	Nonpoint source pollution	Drought	0.47	0.03	2
	Nonpoint source pollution	Low Flows	0.50	0.19	11
	Nonpoint source pollution	Extreme Storms	0.48	0.84	49
	Nonpoint source pollution	Landslides	0.17	0.00	0
	Nonpoint source pollution	Salt Water Intrusion	0.07	0.00	0
	Nonpoint source pollution	Increasing avg. Temps	0.15	0.05	3
	Nonpoint source pollution	High Temps	0.18	0.00	0
	Nonpoint source pollution	Wildfire	0.35	0.03	2
	Nonpoint source pollution	No extreme event trigger	0.07	0.07	4
	Point source pollution	Drought	0.46	0.00	0

	Point source pollution	Low Flows	0.36	0.40	6
	Point source pollution	Extreme Storms	0.48	0.80	12
	Point source pollution	Landslides	0.25	0.00	0
	Point source pollution	Salt Water Intrusion	0.09	0.00	0
	Point source pollution	Increasing avg. Temps	0.09	0.00	0
	Point source pollution	High Temps	0.13	0.00	0
	Point source pollution	Wildfire	0.37	0.00	0
	Point source pollution	No extreme event trigger	0.03	0.07	1
	Salinity	Drought	0.77	0.12	3
	Salinity	Low Flows	0.37	0.15	4
	Salinity	Extreme Storms	0.03	0.65	17
	Salinity	Landslides	0.03	0.00	0
	Salinity	Salt Water Intrusion	0.40	0.00	0
	Salinity	Increasing avg. Temps	0.10	0.00	0
	Salinity	High Temps	0.07	0.00	0
	Salinity	Wildfire	0.03	0.04	1
	Salinity	No extreme event trigger	0.03	0.12	3
	Turbidity	Drought	0.28	0.02	1
	Turbidity	Low Flows	0.18	0.15	7
	Turbidity	Extreme Storms	0.75	0.83	38
	Turbidity	Landslides	0.37	0.00	0
	Turbidity	Salt Water Intrusion	0.00	0.00	0
	Turbidity	Increasing avg. Temps	0.05	0.04	2
	Turbidity	High Temps	0.09	0.00	0
	Turbidity	Wildfire	0.35	0.04	2

	Turbidity	No extreme event trigger	0.03	0.13	6

Part II. Groundwater

	Water Quality Threat	Extreme Event	Survey Responses (% of respondents)	Publications (% of articles)	Publications (raw count)
Groundwater Quality	Agricultural contaminants	Drought	0.21	0.00	0
	Agricultural contaminants	Low Flows	0.13	0.00	0
	Agricultural contaminants	Extreme Storms	0.24	0.80	4
	Agricultural contaminants	Landslides	0.12	0.00	0
	Agricultural contaminants	Salt Water Intrusion	0.01	0.00	0
	Agricultural contaminants	Increasing avg. Temps	0.06	0.00	0
	Agricultural contaminants	High Temps	0.09	0.00	0
	Agricultural contaminants	Wildfire	0.16	0.00	0
	Agricultural contaminants	No extreme event trigger	0.27	0.20	1
	Infrastructure impairment or failure	Drought	0.40	0.00	0
	Infrastructure impairment or failure	Low Flows	0.13	0.00	0
	Infrastructure impairment or failure	Extreme Storms	0.25	0.00	0
	Infrastructure impairment or failure	Landslides	0.02	0.00	0
	Infrastructure impairment or failure	Salt Water Intrusion	0.00	0.00	0
	Infrastructure impairment or failure	Increasing avg. Temps	0.02	0.00	0

	Infrastructure impairment or failure	High Temps	0.01	0.00	0
	Infrastructure impairment or failure	Wildfire	0.04	0.00	0
	Infrastructure impairment or failure	No extreme event trigger	0.24	0.00	0
	Naturally occurring contaminants	Drought	0.52	0.00	0
	Naturally occurring contaminants	Low Flows	0.13	0.00	0
	Naturally occurring contaminants	Extreme Storms	0.05	0.00	0
	Naturally occurring contaminants	Landslides	0.00	0.00	0
	Naturally occurring contaminants	Salt Water Intrusion	0.29	0.00	0
	Naturally occurring contaminants	Increasing avg. Temps	0.11	0.00	0
	Naturally occurring contaminants	High Temps	0.09	0.00	0
	Naturally occurring contaminants	Wildfire	0.02	0.00	0
	Naturally occurring contaminants	No extreme event trigger	0.23	0.00	0
	Salinity	Drought	0.30	0.00	0
	Salinity	Low Flows	0.13	0.25	1
	Salinity	Extreme Storms	0.30	0.25	1
	Salinity	Landslides	0.06	0.00	0
	Salinity	Salt Water Intrusion	0.00	0.00	0
	Salinity	Increasing avg. Temps	0.02	0.00	0
	Salinity	High Temps	0.02	0.00	0
	Salinity	Wildfire	0.09	0.00	0
	Salinity	No extreme event trigger	0.30	0.50	2
	Turbidity	Drought	0.54	0.00	0
	Turbidity	Low Flows	0.14	0.00	0

	Turbidity	Extreme Storms	0.11	0.00	0
	Turbidity	Landslides	0.01	0.00	0
	Turbidity	Salt Water Intrusion	0.07	0.00	0
	Turbidity	Increasing avg. Temps	0.05	0.00	0
	Turbidity	High Temps	0.08	0.00	0
	Turbidity	Wildfire	0.05	0.00	0
	Turbidity	No extreme event trigger	0.25	1.00	1
	Urban contaminants	Drought	0.42	0.00	0
	Urban contaminants	Low Flows	0.15	0.00	0
	Urban contaminants	Extreme Storms	0.27	1.00	2
	Urban contaminants	Landslides	0.03	0.00	0
	Urban contaminants	Salt Water Intrusion	0.01	0.00	0
	Urban contaminants	Increasing avg. Temps	0.05	0.00	0
	Urban contaminants	High Temps	0.03	0.00	0
	Urban contaminants	Wildfire	0.05	0.00	0
	Urban contaminants	No extreme event trigger	0.25	0.00	0