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Resilient urban water supply: preparing for the slow-moving consequences of climate change

Pacia Díaz[a,*], Kevin M. Morley[b] and Daniel H. Yeh[a]

[a] Department of Civil & Environmental Engineering, University of South Florida, 4202 E. Fowler Avenue, Tampa, FL 33620, USA

*Corresponding author. E-mail: lapacia@gmail.com

[b] American Water Works Association, 1300 Eye Street, N.W. #701W, Washington, DC 20005, USA

Abstract

Extensive efforts have been made in preparedness and restorative action to mitigate impacts on critical water sector services from extreme events, such as storms, earthquakes, and terrorism. Comparatively, with some exceptions, the more gradual, slow-moving consequences associated with climate change have garnered lower priority in decision-making processes. This research focuses on surface- and ground- water source contamination by elevated chloride levels, which is a common climate-induced effect. Historic and current response actions by water utilities to address elevated chloride levels were analyzed based on a literature review and interviews with water utility professionals. Key lessons and findings were selected to highlight the operational challenges, solutions implemented, and the adaptive measures considered to improve community water supply resilience.

Key words: adaptation, chloride, drought, salinity, sea level rise, water supply

INTRODUCTION

Disasters in the United States, such as the terrorist attacks on September 11, 2001, Hurricane Katrina in 2005, and Superstorm Sandy in 2012, have elevated the need for critical infrastructure preparedness and resilience to national priority level. Administrative policies and directives have been issued to facilitate the implementation of measures designed to respond and mitigate the consequences of risks (HSPD-5 2003; PPD-8 2011; EO 13653 2013; PPD-21 2013; State, Local, and Tribal Leaders Task Force on Climate Preparedness and Resilience (Task Force) 2014). A number of agencies and organizations have contributed to this effort (Table 1). To date, resilience planning has been principally focused on improving preparedness and the restoration of critical services in communities following extreme events, such as hurricanes, earthquakes or terrorism, and less so on the slow-moving consequences of climate change.

The term slow-moving consequence in this paper is used to differentiate between types of impacts caused by extreme events, and those caused by gradual, incremental changes in natural systems, such as drought and sea level rise (SLR) (California State Assembly 2014). Standard responses in the water sector to improve resilience to slow-moving consequences have often been reactive and have not fully considered long-term solutions. For instance, drought and extended low precipitation periods are generally associated with water supply shortages and/or excessive aquifer drawdown. Typical adaptation measures in these circumstances often focus on conservation, water supply demand forecasting, accumulating storage, supply diversification, and implementing drought and water shortage contingency plans (Brown & Skeens 2011; USEPA 2011, 2015a, 2015b, 2015c, 2015d). Similarly, water

Table 1 | Resilience efforts

	Organization	Product	Name	Intended Audience	Purpose	Year Released	Source
All-Hazards Disaster Resilience	AWWA	Network	WARN (Water/Wastewater Agency Response Network)	Water Utilities	A method of providing and receiving emergency aid.	Varies by State	AWWA (2016)
	AWWA	Standard/ Framework	J-100 RAMCAP (Risk Analysis and Management for Critical Asset Protection) for Risk and Resilience Management of Water and Wastewater Systems	Water Utilities	Analyzes and manages risks associated with terrorist attacks and natural hazards.	2010	AWWA (2010)
	AWWA	Manual of practice	M36 Water Audits and Loss Control Programs, Third Edition	Water Utilities	Provides complete operational guidance and data on all aspects of leak detection, water audits, and water-loss control for city water utilities.	2009	AWWA (2009)
	AWWA	Report	Superstorm Sandy After-Action Report	Utilities/State and Federal Partners	Outlines lessons learned and actions in relation to intense storms that can be taken to reduce consequences and increase resilience in the water sector in the future.	2013	AWWA (2013)
	USEPA	Workshop Synthesis Report	Planning for an Emergency Drinking Water Supply	Water Utilities	Provides direction to water utilities to develop an emergency plan in case of an intentional disruption of water supply, or earthquakes, etc.	2011	USEPA (2011)
	USEPA	Tool	TTX Tool (Tabletop Exercise Tool for Water Systems: Emergency Preparedness, Response, and Climate Resiliency)	Water Utilities	Improves utilities' approach to preparedness and response in emergencies.	2005 (Re-released 2010)	USEPA (2015a, 2015b, 2015c, 2015d)
	USEPA	Tool	CREAT (Climate Resilience Evaluation & Awareness Tool)	Water Utilities	Evaluates the risk of impacts from climate related threats.	2010	USEPA (2015a, 2015b, 2015c, 2015d)
	FEMA	Tool	HAZUS (Hazards – United States)	Emergency managers	Assists in preparedness and response to hazards as well as mitigation and recovery processes. Estimates potential losses from disasters and hazards (earthquakes, hurricanes and floods).	2010	FEMA (2015)

(*Continued.*)

Table 1 | Continued

	Organization	Product	Name	Intended Audience	Purpose	Year Released	Source
	NAS	Brief	Disaster Resilience: A National Imperative	Communities	(1) defines 'national resilience' and frames the main issues related to increasing resilience in the USA; (2) provides goals, baseline conditions, or performance metrics for national resilience; (3) describes the state of knowledge about resilience to hazards and disasters; and (4) outlines additional information, data, gaps, and/or obstacles that need to be addressed to increase the nation's resilience to disasters.	2012	National Academy of Sciences (2012)
	TISP	Guide	Regional Disaster Resilience	Organizations and communities	Describes a step-by-step process to develop a cross-sector, multi-jurisdiction strategy, to improve capabilities to deal with major incidents or disasters.	2011	TISP (2011)
Climate Resilience	ACCO	Workshop Synthesis Report	Defense, National Security & Climate Change: Building Resilience and Identifying Opportunities Related to Water, Energy and Extreme Events	Defense	Summarizes a workshop analyzing the effects of climate change on defense operations and how to incorporate solutions in planning.	2012	ACCO (2012)
	USEPA	Initiative (with tools, resources and training)	CRWU (Climate Ready Water Utilities)	Water Sector	Provides resources by promoting a clear understanding of climate science and adaptation options, and by promoting consideration of integrated water resources management (IWRM) planning in the water sector.	2009	USEPA (2013)
	USEPA	Document	Adaptation Strategies Guide for Water Utilities	Water Utilities and stakeholders	Overview of what impacts from changes in the climate may have on utilities and common adaptation options being implemented.	2012	USEPA (2015a, 2015b, 2015c, 2015d)

supply impacts related to SLR are often associated with salt water intrusion (SWI) in coastal aquifers. SWI is common in coastal locations and is often due to supply wells being over-pumped to meet the demands of growing development and population densities (Galloway *et al.* 2010). Remedies for mitigating SWI of groundwater resources vary from reducing abstraction to developing alternative sources.

It is often difficult to discern the slow-moving consequences of change in natural systems and the resulting impacts on engineered systems. Ensuring the resilience of water supply systems is further complicated by the fixed range of design parameters within which they typically operate. Impacts may not become apparent until well after the water supply is compromised. The term resilience is defined and used in many ways, but as applied in the water sector, is 'the ability of an asset or system to withstand an attack or natural hazard without interruption [to its] function' (AWWA 2010). Figure 1 illustrates the resilience of engineered and ecological systems, using a ball and cup diagram. Engineered systems are designed to maintain a desired steady state (the bottom of the cup where the black ball typically resides), while ecological systems can fluctuate within a regime as long as it does not exceed a given threshold. Engineered water systems, connected by infrastructure to natural systems, are subject to the natural systems' fluctuations, which can therefore affect the water utility's resilience and operability. If water quality indicators exceed design parameters, the engineered system could fail because of a seemingly small margin of change (Liao 2012).

Chloride contamination is not limited geographically to coastal locations or to drought areas. USEPA estimates that 'two-thirds of the continental United States is underlain by saline waters that can intrude into fresh water supplies' (USEPA 1999). Chloride contamination has been reported in nearly every state in the USA, and can usually be attributed to anthropogenic causes, such as over-abstraction, or stormwater runoff containing roadway deicers or fertilizers (Todd 1960; Anning & Flynn 2014). In drinking water, chloride can have aesthetic impacts when concentrations exceed 250 mg/L. Under the Safe Drinking Water Act (42 U.S.C. §§300f to 300j-26), chloride is managed as a secondary drinking water standard. Secondary standards are set to provide guidance on removing nuisance contaminants to levels that most consumers will find acceptable (USEPA 2013). Substantial

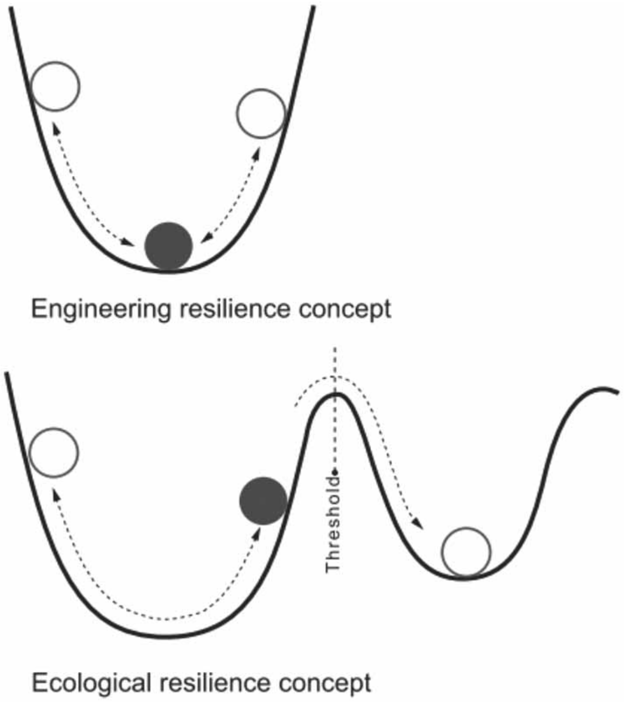

Figure 1 | Resilience of engineered and ecological systems (Liao 2012).

action is often taken to maintain chloride concentrations below the secondary standard to ensure consumer satisfaction with finished water quality.

Health and aesthetics are not the only reasons that chloride is a threat to drinking water systems. It can also cause corrosion of drinking water infrastructure with negative effects on system integrity (Bonds *et al.* 2005; Muylwyk *et al.* 2014). Concerns with potential corrosion include the presence of toxic heavy metals, as well as iron and zinc, in drinking water, the latter rendering it aesthetically undesirable for consumption, and the deterioration of plumbing and distribution systems which frequently result in costly replacement (Kirmeyer & Logsdon 1983).

Given the risk of chloride contamination, coupled with the evolving risks from climate change impacts, challenges, adaptation responses and related operational strategies applied by water systems need to be examined and documented. Utility experiences provide a learning opportunity to enhance preparedness for the future. Integrating potential climate change consequences into decision-making is necessary to ensure long-term resilience in the water sector. Considering climatic impacts that could influence chloride concentrations, the aim of this research is to (1) identify indicators of disruption or reduced water service reliability, and (2) identify successful adaptation measures that may inform utilities evaluating options to manage the consequences of slow-moving climatic impacts.

METHODS

In order to improve water utility resilience to climate change consequences, a literature review was used to evaluate adaptation responses to drought and SLR. Survey questionnaires were also distributed and interviews conducted with water professionals to obtain first hand observations and information. The information collected about the adaptive measures employed by utilities has been compiled in Figure 2, which provides an overview of the issues addressed and shows how the issues leading to salinity impacts on water supply are often inter-related.

Literature review

The primary focus of the literature review was identifying indicators associated with the functional, operational and physical impacts that a water utility may experience. Water utilities across the USA have sought solutions to elevated chloride levels arising from many causes. Such actions were identified to glean information on useful practices and seek out potential survey respondents.

Surveys and interviews

Surveys and interviews were conducted to provide as near term as possible review of current utility activities. The questions elicited indicators or action trigger points related to salinity that could hinder functionality, and the measures used to overcome them. The survey and interviews also helped establish a time horizon for adaptation actions. Some supplementary reports and publications were also obtained for better definition of response actions.

CHLORIDE CONTAMINATION: THE COMMON DENOMINATOR

Elevated chloride concentrations have many causes. Those discussed in this paper are shown in Figure 2.

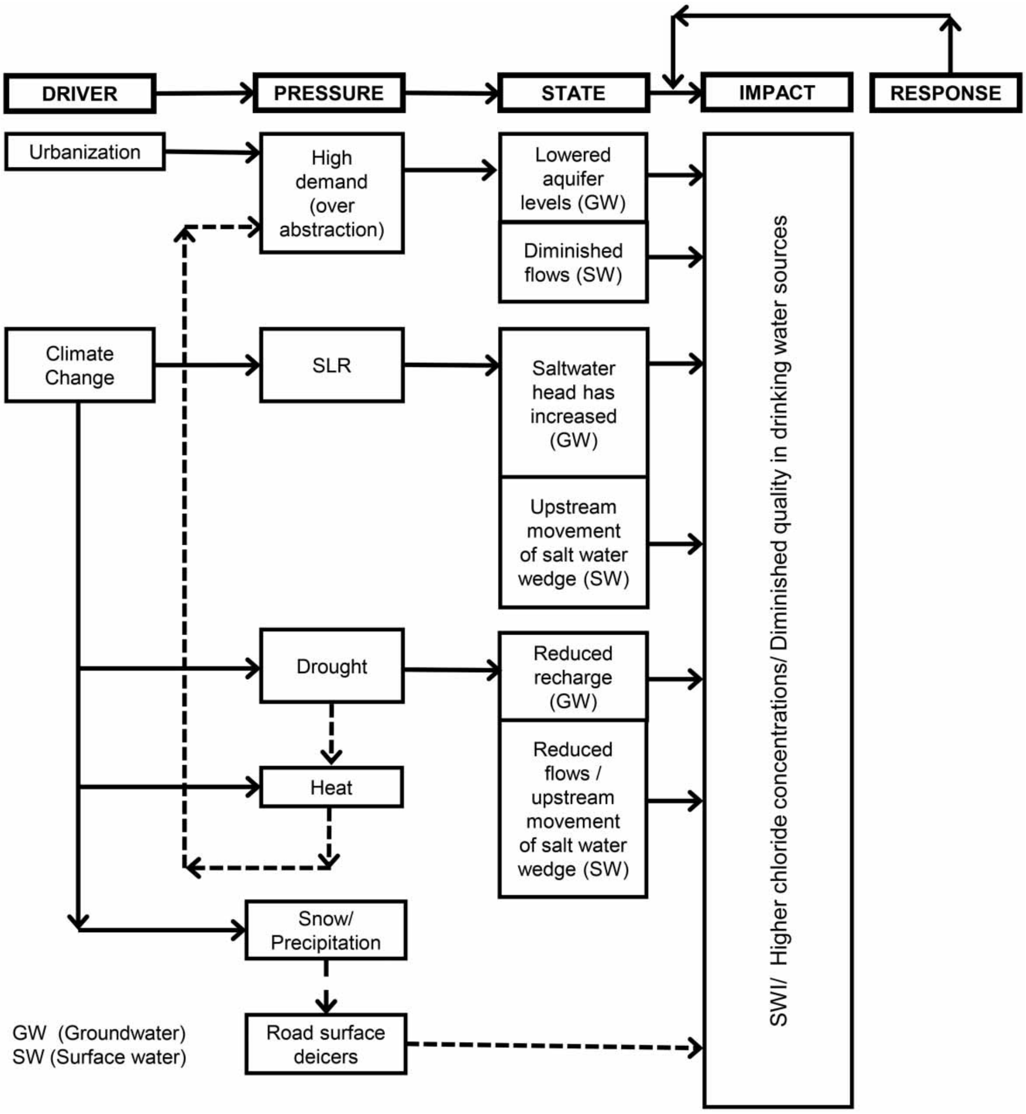

Figure 2 | Chloride contamination threats to water supply

Salt water intrusion

SWI occurs when saline water moves into a body of fresh water, raising the chloride concentration. Increased salinity, affects the aesthetic quality of drinking water negatively. Salt water can intrude laterally or vertically (upward or downward) from ground- or surface- water sources, most often in coastal regions (Todd 1974; Barlow 2003; Johnson 2007; Barlow & Reichard 2010).

Impacts to groundwater

Increased chloride levels in coastal aquifers are primarily caused by over-abstraction, which lowers the water table, enabling seawater infiltration and contamination. Since seawater is denser than freshwater, a relatively tall freshwater column above sea level generally inhibits saltwater intrusion into fresh aquifers. Over-abstraction has already caused ‘permanent’ contamination of several aquifers in urbanized coastal locations (Barlow & Reichard 2010). The Upper Floridan Aquifer, the drinking water source for approximately 10 million people in Florida, Georgia and South Carolina, is just one location where this has occurred. Distance from the coast, however, does not equate automatically to immunity from SWI. The Monterey/Salinas Valley in California has also suffered SWI because of over-abstraction, and seawater has intruded up to 5–8 km (3–5 miles) inland (Nico Martin 2014). Freshwater aquifers that are below sea level can also be susceptible to chloride contamination, as in the Carpinteria Groundwater Basin, California and the Biscayne Aquifer, southern Florida (Trimble *et al.* 1998; Deyle *et al.* 2007).

While snowfall has diminished in many parts of the United States, there is more winter rain (USEPA 2016). Winter rainfall often leads to icy roads that require treatment and salt is a common deicing agent. The runoff from melting snow and ice transports dissolved salts and other contaminants into urban waters, significantly increasing chloride concentrations. Dissolved salts in lakes and streams can permeate through soils, and eventually into groundwater (Hammann & Mantes 1966; Terry 1974; Godwin *et al.* 2003). There are also concerns about these salts corroding water distribution networks (Bonds *et al.* 2005; Muylwyk *et al.* 2014).

RESULTS

The investigation of water utility strategies to address various impacts (see Figure 2) yielded useful results for dissemination about preparing for future impacts. Detailed information from over thirty utilities in the USA was collected and is summarized in Table 2.

Responses addressing lateral and vertical SWI

Adaptation measures implemented in response to SWI by water utilities are often similar for both ground- and surface- waters. Protection from saltwater migration has required physical barriers. Solutions for lateral SWI have included bentonite slurry walls (due to over-pumping) and tide gates (in tidal canals) to protect freshwater sources in California and Florida (Deyle *et al.* 2007; Galloway *et al.* 2010; GPI Southeast Inc. 2012). In Louisiana, the Army Corps of Engineers has built and rebuilt a sill several times for a 14 m (45 foot) section of channel in the Mississippi River. It was rebuilt in 1999 and 2012, due to erosion caused by flow increases following drought, and is expected to require restoration approximately every 5 years. The estimated cost of the original sill – 1988 – was $800,000 (Soileau *et al.* 1990; USACE 2015). Physical barriers have also been installed on the Sacramento and San Joaquin rivers as emergency measures, when surface waters have receded during drought, potentially enabling seawater encroachment (Croyle 2015). Other types of physical barrier include freshwater injection into purpose-built wells along the coast, as a barrier between sea- and ground- water – e.g., the groundwater replenishment system built by the Orange County Water District (California, USA) (Chalmers *et al.* 2010). Basins on the central and west coast of California installed similar SWI barrier wells in the 1950s and 60s as a mitigation measure. They consisted of 290 injection wells up to about 210 m (700 ft) deep along 27 km (17 miles) of the coast. Both potable and reclaimed water, the latter extensively treated, were injected. This cost approximately $14 million in 2007/2008, with $5 million in annual maintenance (USEPA 1999; Johnson 2007).

Integrated solutions beyond monitoring are often required to ensure resilience. Since the economy in Southern California depends on groundwater irrigation of high-value, salt-sensitive crops,a groundwater management plan was implemented. Although the water table elevation remained relatively consistent, chloride concentrations in the Monterey and Salinas Valley kept rising (Nico Martin 2014) because seawater was intruding upward from below. An integrated adaptation measure was adopted which supplies reclaimed water for irrigation to offset potable water use (Feldsher & Wu 2010; MCWRA 2016). The Salinas Valley Water Diversion Project augments this by diverting excess surface water flows during wetter periods. The project included a rubber dam designed to

Table 2 | Summary of adaptation measures implemented by some water supply utilities in the USA

	Challenge (threat/impact)						
Region/Utility	**SWI**	**SLR**	**Drought**	**Over-pumping**	**Description**	**Solutions (adaptation measures)**	**Source**
Arizona – Tucson Water			X		Water shortages	Conservation and wastewater recycling. Wastewater is treated to secondary standards and stored in the aquifer (artificial storage and recovery – ASR).	Megdal & Forrest (2015)
California – City of Long Beach	X		X	X	Increased salinity. Area most threatened by present or future increases in groundwater demand. SWI threatens area's economy as high-value, salt-sensitive crops are grown.	Developed groundwater management plans. Installed barrier (injection) wells (using potable water).	Johnson (2007), Hodges *et al.* (2014), Nico Martin (2014)
California – Monterey, Salinas Valley	X			X	Sudden increase in salinity. Groundwater levels appear stable, yet seawater intrudes (up to 5 to 8 km [3 to 5 miles] inland) and replaces fresh groundwater that has been pumped out.	Provided reclaimed water for irrigation as potable water offset to slow SWI rate. Capture and diversion of surface water to offset pumping within the basin.	Barlow & Reichard (2010)
California – Oceano Community Services, District and Cities of Arroyo Grande, Grover Beach and Pismo Beach			X	X	Water shortages, land subsidence	Implemented drought response plans/ water conservation; maximized surface water deliveries, optimized surface water delivery infrastructure, regional coordination, improved groundwater monitoring (frequency, more transducers), sentry well improvements. Future plans to increase surfacewater storage, develop a groundwater model, increase surface water deliveries, look into recycling water, and enhance conjunctive use of groundwater.	Heimel *et al.* (2012)
California – Pajaro Valley Water Management Agency	X			X	High chloride levels	Adopted basin management plan, proposing several conservation projects to reduce pumping by 90% and halt SWI.	Carollo Engineers (2012)

(*Continued.*)

Table 2 | Continued

	Challenge (threat/impact)						
Region/Utility	**SWI**	**SLR**	**Drought**	**Over-pumping**	**Description**	**Solutions (adaptation measures)**	**Source**
California – Palo Alto	X			X	High chloride levels were documented in studies due to groundwater over-abstraction in the first half of the 20th century (Iwamura 1980). Recent USGS study concluded that modern SWI is the result of mineral dissolution of marine sediments (Metzger 2002).	Conducted studies and diversified supply sources.	Todd Engineering (2005)
California Department of Water Resources	X		X		Water shortages, land subsidence	Installed salinity barriers on two rivers and other measures – increased conservation, surface water curtailments, increased oversight of groundwater use, increased real-time data and information, etc.	Hodges *et al.* (2014), Croyle (2015)
Florida – Boynton Beach	X			X	Action taken because of up-coning of saline waters.	Adjusted wells to make them shallower (from 60 to 40 m [200 to 120 feet]). Installed monitoring wells as a pre-emptive measure. Using of existing water treatment facilities (east and west) to provide source options.	Interdepartmental Climate Change Group (2009)
Florida – City of Dania Beach	X			X	One of the main factors causing the salinity impacting drinking water sources has been development. History of salt issues tied to drainage canals now facilitates SWI into the aquifer.	Moving wellfield away from the coast. Purchased water from nearby utilities.	Bloetscher *et al.* (2010), Trimble *et al.* (1998), Interdepartmental Climate Change Group (2009)
Florida – Dunedin	X			X	Water supply does not currently suffer from salinity issues, but in the 1990s there was a need for it to be addressed. The worst salinity conditions were seen prior to the construction of the RO plant, where water was pumped and treated at each well location, then distributed to nearby areas.	Connect City wells by a raw water main, install an RO (reverse osmosis) water plant and add more wells to the system to spread out pumpage. Improved water management, together with drought restrictions, public education on water conservation, and the implementation of a reclaimed water system.	Diaz *et al.* (2016)

(*Continued.*)

Table 2 | Continued

	Challenge (threat/impact)						
Region/Utility	**SWI**	**SLR**	**Drought**	**Over-pumping**	**Description**	**Solutions (adaptation measures)**	**Source**
Florida – Hillsborough County	X				Salt intrusion into groundwater through channels.	Tide gates installed at two channels of a creek.	Diaz, Seckinger & Associates (1974, 1975), Deyle *et al.* (2007), GPI Southeast Inc. (2012)
Florida – Miami	X				Extensive canal system has allowed salt water to intrude vertically in addition to the high permeability of the aquifer (groundwater)	1940s: Construction of salinity control dams.	Todd (1974), Interdepartmental Climate Change Group (2009)
Florida – Miami-Dade County	X	X	X	X	Salt water movement northwestward from Tamiami Canal towards center of pumping in Miami wellfield. Salt water was detected at a depth of 50 feet and some wells were no longer usable.	Installed salinity barriers (control gates at canals).	Kohout (1960), Trimble *et al.* (1998), Interdepartmental Climate Change Group (2009)
Florida – Peace River Manasota Regional Water Supply Authority, Lakewood Ranch		X			Tidally influenced surface water. Does not currently have a salinity problem, but is definitely at risk. Without a dam or salinity barrier, salinity levels could definitely increase with rising sea levels.	Adaptive management portfolio: • Proactively planning and engineering solutions, • increased pumping capacity, • additional off-stream storage, • alternate sources, and • moving the intake further upstream. Conductivity was modeled and correlated to tide-level-related water quality to anticipate changes in water quality since Peace River flows are tidally influenced.	Morris *et al.* (2015)
Florida – Putnam, Flagler and St. Johns County	X				Diminished yields/crop failure in row crops. Wells depths between 100 and 130 m (300 and 400 feet), with diameters between 150 to 200 mm (6 to 8 inches).	1960s: magnets installed on pipes (paramagnetism) to remove salt from water. Recently installed modern remedy: tile drainage implementation.	Cooper *et al.* (1964), Munch *et al.* (1979), SJRWMD (2015)
Florida – St. Johns County	X			X	High chloride area, coastal location and agricultural use of groundwater	Implemented water conservation programs, created well field optimization program, back-plugged certain wells, developed alternative wellfields, modeling/studies on salinity.	-

(*Continued*.)

Table 2 | Continued

	Challenge (threat/impact)						
Region/Utility	**SWI**	**SLR**	**Drought**	**Over-pumping**	**Description**	**Solutions (adaptation measures)**	**Source**
Georgia – Brunswick-Glynn Joint Water & Sewer Commission (BGJWSC)	X			X	Salinity problem near downtown is not the typical lateral encroachment of saltwater, but one of trapped saline water in a formation that migrates upward from the Lower Floridan aquifer (Fernandina permeable zone) to the Upper Floridan aquifer.	Closure of saline wells and pumped from an alternative source. Installation of real time water level and water quality monitoring equipment to serve as an early warning system. Reductions of groundwater withdrawals.	ARCADIS Geraghty & Miller Inc. (1999), Barlow (2003), NOAA (2011), Barlow & Reichard (2010), USEPA (2015a, 2015b, 2015c, 2015d), USGS (2015)
Georgia – City of Savannah	X			X	Tidally influenced surface water. Water sources impacted by high salinity levels. Dredging has increased this vulnerability.	Reduced withdrawals. Implementation of a regional SWI plan.	ARCADIS Geraghty & Miller Inc. (1999), Barlow (2003), GAEPD (2006), CDM (2011); Roehler *et al.* (2013)
Louisiana – Mississippi River (at Alliance in Plaquemines)	X		X		Salt water wedge moved up the Mississippi river and was going to affect the water quality at intakes	Constructed a salt water sill in 1988, 1999, 2012 (a new sill will be needed approximately every 5 years).	Rainey (2012), Soileau *et al.* (1990), USACE (2015)

retain water released from two reservoirs. When activated, it creates a detention pond and mixes diverted water with reclaimed water for irrigation when needed. In combination, these projects provide multiple benefits: retarding SWI into aquifers, reducing groundwater demand, ensuring reliable alternative irrigation sources, and minimizing wastewater discharges into the Monterey Bay National Marine Sanctuary.

Responses to over-abstraction

Coastal aquifer SWI due to over-abstraction can yield insights into salinity that may be caused by SLR. The Upper Floridan Aquifer, a primary water source in Florida, Georgia and South Carolina, was first pumped in the 1800s and has been used extensively ever since. High demand has led to over-abstraction causing SWI in Brunswick, Georgia, and elsewhere. High chloride concentrations, sometimes exceeding 2,000 mg/L, have increased source sensitivity awareness. Further development has been limited since then, with real time water level and quality monitoring equipment installed as part of an early warning system. The United States Geological Survey (USGS) monitors the data and maintains the equipment (USGS 2015). Industrial consumption has also been reduced by between 25 and 50% as part of the regional *Coastal Georgia Water & Wastewater Permitting Plan for Managing Salt Water Intrusion* (GAEPD 2006). This included mandatory audits by Georgia Environmental Protection Division (GAEPD) when industrial permit holders' groundwater abstraction permits needed renewal and, potentially, revised permit/use conditions, as well as new abstraction limits. Abstraction was also moved to shallower sources, e.g., local surficial aquifer systems, where SWI is less likely to be a problem. The plan's primary focus was to stabilize and reverse SWI by managing the urban water cycle, involving water conservation and wastewater reuse, as well as surface- and ground- water abstraction permitting. The plan includes policies and actions for managing wastewater discharges into sensitive ecosystems in coastal Georgia.

Wichita (Kansas) monitors a chloride plume caused by a variety of activities, as well as natural salt deposits and sporadic drought. The USGS simulated chloride transport over 18 years and modeled wellfield management scenarios to control groundwater levels and chloride movement. Scenarios were designed to determine the aggravation causes (groundwater abstraction in different locations) and the best response (e.g., amount of artificial groundwater recharge). Similar work has helped not only define and understand the water quantity and quality needed to ensure supplies, but also provide information on the effectiveness of aquifer storage and recovery (ASR) in other states (Lavista 2014).

Responses to SLR

Saline water can migrate up rivers, increasing water salinity. The Atlantic coast of South Florida has seen significant development, which can be the main driver for elevated chloride concentrations in some areas. In some cases, land drainage canals, for development, have allowed seawater to migrate and infiltrate freshwater aquifers. Current remedies in South Florida include salinity control dams on various canals, abandoning wellfields contaminated by saltwater, and drilling new water supply wellfields to the west (away from the coast). Coastal canal water levels will probably need to be raised eventually, however, to recharge the Biscayne Aquifer and protect it against further SWI (Trimble *et al.* 1998; Bloetscher *et al.* 2010).

Responses to drought

Integrated solutions generally provide the best flexibility towards climate and demand fluctuations affecting long-term water supplies. El Paso Water Utilities (Texas) had used reclaimed water for non-potable reuse and recharged the aquifer for indirect potable reuse. The utility then implemented strong conservation measures and built a very large inland desalination plant to treat brackish groundwater. An extended drought and limited surface- and ground- water resources led it to pioneer direct potable reuse. In this case, it was realized that, given its arid climate, population growth and drought, this solution diversifies its water resource portfolio and bolster drought mitigation efforts, with a controlled and reliable year-round and drought tolerant supply. The treatment was designed to maximize public health protection using advanced processes, rigorous critical process monitoring, risk management, and public outreach (Maseeh *et al.* 2015; Megdal & Forrest 2015).

Typical drought responses are focused on meeting demand. Lessons from the multi-year drought in California, which began in 2011, show the challenges that might be faced by water utilities. The current drought is expected to last long past 2016, and various actions have been taken to improve water conservation and minimize water loss. Bulk water transfers are another emergency measure that can be used (Hodges *et al.* 2014). Mediterranean coastal cities, such as Barcelona, Spain, received water by barge from France to overcome source supply deficits (Sauri & Domene 2006).

It is clear from this study that emergency measures implemented now and in the past are strongly linked to water resource protection from chloride (NRC 1987; Roehler *et al.* 2013). The issues that dictate response type are salinity levels and available funds. Acceptable chloride concentrations vary, and seasonality, tidal influence and time-scales all affect the type of response implemented. Cost also has a major influence on community.

In general, actions were reactive, rarely including infrastructure retrofits or modifications to operations, which have not been considered as potential responses. Peace River Manasota Regional Water Supply Authority (Lakewood Ranch, FL), however, modeled groundwater conductivity data relative to tide-levels, which enabled proactive planning to improve water quality. Potential salinity problems are at their most serious during the dry season (April–June), when river flows are low, at high tide and when the wind is onshore from the Gulf of Mexico. To guard against these risks, greater reliance is placed on off-stream reservoirs, and ASR. The utility continues to track future developments because of the dynamic water quality situation (Morris *et al.* 2015).

CONCLUDING REMARKS

Chloride contamination is a real threat to water source quality. There is potential for saline intrusion into fresh water sources across the USA and climate change is likely to make it increasingly common. The impacts of urbanization – over-pumping to meet high demand – SLR and drought, can all be linked to increased chloride levels that threaten drinking water supply quality (Figure 2).

In this study, the challenges and adaptive actions taken in various places to protect water supply sources and manage water quality resilience were observed. If insufficient consideration is given to the threat of SWI, then service disruptions, reduced reliability and potential long-term consequences of source water contamination are likely to occur. The effects on individual water supplies will vary and a common recommendation for protective measures is not suitable. Strategies must be developed to fit the needs of individual communities. Key observations from this study are:

- ***Be proactive, not reactive.*** Emergency measures can be effective, but plans for investing in capital infrastructure projects that consider both current and future threats may be a wiser course of action.
- ***Monitor and be aware of local threats.*** Establish a source water quality awareness and monitoring program. Monitoring water levels, flows and key parameters such as chloride levels may serve to alert of potential/imminent water supply issues.
- ***Develop a portfolio of alternative water sources.*** Invest in alternative water infrastructure – e.g., for water recovery and reuse – to reduce raw water consumption. Other options may include using

seawater in sanitation and/or industry. Higher-level treatment may be required in some cases – e.g., reverse osmosis or desalination plants.

- ***Conduct modeling studies.*** Salinity issues are complex but mathematical models can be used to clarify major issues, while pilot- or lab- scale tests can help define water quality boundaries, etc.

Future research should include investigation of best practice, and strategies and operational techniques for dealing with salinity issues, including the effects of corrosion. As communities evaluate the potential consequences of climate change on water supplies, solutions will be needed to strengthen long-term water supply resilience.

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