Addressing Salinity Challenges to the Beneficial Uses of Water

By Christopher H. Conaway, Nancy T. Baker, and John K. Böhlke

Chapter B of

Knowledge Gaps and Opportunities for Understanding Water-Quality Processes Affecting Water Availability for Beneficial Uses

Edited by Anthony J. Tesoriero, Melinda L. Erickson, Christopher H. Conaway, Elizabeth J. Tomaszewski, and Christopher T. Green

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Abbreviations

BGW	brackish groundwater
DIC	dissolved inorganic carbon
DRBC	Delaware River Basin Commission
EPA	U.S. Environmental Protection Agency
SC	specific conductance
USGS	U.S. Geological Survey
WMA	Water Resources Mission Area

Chemical Symbols

As	arsenic
Ba	barium
B	boron
Ca	calcium
Cl	chlorine
Cu	copper
F	fluorine
Pb	lead
Mg	magnesium
K	potassium
Ra	radium
Se	selenium
Na	sodium

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Chapter B

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Purpose and Scope

This chapter is focused on identifying knowledge and data gaps, that if filled, could improve predictions of the effects salinity has on the beneficial uses of water resources. The gaps identified in this chapter are not intended to be comprehensive but are instead focused on key opportunities for the U.S. Geological Survey (USGS) Water Resources Mission Area (WMA, https://www.usgs.gov/mission-areas/water-resources). Salinity effects on ecosystems are not addressed in this chapter but are covered in chapter E of Harvey and others (2024), “Knowledge Gaps in Salinity Drivers of Aquatic Ecosystem,” the companion Open-File Report to this publication.

Statement of the Problem

Salinity and salinization have long been leading water-quality issues nationally and globally. Salinity, defined here as the sum of dissolved salts (Anning, 2011), is a primary limitation to the beneficial use—and sometimes reuse—of water for drinking, irrigation, livestock, power generation, and oil, gas, and mineral resource extraction (McMahon and others, 2016). Salinity is an increasing challenge for water availability assessment and prediction for several reasons, including (1) readily accessible freshwater resources are threatened by increasing salinity, with more rapid increases occurring in recent decades (Kaushal and others, 2018a, b; Lindsey and others, 2018; Stets and others, 2020); and (2) there is increasing demand for alternative water resources such as brackish and saline groundwater, but the distribution, quantity, and quality of those resources are not well known (Stanton and others, 2017).

Whereas salinity may be composed of a range of dissolved salts in various concentrations—for example, calcium (Ca), chloride (Cl), magnesium (Mg), potassium (K), and sulfate (SO_4)—salinity in seawater is predominantly from sodium (Na) and Cl. Porewater or groundwater can range from fresh to highly saline. These waters are sometime classified based on their major cation and anion chemistry into water types such as sodium-bicarbonate type, calcium sulfate type, and sodium chloride type (Stanton and others, 2017). The major chemical composition varies as a result of processes such as evaporation, water-rock interactions, human modifications, and mixing of different water types, including mixing with deep groundwaters that contain relict seawater or brine (Kharaka and Hanor, 2014).

Freshwaters are being salinized rapidly in all human-dominated land use types (fig. B1). Rapid salinity increases can alter biodiversity, mobilize sediment-bound contaminants, and increase lead (Pb) contamination of drinking water, but these and other effects are not well integrated into current paradigms of water management (Stets and others, 2020). Increasing major ion concentrations from pollution, human-accelerated weathering, and saltwater intrusion contribute to multiple stressors such as changing ionic strength and pH and mobilization of chemical mixtures resulting in the freshwater salinization syndrome (Kaushal and others, 2018b; (Kaushal and others, 2021). Furthermore, salt pollution can enter groundwaters, which can become dominant stream-water sources at baseflow and thereby affect biota during low-flow times of the year when they may be most sensitive to fluctuations in water quality (Stets and others, 2020). Extensive monitoring has increased our understanding of the spatial and temporal patterns of elevated salinity in rivers and streams; however, there are major gaps in our understanding of the relative contributions of human activities and other drivers, spatial and temporal patterns in groundwater, ecological and human consequences, and the effects of climate change on salinity. The U.S. Environmental Protection Agency (EPA) considers most dissolved salts associated with salinity to be nuisance chemicals and has established non-mandatory secondary standards as guidelines to assist public water systems in managing drinking water for aesthetic considerations, such as taste, color, and odor (https://www.epa.gov/sdwa/secondary-drinking-water-standards-guidance-nuisance-chemicals). In recognition that some combinations of these salts can cause life-threatening corrosion and mobilization of Pb and copper (Cu) in plumbing systems, the EPA developed technical recommendations for optimal corrosion control treatment evaluation (EPA, 2016). As the effects from freshwater salinization become more recognized and the processes better understood, it is possible that future guidelines and criteria will be developed to prevent and mitigate these threats. The results of freshwater salinization may be compounded if projections of increasing surface water and groundwater demand coupled with projected effects of climate change are realized (Stanton and others, 2017; Stets and others, 2020).

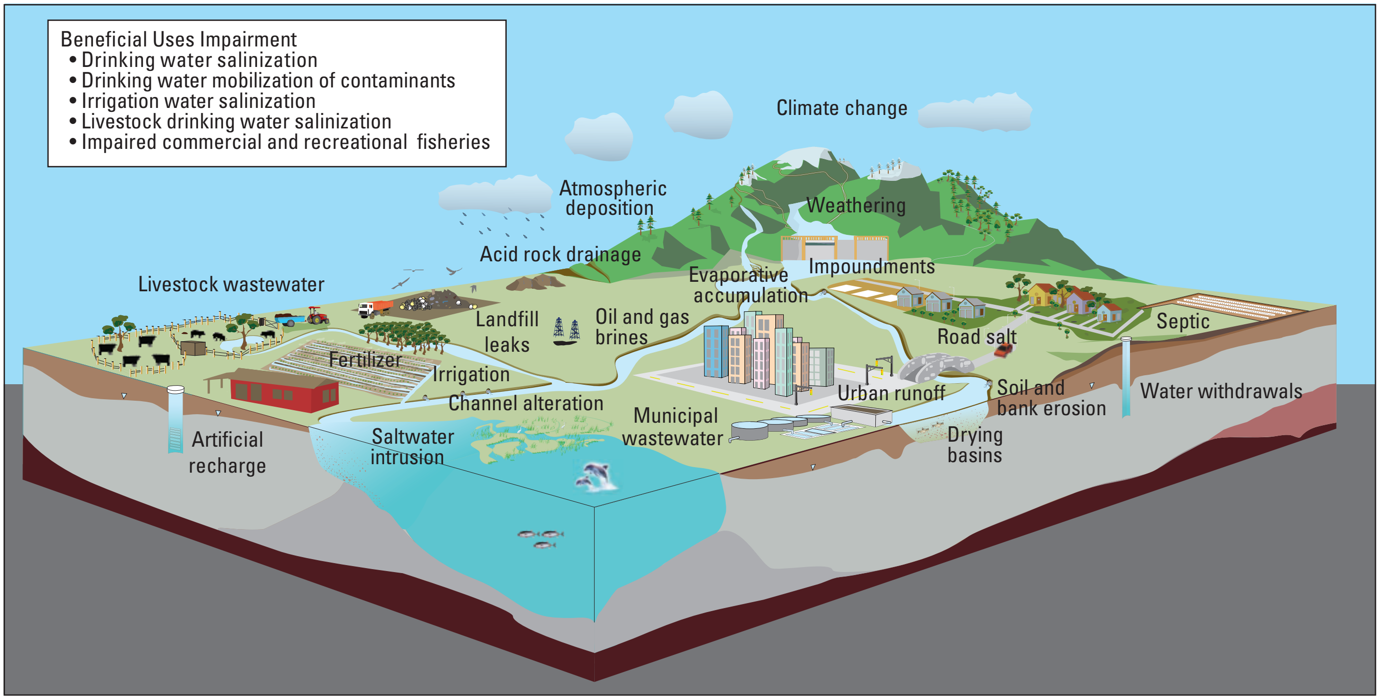

Figure B1. Diagram of sources and drivers of salinization that impair beneficial uses of water resources in the United States.

Status of Knowledge and Capabilities

Salinity and salinization have long been leading water-quality issues in the United States and globally (Vengosh, 2014). Some of the major issues related to salinization effects on beneficial uses of freshwater resources include corrosion issues and the safety of drinking water (corrosion of pipes) and infrastructure (corrosion of roads and bridges), elevated salts leaching essential elements from soil where saline water is applied to soils, and suitability for other agricultural purposes (Kaushal and others, 2018b; Stets and others, 2020). A recent analysis of USGS water-quality measurements made across the United States identified a multi-decadal trend of increasing salinity on a continental scale (Kaushal and others, 2018b; Stets and others, 2020), particularly in urban-influenced watersheds. Increases in alkalinity are also associated with salt pollution, although the environmental effects of alkalinization have received comparatively less attention and are perhaps less well understood than those of salinity (Kaushal and others, 2018b). In addition, natural occurrences of deep saline groundwater can contaminate water-supply wells because of overpumping. Conversely, saline groundwater may be a useful resource in areas lacking freshwater resources, depending on the chemical composition of the saline groundwater, the types of water uses in those areas, and the viability of water-treatment options (McMahon and others, 2016; Stanton and others, 2017).

The predominant sources of salinity are well known. Sources and causes of observed salinity changes include: (1) anthropogenic inputs of salt such as road salt, wastewater, water treatment, brine disposal, and agricultural runoff; (2) acceleration of natural weathering or water-rock interaction via acid rain, fertilizers, and acid-mine drainage; and (3) weathering of construction and manufacturing materials such as cement, lime, and concrete (Kaushal and others, 2018b). Some of the anthropogenic practices and environmental factors driving changes in salinity include climate change (for example, timing and amount of precipitation related to various kinds of runoff or chemical weathering), changes in water use (for example, surface water diversion, groundwater withdrawal, irrigation), changes in land use and land cover, and sea-level rise (seawater intrusion).

Watershed chemical transport is increasingly dominated by novel combinations of constituents (“chemical cocktails”) because human activities greatly enhance elemental concentrations, increasing the probability for biogeochemical interactions and shared transport along hydrologic flowpaths (Kaushal and others, 2021). Interactions with chemical cocktails can produce environmental effects greater than the sum of individual parts, however, the causes and consequences of water-quality problems often focus on one or a few constituents and do not consider potential interactions. Increases in chemical cocktails linked with salinization (for example, hydrogen [H^+], Ca^{2+}, Mg^{2+}, Na^+, and Cl^-) influence acid-base status of fresh waters and can affect mobilization of other chemical cocktails such as those associated with brownification (increase in brown color caused mainly by dissolved humic matter) or eutrophication. In addition, these ions tend to be eluted from soil and sediment exchange sites and can be rapidly flushed in a primary pulse if they have accumulated in near surface environments from urban road salts, agricultural liming, and natural or human accelerated weathering. Significant quantities of these ions are also commonly located deeper in soil profiles leading to transport through the subsurface and eventual accumulation in groundwater and (or) discharge to streams (Kaushal and others, 2018a).

There are many examples of how salinity has affected water quality in the United States, including existing and proposed IWS basins. In the Delaware River Basin, salinity is a concern where (1) the marine salt wedge travels up the Delaware River and enters public water supply intakes at low flow, (2) sea level rise leads to saltwater intrusion into public water supply and domestic wells, and (3) road salt contaminates fresh-water systems. In the Upper Colorado River Basin salinity, caused by irrigated agriculture and by natural and human accelerated weathering of saline geologic formations, is a major threat to water use (Kenney and others, 2009). Damages across the entire Colorado River Basin are estimated to exceed hundreds of million dollars per year due to decreased crop yields, increased water treatment costs, degraded river health, clogged pipes, and damaged equipment (Vengosh, 2014). In the Illinois River Basin, sources of elevated salinity in streams and groundwater resources include road salt and brine in the Cambrian–Ordovician aquifers.

Gap Analysis and Approaches

Research needs related to salinity in surface water and groundwater were identified by reviewing the results, discussion, and conclusion of recent major works (Stanton and others, 2017; Kaushal and others, 2018b; Kang and others, 2020; Moore and others, 2020; Stets and others, 2020) and by discussions with USGS Water Enterprise researchers focused on salinity in IWS basins and nationwide. We divided core research areas into four main gap categories with detailed descriptions of each area presented in the following sections along with a summary in table B1:

1. Identifying salinity sources and drivers,
2. Predicting and understanding trends in freshwater salinization,
3. Improving assessments of brackish water resources, and
4. Identifying the components of salinity and their effect on contaminant mobility.

Table B1. Summary table for salinity gap analysis for understanding water-quality processes affecting water availability for beneficial uses in the United States.

Topic	Knowledge Gap	Importance	Proposed Approaches
Identifying salinity sources and drivers	Ability to distinguish various salinity sources and multiple transport pathways from sources to receptors.	Essential for model prediction, resource management, and remediation.	Watershed or aquifer mass balance approaches combined with flow modeling to better understand the interactions between surface water, the unsaturated zone, and groundwater. Development and application of geochemical and isotopic tools for identifying sources.
Predicting and understanding trends in freshwater salinization	Understanding of hourly, seasonal, and long-term changes in sources, peaks, and trends of salinization.	To extrapolate salinity measurements and models over a wide range of hydrologic and climate variables and gradients and time scales, including direct and indirect human effects.	Monitoring salinity with high-frequency sampling sensors. Develop long-term continuous data. Conduct studies in areas where human activities cause redistribution of salts or saline water.
Improving assessments of brackish water resources	Improved knowledge of availability and sustainability of groundwater and saline water resources.	Demand for freshwater is increasing as water quality is degrading and some regions are becoming more arid.	Refine knowledge of the distribution of brackish groundwater resources. Refine knowledge of the sustainable use and (or) treatment of brackish groundwater resources. Conduct research related to water treatment and desalination technologies and limitations.
Identifying the components of salinity and their effect on contaminant mobility	Ability to predict how saline water chemistry affects beneficial uses, mobilization of contaminants, and compatibility with water treatment technologies.	Different major ion ratios have different properties related to corrosion, scaling, or water treatment processes that may affect drinking water infrastructure. Ion ratios in irrigation water can affect soil fertility or have undesirable effects on the chemistry of agricultural return water.	Survey of data on major ion ratios and trace elements related to salinity in fresh and brackish water systems. Develop predictive models for geochemical water type in groundwater based on local geologic, hydrologic, and climatic conditions.

Gap 1. Identifying Salinity Sources and Drivers

Although the primary sources of salts driving freshwater salinization are known, the relative contributions—especially on a temporal scale—of these sources is a knowledge gap in many areas (for example, the contribution of road salt to groundwater and release to streams in areas where there is a low-flow pulse of Cl during non-winter months). Also, the contribution and chemical nature of groundwater as a saline input to surface water is an important avenue of study (Anning, 2011; Rumsey and others, 2017; Stets and others, 2020).

Salinization and the Storage of Salts in the Environment

Salt from atmospheric deposition, naturally occurring deposits of saline minerals, evaporation of surface water, or anthropogenic salinity sources can accumulate in the unsaturated zone and later be flushed downward or laterally (in the presence of low permeability strata) to the saturated zone. The flushing can be caused by changes in land use such as removing vegetation or changing vegetation type (for example, natural to cropland), or changes in hydrologic budget through increased rainfall and (or) snowfall, irrigation, or even sea-level rise. Storage and flushing of salinity are well-documented in dryland environments (Vengosh, 2014), but less so in urban areas or basins with anthropogenic salinization (Lax and Peterson, 2009). To quantitatively address “salinity storage” in target basins, the balance of saline inputs and outputs and storage should be addressed, and processes moving salinity from land surface to lakes, rivers, and streams, or through the unsaturated zone to groundwater in urban, suburban, and regions of anthropogenic salinization should be characterized. Deliverables for projects could include mass balance of salinity in a region, identification of important zones of salt accumulation (in both the unsaturated zone and groundwater), an understanding of steady-state chloride concentration in groundwater for current and predicted salinization, and an understanding of processes controlling movement of salinity from land surface through the unsaturated zone to groundwater or discharge to streams.

Evaluation of Sources of Salinity

Determining the salinity sources affecting beneficial uses is an essential component in water-quality management and prediction. When there are multiple sources of salinity to a system, the integration of multiple chemical and isotopic analyses is required to distinguish between these sources (Vengosh, 2014). Common tracers for salinity sources include chemical ratios (for example, Na/Cl, Br/Cl, B/Cl, Ca/Cl, SO_4/Cl) and isotopic ratios (for example, $\delta^{18}O$ and $\delta^{2}H$ in H_2O, $\delta^{11}B$, $\delta^{34}S$, $\delta^{34}S$ and $\delta^{18}O$ in SO_4, $^{36}Cl/Cl$, $^{129}I/^{127}I$, and $^{87}Sr/^{86}Sr$). To quantitatively attribute sources of salinity to water-quality observations and predictions in target basins, projects could apply these geochemical modeling tools when data are available. This work is also applicable and relevant to seawater intrusion and saltwater displacement in coastal aquifers. Deliverables for projects could include identification of the best combination or integration of tracers in these systems, a compilation of available data, and include potential tracers for reuse water. When data are not available, collection of new data or development of models may be warranted to better distinguish various salinity sources and multiple transport pathways from sources to receptors.

Gap 2. Predicting and Understanding Trends in Freshwater Salinization

One of the major gaps in understanding salinization and its effects is the influence of seasonal, interannual, and long-term changes and drivers (Kaushal and others, 2021). The most important drivers on these temporal scales are climate change, landscape and water use change, hydrologic characteristics of the underlying aquifer, and sea level rise. Climate driven changes include reduction in precipitation and increases in aridity. Other long-term changes contributing to salinization include increasing urbanization and water use, converting forests to agricultural land, and in some cases afforestation of grasslands which draws water from shallow groundwater leaving its salt load in the unsaturated zone (Vengosh, 2014). Seasonal and long-term salinity fluctuations can be important because changes in salinity can affect the suitability of water for agriculture or can mobilize health-related contaminants (Vengosh, 2014; Stets and others, 2020; Kaushal and others, 2021). Better understanding of these short-term and long-term drivers can allow us to better predict and manage salinity in the future. Consequently, integrated water availability studies could be improved by additional process-oriented research related to the following issues (among others).

Climate Factors

How are seasonal or interannual salinity trends in rivers and lakes affected by climatic fluctuations, such as storm events, droughts, and snow events? Climate change is an underlying part of many of the issues related to freshwater salinization. Here we focus predominantly on temporal changes that have effects on landscape-scale or over major geochemical processes. For example, changes in precipitation, phase, amount, and timing can affect the relative importance of salinity sources, such as groundwater inputs or agricultural water returns. Antecedent conditions and how climatic fluctuations interact with variable conditions on the landscape can alter the response of salinity to a given climatic event. During drought conditions, salt may accumulate in the subsurface over many years and as a region transitions to a wet period, accumulated salts are flushed; however, little is known about the timing and magnitude of these events. Climatic fluctuations can also affect groundwater and surface water interactions over time (Kløve and others, 2014), which may be an important consideration for salinity transport in some regions. In another example, freeze-thaw episodes followed by intense winter rainstorms can cause episodic salinization lasting from hours to days after snowstorms in response to road salting, triggering mobilization of different chemical cocktails and shifting acid-base status (Haq and others, 2018).

Hydrologic Characteristics of the Aquifer

In the Upper Colorado River Basin, climate driven changes in baseflow may increase dissolved solids loading and reverse the long-term dissolved solids decline observed in streams throughout the twentieth century (Miller and others, 2021; Rumsey and others, 2021). In some groundwater systems, the lag time between the start of a land-use practice and arrival of contaminants in deep parts of aquifers can be long. Therefore, hydrologic characteristics of aquifers are also important factors with respect to temporal change. Some of the limitations regarding the availability of this sort of data related to aquifer storage and transmissivity are outlined for brackish water resources in Stanton and others (2017), which is described in the section “Gap 3. Improving Assessments of Brackish Water Resources,” but filling those data gaps may also apply here, particularly in the case of compiling additional data from multiple sources that provide estimates of needed parameters (for example, porosity, permeability, and storage coefficients).

Land and Water Use Change

In areas of major water diversion or where beneficial uses will be affected by salinization, how is salinity affected by withdrawals and hydrology? Climate change, increasing population, and increasing power generation are all drivers of water scarcity. How land and surface water is managed to address that scarcity and how that management can alter water quality is a consideration that we focus on here. Water diversions or interbasin transfers are a major tool in addressing water availability in areas of increasing water scarcity. Droughts are increasing in frequency and severity in many areas (Williams and others, 2020) resulting in decreased flow and volume in streams and increased saline groundwater inputs leading to increased salinity due to reduced dilution and concentration of mass (Mosley, 2015). Droughts are associated with increases in lake and reservoir salinity as a result of reduced outflows and evapoconcentration (Mosley, 2015). Land use and landscape changes and drought can negatively affect salinity in a region, while implementing land management practices such as improving irrigation systems, recovery of vegetation and soil condition, and construction of reservoirs may substantially affect how salinity is transported to streams (Rumsey and others, 2021). Migration of the salt front upstream during droughts in estuaries has also been reported (McAnaly and Pritchard, 1997). Release of water from impoundments during periods of low flow can be used to prevent upstream movement of saltwater. The Delaware River Basin Commission (DRBC) Flexible Flow Management Plan is an agreement between New York City (which transfers a large amount of water outside of the watershed) and the DRBC to maintain sufficient flows during periods of low flow in the Delaware River to prevent upstream migration of the salt front which threatens water supply intakes in Philadelphia and other communities (DRBC, 2020).

Sea-Level Rise

Effects from coastal flooding and inundation, exacerbated by sea-level rise and population growth in coastal regions, are expected to increase in upcoming decades (Strauss and others, 2012). Flooding and storm surges inundate lands trapping saline water in depressions and soils in areas previously not exposed to saltwater. Along coastal wetlands, saltwater is seeping further inland through soils causing woodlands to die and be replaced with more salt-tolerant shrubs and grasses threatening wildlife, ecosystems and local farms and forestry businesses. Increasing sea-level rise and storm surge can drive salt water up coastal rivers placing water supply intakes at risk. In addition, lateral encroachment of seawater along coastal areas combined with excessive groundwater pumping can reduce freshwater flow toward coastal areas and cause saltwater to be drawn toward freshwater zones in coastal aquifers decreasing freshwater storage and potentially making the resource unsuitable for use or increasing the cost of desalinization.

Approaches for Predicting and Understanding Trends

To evaluate seasonal, interannual, and long-term trends, continuous sensors allow salinity to be monitored frequently, preferably across a range of land use types and precipitation patterns (rain, snow, snow melt, arid, humid, urban, agriculture). Continuous sensors typically measure specific conductance (SC) which can then be used as a proxy for chloride concentrations. Because the relation between SC and chloride concentrations varies by region, these high-frequency data will need to be combined with new approaches to modeling and links to other geochemical data (McCleskey and others, 2012; Kaushal and others, 2021) to fully understand temporal variability and drivers of salinity change. Establishing relations between SC, chloride, and other constituents may be more difficult to achieve for groundwater than for surface water because groundwater-quality data are usually sparser. Increased groundwater-quality data collection with special consideration for areas where groundwater discharges to surface water may greatly improve our understanding of salinity trends in different hydrologic compartments. Short to long-term changes in drivers should also consider shifts in relative contributions of mixing water (seawater, stormwater, urban sources, groundwater, and so forth) or water-rock interaction (as water is displaced or water tables rise or fall) and the resulting changes in water quality. Deliverables for this work could be high-frequency sampled salinity data for target basins that can be used to better understand and predict natural and human-accelerated salinization on short-term to decadal scales, and an interpretation of the chemical and physical processes driving these changes.

Gap 3. Improving Assessments of Brackish Water Resources

The increasing reliance on brackish water resources seems a certainty in the face of decreasing water supply and deteriorating water quality (Vengosh, 2014). Because of the importance of brackish water as a groundwater resource, Stanton and others (2017) proposed next steps and identified data gaps in an expanded effort to understand the distribution and chemistry of brackish groundwater (BGW) resources in the United States. Their gap identification was distributed into five categories: (1) “Occurrence and Distribution of Brackish Groundwater,” (2) “Hydrogeologic Characterization,” (3) “Geochemistry,” (4) “Brackish Groundwater Use,” and (5) “Sustainability.” Specific recommendations in these categories that are most related to USGS water-quality process research are in the categories of “Geochemistry” and “Sustainability.” Their primary recommendations related to geochemistry include: (1) complete a more thorough review and compilation of existing geochemistry data that are not readily accessible in digital format, and (2) explore links between geochemistry, required water treatment, and potential end users with the aid of geochemical modeling and simulations. Stanton and others (2017, p. 144) primary recommendations related to sustainability are to do the following:

> Assess BGW sustainability with use of appropriate tools (models to simulate water movement and transport) to quantify the response (flow and chemistry) of a principal aquifer to extraction of BGW. Numerical models, groundwater age dating, and time-series water-quality sampling would aid in understanding effects of development, such as the alteration of hydraulic properties because of changes in water chemistry; effects on geochemistry of the inflow of more mineralized or fresher water into the reservoir (for example, mobilization of other unwanted constituents); possibility for subsidence; and whether or not BGW resources are renewable at a timescale of human use.

Based on our review and the recommendations of Stanton and others (2017), we identify the next steps and data gaps to understand the distribution and chemistry of BGW resources in the United States.

Refining Knowledge of the Distribution of Brackish Groundwater Resources

The recent USGS national brackish groundwater resource assessment (Stanton and others, 2017) estimated the distribution of saline and brackish groundwater in the United States by using a compiled database of chemistry data from wells. Results of that study could be refined and extended in several different ways. For example: ensuing research to address the recommendations of Stanton and others (2017) could include a more thorough review and compilation of existing geochemistry data and the addition of geophysical data, such as existing surface geophysical surveys and borehole logs, to refine spatial resolution. Borehole logs of electrical properties could provide improved resolution of the depths and shapes of salinity gradients that are needed for delineating boundaries and determining actual volumes of fresh, brackish, and saline groundwater (Williams and others, 2013; Stephens and others, 2019). Borehole logs also could be used to refine the distribution of geologic features that control the distribution of groundwater salinity, potentially leading to improved interpolation models.

Refining Knowledge of the Sustainable Use of Brackish Groundwater Resources

Understanding the sustainable use of BGW resources is an essential area of research. This includes efforts to refine the distribution of hydrogeologic properties affecting the sustainable use of brackish and saline groundwater. Sustainability of deep groundwater resources depends on hydrogeologic properties such as porosity, permeability, recharge, discharge, confinement, and connection with adjacent aquifers. The subsurface distribution of such properties could be refined with three-dimensional (3-D) geologic maps, borehole descriptions, well yields, and pump tests. Research on sustainability of use also includes efforts to investigate temporal salinity variations in existing chemical data from wells. The previous national-scale BGW study (Stanton and others, 2017) focused on spatial variations by selecting single analyses from each well. Further analysis of the data could determine if there are trends in some wells indicating responses to pumping, seawater intrusion, anthropogenic contamination, or other processes. Predictions of BGW trends and sustainability could be improved with additional knowledge of groundwater ages and flow velocities. Such information could be obtained by using groundwater models calibrated with analyses of environmental tracers of groundwater chemical and isotopic age ranging from decades to more than one million years. Further work on sustainability includes incorporating brackish and saline groundwater within regional integrated water availability assessments for multiple uses. Local water availability and water needs commonly are not well matched and may require multiple water sources with a range of salinities that need to be integrated and combined with various treatment and distribution options. Water use sustainability could be improved by comprehensive collaborative (interagency) regional investigations of potable and non-potable groundwater and surface water resources in context with various use requirements and treatment options.

Water Treatment and Essential Research on Desalination

Desalination or other water treatments are a technical solution to freshwater scarcity, but there are essential research needs in the creation of this new fresh water (Vengosh 2014; Ahdab and Lienhard, 2021). Research in this category includes the need to develop geochemical modeling tools to assist water treatment and planning. Variability in the chemical composition of brackish and saline water resources affects the evaluation of water treatment needs and the design and energy requirements of treatment processes (McMahon and others, 2016; Ahdab and others, 2018). Geochemical modeling software could facilitate such work, with reference to the natural distribution of geochemical conditions. Geochemical modeling could also support water-quality models through the prediction of the chemical compositions of desalinated water and brine wastewaters and their return to the environment. Forensic tools described above could assist in evaluating the fate of these "anthropogenic" waters in the environment (Vengosh, 2014). There is also a need to evaluate the distribution of potentially valuable byproducts associated with desalination processes. Desalination facilities can include processes that recover valuable commodities from the waste stream. Geochemical databases could be evaluated for the distribution of metals and other potentially useful constituents in non-potable waters. California Energy Commission's Energy Research and Development Division is investigating the potential for co-production of power and lithium carbonate (used in electric vehicle batteries), from geothermal brines like those found in the Salton Sea (Ventura and others, 2020).

Gap 4. Identifying the Components of Salinity and Their Effect on Contaminant Mobility

Whereas high salinity water tends to be predominantly NaCl-type water, brackish water occurs in a range of geochemical types such as sodium bicarbonate, calcium sulfate, Na, Cl, and mixed (Stanton and others, 2017). Much of the work on the environmental effects of salinization has focused on Na and Cl; but different components of salinity—Na, Mg, barium (Ba), bicarbonate (HCO_3^-), sulfate, and silica—are recognized to limit the beneficial uses of water in different ways (Vengosh, 2014; McMahon and others, 2016). Examples include: (1) groundwater saturated with barite can cause scaling problems when water is used or treated; (2) different major ion ratios have different properties related to corrosion that may affect drinking water infrastructure; and (3) ion ratios in irrigation water can affect soil fertility or have undesirable effects on the chemistry of agricultural return water. A survey of the importance and availability of data on major ion ratios (for example, Cl and SO_4^{2-}, Na and K, and Cl and HCO_3^-) related to salinity in freshwater systems would be beneficial for understanding the effects of salinization. In addition, predictive models for geochemical water type in groundwater based on local geologic, hydrologic, and climatic conditions could be applied more widely. There is also an important link between salinization and the mobilization of health-based contaminants (Vengosh, 2014). Consequently, a vital area of research in salinity is the evaluation and geochemical modeling of chemical composition of saline water and associated contaminants (see the geogenic section of this report, chapter C "Geogenic Water-Quality Effects on Beneficial Uses"). Examples of this kind of research include:

- The prediction of major ion ratios and effects on beneficial uses via corrosion, mobilization of contaminants, and suitability for use.
- An examination of the role of salinity in the prediction of health-related geogenic constituents (for example, fluorine [F], arsenic [As], selenium [Se], boron [B], and radium [Ra])
- Inclusion in models of prediction of water types based on geochemical processes (for example, base cation exchange, freshening, generation of dissolved inorganic carbon (DIC) by oxidation of organic matter).

Expected Outcomes

The significance of data gaps with regards to addressing the challenge of salinization and assessing groundwater resources is captured in three quotes from USGS research papers that we present here. From Stets and others (2020, p. 4336):

> "… increasing salinity negatively affects biodiversity, mobilizes sediment-bound contaminants, and increases lead contamination of drinking water, but the effects are not well integrated into current paradigms of water management…"

> and on p. 4241:

> "…Water-quality regulations and best management practices designed to address the problems of excess nutrients and sediments in surface waters are not adequate to curtail the growing problem of salinization, which is driven by different sources. More research is needed to understand how increases in salinity, and in specific major ion concentrations, might be affecting aquatic ecology and ecosystem services. Regular, broad, large-scale studies are crucial to provide appropriate context of the largest changes in water quality and can serve as a basis for up-to-date research and decision-making to respond appropriately to the most important threats facing water supplies for human and ecological well-being."

> Stanton and others (2017, p. 6) note that:

> "Future water demand is projected to heighten the stress on groundwater resources…this increased water demand coupled with projected climate change could produce moderate to extreme risk to water-supply sustainability for most of the United States…To ensure the water security of the Nation, untapped water sources may need to be developed in some areas. Brackish is a nontraditional water source that may offer a partial solution to current and future water challenges."

The research gaps discussed are crucial areas of research in an emerging national problem, which is comparable in scale to acid rain, eutrophication, loss of biodiversity, and other mainstream environmental issues (Kaushal and others, 2021). Essential in developing a management approach for salinization and increasing water scarcity, the following are needed to identify the next generation of research and management topics: (1) the development of regional mass balance and forensic tools to identify salinity sources and drivers, (2) deployment of high-frequency sampling sensors to improve trend assessments, (3) refining knowledge of the distribution and chemistry of brackish groundwater, and (4) developing geochemical modeling approaches for the examination of the components of salinity and mobilization of contaminants.

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