ANNUAL REVIEWS

Annual Review of Marine Science

Hidden Threat: The Influence of Sea-Level Rise on Coastal Groundwater and the Convergence of Impacts on Municipal Infrastructure

Shellie Habel, Charles H. Fletcher, Matthew M. Barbee, and Kyrstin L. Fornace

Department of Earth Sciences, School of Ocean and Earth Science and Technology, University of Hawaiʻi at Mānoa, Honolulu, Hawaiʻi, USA; email: skey@hawaii.edu

Annu. Rev. Mar. Sci. 2024. 16:9.1–9.23

The *Annual Review of Marine Science* is online at marine.annualreviews.org

https://doi.org/10.1146/annurev-marine-020923-120737

Keywords

coastal groundwater, sea-level rise, shallow water table, groundwater inundation, saline groundwater, infrastructure impacts

Abstract

Sea-level rise (SLR) is influencing coastal groundwater by both elevating the water table and shifting salinity profiles landward, making the subsurface increasingly corrosive. Low-lying coastal municipalities worldwide (potentially 1,546, according to preliminary analysis) are vulnerable to an array of impacts spurred by these phenomena, which can occur decades before SLR-induced surface inundation. Damage is accumulating across a variety of infrastructure networks that extend partially and fully beneath the ground surface. Because the resulting damage is largely concealed and imperceptible, it is largely overlooked as part of infrastructure management and planning. Here, we provide an overview of SLR-influenced coastal groundwater and related processes that have the potential to damage societally critical infrastructure and mobilize urban contamination. In an effort to promote research efforts that can inform effective adaptation and management, we discuss various impacts to critical infrastructure and propose actions based on literature focused specifically on SLR-influenced coastal groundwater.

1. INTRODUCTION

SLR: sea-level rise

Low-lying coastal regions are host to the largest concentrations of urban development on Earth (Small & Cohen 2004). Coastal hazards in the form of urban flooding have produced severe economic and social impacts in the past and have become increasingly severe in recent decades (Natl. Acad. Sci. Med. Eng. 2019). The convergence of sprawling coastal municipalities and the exacerbation of coastal hazards by sea-level rise (SLR) have highlighted the need among the urban planning community for evolved approaches to land management and risk reduction (Natl. Acad. Sci. Med. Eng. 2019). In response, vulnerability assessments have become a common approach toward informing policy and planning efforts. While well intentioned, such assessments have rarely considered the contribution of groundwater-related impacts, which can occur decades prior to SLR-induced surface inundation (Rozell 2021). Even forward-looking vulnerability assessments that consider SLR and storm surge have focused largely on the vulnerability of aboveground infrastructure (Abuodha & Woodroffe 2010, Buchanan et al. 2016, Parkinson 2021). Such focus can result in management efforts that are partially ineffective and can take the form of maladaptation. For example, installation of seawalls and tide gates is the most common management strategy considered by coastal municipalities, yet neither addresses changes in coastal groundwater (Azevedo de Almeida & Mostafavi 2016).

This review is organized to first provide a brief general introduction on coastal groundwater and the processes that influence it. Classic equations that illustrate physical principles behind tidal and SLR influence are provided as a resource and to illustrate that these phenomena are well understood from a theoretical standpoint in addition to being observed. The article then describes how SLR-influenced groundwater is damaging various components of critical infrastructure as a result of increased groundwater salinization and water-table rise. Issues regarding contamination are also discussed. Finally, a preliminary analysis is presented that identifies global municipalities and populations potentially vulnerable to the damage described. While it is understood that degradation of drinking-water resources is a critical impact of SLR-induced groundwater salinization, we have chosen to omit this topic owing to its thorough coverage elsewhere (Ketabchi et al. 2016, Lassiter 2021). Also not covered is the elevated risk of liquefaction by SLR-influenced groundwater, specifically in seismically active coastal areas (Abueladas et al. 2021, Grant et al. 2021, Quilter et al. 2015, Risken et al. 2015). This review is intended to provide a helpful tool for those concerned about the obscured realm of marine-influenced groundwater and how it surreptitiously affects some of the most heavily populated and developed environments.

1.1. Coastal Groundwater

Along coastal zones, groundwater and seawater are directly connected. From a hydrogeological perspective, coastal zones are defined as regions where salty waters of marine origin and fresh groundwater of meteoric origin interact (Jiao & Post 2019). A shared characteristic of all coastal aquifers is the presence of an interface between saltwater and freshwater that extends along all coastal boundaries. The general location and shape of that interface are a product of density differences between saltwater and freshwater, which results in an interface that extends inland from the coastline as a wedge shape between the base of the aquifer and overlying freshwater (du Commun 1828). However, the specific location and sharpness of that interface are unique for each location and depend on the local climate, properties of the aquifer, and presence of anthropogenic activities (e.g., groundwater extraction).

Another shared characteristic of aquifers is the presence of a hydraulic gradient, or flow from higher to lower hydraulic head, in which the hydraulic head in an unconfined coastal aquifer is a measure of the elevation of groundwater above sea level (i.e., the water table). Generally, the hydraulic gradient slopes downward from inland areas toward the ocean as water infiltrating from rainfall flows toward a lower hydraulic head at sea level. Similar to the saltwater interface, natural factors that influence the shape of the hydraulic gradient are the rates of recharge (e.g., rainfall) and properties of the aquifer. Nonnatural processes, such as land-use changes or groundwater extraction, can also influence the hydraulic gradient and can even reverse it, which can draw the saltwater interface farther inland [i.e., saltwater intrusion (SWI)].

SWI: saltwater intrusion

In coastal aquifers, hydraulic head is also controlled by variations in sea level, such as those produced by ocean tides, in which water is forced into and out of unconfined coastal aquifers and pressure is loaded onto and off of confined coastal aquifers. This results in groundwater levels near the ocean rising and falling. This effect has been recognized for centuries through descriptions made by early scholars, and even noted in the work of Charles Darwin (Darwin 1852, Jiao & Post 2019). Over the nineteenth and twentieth centuries, that understanding was honed such that aquifer properties could be estimated based on tide–groundwater relationships (Ferris 1952, Jacob 1940, Merritt 2004). General takeaways from this work are that tidal signals propagate inland through groundwater at a rate that varies based on aquifer properties and the period of the tidal signal (Equations 1 and 2 below). The amplitude of that signal decays exponentially and becomes more delayed as it travels inland (**Figure 1**).

Tidal influence on water-table elevations can be expressed by the following, as adapted from Jacob (1950) by Jiao & Post (2019):

$$h(x,t) = A_s e^{-x\sqrt{\pi S/\tau T}} \cos\left[\omega\left(t - t_{\mathrm{lag}}\right)\right], \qquad 1.$$

where h [in length (L) units] is the groundwater head (i.e., water-table elevation) at distance x (L) from the tidal boundary (e.g., coastline) at time t [in time (T) units], A_s (L) is the tidal amplitude, τ (T) is the period of the tidal harmonic oscillation, ω (T^{-1}) is the frequency of the tidal harmonic oscillation, t_{lag} (T) is the time between the peak of high tide and the corresponding peak of the

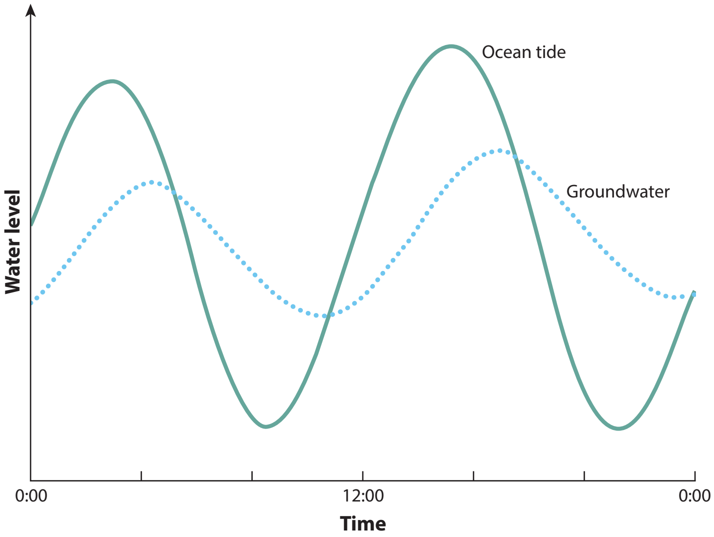


Figure 1

Example of influence of the ocean tide on coastal groundwater. Note the dampening of the tidal amplitude and lag of the signal owing to propagation through the aquifer. Figure adapted from the book *Coastal Hydrogeology* by Jimmy Jiao and Vincent Post (Jiao & Post 2019) with permission of the Licensor through PLSclear; copyright 2019 Jimmy Jiao and Vincent Post.

groundwater level, S (unitless) is the aquifer storage coefficient (i.e., the aquifer property characterizing the relationship between water-volume loss per unit drop in water-table level), and T (L^2 T^{-1}) is the aquifer transmissivity (i.e., the aquifer property characterizing the rate of horizontal groundwater flow). Tidal lag can be expressed by the following (Jiao & Post 2019):

$$t_{\text{lag}} = x\sqrt{\tau S/4\pi T}. \qquad 2.$$

General assumptions include that the subject aquifer is homogeneous and isotropic, extends an infinite distance inland, and does not feature appreciable vertical flow and that the saturated aquifer thickness is sufficiently large relative to the amplitude of water-table fluctuations. Tidal oscillation is represented by a single cosine function that can consist of superimposed tidal constituents or an individual tidal constituent. When the solution is applied to an unconfined aquifer, the storage coefficient (S) may be orders of magnitude larger than that of a confined aquifer. This has the effect of quickly reducing the amplitude of tidally forced head with distance inland (Jiao & Tang 1999); however, these solutions have been applied successfully to unconfined aquifers (Erskine 1991). If the transmissivity of an unconfined aquifer is very high, which is not uncommon of coastal aquifers, oscillations can be observed more than 400 m inland (Merritt 2004).

The influence on an aquifer of long-term changes in sea level, such as by present-day SLR, is a phenomenon that has been theoretically established (Equations 3 and 4 below) in addition to being physically observed. Sea level forms the hydrological base level of a coastal aquifer, and correspondingly, the dynamic equilibrium of the water table and the saltwater interface migrates based on long-term changes in sea level (Jiao & Post 2019).

The direct influence of long-term sea-level change on groundwater elevation has been documented in various studies. In Cape Cod, Massachusetts, groundwater levels recorded over a 50-year period illustrate groundwater rise at rates approximately equivalent to the local rate of SLR observed at the Boston tide gauge (McCobb & Weiskel 2003). In Miami-Dade County, Florida, groundwater-level observations recorded from 1959 to 2017 similarly illustrate an upward trend in groundwater level consistent with the local rate of SLR observed at the Key West tide gauge (Sukop et al. 2018). In Honolulu, Hawaiʻi, groundwater levels measured at four shallow monitoring wells approximately track long-term variations in ocean levels observed at the Honolulu tide gauge (Habel et al. 2017).

These observations align with conceptual models of SLR and the resulting groundwater rise. Models indicate that the magnitude of rise in coastal groundwater is equivalent to SLR, specifically in aquifers that feature enough vertical unsaturated space to accommodate the elevated hydraulic gradient (Michael et al. 2013) (**Figure 2**).

The elevated height of groundwater considering SLR influence is expressed as follows based on the Ghijben–Herzberg principle (du Commun 1828, Herzberg 1901) and the Dupuit assumption (Dupuit 1863):

$$h = \sqrt{\frac{w\,(\rho_{\text{s}} - \rho_{\text{f}})}{K\rho_{\text{s}}}\,(L^2 - x^2)} + (H_0 + \Delta H)\,,(x_{\text{tn}} \leq x \leq L), \qquad 3.$$

where h (L) is the groundwater head (i.e., water-table elevation) at distance x (L) from the shoreline; w (L T^{-1}) is the volumetric recharge rate per unit area (e.g., rainfall); ρ_{f} and ρ_{s} [mass (M) L^{-3}] are the density of freshwater and saltwater, respectively; K (L T^{-1}) is the hydraulic conductivity [i.e., the aquifer property that describes how quickly water can flow through soil or rock; in general, hydraulic conductivity values can range from 10^{-9} cm s^{-1} in clay materials to 1 cm s^{-1} in gravel materials (Fetter 2001)]; L (L) is the distance from the groundwater divide to the shoreline (the groundwater divide is the location where the hydraulic gradient becomes flat, separating the direction of flow); H_0 (L) is the height of sea level from a set vertical origin; ΔH (L) is the increase

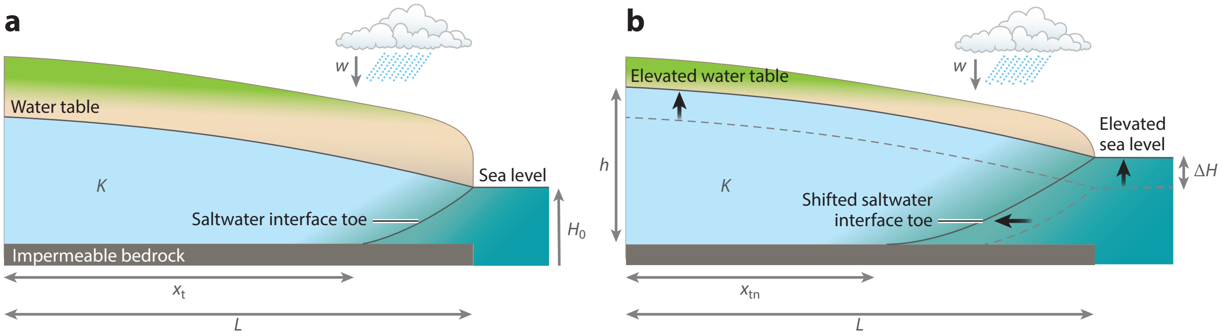


Figure 2

Conceptual model of an unconfined coastal aquifer (*a*) prior to and (*b*) following a rise in sea level. Figure adapted from the book *Coastal Hydrogeology* by Jimmy Jiao and Vincent Post (Jiao & Post 2019) with permission of the Licensor through PLSclear; copyright 2019 Jimmy Jiao and Vincent Post.

in sea-level elevation; and x_{tn} (L) is the horizontal distance from the groundwater divide after the sea-level perturbation.

In areas inland of influence from the saltwater interface, the groundwater level increases as a result of SLR; however, the resulting increases are not linear (Jiao & Post 2019). The following expression of SLR influence connects continuously with the expression above (Equation 3):

$$h = \sqrt{\left(\frac{w}{K}\right)(L^2 - x^2) + \frac{\rho_{\mathrm{s}}}{\rho_{\mathrm{f}}}(H_0 + \Delta H)^2}, 0 \leq x \leq x_{\mathrm{tn}}. \qquad 4.$$

General assumptions include that the subject aquifer is homogeneous and isotropic and extends infinitely along a straight shoreline and that, per the Dupuit assumption, vertical flow in the freshwater region is negligible, such that the elevation of freshwater above sea level is equal to the water-table elevation.

In addition to illustrating the influence of SLR on groundwater elevation, Equations 3 and 4 show that higher ratios of recharge (w) to hydraulic conductivity (K) produce elevated groundwater levels relative to conditions featuring lower w/K ratios. Thus, conditions featuring high rates of recharge and low hydraulic conductivities can be expected to host elevated water levels relative to conditions featuring low rates of recharge and high hydraulic conductivities.

The location of the SLR-influenced saltwater interface can be expressed as follows by letting h equal $\rho_{\mathrm{s}}(H_0 + \Delta H)/\rho_{\mathrm{f}}$ and solving for x in Equation 3 (Jiao & Post 2019):

$$x_{\mathrm{tn}} = \sqrt{L^2 - \frac{K\left(\rho_{\mathrm{s}}^2 - \rho_{\mathrm{s}}\rho_{\mathrm{f}}\right)}{w\rho_{\mathrm{f}}^2}(H_0 + \Delta H)^2}. \qquad 5.$$

Equation 5 illustrates that a higher rate of recharge (w) will result in a more seaward location of the interface, while a higher hydraulic conductivity (K) will result in a more landward location of the interface.

The above conceptual models assume the presence of adequate vertical space to accommodate the elevated hydraulic gradient. In cases where the hydraulic gradient either reaches the land surface or inundates features that allow it to drain (e.g., buried drainage or wastewater conveyance infrastructure), groundwater levels do not rise linearly since water is drained from the aquifer. When this occurs, the nonlinear aquifer response to SLR is termed the topography-limited or head-controlled response (Befus et al. 2020, Michael et al. 2013). When a coastal aquifer drains as such, SWI intensifies as saline water moves inland to areas originally occupied by freshwater.

When an aquifer reaches the topography-limited mode, there are serious implications for urban coastlines that include direct flooding of the ground surface and/or inundation of buried infrastructure, in addition to increased salinity and corrosion potential of subsurface soils (Befus et al. 2020).

GMSL: global mean sea level

1.2. Present Observations and Future Projections of Sea-Level Rise

Ongoing global mean SLR and acceleration have been well established and clearly observed and provide the basis for projections of future SLR magnitudes (IPCC 2022, Nerem et al. 2022, Sweet et al. 2022). From 1901 to 2018, global mean sea level (GMSL) has risen 0.2 m, which is the fastest century-long rise experienced over the last three millennia (IPCC 2022). Since the late 1960s, the rate of GMSL rise has ticked up from 2.3 mm y^{-1} (1971–2018) to 2.7 mm y^{-1} (2006–2018), illustrating that acceleration is indeed occurring (IPCC 2022). Overall, climate projections point to a likely rise in GMSL of between 0.15 and 0.30 m by 2050 and between 0.28 and 1.01 m by 2100 (relative to 1995–2014); however, these projections do not consider the possibility of poorly understood ice-instability processes that could strongly increase Antarctic mass loss and in turn lead to more extreme rates of rise (IPCC 2022). A combination of expert judgment (Bamber et al. 2019), model results incorporating ice-shelf hydrofracturing and collapse (DeConto et al. 2021), and the IPCC's very-high-emissions scenario [shared socioeconomic pathway 5-8.5 (SSP5-8.5)] (IPCC 2022) indicates that there is a 20% probability of exceeding 1.5 m of GMSL rise (relative to 2005) (Sweet et al. 2022).

Some regions have more to worry about than others. Rates of regional SLR are not uniform; some locations experience rates three times higher than the global average, while others have experienced very little rise over the same time period (Church et al. 2013, Nerem et al. 2010). A region's relative rate of SLR includes the sum of contributions from vertical land motion, ocean thermal expansion, mass loss from glaciers, and ocean dynamics, as well as variations in Earth's gravity, rotation, and deformation due to land-ice and land-water distribution changes (IPCC 2022). Increased relative SLR due to vertical land motion has become a considerable issue, caused in part by overpumping of coastal aquifers (Chen et al. 2003), draining of lowlands (Erkens et al. 2016), and loading by construction of high-rise buildings (Xu et al. 2012). A study that investigated subsidence rates in 99 coastal cities around the world found that the majority of sites featured land subsidence at rates higher than that of global SLR (Wu et al. 2022). As a consequence, municipalities will be challenged by both direct marine and groundwater-related flooding much sooner than would be anticipated when considering rates of global SLR alone.

1.3. Research Regarding Sea-Level-Rise-Induced Groundwater Impacts

Acknowledgment of the role SLR-influenced groundwater plays in flooding began in the early 1990s, when it was recognized that elevated groundwater would result in increased surface runoff during rainfall events. As groundwater shallows, there exists less unsaturated soil space to accommodate infiltration (Nuttle & Portnoy 1992). Studies in the 1990s also recognized the role SLR plays in accelerating salinization of coastal aquifers, as well as the irreversibility of the impact owing to mitigation measures being highly difficult and potentially infeasible (Oude Essink 1996).

In 2012, two prominent studies were published that recognized the role of SLR-influenced groundwater in producing potentially severe urban impacts through inundation. These case studies focused on impacts to Honolulu, Hawai‘i (Rotzoll & Fletcher 2012), and New Haven, Connecticut (Bjerklie et al. 2012), respectively; they represented locations on opposite coasts of the United States featuring very different subsurface geologies and yet identified similar impacts of this phenomenon. Specifically, Rotzoll & Fletcher (2012) were successful in bringing widespread awareness to the issue that SLR could generate additional flooding that seeps directly from the ground up, thus complicating adaptation efforts that attend solely to direct marine flooding. Their focus remained largely on the surface inundation of groundwater because their study took place on the low-elevation coastal plain of Honolulu. Bjerklie et al. (2012) identified increased risks to subsurface infrastructure, including basements, subsurface conveyance networks, and utility corridors, in addition to highlighting implications of increased runoff, similar to the findings of Nuttle & Portnoy (1992).

Since the publication of these landmark studies, this field of research has exploded and diversified into niches that focus on impacts to specific elements of society, the environment, and so on. In the following sections, we summarize findings related to various components of urban infrastructure and contamination.

2. IMPACTS OF SEA-LEVEL-RISE-INFLUENCED COASTAL GROUNDWATER

Municipalities worldwide host complex infrastructure networks that exist partially or entirely belowground. Components of this infrastructure facilitate transportation, provide structural support for buildings, distribute drinking water, enable sanitation, and manage stormwater (Zaini et al. 2015). Shallowing of coastal groundwater is known to cause an array of impacts on the various network components that perform these crucial functions (Abdelhafez et al. 2022, Knott et al. 2017, Luo et al. 2015, Miranda et al. 2019, Osman et al. 2017) (**Figure 3**).

The direct inundation of floodwater is often thought of as the main SLR-related threat, and one that is expected to progressively manifest over the coming decades (Sweet et al. 2018). However, the impacts related to elevated groundwater are arguably more immediate since many urban coastal areas already host critically shallow groundwater. For example, shallow groundwater has become problematic in low-lying urban areas of Australia (Morgan & Werner 2015), Bangladesh (Shamsudduha et al. 2020), the Dutch Delta cities (Amsterdam, Rotterdam, the Hague, and Utrecht) (Oude Essink et al. 2010), California (Befus et al. 2020), southeast Florida (Renken et al. 2005), and Hawai‘i (Habel et al. 2020). In coastal New Hampshire, the average depth to water is 3.6 m (Knott et al. 2018); in the urban district of Waikīkī, Hawai‘i, 42% of the area features groundwater depths shallower than 1.3 m (Habel et al. 2017); and Maryland barrier islands feature groundwater depths generally less than 1 m (Masterson et al. 2014).

Present and anticipated impacts to particular components of infrastructure are summarized below, including potential responses suggested by researchers in their respective fields.

2.1. Roadways

Groundwater rise affects roadways by infiltrating into their structural unbound base layers, reducing both their service life and their ability to carry heavy loads (Knott et al. 2017, Roshani 2014). Such damage is known to occur in areas with critically shallow groundwater tables (<1.5 m below ground level) (Knott et al. 2018). A study of SLR-induced roadway failure found that simulated groundwater shallowing reduces the service life of coastal pavement by half owing to fatigue-cracking distress and by up to 90% owing to rutting distress as base-layer saturation occurs (Knott et al. 2017). Furthermore, capillary rise through certain soil types can cause water ingress at elevations higher than the water table itself, particularly in areas hosting predominantly clay subsurface geologies (Roshani 2014).

Shallow groundwater also damages roadways through pressure-induced uplift (i.e., heaving effects) generated by tidally produced air pressure on the underside of pavements. Roadways are generally designed to accommodate downward loads that are monotonic (not cyclical, like that of

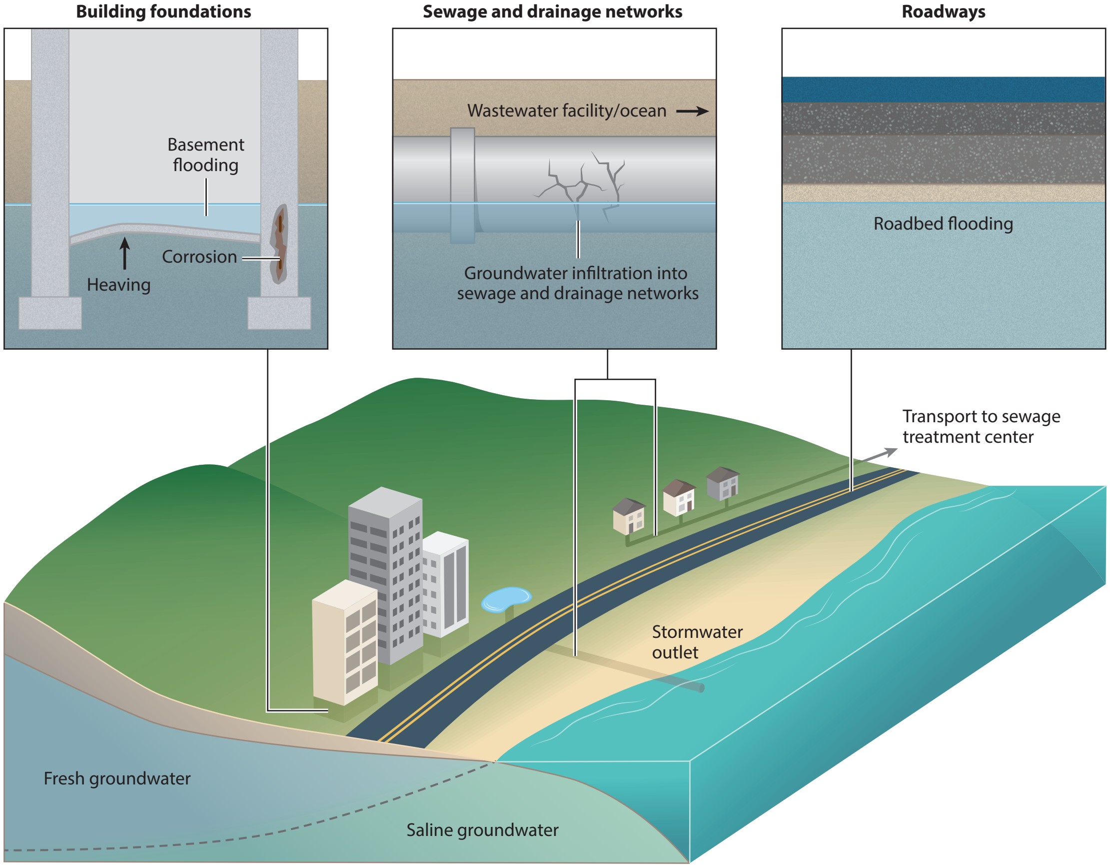


Figure 3

Groundwater inundation and resulting structural impacts on various types of submerged and low-lying infrastructure (building foundations, sewage and drainage networks, and roadways).

the tide); thus, upward cyclic loads can be particularly damaging even if loads are minimal (Jiao & Post 2019). An example of such effects impacted a main runway at Hong Kong International Airport, spurred by a combination of high tides and heavy rainfall; during this event, heaving induced by tidally influenced shallow groundwater caused premature wear, cracking, localized bulging, and temporary closure of the runway (Jiao & Li 2004, Leung et al. 2007). Groundwater shallowing has the potential to exacerbate these effects, particularly in extensively paved areas.

2.1.1. Management needs.

The findings described above have serious implications since reductions in roadway performance (e.g., by closure and degradation) are known to have severe social and economic impacts (Arkell & Darch 2006, Hooper et al. 2014, Sweet & Park 2014). Strategies that can be employed to reduce future damage include the enhancement of roadway design standards based on regional groundwater monitoring and simulations of SLR influence (Knott et al. 2018). Monitoring and modeling data can also be used to develop no-regrets and gradual adaptive management strategies in transportation planning (Berry et al. 2012, Knott et al. 2018).

An example of research-led adaptation planning was conducted by Knott et al. (2018). The authors considered projections of SLR-influenced groundwater in coastal New England, and their results suggested that the implementation of relatively simple structural pavement modifications over midterm timescales, such as adding material to the topmost roadway layer, would be highly effective in reducing structural damage. Over more long-term timescales, they proposed the development of a staged approach to roadway adaptation that could include building a more robust road base as part of major road maintenance projects. With regard to heaving effects, the installation of small-diameter pressure-relief holes in the asphalt pavement has been useful in reducing damage from upward loading (Leung et al. 2007).

2.2. Buildings

One of the main impacts of SLR-influenced groundwater on buildings is the degradation of their foundations by increased soil salinity (Abdelhafez et al. 2022, Medeiros-Junior 2018). Corrosion of these structural components can lead to reductions in carrying capacity, as well as cracking or spalling spurred by corrosion-induced expansion of reinforcing materials (e.g., rebar). Furthermore, such damage can go undetected as part of periodic inspections since buried building components are more difficult to access. This can result in the undetected spread of corrosion into a building's superstructure, causing the need for more costly and challenging repairs (Abdelhafez et al. 2022). Such corrosion can occur prior to direct contact with coastal groundwater owing to capillary rise that can draw moisture and salts up into building materials; materials featuring large pore sizes and fine cracks (e.g., concrete and brick) are particularly vulnerable to this process (Dep. Environ. Clim. Change N.S.W. 2008).

Other damaging impacts to buildings include direct inundation of basements by groundwater and disruption of foundations by water-pressure-induced uplift (i.e., heave) (Chaudhary 2012). In locations that host expansive soils, uplift can also result from partial soil saturation by capillary rise (Abdelhafez et al. 2022, Jones & Holtz 1973).

The various types of damage described above can lead to unexpected costs of upkeep and maintenance since SLR-influenced groundwater considerations are generally overlooked by building managers. However, increased awareness of SLR-influenced groundwater was recently spurred by the tragic collapse of the Champlain Towers South condominium in Surfside, Florida. The collapse occurred without warning on June 24, 2021, causing the deaths of 98 residents. Data resulting from an investigation into the incident indicated near-constant exceedance of the building's basement floor by groundwater-level fluctuations over the course of a year (2019–2020) (Parkinson 2021), although whether increased groundwater level and/or increased soil salinity contributed to the collapse remains inconclusive. However, the possibility reinforces the need for additional groundwater-related research, monitoring, and construction/structural assessment requirements across all coastal urban municipalities.

2.2.1. Management needs. Specific management strategies proposed by researchers include the use of anticorrosion technologies as part of construction in coastal municipalities, such as thicker protective coatings, impervious layers, or alternative building materials (Abdelhafez et al. 2022, Dep. Environ. Clim. Change N.S.W. 2008, Saha & Eckelman 2014). Researchers also suggest that frequent structural assessment become a general requirement for high-rise buildings, particularly in areas that host critically shallow groundwater (Abdelhafez et al. 2022). Such assessments would be useful in detecting deterioration and structural defects long before they become dangerous (Abdelhafez et al. 2022).

2.3. Water, Waste, and Stormwater Conveyance Infrastructure

A municipality's critical infrastructure includes a complicated underground conveyance network responsible for delivering drinking water, disposing of stormwater, and transporting wastewater to treatment centers. The buried location of this infrastructure subjects it to coastal groundwater and SLR influences that, similar to corrosion-induced damage in buildings, have the potential to go largely undetected. General impacts on these infrastructure components include physical damage from heaving as well as chemical corrosion exacerbated by tidally induced wetting and drying and the resulting formation of salt crystals that develop during moisture evaporation. Periodic wetting and drying cycles cause an increase in the concentration of salts over time, which in turn prompts accelerated damage to corrodible elements of these networks (Dep. Environ. Clim. Change N.S.W. 2008). Furthermore, groundwater contains aggressive ions that can cause electrochemical corrosion. Across large municipalities, buried networks are commonly composed of steel components owing in part to the material's strength and watertightness. However, steel is particularly prone to both chemical and electrochemical corrosion (Luo et al. 2015).

Consequences of network deterioration include increased leaks, main breaks, and frequent road closures due to pipeline repairs (EPA 2002). Failures of these systems also cause service interruptions and provide avenues for water and soil contamination, which have the potential to impact human health and the environment (Tansel & Zhang 2022). Below, we consider more specific impacts on individual components of conveyance infrastructure and potential responses to the impacts of SLR-influenced groundwater.

2.3.1. Drinking-water infrastructure.

The condition of municipal drinking-water infrastructure is in a general state of decline, increasing the risks related to water contamination, unnecessary water loss, and service disruption (Folkman 2018). This decline in the condition of water infrastructure is occurring in tandem with the direct impacts of SWI on drinking-water resources (Ketabchi et al. 2016, Lassiter 2021). A study that compiled data from municipalities across the United States and Canada found that over a period of six years (2012–2018), water-main breaks increased by 27% (Folkman 2018). This increase is in part due to aging systems; the national average time between water-main replacements is 125 years, but the average expected service life of an installed pipe is only 84 years, depending on soil corrosivity and installation practices (Folkman 2018). There is a direct correlation between soil corrosiveness and the break rates of metallic pipes (Folkman 2018), which, as previously described, is expected to increase as a result of SLR. Water loss due to leakage from defective drinking-water conveyance is approximately 10% of what is being conveyed (Folkman 2018), which exacerbates stresses on water resources already diminished by SWI and increased demand (Vorosmarty et al. 2000).

2.3.1.1. Management needs.

Effective management strategies for maintaining drinking-water infrastructure include timely pipe replacement and use of materials less susceptible to corrosion. Overall, there is a need for increased government resources allocated to infrastructure management agencies, specifically for those that oversee buried infrastructure in coastal areas. Additional resources could assist in identifying highly corrosive subsurface environments through soil testing and could be used to expand monitoring of infrastructure defects for use in targeted repair (Folkman 2018).

2.3.2. Storm drainage.

Coastal municipalities worldwide commonly manage precipitation-driven flooding using gravity-flow drainage networks (Kuo 1980). This type of system functions via elevation differences between wastewater inlets and discharge outlets that drive stormwater flow to receiving waters (e.g., ocean waters) (Gold et al. 2022). Generally, these networks have been designed to accommodate stationary climate conditions and a stationary discharge elevation (i.e., sea level). However, a changing climate has antiquated these design standards in two ways (Milly et al. 2008): (*a*) by increasing the elevation of receiving waters (also known as the tailwater level), thus reducing the rate and capacity at which these systems can drain, and (*b*) by altering capacity needs owing to anticipated increases in extreme rainfall (Fischer et al. 2014, Trenberth 2011). In short, the progressively hindered functionality of these systems can be expected to cause increasing amounts of urban flooding during both dry and wet weather.

An effective strategy for managing a high-tailwater condition is to install check valves that allow flow in only one direction, blocking ocean water from inundating the network (Sadler et al. 2020). Reducing ocean-water inundation in this way has multiple benefits that include reducing backflow into inland areas (streets, buildings, etc.), reducing the potential for increased corrosion and biofouling of drainage networks, and limiting salinization of inland coastal aquifers from this source (Gold et al. 2022). However, these strategies do not mitigate groundwater inundation of the network via pipe defects in areas where the drainage network intercepts elevated groundwater, such that capacity issues and reduced stormwater conveyance remain (Gold et al. 2022). Furthermore, elevated groundwater is expected to increase runoff potential resulting from reduced infiltration, in turn augmenting drainage capacity needs (Nuttle & Portnoy 1992).

An arguably positive effect of drainage inundation is that it can inhibit surface inundation by controlling groundwater elevation, turning the aquifer into a topography-limited system (see Section 1.1). In models of SLR, the extent of groundwater inundation in areas where shallow water tables intercept drainage networks is dampened in 70% of simulated coastal groundwater tables (Befus et al. 2020). This finding may suggest a means of controlling rising groundwater elevations without the use of extraction wells, by instead harnessing attributes of existing drainage infrastructure. However, managing groundwater elevations in this way increases the vulnerability of the aquifer to SWI (Befus et al. 2020, Michael et al. 2013). Defective drainage networks also have the added drawback of inducing sinkholes in areas where these networks intercept the wetting and drying zones of the tidally influenced aquifer (Burgos 2022, Luo et al. 2015).

2.3.2.1. Management needs. Effective management of these impacts requires identifying locations vulnerable to present and future drainage failure. Useful data products include regionally specific geospatial data that characterize locations and elevations of various network elements (Gold et al. 2022, Sadler et al. 2020). The combination of geospatial data and monitoring of system functionality can be used to validate tailwater conditions estimated by stormwater system modeling studies (Gold et al. 2022). The development of such models can help optimize network performance as part of short-term management strategies through targeted implementation of check valves, storm actuators, and pumps (Sadler et al. 2020).

Over the long term, management strategies will need to address stormwater network inundation and increases in stormwater runoff in tandem through efforts that include backflow prevention, stormwater harvesting, landscape planning, and potential managed retreat of highly vulnerable locations (Gold et al. 2022, Titus et al. 1987).

2.3.3. Sewage disposal and treatment. Since the nineteenth century, the implementation of widespread centralized sewage collection, conveyance, and treatment has led to improvements in both public health and population growth in metropolitan areas (EPA 2004). Like other components of buried infrastructure, wastewater assets in coastal areas are often located in tidal wetting and drying zones, which causes corrosion and the formation of defects. Brackish groundwater can then enter through defects, augmenting wastewater volumes being transported to treatment centers. Groundwater infiltration into sewage systems can account for 30–72% of total sewage flow (Zhao et al. 2020), which can be expected to increase with elevated groundwater (Fung & Babcock 2020). High tides have already been found to drive higher influent flows in wastewater collection systems serving coastal areas (Flood & Cahoon 2011).

Consequences of groundwater infiltration include erosion of soil surrounding pipe infrastructure and resulting structural damage to piping, overwhelming of wastewater treatment plants, and more frequent discharge of untreated wastewater to surface water bodies resulting from combined sewer-system overflows (Liu et al. 2018). The prevalence of such overflows is increasing and has been linked to the presence of high concentrations of dangerous contaminants such as antibiotic-resistant bacteria (Young et al. 2013).

OSDS: on-site sewage disposal system

With regard to increased loads on treatment centers, elevated effluent salinity originating from coastal groundwater infiltration has an array of its own impacts. In addition to intensifying the corrosion of treatment-center infrastructure, elevated salinity can limit the reusability of treated water, increase the production of hydrogen sulfide (a toxic gas), and impede treatment success by reducing microbial activity and diversity during treatment (Osman et al. 2017, Wu et al. 2008).

2.3.3.1. Management needs. An effective way to lower wastewater salinities and decrease infiltration-related loading at treatment centers is to attend to pipe defects (Fung & Babcock 2020, Miranda et al. 2019). Studies have detected likely areas of sewer-pipe defects by monitoring variations in flow rate across a network over spring- and neap-tide events (Miranda et al. 2019). Wastewater salinity monitoring has also been useful for adapting wastewater assets and treatment methods (Wu et al. 2008). Adverse effects of elevated salinity as part of sewage treatment can be overcome by adaptation of activated sludge to organic salts (Wu et al. 2008).

2.4. On-Site Sewage Disposal

A common alternative to municipal sewage treatment is the treatment of sewage on-site, through the use of on-site sewage disposal systems (OSDSs). Typically, these systems comprise either septic systems or cesspools. The United Nations and World Health Organization have estimated that 24% of global domestic wastewater (sewage effluent and wastewater) is generated by homes that employ OSDSs for treatment (UN-Habitat & WHO 2021).

OSDSs generally treat wastewater through various physical and biogeochemical subsurface processes that reduce, transform, absorb, or remove contaminants from household wastewater (Lusk 2022). Proper treatment requires sufficient vertical space above saturated soil to accommodate filtration (typically >60 cm) (Lusk 2022). However, reports by the United Nations and World Health Organization suggest that globally only 48% of these systems are properly treating domestic wastewater (UN-Habitat & WHO 2021).

Elevation of groundwater further diminishes the vertical space required for treatment (Cox et al. 2019, 2020). For example, viruses in wastewater are often neutralized when the viral outer protein coat is absorbed by the surfaces of unsaturated soil grains, degrading or deactivating those viruses. If soils underlying an OSDS are saturated by elevated groundwater, then the process of treatment through deactivation fails, allowing viruses to remain infectious (Lusk 2022). Dense urban areas, including Boston, New York City, and Miami, have already reported loss in OSDS functionality due to rising groundwater (Cox et al. 2019). In Miami-Dade County, 56% of septic systems are periodically compromised during storms. It is estimated that by 2040, this percentage will climb to 64% due to SLR-induced groundwater rise (Pierre-Louis 2021).

A study focusing on such impacts in Honolulu, Hawaiʻi, found that nearly 90% of OSDSs featured within the study area, particularly cesspools, are likely compromised during present-day king-tide events, suggesting that contamination of coastal groundwater by dysfunctional OSDSs is potentially pervasive (Habel et al. 2020). This finding was verified and expanded upon in a study by McKenzie et al. (2021), who found that contamination from defective wastewater infrastructure, including sewage conveyance infrastructure and OSDSs, is being transported into public spaces by groundwater (**Figure 4**). As part of the study, the authors used chemical tracers and contaminants of emerging concern to identify the presence of sewage effluent and verified that this effluent is

Figure 4

Example of a direct contamination pathway between public spaces and groundwater-inundated on-site sewage disposal systems. Figure reproduced with permission from Elle Wibisono and Hawai‘i Sea Grant.

indeed being carried to nearshore coastal waters of Waikīkī and backing up through inundated storm-drain infrastructure and into inland areas of urban Honolulu.

The situation revealed in Honolulu is a harbinger of a growing issue universal to any low-lying urbanized coastline featuring dysfunctional wastewater systems and local SLR. Thus, public-health concerns brought about by such factors can similarly be considered universal to such areas.

2.4.1. Management needs. Management strategies for dysfunctional OSDSs consist of identifying where upgrades are most necessary in terms of protecting public health and deciding how to best upgrade those systems (Mezzacapo 2019). Identification analyses can also be used to target where monitoring of OSDS functionality is most necessary (Mezzacapo 2019). An effective strategy for such identification includes comparing geospatial databases characterizing OSDS locations with monitoring and modeling products that illustrate present and future deficiencies in unsaturated soil (Habel et al. 2020, Whittier & El-Kadi 2014).

The development of funding and regulatory mechanisms has been highlighted as a fundamental need in the implementation of OSDS upgrades and connection to municipal sewer services (Mezzacapo 2019). Funding is also necessary to support the development of enhanced OSDS treatment capabilities specific for use in challenging environmental conditions like those presented by low-lying coastal areas (Lusk et al. 2017, Mezzacapo 2019).

2.5. Additional Sources of Coastal Groundwater Contamination

Owing to past land-use and reclamation practices, urban coastal zones often host large amounts of buried chemical contamination (Jiao & Post 2019, Lumb 1976). In coastal municipalities, common contaminants known to reside in the subsurface include petroleum, heavy metals, solvents, and persistent organic pollutants originating mainly from historical industrial and agricultural uses and releases (Felton & van der Zander 2021, May et al. 2020, Romero 2023). Across the state of Hawai‘i, for example, approximately 1,000 sites with known chemical contamination are monitored by the state’s Department of Health, many of which are situated in low-lying areas at risk of submersion (Felton & van der Zander 2021). Similarly, in Richmond

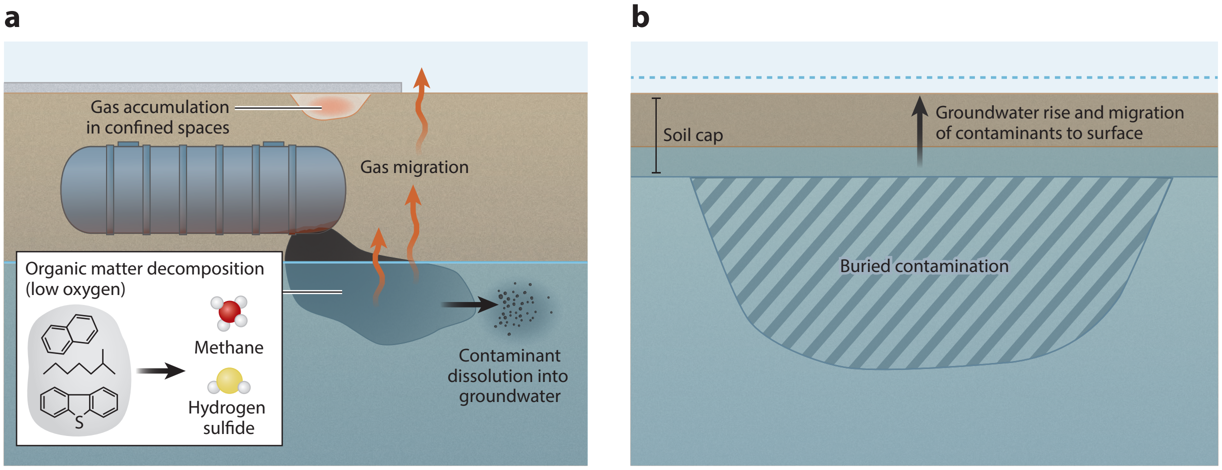


Figure 5

Two examples of how contamination can become a hazard to the public: (*a*) through increased generation of methane and hydrogen sulfide and elevation of those gases nearer to the ground surface and (*b*) by direct transport of buried contaminants to the ground surface.

City, California, housing development atop a heavily contaminated waterfront has drawn concern from researchers and state regulators regarding potential entrainment of contaminants by SLR-influenced groundwater (Romero 2023).

In-place management of contamination is a frequently employed strategy to prevent public exposure. However, it is one that assumes a stationary climate and thus is at risk of being rendered ineffective by SLR-influenced groundwater (**Figure 5**). Locations of particular concern are former coastal industrial sites, including harbors, airports, bulk fuel terminals, and formal landfill sites (Felton & van der Zander 2021).

There is additional concern regarding the potential for increased generation of methane and hydrogen-sulfide gas resulting from SLR-influenced groundwater submersion and anaerobic degradation of petroleum contamination. Elevated groundwater has the dual effect of expanding areas conducive to methane and hydrogen-sulfide generation and elevating these gases nearer to the ground surface, where they are more likely to encounter a source of ignition. Methane is known to migrate into buried spaces such as utility corridors and accumulate below paved surfaces, presenting a serious hazard to maintenance and construction crews and others who work in these spaces (Felton & van der Zander 2021) (**Figure 5**).

2.5.1. Management needs. The identification of high-risk sites can assist regulators in initiating remediation as staged triage through prioritization of areas where public exposure to emergent contaminants is imminent. An effective strategy for such identification includes comparing geospatial databases characterizing known sites of contamination with monitoring and modeling products that illustrate present and future groundwater levels (Felton & van der Zander 2021, May et al. 2020). Areas that often host contamination include dump sites, landfills, former bulk fuel terminals and associated pipeline networks, and areas of heavy contamination associated with past industrial activity (Felton & van der Zander 2021). Public areas can also host elevated contamination since many coastal municipalities are constructed on fill that may contain residential and industrial refuse (Felton & van der Zander 2021). Also, former landfills have commonly been transformed into public parks under which contaminants remain (Felton & van der Zander 2021, May et al. 2020).

3. GLOBAL IDENTIFICATION OF MUNICIPAL AREAS POTENTIALLY VULNERABLE TO SHALLOW GROUNDWATER IMPACTS

FUA: functional urban area

To identify urban locations potentially vulnerable to the impacts discussed here, we use the hydrostatic approach as described by Habel et al. (2019), assuming an SLR of 1.5 m. This method produces conservative estimates of groundwater inundation because it essentially simulates a flat hydraulic gradient positioned at an elevation equal to that of simulated sea level (Habel et al. 2019). It is reasonable to assume that the hydrostatic method represents a minimum estimate of groundwater elevation, and in turn of groundwater inundation, since in reality coastal groundwater elevations generally exceed that of their local mean sea level (Turner et al. 1997). Note that under this assumption, locations identified as featuring surficial inundation with an SLR of 1.5 m likely also feature groundwater depths of less than 1.5 m at present.

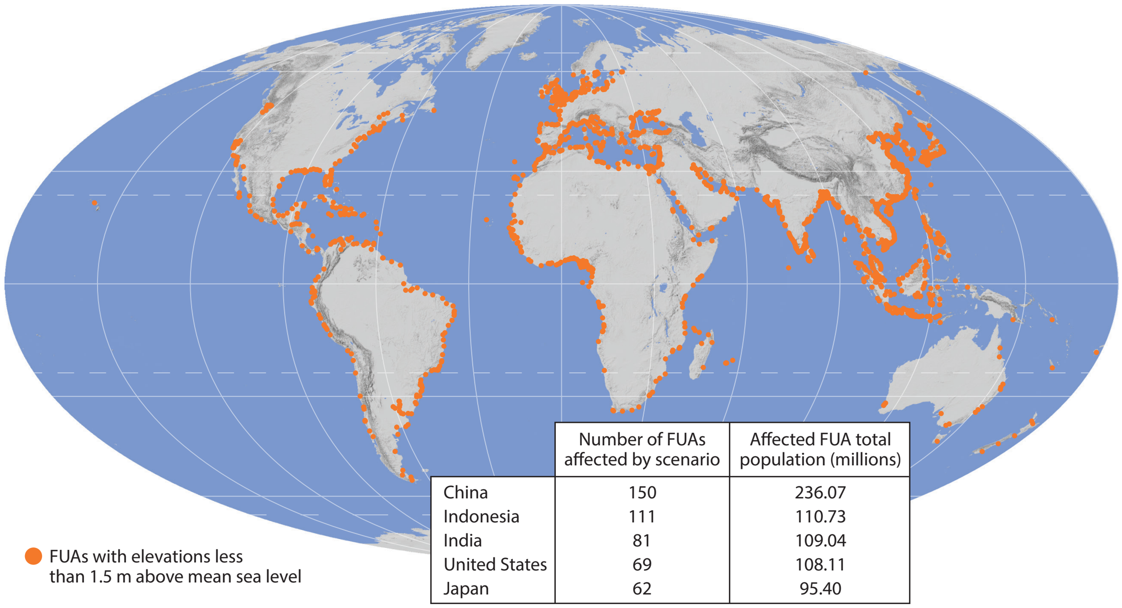
As part of this analysis, the CoastalDEM v2.1 elevation dataset (Kulp & Strauss 2021) was used to identify locations featuring elevations below a 1.5-m threshold. Identified locations were then compared with datasets characterizing functional urban areas (FUAs) to highlight where urban infrastructure may be impacted by critically shallow groundwater. Data characterizing global FUAs were sourced from the European Commission's Joint Research Centre Global Human Settlement Layer (Schiavina et al. 2019), and the population densities within the FUAs were sourced from a Global Human Settlement Layer population grid (2015 epoch) (Schiavina et al. 2022). FUAs are delineated according to the definition developed by the Organisation for Economic Co-operation and Development and the European Union as areas composed of high-density urban centers featuring at least 50,000 inhabitants plus their modeled surrounding commuter zones (Schiavina et al. 2019). As discussed, critically shallow groundwater and SWI can impact a myriad of urban infrastructure elements. These impacts affect both the residents and commuters that use the urban infrastructure. **Figure 6** depicts the global distribution of coastal urban areas featuring elevations less than 1.5 m within their extents.

Our analysis shows that, globally, 1,546 FUAs feature elevations of less than 1.5 m within their spatial extents. The sum population represented by the identified FUAs totals 1.42 billion people, illustrating the extent of humanity potentially affected by the impacts described in previous sections.

While this approach is useful for understanding the scope of the issues described, identifying vulnerabilities in this way is a preliminary approach, and researchers in their respective locations are encouraged to follow up with more intensive study. For instance, municipalities located in rural coastal areas falling outside FUAs are not considered in this analysis, even though they may be threatened by the described impacts. The 1.5-m scenario value does not exceed the errors (root mean square error or 90% linear error) associated with the global dataset (Kulp & Strauss 2021), as the quality and sources from which it was derived vary spatially across the globe (Uuemaa et al. 2020). Furthermore, regarding the hydrostatic approach, processes affecting vertical land motion are ignored, as are any time-dependent processes that would affect water-table elevations, such as tidal influence, rainfall, groundwater extraction or injection, and dynamic changes in landscape (erosion).

4. CONCLUSION AND RECOMMENDATIONS

The multifaceted degradation of buried and partially buried infrastructure is a daunting prospect, especially considering the likelihood of additional and accelerated degradation resulting from ongoing and accelerating SLR. In many of the studies cited here, the call for improved groundwater monitoring is highlighted as an obvious first step, and one that should become fundamental for generally all low-lying coastal municipalities. A recent report by NOAA (2022) specifically calls



	Number of FUAs affected by scenario	Affected FUA total population (millions)
China	150	236.07
Indonesia	111	110.73
India	81	109.04
United States	69	108.11
Japan	62	95.40

Figure 6

Global distribution of coastal urban areas identified as potentially vulnerable to groundwater inundation as a function of low-lying elevation (<1.5 m) and existence within FUAs. This preliminary analysis reveals the scope of the issue and the importance of incorporating consideration of SLR-influenced groundwater into SLR impact analyses. The inset table lists the five most heavily impacted countries according to number of FUAs and total populations potentially affected. Abbreviations: FUA, functional urban area; SLR, sea-level rise.

for data and products related to groundwater-level changes, SWI, and associated drivers of these phenomena. This call for information has been followed up by decision-makers expressing sincere interest in receiving such products to inform effective management of the infrastructure they oversee (May et al. 2022).

The following is a list of actions and products for consideration in addressing issues described throughout this review, in approximate order from least to most costly in terms of time commitment and monetary costs (the cited studies represent examples of such actions):

- Install groundwater monitoring networks, particularly in low-lying urban coastal areas, that provide a continuous record of groundwater levels and salinity. The locations should be chosen to reflect a range of geologies (i.e., aquifer properties) representative of a region, and should be at various distances from the coastline to capture disparities in hydraulic gradient and influence from rainfall, tides, SLR, and so on (Habel & Fletcher 2022, Yan et al. 2015). As we move into the future of monitoring and simulation, coastal aquifers will require a comprehensive analysis of changing natural and anthropogenic influences.
- Generate simulations of groundwater levels that consider wet, dry, and average rainfall conditions and various stages of the tide (average daily high tide, spring tide, perigean spring tide, etc.). Simulations should be made publicly available in a format that can be easily visualized, downloaded, and used by a wide range of general users and decision-makers (May et al. 2022, Plane et al. 2019).
- Generate transient (i.e., time-varying) simulations of groundwater-level influence from heavy rainfall, high tides, storm surge, SLR, and other phenomena (Housego et al. 2021).

Review in Advance first posted on August 4, 2023. (Changes may still occur before final publication.)

- Generate simulations of SWI across low-lying municipalities that consider present-day and continued SLR influence as well as influence from other local phenomena and land uses (drought, extreme rainfall, pumping, fill placement/reclamation, etc.) (Xiao et al. 2016).
- Generate simulations that consider multiple flood sources. An evolving sector of flood modeling considers compound sources of flooding through simulations of groundwater, pluvial, fluvial, and marine interactions (Gallien et al. 2018, Rahimi et al. 2020). Such models have the potential to produce more realistic estimations of flooding as flood events generally result from combinations of phenomena.

In cases where resources are lacking, bathtub (i.e., hydrostatic) modeling can be used to obtain a preliminary understanding of groundwater inundation impacts (Habel et al. 2019), as conducted here in Section 3. Hydrostatic simulations of coastal flooding are relatively simple to produce and have already been produced for many coastal regions by reputable organizations such as NOAA and Climate Central (Clim. Cent. 2023, NOAA 2023). Past studies have used such methods to characterize locations where groundwater inundation will likely impact low-lying coastal locations (Cooper & Chen 2013, Cooper et al. 2013). While data-assimilating numerical modeling is more appropriate for use in critical infrastructure planning, simple hydrostatic methods are helpful in ensuring that groundwater-related issues are considered in assessments that inform long-term planning.

To conclude, this complex issue will be difficult to manage, but there are universal concepts that can be considered:

- Resist the knee-jerk reaction to implement aquifer pumping as a primary flood-mitigation strategy. In areas where water is pumped as a flood-control measure, groundwater pumping and the resulting land subsidence have led to a vicious cycle where both flood risk and flood-management costs increase over time. Even the Dutch, who have led water-management methods over centuries, struggle with the balance between mitigating flooding and instigating subsidence, which has resulted in widespread structural damage to building foundations, sinkholes, and destabilization of roads (Quell 2020, Rozell 2021). Elevating on fill may be the most all-encompassing way to manage groundwater inundation while also reducing public interaction with contamination; however, implementation is not trivial.
- Keep infrastructure maintenance timely and use periodic maintenance cycles as opportunities to incorporate adaptation. Delaying structural repairs significantly increases damage and related costs (Abdelhafez et al. 2022).
- Groundwater does not have to reach the ground surface to be damaging, and in many locations it is a present-day issue. However, when groundwater does breach the surface, new impacts will develop, such as public exposure to contamination and chronic flooding that occurs regardless of rainfall.
- While not specifically addressed by this review, it is important to highlight that adaptation measures will need to consider socioeconomic factors such as race, income, public health, and education level to properly account for the overall vulnerability of a community (Reddy Bathi et al. 2016). This vulnerability must be a primary consideration universal to all adaptation actions. As discussed, elevated groundwater has the potential to heavily degrade a wide range of critical infrastructure. Regions that fail to receive adequate resources to manage these impacts are much more likely to experience extreme levels of adversity and disruption. A thorough recognition of climate-induced threats is crucial to effectively address the array of challenges posed.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

We thank the Harold K.L. Castle Foundation, the US Office of Naval Research, NOAA, and the Hawai‘i Community Foundation. This article was funded in part by a grant/cooperative agreement from NOAA, project A/AS-1, which is sponsored by the University of Hawai‘i Sea Grant College Program, School of Ocean and Earth Science and Technology (SOEST), under institutional grant NA18OAR4170076 from the NOAA Office of Sea Grant, Department of Commerce. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies. This is Sea Grant contribution number UNIHI-SEAGRANT-JC-21-52 and SOEST contribution number 11656.

LITERATURE CITED

Abdelhafez MA, Ellingwood B, Mahmoud H. 2022. Hidden costs to building foundations due to sea level rise in a changing climate. *Sci. Rep.* 12:14020

Abueladas A-RA, Niemi TM, Al-Zoubi A, Tibor G, Kanari M, Ben-Avraham Z. 2021. Liquefaction susceptibility maps for the Aqaba-Elat region with projections of future hazards with sea-level rise. *Q. J. Eng. Geol. Hydrogeol.* 54(2):qjegh2020-039

Abuodha PAO, Woodroffe CD. 2010. Assessing vulnerability to sea-level rise using a coastal sensitivity index: a case study from southeast Australia. *J. Coast. Conserv.* 14(3):189–205

Arkell B, Darch G. 2006. Impact of climate change on London's transport network. *Proc. Inst. Civil Eng. Munic. Eng.* 159:231–37

Azevedo de Almeida B, Mostafavi A. 2016. Resilience of infrastructure systems to sea-level rise in coastal areas: impacts, adaptation measures, and implementation challenges. *Sustainability* 8(11):1115

Bamber JL, Oppenheimer M, Kopp RE, Aspinall WP, Cooke RM. 2019. Ice sheet contributions to future sea-level rise from structured expert judgment. *PNAS* 116(23):11195–200

Befus KM, Barnard PL, Hoover DJ, Finzi Hart JA, Voss CI. 2020. Increasing threat of coastal groundwater hazards from sea-level rise in California. *Nat. Clim. Change* 10(10):946–52

Berry L, Arockiasamy M, Bloetscher F, Kaisar E, Rodriguez-Seda J, et al. 2012. *Development of a methodology for the assessment of sea level rise impacts on Florida's transportation modes and infrastructure: synthesis of studies, methodologies, technologies, and data sources used for predicting sea level rise, timing, and affected areas in Florida*. Rep., Fla. Atl. Univ., Boca Raton, FL

Bjerklie DM, Mullaney JR, Stone JR, Skinner BJ, Ramlow MA. 2012. *Preliminary investigation of the effects of sea-level rise on groundwater levels in New Haven, Connecticut*. Open-File Rep. 2012-1025, US Geol. Surv., Reston, VA

Buchanan MK, Kopp RE, Oppenheimer M, Tebaldi C. 2016. Allowances for evolving coastal flood risk under uncertain local sea-level rise. *Clim. Change* 137(3–4):347–62

Burgos A. 2022. A sinkhole in Kakaako is proving a bear to fix—and a big headache for businesses. *HawaiiNewsNow*, Dec. 1. **https://www.hawaiinewsnow.com/2022/12/02/businesses-residents-feel-impact-cooke-street-closure**

Chaudhary MTA. 2012. Implications of rising groundwater level on structural integrity of underground structures-investigations and retrofit of a large building complex. *Struct. Surv.* 30(2):111–29

Chen C, Pei S, Jiao J. 2003. Land subsidence caused by groundwater exploitation in Suzhou City, China. *Hydrogeol. J.* 11(2):275–87

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, et al. 2013. Sea level change. In *Climate Change 2013: The Physical Science Basis; Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. TF Stocker, D Qin, G-K Plattner, M Tignor, SK Allen, et al., pp. 1137–216. Cambridge, UK: Cambridge Univ. Press

Clim. Cent. 2023. Coastal risk screening tool. *Climate Central.* **https://coastal.climatecentral.org**

Cooper HM, Chen Q. 2013. Incorporating uncertainty of future sea-level rise estimates into vulnerability assessment: a case study in Kahului, Maui. *Clim. Change* 121(4):635–47

Cooper HM, Chen Q, Fletcher CH, Barbee MM. 2013. Assessing vulnerability due to sea-level rise in Maui, Hawaiʻi using LiDAR remote sensing and GIS. *Clim. Change* 116(3):547–63

Cox AH, Dowling MJ, Loomis GW, Engelhart SE, Amador JA. 2020. Geospatial modeling suggests threats from stormy seas to Rhode Island's coastal septic systems. *J. Sustain. Water Built Environ.* 6(3):04020012

Cox AH, Loomis GW, Amador JA. 2019. Preliminary evidence that rising groundwater tables threaten coastal septic systems. *J. Sustain. Water Built Environ.* 5(4):04019007

Darwin C. 1852. *Journal of Researches into the Natural History and Geology of the Countries Visited During the Voyage of H.M.S. Beagle Round the World, Under the Command of Capt. Fitz Roy, R.N.* London: Murray

DeConto RM, Pollard D, Alley RB, Velicogna I, Gasson E, et al. 2021. The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature* 593(7857):83–89

Dep. Environ. Clim. Change N.S.W. 2008. *Building in a saline environment*. Rep., Dep. Environ. Clim. Change N.S.W., Sydney South, Aust.

du Commun J. 1828. On the cause of fresh water springs, fountains, etc. *Am. J. Sci. Arts* 14:174–76

Dupuit JE. 1863. *Etudes théoriques et pratiques sur le mouvement des eaux dans les canaux découverts et à travers les terrains perméables avec des considérations relatives au régime des grandes eaux, au débouché à leur donner, et à la marche des des alluvions dans les rivières à fond mobile*. Paris: Dunod

EPA (Environ. Prot. Agency). 2002. *Deteriorating buried infrastructure management challenges and strategies*. White Pap., EPA, Washington, DC

EPA (Environ. Prot. Agency). 2004. *Primer for municipal wastewater treatment*. Rep., EPA, Washington, DC

Erkens G, van der Meulen MJ, Middelkoop H. 2016. Double trouble: subsidence and CO_2 respiration due to 1,000 years of Dutch coastal peatlands cultivation. *Hydrogeol. J.* 24(3):551–68

Erskine AD. 1991. The effect of tidal fluctuation on a coastal aquifer in the UK. *Groundwater* 29(4):556–62

Felton D, van der Zander I. 2021. *Risks of sea level rise and increased flooding on known chemical contamination in Hawaii*. Memo., Hawaii Dep. Health, Honolulu

Ferris JG. 1952. *Cyclic fluctuations of water level as a basis for determining aquifer transmissibility*. Rep., Ground Water Branch, Water Resour. Div., US Geol. Surv., Washington, DC

Fetter CW. 2001. *Applied Hydrology*. Upper Saddle River, NJ: Prentice Hall. 4th ed.

Fischer EM, Sedláček J, Hawkins E, Knutti R. 2014. Models agree on forced response pattern of precipitation and temperature extremes. *Geophys. Res. Lett.* 41(23):8554–62

Flood JF, Cahoon LB. 2011. Risks to coastal wastewater collection systems from sea-level rise and climate change. *J. Coast. Res.* 27(4):652–60

Folkman S. 2018. *Water main break rates in the USA and Canada: a comprehensive study.* Rep., Utah State Univ., Logan, UT

Fung A, Babcock R. 2020. A flow-calibrated method to project groundwater infiltration into coastal sewers affected by sea level rise. *Water* 12(7):1934

Gallien TW, Kalligeris N, Delisle M-PC, Tang B-X, Lucey JTD, Winters MA. 2018. Coastal flood modeling challenges in defended urban backshores. *Geosciences* 8(12):450

Gold AC, Brown CM, Thompson SP, Piehler MF. 2022. Inundation of stormwater infrastructure is common and increases risk of flooding in coastal urban areas along the US Atlantic coast. *Earth's Future* 10(3):e2021EF002139

Grant ARR, Wein AM, Befus KM, Hart JF, Frame MT, et al. 2021. Changes in liquefaction severity in the San Francisco Bay Area with sea-level rise. In *Geo-Extreme 2021: Climatic Extremes and Earthquake Modeling*, ed. CL Meehan, MA Pando, BA Leshchinsky, NH Jafari, pp. 308–17. Reston, VA: Am. Soc. Civil Eng.

Habel S, Fletcher CH. 2022. *Development of a coastal groundwater monitoring network in Honolulu, Hawaii and initial observations*. Paper presented at the American Geophysical Union Fall Meeting, Chicago, IL, Dec. 12–16

Habel S, Fletcher CH, Anderson TR, Thompson PR. 2020. Sea-level rise induced multi-mechanism flooding and contribution to urban infrastructure failure. *Sci. Rep.* 10:3796

Habel S, Fletcher CH, Rotzoll K, El-Kadi AI. 2017. Development of a model to simulate groundwater inundation induced by sea-level rise and high tides in Honolulu, Hawaii. *Water Res.* 114:122–34

Habel S, Fletcher CH, Rotzoll K, El-Kadi AI, Oki DS. 2019. Comparison of a simple hydrostatic and a data-intensive 3D numerical modeling method of simulating sea-level rise induced groundwater inundation for Honolulu, Hawai'i, USA. *Environ. Res. Commun.* 1(4):041005

Herzberg A. 1901. Die wasserversorgung einiger Nordseebader. *J. Gasbeleucht. Verw. Beleuchtungsarten Wasserversorg.* 44:842–44

Hooper E, Chapman L, Quinn A. 2014. Investigating the impact of precipitation on vehicle speeds on UK motorways. *Meteorol. Appl.* 21(2):194–201

Housego R, Raubenheimer B, Elgar S, Cross S, Legner C, Ryan D. 2021. Coastal flooding generated by ocean wave-and surge-driven groundwater fluctuations on a sandy barrier island. *J. Hydrol.* 603:126920

IPCC (Intergov. Panel Clim. Change). 2022. *Climate Change 2022: Impacts, Adaptation and Vulnerability; Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. H-O Pörtner, DC Roberts, M Tignor, ES Poloczanska, K Mintenbeck, et al. Cambridge, UK: Cambridge Univ. Press

Jacob CE. 1940. On the flow of water in an elastic artesian aquifer. *Eos Trans. AGU* 21(2):574–86

Jacob CE. 1950. *Flow of Groundwater in Engineering Hydraulics*. New York: Wiley & Sons

Jiao J, Li H. 2004. Breathing of coastal vadose zone induced by sea level fluctuations. *Geophys. Res. Lett.* 31(11):11502

Jiao J, Post V. 2019. *Coastal Hydrogeology*. Cambridge, UK: Cambridge Univ. Press

Jiao J, Tang Z. 1999. An analytical solution of groundwater response to tidal fluctuation in a leaky confined aquifer. *Water Resour. Res.* 35(3):747–51

Jones DE Jr., Holtz WG. 1973. Expansive soils—the hidden disaster. *Civil Eng.* 43(8):49–51

Ketabchi H, Mahmoodzadeh D, Ataie-Ashtiani B, Simmons CT. 2016. Sea-level rise impacts on seawater intrusion in coastal aquifers: review and integration. *J. Hydrol.* 535:235–55

Knott JF, Daniel JS, Jacobs JM, Kirshen P. 2018. Adaptation planning to mitigate coastal-road pavement damage from groundwater rise caused by sea-level rise. *Transp. Res. Rec.* 2672(2):11–22

Knott JF, Elshaer M, Daniel JS, Jacobs JM, Kirshen P. 2017. Assessing the effects of rising groundwater from sea level rise on the service life of pavements in coastal road infrastructure. *Transp. Res. Rec.* 2639(1):1–10

Kulp SA, Strauss BH. 2021. *CoastalDEM v2.1: a high-accuracy and -resolution global coastal elevation model trained on ICESat-2 satellite lidar*. Sci. Rep., Clim. Cent., Princeton, NJ. Available at **http://www.climatecentral.org/coastaldem-v2.1**

Kuo CY. 1980. *Proceedings of the National Symposium on Urban Stormwater Management in Coastal Areas, Virginia Tech, Blacksburg, Virginia, June 19–20, 1980*. New York: Am. Soc. Civil Eng.

Lassiter A. 2021. Rising seas, changing salt lines, and drinking water salinization. *Curr. Opin. Environ. Sustain.* 50:208–14

Leung RWK, Li DCH, Pickles AR. 2007. *Heaving of airfield pavement in Hong Kong International Airport*. Paper presented at the FAA Worldwide Airport Technology Transfer Conference, Atlantic City, NJ, Apr. 16–18

Liu T, Su X, Prigiobbe V. 2018. Groundwater-sewer interaction in urban coastal areas. *Water* 10(12):1774

Lumb P. 1976. *Land reclamation in Hong Kong*. Paper presented at the Residential Workshop on Materials and Methods for Low Coast Road, Rail, and Reclamation Works, Leura, Aust., Sept. 6–10

Luo CY, Shen SL, Han J, Ye GL, Horpibulsuk S. 2015. Hydrogeochemical environment of aquifer groundwater in Shanghai and potential hazards to underground infrastructures. *Nat. Hazards* 78(1):753–74

Lusk MG. 2022. Public health threats of diminished treatment of onsite sewage. *Lancet Planet. Health* 6(9):e707–8

Lusk MG, Toor GS, Yang YY, Mechtensimer S, De M, Obreza TA. 2017. A review of the fate and transport of nitrogen, phosphorus, pathogens, and trace organic chemicals in septic systems. *Crit. Rev. Environ. Sci. Technol.* 47(7):455–541

Masterson JP, Fienen MN, Thieler ER, Gesch DB, Gutierrez BT, Plant NG. 2014. Effects of sea-level rise on barrier island groundwater system dynamics—ecohydrological implications. *Ecohydrology* 7(3):1064–71

May CL, Mohan AT, Hoang O, Mak M, Badet Y. 2020. *The response of the shallow groundwater layer and contaminants to sea level rise*. Rep., Silvestrum Clim. Assoc., Sausalito, CA

May CL, Mohan AT, Plane E, Ramirez-Lopez D, Mak M, et al. 2022. *Shallow groundwater response to sea-level rise: Alameda, Marin, San Francisco, and San Mateo Counties*. Rep., Pathw. Clim. Inst. and San Franc. Estuary Inst., San Francisco, CA

McCobb TD, Weiskel PK. 2003. *Long-term hydrologic monitoring protocol for coastal ecosystems*. Open-File Rep. 02-497, US Geol. Surv., Northborough, MA

McKenzie T, Habel S, Dulai H. 2021. Sea-level rise drives wastewater leakage to coastal waters and storm drains. *Limnol. Oceanogr. Lett.* 6(3):154–63

Medeiros-Junior RA. 2018. Impact of climate change on the service life of concrete structures. In *Eco-Efficient Repair and Rehabilitation of Concrete Infrastructures*, ed. F Pacheco-Torgal, RE Melchers, X Shi, N De Belie, K Van Tittelboom, A Sáez, pp. 43–68. Amsterdam: Elsevier

Merritt ML. 2004. *Estimating hydraulic properties of the Floridan aquifer system by analysis of earth-tide, ocean-tide, and barometric effects, Collier and Hendry Counties, Florida*. Water-Resour. Investig. Rep. 02-4267, US Geol. Surv., Tallahassee, FL

Mezzacapo M. 2019. *A multi-state regulation and policy survey of onsite wastewater treatment system upgrade programs*. Spec. Rep. SR-2020-02, Water Resour. Res. Cent., Univ. Hawai‘i Mānoa, Honolulu, HI

Michael HA, Russoniello CJ, Byron LA. 2013. Global assessment of vulnerability to sea-level rise in topography-limited and recharge-limited coastal groundwater systems. *Water Resour. Res.* 49(4):2228–40

Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, et al. 2008. Stationarity is dead: whither water management? *Science* 319(5863):573–74

Miranda T, Hill T, Lockett R, Schnelle M, Bustamante H. 2019. Salt water ingress in coastal wastewater catchments: a novel methodology for assessing salt water ingress. *Water e-J.* 4(2):16

Morgan LK, Werner AD. 2015. A national inventory of seawater intrusion vulnerability for Australia. *J. Hydrol. Reg. Stud.* 4:686–98

Natl. Acad. Sci. Med. Eng. 2019. *Framing the Challenge of Urban Flooding in the United States*. Washington, DC: Natl. Acad. Press

Nerem RS, Chambers D, Choe C, Mitchum GT. 2010. Estimating mean sea level change from the TOPEX and Jason altimeter missions. *Mar. Geodesy* 33(1 Suppl. 1):435–46

Nerem RS, Frederikse T, Hamlington BD. 2022. Extrapolating empirical models of satellite-observed global mean sea level to estimate future sea level change. *Earth's Future* 10(4):e2021EF002290

NOAA (Natl. Ocean. Atmos. Adm.). 2022. *A NOAA capability for coastal flooding and services at climate timescales to reduce risk and improve resilience*. Rep., NOAA, Washington, DC

NOAA (Natl. Ocean. Atmos. Adm.). 2023. Sea level rise viewer. *NOAA*. **https://coast.noaa.gov/slr**

Nuttle WK, Portnoy JW. 1992. Effect of rising sea level on runoff and groundwater discharge to coastal ecosystems. *Estuar. Coast. Shelf Sci.* 34(2):203–12

Osman O, Ahmad F, Aina OD. 2017. Chemical fingerprinting of saline water intrusion into sewage lines. *Water Sci. Technol.* 76(8):2044–50

Oude Essink GHP. 1996. *Impact of Sea Level Rise on Groundwater Flow Regimes: A Sensitivity Analysis for the Netherlands*. Delft, Neth: Delft Univ. Press

Oude Essink GHP, van Baaren ES, de Louw PGB. 2010. Effects of climate change on coastal groundwater systems: a modeling study in the Netherlands. *Water Resour. Res.* 46:W00F04

Parkinson RW. 2021. Speculation on the role of sea-level rise in the tragic collapse of the Surfside condominium (Miami Beach, Florida U.S.A.) was a bellwether moment for coastal zone management practitioners. *Ocean Coast. Manag.* 215:105968

Pierre-Louis K. 2021. How rising groundwater caused by climate change could devastate coastal communities. *MIT Technology Review*, Dec. 13. **https://www.technologyreview.com/2021/12/13/1041309/climate-change-rising-groundwater-flooding**

Plane E, Hill K, May C. 2019. A rapid assessment method to identify potential groundwater flooding hotspots as sea levels rise in coastal cities. *Water* 11(11):2228

Quell M. 2020. Blowing in the wind: why the Netherlands is sinking. *Undark*, Jan. 15. **https://undark.org/2020/01/15/windmills-netherlands-sinking**

Quilter PW, van Ballegooy S, Russ M. 2015. *The effect of sea level rise on liquefaction vulnerability*. Paper presented at the 6th International Conference on Earthquake Geotechnical Engineering, Christchurch, N.Z., Nov. 1–4

Rahimi R, Tavakol-Davani H, Graves C, Gomez A, Valipour MF. 2020. Compound inundation impacts of coastal climate change: sea-level rise, groundwater rise, and coastal precipitation. *Water* 12(10):2776

Reddy Bathi J, Das HS, Edberg M, Hayes BE, Montgomery Rice V. 2016. Vulnerability of coastal communities from storm surge and flood disasters. *Int. J. Environ. Res. Public Health* 13(2):239

Renken RA, Dixon J, Koehmstedt J, Ishman S, Lietz AC, et al. 2005. *Impact of anthropogenic development on coastal ground-water hydrology in southeastern Florida, 1900–2000*. Circ. 1275, US Geol. Surv., Reston, VA

Risken JL, Fraser JG, Rutter H, Gadsby M. 2015. *Implications of sea level rise on liquefaction vulnerability in Christchurch*. Paper presented at the 6th International Conference on Earthquake Geotechnical Engineering, Christchurch, N.Z., Nov. 1–4

Romero ED. 2023. State regulators scrutinize climate plan for controversial Richmond housing development. *KQED*, Jan. 12. **https://www.kqed.org/science/1981077/state-regulators-scrutinize-climate-plan-for-controversial-richmond-housing-development**

Roshani A. 2014. *Road infrastructure vulnerability to groundwater table variation due to sea level rise*. MS Thesis, Qld. Univ. Technol., Brisbane, Aust.

Rotzoll K, Fletcher CH. 2012. Assessment of groundwater inundation as a consequence of sea-level rise. *Nat. Clim. Change* 3(5):477–81

Rozell DJ. 2021. Overestimating coastal urban resilience: the groundwater problem. *Cities* 118:103369

Sadler JM, Goodall JL, Behl M, Bowes BD, Morsy MM. 2020. Exploring real-time control of stormwater systems for mitigating flood risk due to sea level rise. *J. Hydrol.* 583:124571

Saha M, Eckelman MJ. 2014. Urban scale mapping of concrete degradation from projected climate change. *Urban Clim.* 9:101–14

Schiavina M, Freire S, MacManus K. 2022. *GHS-POP R2022A - GHS population grid multitemporal (1975–2030)*. Dataset, Joint Res. Cent., Eur. Comm., Brussels, Belg. **https://doi.org/10.2905/D6D86A90-4351-4508-99C1-CB074B022C4A**

Schiavina M, Moreno-Monroy A, Maffenini L, Veneri P. 2019. *GHS-FUA R2019A - GHS functional urban areas, derived from GHS-UCDB R2019A (2015)*. Dataset, Joint Res. Cent., Eur. Comm., Brussels, Belg. **https://doi.org/10.2905/347F0337-F2DA-4592-87B3-E25975EC2C95**

Shamsudduha M, Joseph G, Haque SS, Khan MR, Zahid A, Ahmed KMU. 2020. Multi-hazard groundwater risks to water supply from shallow depths: challenges to achieving the sustainable development goals in Bangladesh. *Expo. Health* 12(4):657–70

Small C, Cohen J. 2004. Continental physiography, climate, and the global distribution of human population. *Curr. Anthropol.* 45(2):269–77

Sukop MC, Rogers M, Guannel G, Infanti JM, Hagemann K. 2018. High temporal resolution modeling of the impact of rain, tides, and sea level rise on water table flooding in the Arch Creek basin, Miami-Dade County Florida USA. *Sci. Total Environ.* 616–17:1668–88

Sweet WV, Dusek G, Obeysekera J, Marra JJ. 2018. *Patterns and projections of high tide flooding along the US coastline*. Tech. Rep. NOS CO-OPS 086, Natl. Ocean. Atmos. Adm., Washington, DC

Sweet WV, Hamlington BD, Kopp RE, Weaver CP, Barnard PL, et al. 2022. *Global and regional sea level rise scenarios for the United States: updated mean projections and extreme water level probabilities along US coastlines*. Rep., Natl. Ocean. Atmos. Adm., Washington, DC

Sweet WV, Park J. 2014. From the extreme to the mean: acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future* 2(12):579–600

Tansel B, Zhang K. 2022. Effects of saltwater intrusion and sea level rise on aging and corrosion rates of iron pipes in water distribution and wastewater collection systems in coastal areas. *J. Environ. Manag.* 315:115153

Titus JG, Kuo CY, Gibbs MJ, LaRoche TB, Webb MK, Waddell JO. 1987. Greenhouse effect, sea level rise, and coastal drainage systems. *J. Water Resour. Plan Manag.* 113(2):216–27

Trenberth KE. 2011. Changes in precipitation with climate change. *Clim. Res.* 47(1–2):123–38

Turner IL, Coats BP, Acworth RI. 1997. Tides, waves and the super-elevation of groundwater at the coast. *J. Coast. Res.* 13(1):46–60

UN-Habitat (UN Hum. Settl. Programme), WHO (World Health Organ.). 2021. *Progress on wastewater treatment: global status and acceleration needs for SDG indicator 6.3.1*. Rep., UN-Habitat and WHO, Geneva

Uuemaa E, Ahi S, Montibeller B, Muru M, Kmoch A. 2020. Vertical accuracy of freely available global digital elevation models (ASTER, AW3D30, MERIT, TanDEM-X, SRTM, and NASADEM). *Remote Sens.* 12(21):3482

Vorosmarty CJ, Green P, Salisbury J, Lammers RB. 2000. Global water resources: vulnerability from climate change and population growth. *Science* 289(5477):284–88

Whittier RB, El-Kadi A. 2014. *Human health and environmental risk ranking of on-site sewage disposal systems for the Hawaiian Islands of Kauai, Molokai, Maui, and Hawaii*. Rep., Safe Drink. Water Branch, Hawai‘i Dep. Health, Honolulu, HI

Wu G, Guan Y, Zhan X. 2008. Effect of salinity on the activity, settling and microbial community of activated sludge in sequencing batch reactors treating synthetic saline wastewater. *Water Sci. Technol.* 58(2):351–58

Wu P, Wei M, D'Hondt S. 2022. Subsidence in coastal cities throughout the world observed by InSAR. *Geophys Res. Lett.* 49(7):e2022GL098477

Xiao H, Wang D, Hagen SC, Medeiros SC, Hall CR. 2016. Assessing the impacts of sea-level rise and precipitation change on the surficial aquifer in the low-lying coastal alluvial plains and barrier islands, east-central Florida (USA). *Hydrogeol. J.* 24(7):1791–806

Xu Y-S, Ma L, Du Y-J, Shen S-L. 2012. Analysis of urbanisation-induced land subsidence in Shanghai. *Nat. Hazards* 63(2):1255–67

Yan S, Yu S, Wu Y, Pan D, She D, Ji J. 2015. Seasonal variations in groundwater level and salinity in coastal plain of eastern China influenced by climate. *J. Chem.* 2015:905190

Young S, Juhl A, O'Mullan GD. 2013. Antibiotic-resistant bacteria in the Hudson River Estuary linked to wet weather sewage contamination. *J. Water Health* 11(2):297–310

Zaini F, Hussin K, Jamalludin NA, Zakaria SRA. 2015. The principle of depth for underground land development: a review. *J. Teknol.* 75(10):71–78

Zhao Z, Yin H, Xu Z, Peng J, Yu Z. 2020. Pin-pointing groundwater infiltration into urban sewers using chemical tracer in conjunction with physically based optimization model. *Water Res.* 175:115689