Groundwater Dynamics and Coastal Resilience Research Hub

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Designing a Hub to address a grand challenge

The "grand challenge" that confronts us is to understand how the land is changing next to the sea - in particular, how are groundwater elevations and flow directions changing, as rainfall and tidal elevations change? Groundwater represents the critical intersection among various hydrologic system elements because it can affect infiltration rates, can emerge as surface flooding behind coastal levees and walls, flows into existing underground pipes, can remobilize existing soil contaminants, and increases seismic risks. Most coastal cities have not taken this dynamic into account and know very little about groundwater locally. Urban site and infrastructure managers are already responding to high water tables by pumping - which creates new subsidence risks on former wetland soils. Unrestricted pumping could make adaptation to sea level rise and extreme storms more difficult, while emergent groundwater could cause key adaptation strategies to fail.

In order to produce results that impact societal needs, the Hub must include national organizations for the professions (National Academy of Engineering, Landscape Architecture Foundation, AIA, APA, ULI). These professions need a close link to science for their recommendations to major public clients, but often lack this connection. Large firms from engineering and design provide critical on-the-ground project advice to elected officials and developers, because they are trusted sources of technical solutions. The Hub must also include local non-profits who represent underserved urban districts, which are least likely to receive the best information from existing sources. By bringing them in at a high level to shape the questions asked, the Hub can support adaptation with equity instead of adaptation that contributes to the ongoing urban displacement of communities of color.

There is a fundamental need to collect new groundwater data using sensors, archives and human observations. Very few cities know where there water table is and how it is influenced by rainfall, tides, and human activities such as pumping. These data need to be organized into interpolated surfaces and numerical models that can reveal the extent and interactions among these influences. The models can be used to anticipate the future effects on health, pipes, roads, and building structures. By incorporating the results into vulnerability studies and adaptation plans, the research would have a major lasting effect after the grant period is over.

Recommendation

We recommend that NSF support a CoPe Hub (or ideally, several regional hubs) focused on understanding the dynamics and impacts of groundwater at the land-sea interface. These hub(s) would support interdisciplinary, data-intensive research on the dynamics of human activities, climate change and groundwater transport and quality. They would also support the co-generation of knowledge among researchers, practitioners, public agencies, private utility providers, and the general public.

As examples, both New York City and the San Francisco Bay metropolitan region face serious new groundwater vulnerabilities that will be driven by sea level rise and extreme rain events. Honolulu, Hawaii; Miami, Florida and Norfolk, Virginia also have studies that indicate their vulnerability to rising groundwater. But none of these regions have incorporated this new groundwater information into vulnerability studies and adaptation plans as of yet, or built numerical models that link rainfall, pumping and sea level rise to a resulting water table elevation.

We recommend that the Hub involve a consortia of universities, but should include practitioners and local tribal organizations or non-profits that work closely with neighborhood residents using a steering committee structure. Large engineering firms, landscape architecture firms, and multi-disciplinary planning firms need to understand the extent of the threat posed by a rising water table, because it impacts the likely success of other adaptation strategies, whether “green” or “gray.” Currently, very few practitioners are aware of this threat or able to incorporate it into vulnerability studies and adaptation plans related to sea level rise, extreme storms, water quality, and ecosystem change. National organizations such as the Landscape Architecture Foundation and the National Academy of Engineering could help identify the firms that would participate, or firms could be chosen based on their significant contributions to existing vulnerability studies and adaptation plans.

Why is it valuable?

The elevation, quality and flow directions of groundwater affect many aspects of water management, from flood management to the siting of green infrastructure and the provision of municipal water supplies and wastewater services. Sea level rise, altered precipitation patterns and human activities synergistically impact groundwater processes but, to date, these potential effects have been poorly studied. Understanding these interactions presents a ‘grand challenge’ for researchers across disciplines, with consequences for human health and safety, public and private infrastructure and ecosystem function.

Most current assessments of vulnerability do not take a rising groundwater table into account. Similarly, very few if any plans for adaptation consider a rising water table. Strategies that rely on levees, for example, will fail to prevent flooding from groundwater on their landward side since the levee will not prevent a rising water table. Pumps are essential to maintain a controlled water table, but past experience shows that pumping in former wetland soils (which are the substrate for many coastal urban areas built on fill) can cause them to subside rapidly, creating an even larger flooding problem from both rain events and higher seas (Yin et al. 2016). Infrastructure systems in most coastal cities depend upon having a relatively dry condition down to 2 meters or more below the surface of roadways, in order for aging sewer pipes to function. Everything from internet cable lines to gas lines are run through conduits within this dry zone that are typically not designed to be submerged in groundwater that will be increasingly saline and therefore cause higher rates of corrosion (Durairajan et al. 2018). Residents who live in industrial districts or former industrial districts are particularly at risk of re-mobilizing soil contaminants, as are ecosystems such as coastal wetlands and the nearshore environment generally.

Stakeholders include property owners, developers, and residents in areas affected by flooding and soil contamination risks, tribal governments, environmental organizations seeking to protect and enhance nearshore and riparian ecosystems, and major infrastructure agencies (public and private) who manage highways, local roads, rail lines, sewer systems, flood control structures, and other underground utilities. This topic presents numerous opportunities for co-learning among these stakeholders.

Through partnerships with educators and the general public, groundwater research provides opportunities for formal and informal STEM learning. This type of work provides opportunities to engage community scientists in crowd-sourced data collection and co-interpretation of results. Through collaboration between researchers and K-12 educators, the principles of groundwater hydrology and modeling can also be incorporated as modules into earth science and high school mathematics curricula.

Supporting evidence

There is strong evidence supporting individual mechanisms by which human activities and climate non-stationarities affect groundwater. For example, sea level rise is expected to raise coastal groundwater levels, affecting a geographic area that could be much larger than the area influenced by saltwater flooding. Studies have shown that these increased water tables will have a variety of societal and ecosystem impacts, including:

1. The reduced capacity of soil to infiltrate and store rainwater in extreme storms, increasing the spatial extent and duration of rain-driven flooding (Sophocleus 2002).
2. Increased groundwater infiltration into underground sewer pipes, where groundwater enters the pipe through cracks and reduces the pipe’s capacity to convey sewer and storm water, causing back-ups and overflows in basements, manholes, and storm drains (Joyce 2017, Thorndahl 2016).
3. Increase infiltration into other subterranean infrastructure, such as subway tunnels, basements, septic tanks and utilities, disrupting operations of these critical infrastructure (Azevedo de Almeida et al. 2016, Colombo et al. 2018, Durairajan et al. 2018)
4. Re-mobilization of soil contaminants, creating new exposure pathways affecting human health as a vapor component of buried contaminants migrates to penetrate pipes and basements. This can also cause serious new pollution in coastal ecosystems, as landfills and leaky underground tanks that are capped from above but not lined from below generate new contaminant plumes (Noyes et al. 2009).
5. Rising water tables can change the redox zonation of shallow aquifers, with

implications for urban biogeochemical cycling and groundwater quality (Sinke et al. 1998).

6. Subterranean groundwater discharge has been found to be an important contributor to biogeochemical cycling in coastal estuaries (Beck et al. 2009, Beusen et al. 2013, Dulai et al. 2016) The changes in these discharge rates resulting from rising sea levels have not been studied and the potential implications for coastal water quality remain poorly understood.
7. The pressure of the rising groundwater can cause foundations and other underground structures to heave over time (Soren 1976).
8. A rising water table increases the spatial extent and risks of liquefaction in urban fill and other soil types that are prone to more intense shaking during a seismic event. This will have implications for the risks to buildings, underground infrastructure, bridge foundations, and roadway surfaces in an earthquake (Murakami et al. 2005).
9. In some geographic and topographic settings, increased water tables from sea level rise can lead to inland surface inundation through groundwater flooding (Masterson et al. 2017, Rotzoll and Fletcher 2013)

Along with changes in sea levels, changes in precipitation will directly and indirectly affect groundwater levels and quality. Increased water tables in coastal areas with rising sea levels will be augmented by concurrent increases in annual precipitation. In areas where annual precipitation is reduced, the impact on water table levels from rising seas may be mitigated, but saltwater intrusion and the resulting impacts on soil biogeochemistry, water quality and infrastructure would be exacerbated. These processes will also be directly and indirectly impacted by human activities such as groundwater for municipal supply or dewatering and coverage by impervious surface.

In Honolulu, Rotzoll and Fletcher (2012, 2013) found that twice as much land would be affected by flooding if researchers took rising groundwater into account as well as rising seas. Habel et al (2017) developed a model to link tidal action to effects on groundwater elevation for the Waikiki district of Honolulu, emphasizing the need to understand the efficiency of this interaction. Changes in tides can produce a change in water table elevation of the exact same magnitude, or lesser magnitudes as efficiency decreases with distance or with changes in geomorphology.

Willis developed the first conceptual model of interactions between sea level rise and coastal groundwater in California (2013). Hoover et al (2016) identified major risks of groundwater-driven emergence and shoaling with sea level rise magnitudes of 1 and 2 m in three different case study locations on the California coast (Arcata, Stinson Beach, and Malibu). Plane and Hill (2017) found that the maximum elevation of the water table within a kilometer of the edge of San Francisco Bay is often within a meter of the surface under current sea level/tidal conditions, by creating an interpolated surface using thousands of individual well data points where groundwater quality is being monitored because of past contamination events. In cities such as Oakland, their maps indicate that between 10-30% more land may be at risk from emergent groundwater, but much more will be affected by the other impacts (remobilized contaminants, liquefaction risk, etc.).

However, to date, there has been very little integrated research on the dynamics of these effects when they occur concurrently within a coastal system. Since groundwater observations are often scarce in human-dominated systems, our predictive understanding of these processes remains extremely limited. We are not aware of any studies that have combined the effects of rain-driven events and tidal surges when modeling water table elevations for a specific location, or that have considered the likely impacts we noted above on underground utilities, soil contaminants, structural effects and seismic risks.

Defining success

“Success” can be defined and validated in several ways. First, the existence of a validated regional groundwater elevation dataset would be a success. Most coastal regions don’t have this dataset to use in vulnerability mapping or adaptation decision-making. The USGS is embarking on a research effort to include an equilibrium groundwater level (which does not represent maximum local elevations) in their coastal modeling studies for California. This mapping effort will identify some vulnerable areas, but will not identify the local dynamics that will drive flooding and contamination risks in specific areas. This effort would be different from the USGS work in that it would expand scientific knowledge of how urban heterogeneity and synergies among influences on groundwater could limit adaptation success, or require new typologies for adaptation (Hill 2015, 2016). Successful scientific research will identify quantitative linkages between tides, rainfall, and soil heterogeneity that allows predictions of flooding and contamination risks in local urban districts, and informs large-scale public investments in adaptation.

Second, it would be a major success to produce an awareness among decision makers that levees and seawalls will not prevent groundwater-driven flooding without adding pumps. In addition, pumping may accelerate local subsidence. Maps of soil vulnerability to this type of subsidence would be critical for limiting the expansion of pumping as an adaptation strategy, which is rapidly expanding in many regions. Surveys and interview techniques, as well as published vulnerability reports at the local and county scales, could be used to validate whether or not this goal has been achieved.

Third, success could be defined as co-creation of knowledge with local residents and other stakeholders, particularly in areas that are most likely to be affected by rising sea levels, surface flooding and rising water tables. The participation of local groups can be documented, particularly with regard to the questions they shaped and the data they helped to collect, or adaptation strategies that they suggested or prioritized, as well as the level of awareness achieved in a specific population (eg, members of a particular neighborhood group, or residents of a specific zone).

This is a critical topic and approach now because many regions are engaged in vulnerability studies and are discussing proposals for adaptation. If this issue is missed, as it has been in many regions to date, funds and effort may well be wasted and strategies for adaptation may fail (Hirschfeld and Hill, 2017). This is the time to include groundwater in vulnerability studies and adaptation plans. Adding it as a future consideration will result in stranded assets and permanent liabilities (levees and seawalls that don’t prevent flooding, pumps that don’t have sufficient capacity, and subsided soils that cannot be restored to their original elevations).

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