United States Environmental Protection Agency

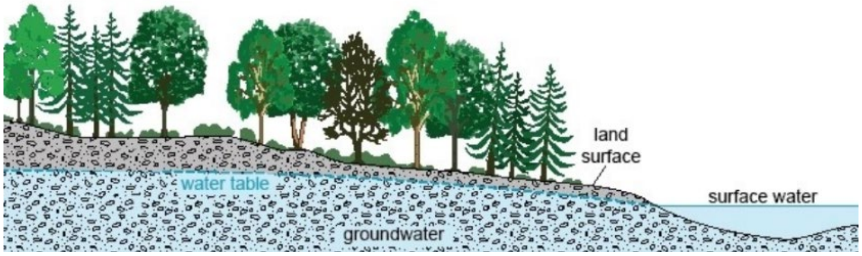
Consideration of Climate Change at Contaminated Groundwater Sites

In October 2021, the U.S. Environmental Protection Agency (EPA) released its updated *U.S. Environmental Protection Agency Climate Adaptation Plan.*[1] The plan examines how EPA programs may be vulnerable to a changing climate and how the Agency can accordingly adapt in order to continue meeting its mission of protecting human health and the environment. Under the Superfund Program, existing processes for assessing and remediating contaminated sites provide a robust structure that enables consideration of climate changes such as increasing temperatures, decreasing precipitation and sea level rise. Examination of associated vulnerabilities is most effective through use of a place-based strategy due to wide variations in the hydrogeologic characteristics of sites, the nature of remediation systems operating at contaminated sites, and local or regional climate and weather regimes.

Background

Groundwater remediation systems are common elements of contaminated site cleanup projects and may function ex situ or in situ. Ex situ processes often involve extracting contaminated groundwater from an aquifer and transferring it to an aboveground system where the water is treated, an approach often referred to as "pump and treat." The groundwater may be extracted through a single well or a network of wells equipped with pumps and interconnecting pipes. Treatment of the extracted groundwater commonly involves removing contaminants by way of activated carbon sorption, air stripping, filtration, ion exchange or metals precipitation. The treated water can then be routed for onsite or offsite beneficial use, reinjected into the aquifer for storage, or discharged into nearby surface water.

In contrast, in situ processes often involve injecting reagents into the subsurface through one or more wells to promote desired biological or chemical reactions in contaminated groundwater. Another common process involves constructing one or more permeable reactive barriers, which are engineered subsurface cells containing selected biological or chemical materials that are strategically emplaced to intercept and treat a plume of contaminated groundwater. Other in situ processes include thermal treatment, air sparging, and phytotechnologies.



Remedies for contaminated groundwater also may involve monitored natural attenuation (MNA), which relies on existing in situ processes to reduce the mass, toxicity, mobility, volume or concentration of contaminants. The processes may include biodegradation, sorption, dilution, evaporation and chemical transformation of contaminants. MNA is most suited to sites where the source of pollution has been removed, contaminant concentrations and the potential for contaminant migration are low, and geochemical and biological conditions are favorable.

Approximately 83 percent of the Superfund site remedies selected since 1982 address contaminated groundwater. About 31 percent of the groundwater remedies selected during fiscal years 2018 through 2020 involved ex situ treatment. During the same period, about 47 percent of the selected groundwater remedies involved in situ treatment. Approximately 30 percent of the groundwater remedies included an MNA component.[2]

Use of ex situ or in situ technologies to remediate a site with contaminated groundwater relies on a thorough understanding of the site's unique hydrogeological conditions. It also relies on an understanding of groundwater characteristics that may change under future climate scenarios. The changes should be considered throughout the site cleanup pipeline, from site assessment through long-term remedy maintenance.

Climate change considerations described in this fact sheet are based on the findings of climate vulnerability assessments conducted by EPA for multiple National Priorities List sites. EPA's Groundwater Forum provided key input on related technical factors.

Evaluation of changes in the behavior and nature of groundwater in response to climate change is complex. Addressing the complexities at a given site may be aided by a climate vulnerability assessment (CVA), which involves screening a site's exposure and sensitivity to climate change hazards such as altered temperature and precipitation patterns.[3] EPA's Office of Superfund Remediation and Technology Innovation collaborated with EPA's Engineering Forum in developing a related issue paper, Conducting Climate Vulnerability Assessments at Superfund Sites, to help site cleanup teams understand whether climate change may affect remedy protectiveness.[4]

Potential Climate Change Vulnerabilities

Consideration of climate change when investigating or planning remediation of contaminated groundwater involves assessing numerous parameters that may change gradually or relatively abruptly. Examples include:

- Altered directions of groundwater flow.
- Different chemistry, biochemistry, geochemistry and contaminant loading of groundwater.
- Changes in seasonal highs or lows of a water table.
- Decreased aquifer recharge and increased aquifer withdrawal.
- Higher influx of surface water.

Climate parameters most commonly affecting groundwater remediation relate to a site's precipitation and atmospheric temperatures. In coastal settings, sea level rise also plays a major role. Changing climate parameters may be incorporated into groundwater remediation planning and implementation by using future climate data to develop or update the site's conceptual site model (CSM).[5] An effective CSM helps manage and communicate uncertainties associated with key site characteristics such as the nature and extent of contamination and the geologic/hydrogeologic features controlling fate and transport processes.

Site-specific climate projections typically draw information from one or more models that utilize multiple scenarios of greenhouse gas (GHG) emissions or concentrations over selected timeframes. For example, the U.S. Global Change Research Program Climate Mapping for Resilience and Adaptation assessment tool provides early-century (2016-2030), mid-century (2036-2065) and late-century (2070-2099) climate projections based on generally lower or higher emissions compared to historical emissions. In contrast, climate models based on GHG concentrations rather than emissions utilize four RCPs established by the Intergovernmental Panel on Climate Change.[6]

The potential for sea level rise was considered in designs of shoreline protection measures as cleanup of certain parcels continues at the Hunters Point Naval Shipyard Superfund site in San Francisco, California. The designs account for a 3-foot rise in sea level based on climate projections developed by the California Ocean Protection Council and California Natural Resources Agency. Using historical data collected at the Golden Gate tide gauge, the projections considered three representative concentration pathways (RCPs) that were incorporated into the site's CSM:

1) RCP 8.5, which is consistent with a future in which there are no significant global efforts to limit or reduce emissions. In 2100, the likely sea level rise associated with this scenario ranges from 1.6 to 3.4 feet.
2) RCP 4.5, which is a moderate emissions reduction scenario and assumes that global greenhouse gas emissions will be curtailed. In 2100, the likely sea level rise associated with this scenario ranges from 1.2 to 2.7 feet.
3) RCP 2.6, which is a stringent emissions reduction scenario and assumes that global greenhouse gas emissions will be significantly curtailed. In 2100, the likely sea level rise associated with this scenario ranges from 1.0 to 2.4 feet.

Future five-year reviews will evaluate updated sea level rise data becoming available to verify that the shoreline protection structures can adequately control erosion associated with San Francisco Bay tidal and wave action.

Monitoring of the groundwater remedy, which includes in situ components such as MNA and contaminant stabilization, continues. Due to the proximity of saline groundwater and surface water from San Francisco Bay, these components may be vulnerable to saltwater intrusion. The site's groundwater elevations range from about -1 to +8 feet relative to mean sea level.

Climate change parameters often differ across climate models and therefore require consistent interpretation and application. For example, the U.S. Climate Resilience Toolkit uses the following parameters concerning temperature and precipitation:

- Extreme temperature: 1-in-10 year temperature (the hottest temperature occurring once every ten years).
- Heavy precipitation: maximum 5-day precipitation (the largest 5-day precipitation total each year, on average).
- Drought/dry days: maximum consecutive dry day (the length of largest number of dry days each year, on average).

Environmental models that use projected as well as historic climate data may indicate a broad range of groundwater parameters anticipated to change over time. Table 1 provides examples of such changes, which in turn could affect the performance of ex situ or in situ technologies involved in remedies for groundwater as well as other environmental media. At many sites, groundwater remedies are designed to operate in conjunction with remedies targeting contaminated soil, sediment or surface water.

Groundwater conditions and parameters are integral to the selection and implementation of multiple types of remedies at contaminated sites.

Table 1. Examples of Climate Change Impacts

Climate Change Variable	Potential Impact on Groundwater	Potential Impact on Remedies and Remediation Technologies
Precipitation (higher total per year)	• Increased aquifer recharge • Elevated zones of saturation • Directional change in groundwater flow • Localized groundwater mounding that may impact flow directions • Greater influx of pollutants or excess nutrients carried by stormwater	• Increased mobilization of contaminants in the vadose zone • Increased rate of metals leaching due to contaminant mobilization • Shallow contaminants becoming submerged and mobilized • Increased infiltration through an overlying evapotranspiration cover • Increased volumes of groundwater requiring treatment • Increased rainwater infiltration into near-surface soil vapor extraction systems • Altered rates of water uptake and transpiration involved in phytoremediation
Drought (sustained)	• Lower groundwater table • Directional change in groundwater flow • Reduced subsurface hydrostatic pressure • Salt water intrusion due to dropping fresh water levels	• Incomplete capture of contaminated groundwater due to groundwater extraction or monitoring wells running dry • Increased operations and maintenance costs for existing wells • Increased contaminant migration to a deep aquifer • Cracking of waste covers and contaminated soil/sediment caps • Altered rates of water uptake and transpiration involved in phytoremediation • Subsidence of soil below site infrastructure • Increased risk of fire and associated damage to aboveground infrastructure
Temperature (cold periods)	• Decreased microbial activity • Decreased infiltration	• Reduced biodegradation of contaminants • Reduced passage of groundwater through a permeable reactive barrier and associated decreases in contaminant removal rates
Sea level rise	• Increased salinity of groundwater • Higher groundwater table	• Changes in groundwater classification status • Changes in pumping rates • Increased salt wedge management

Climate Change Variable	Potential Impact on Groundwater	Potential Impact on Remedies and Remediation Technologies
	• Reversed direction of groundwater flow • Increased soil erosion	• Increased migration of contaminants • Impairment of in situ processes and technologies such as MNA, permeable reactive barriers and bioremediation
Wind force (increased velocity)	• Greater inland reach of tides • Increased soil erosion • Less aquifer recharge due to reduced snow pack	• Physical damage to aboveground infrastructure • Increased risk of wildfire and associated damage to aboveground infrastructure • Changes in building pressurization and vapor intrusion
Riverine flooding (increased)	• Increased soil erosion • Greater interaction between groundwater and surface water	• Recontamination of a shallow aquifer • Increased plume migration
Ice/snow melt (accelerated)	• Reduced infiltration due to frozen ground conditions • Timing shifts in seasonal aquifer recharge and surface water replenishment	• Greater burdens on stormwater controls due to higher spring-time spikes in water volumes • Increased risk of widespread spring flooding and associated damage to aboveground infrastructure • Reduced availability of fresh water in late summer and autumn • More variable contaminant loading that affects P&T systems, permeable reactive barriers and evapotranspiration covers

Emerging Patterns

Analysis of the manners in which climate change may impact groundwater reveals certain patterns. For example, increased frequency or duration of intense rainfalls commonly increases pollutant runoff and sedimentation in streams and other surface water bodies. This may alter the background concentrations and classification of connected groundwater, increase mobility of contaminants, and potentially complicate treatment of contaminated groundwater. Additionally, a sustained increase in precipitation frequently raises the water table in an unconfined aquifer over time and consequently increases the risk of groundwater recontamination via soils or the vadose zone or the risk of vapor intrusion.

Variations in the nature, timing and extent of impacts in unconfined and unconfined aquifers would be anticipated. For example, reduced pressure in an unconfined aquifer can reverse the vertical direction of contaminant migration from downward to upward. Other potential impacts in an unconfined aquifer include precipitation decreases that can quickly lower the water table. This may directly cause one or more existing wells to run dry, thereby prompting decisions to lower the well pumps, extend the wells to greater depths, or abandon the wells. Additionally, sustained decreases in precipitation commonly cause reduced groundwater discharge into surface water bodies or changes in local groundwater flow directions. These impacts could alter the efficacy of contaminated groundwater remedies or lead to plume migration in unexpected directions.

A confined aquifer is typically impacted by precipitation decreases in indirect manners. Precipitation decreases in the aquifer's recharge areas often lower water levels in wells that penetrate the aquifer. Such wells may be increasingly used to meet local or regional demands for water, particularly in communities heavily relying on surface water resources. Increased use of these wells can change the rate and direction of groundwater flow, potentially causing an increased rate of plume migration. It could also lead to gradual depletion of the aquifer, thereby impacting the functions and utility of wells constructed for groundwater remediation and potentially limiting anticipated beneficial use of treated groundwater.

Significantly lower water levels in confined aquifers often cause changes in hydrostatic pressure. Reduced pressure could lead to vertical migration of contaminants from an overlying aquifer. Conversely, higher pressure may prevent flow of water (and contaminants) from an overlying aquifer. Significantly more pumping associated with such pressure changes also may lead to a confined aquifer behaving as an unconfined aquifer in the future.

In general, more intensive groundwater withdrawal from an unconsolidated aquifer increases the risk of land subsidence. The subsidence may alter surface drainage patterns or could result in damage to onsite or nearby infrastructure, which may include one or more groundwater remediation systems.

Sustained changes in temperatures that affect the behavior and quality of groundwater are similarly diverse. For example, increasing winter temperatures at high elevations leads to reduced levels of annual snowpack. The reduction in insulation offered by snowpack results in more rapid snowmelt and ice thaw in spring, which can significantly increase the rate of spring runoff and decrease streamflow in late spring and summer. Proper maintenance of a site's total water balance is critical to effectively remediating contaminated groundwater.

Future decreases in temperatures often need to be considered in groundwater remedies involving biodegradation of contaminants. For example, a reliance upon the activity of microbial organisms to naturally degrade certain contaminants may be negatively affected in an area that increasingly experiences extremely low winter temperatures. The alteration in microbial activity would impact MNA progress or reduce efficacy of remediation technologies that involve subsurface injection or emplacement of biological materials intended to beneficially react with (treat) contaminated groundwater.

Cleanup at the Torch Lake Superfund site in Michigan includes maintenance of capped mining waste containing high concentrations of contaminants such as lead, arsenic and polychlorinated biphenyls. Monitoring of the groundwater, surface waters and submerged tailings and sediments in Torch Lake and other onsite waterbodies is underway. Additionally, institutional controls such as prohibition of well installations are in place in certain areas impacted by residual mining wastes.

The remedies are vulnerable to precipitation changes and associated levels in onsite surface water bodies, which can alter interconnections between the surface waters and groundwater. Due to a sustained decrease in precipitation, the lakes experienced historical low water levels in 2007. The reduced precipitation impacted vigor of the caps' vegetation layers that help prevent leaching to groundwater.

The remedies also are vulnerable to potential flooding of Torch Lake and the adjacent Lake Superior due to intense or prolonged rainfalls. Cap repairs were performed to address damage incurred during a 2018 flash flood.

A shoreline protection system consisting of geotextile and riprap was constructed along portions of the site's former smelter area to help address these vulnerabilities. The system's riprap layer is periodically replenished where needed to prevent erosion associated with ice formation or high water levels.[8]

In coastal settings, the biodegradation of contaminants is additionally impacted by saltwater intrusion associated with continued sea level rise. The impacts are exacerbated in areas where groundwater is increasingly pumped to meet local or regional water demands. Remediation of groundwater affected by saltwater intrusion requires consideration of the groundwater's elevated concentrations of certain chemicals such as sodium and chloride, the altered conductivity of relevant geologic unit(s) (particularly clay), and the shifting location of the transition zone where mixing of saltwater and freshwater occur. Increased vulnerability to saltwater intrusion in the future also could lead to a different classification of the groundwater.

Documentation of Findings

Dynamic information is available from several federal agencies to help identify and document potential climate change hazards in a given spatial area within the United States. Federal Web-based platforms and tools relevant to groundwater resources potentially affected by climate change include the:

- U.S. Global Change Research Program Climate Explorer.
- National Aeronautics and Space Administration IPCC AR6 Sea Level Projection Tool.
- National Drought Mitigation Center Drought Risk Atlas.
- National Oceanic and Atmospheric Administration (NOAA) National Integrated Drought Information System portal, including downloadable LIDAR data.
- NOAA Sea Rise Viewer.
- U.S. Army Corps of Engineers (USACE) Sea Level Tracker.
- USACE Climate Hydrology Assessment Tool (CHAT).
- U.S. Geological Survey Hazard Exposure and Reporting Analytics (HERA) website addressing coastal hazards.

Information also may be available from state agencies, regional or local sources such as watershed and forestry management authorities, non-profit groups and academia. At many sites, the characteristics of groundwater requiring remediation may be influenced by ongoing or anticipated use and associated infrastructure of the site as well as adjacent properties.

Additional techniques for documenting groundwater characteristics that may be influenced by future climate scenarios at a given site include:

- Collecting past and current photographs of observable field conditions such as soil erosion, land subsidence and vegetation loss.
- Using thermal imaging units with sensors to identify locations of groundwater seepage.
- Compiling data charts for use in tracking and projecting groundwater parameters of concern.
- Developing maps of onsite or adjacent areas exhibiting sustained changes in surface or geochemical conditions that warrant periodic reassessment.

Remediation of contaminated groundwater, intertidal and subtidal sediments, and soil is underway at the Wyckoff Co./Eagle Harbor site in Bainbridge Island, Washington. Due to its past use as a wood-treating facility, the site is contaminated by creosote, other wood-preserving chemicals and nonaqueous-phase liquid (NAPL).

The site is vulnerable to sea level rise, which is projected to increase by one foot by 2060.[9] It is also vulnerable to erosion in intertidal areas along an onsite engineered sediment cap and to seismic activity associated with the Seattle Fault.

A groundwater extraction and treatment system with nine recovery wells screened in the upper aquifer draws contaminated groundwater and NAPL away from the site perimeter. The system also maintains an upward vertical gradient that minimizes transport of contaminants from the upper aquifer to the lower aquifer.

A soil-bentonite slurry "cutoff" wall is being installed below ground surfaces to reroute upgradient groundwater around contaminated soil and groundwater. The contaminated soil will be treated through in situ soil solidification and stabilization at depths below the water table.

A perimeter wall made of reinforced concrete wall is being built along seaward portions of the former wood-treating area to protect the site from sea level rise and reduce the effect of erosive forces entering from the harbor. Designs for the wall meet stringent standards regarding site-specific earthquake threats. EPA and the Washington Department of Ecology are collaborating with the Suquamish Tribe, which maintains treaty rights to gather Eagle Harbor resources, to assure the new wall does not interfere with habitat restoration.

EPA also is working with the Washington Department of Natural Resources to restore the population of eelgrass in Eagle Harbor. The existing eelgrass community is anticipated to help reduce erosion during ongoing remedial activities.

Groundwater modeling that uses climate data projected for the future will help project teams understand the risks associated with parameters likely to change, such as plume boundaries or groundwater depths. It also will facilitate broader decisions regarding other aspects such as:

- End use of groundwater that is treated ex situ, which often includes industrial processes, regional or municipal recreation, irrigation, wetland restoration or water reservoir replenishment.
- Site-wide stormwater management and erosion controls.
- Designs of onsite waste cover systems, which include controls to prevent leachate seepage into groundwater.
- Leverage of technologies that may be used in remedies focused on treating or removing the source(s) of contamination, such as physical separation and solidification or stabilization.[2]
- Contaminant fate and transport in context of future climate scenarios.
- Effects of onsite or nearby infrastructure with impermeable surfaces that inhibit infiltration of precipitation and consequently reduce groundwater recharge.

Ready access to this type of information as groundwater cleanup progresses will aid development of primary Superfund documentation such as feasibility studies and remedy designs and inform periodic reassessments such as five-year reviews and optimization evaluations. Over time, an updated CVA may be needed to reassess the site and remedy vulnerabilities and identify any need to update existing environmental models.

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Web access date: January 2024

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