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Climate Resilience Technical Fact Sheet: Contaminated Waste Containment Systems

In June 2014, the U.S. Environmental Protection Agency (EPA) released the *U.S. Environmental Protection Agency Climate Change 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 planning and implementing site remedies provide a robust structure that allows consideration of climate change effects. Examination of the associated implications on site remedies 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. Measures to increase resilience to a changing climate may be integrated throughout the Superfund process, including feasibility studies, remedy designs and remedy performance reviews.

As one in a series, this fact sheet addresses the climate resilience of Superfund remedies involving waste containment systems. It is intended to serve as a site-specific planning tool by (1) describing an approach to assessing potential vulnerability of a containment system, (2) providing examples of measures that may increase resilience of a containment system, and (3) outlining steps to assure adaptive capacity of a containment system as climate conditions continue to change. Concepts described in this tool may also apply to site cleanups conducted under other regulatory programs or through voluntary efforts.

Remediation of contaminated sites often involves waste containment systems to address sources such as contaminated soil or sediment, sludge, solid waste, nonaqueous-phase liquids or storage tanks. In many cases, the waste exists in abandoned landfills or industrial waste piles.

Onsite waste containment systems may operate ex situ or in situ. Ex situ systems may involve excavating and placing the source material in other onsite areas, such as a newly engineered containment area (cell) with a bottom liner consisting of compacted clay, geotextiles or both. At other sites, excavated source material may be placed in an unlined consolidation unit. Such systems typically include a cover (cap) placed above the waste and in some cases processes for collecting and treating leachate and managing landfill gas (LFG).

In situ containment systems focus on stabilizing contaminated waste to be left in place. For example, a final cover utilizing impervious geosynthetic fabric may be placed over assorted wastes; in contrast, a composite soil cover may be placed over certain materials such as waste rock. In situ systems also could involve one or more subsurface barriers constructed at strategic locations to prevent movement of dissolved or free-phase contaminants. Such barriers commonly consist of clay (typically bentonite) or cement slurry poured into a trench, geosynthetic materials placed in trenches, or sheet piles driven into the subsurface. Containment barriers often operate in conjunction with groundwater extraction and treatment systems.

Climate resilience planning for a waste containment system generally involves:

(1) Assessing vulnerability of the system's elements and associated site infrastructure.
(2) Evaluating measures potentially increasing the system's resilience to a changing climate.
(3) Assuring the system's capacity to adapt to a changing climate, which helps the cleanup remedy continue to be protective of human health and the environment (Figure 1).

Resilience: A capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.[2]

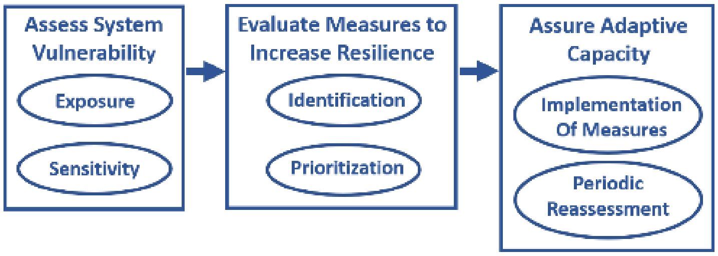

Figure 1. Climate Change Adaptation Management

Assessment of Waste Containment System Vulnerability

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed; its sensitivity; and its adaptive capacity.[2]

Assessing a waste containment system's vulnerability to the effects of climate change involves:

- Determining the system's exposure to climate or weather hazards.
- Determining the system's sensitivity to the hazards.

A **climate change exposure assessment** identifies particular hazards of concern and characterizes exposure to those hazards in light of various climate and weather scenarios. Examples of potential hazards for a waste containment system include high floodwater, soil washout in sloped areas, or unexpected changes in the water table.

The hazards may arise abruptly due to extreme weather events, which are expected to occur at increasing intensities, durations and frequencies as long-term climate conditions continue to change. Depending on a site's location and attributes, hazards associated with an extreme weather event may generate different outcomes and degrees of severity in onsite or offsite areas and infrastructure. For example, a heavy rainfall within a 24-hour period across an urban industrial area could generate stormwater flow that inundates a site and overloads an aged combined sewer system into which leachate treatment wastewater discharges. In contrast, a comparable rainfall across a steep mountain valley could lead to onsite flooding that disrupts the critical water balance of a containment system and generates runoff contributing to flash flooding in downgradient areas.

Changing climate conditions include sustained changes in average temperatures, increased heavy precipitation events, increased coastal flooding, increased intensity of storm surge, sea level rise and increased wildfire severity.[3] A vulnerability assessment helps project decision makers:

- Understand which conditions may change at a site.
- Understand how altered conditions may affect the site remedy.

Climate parameters that significantly influence hydrologic processes and ultimate performance of a containment system include precipitation, ambient temperatures, wind speeds and solar radiation.[4] For example, a prolonged rainfall event could lead to water seepage at vulnerable edges of a cover. In contrast, drought conditions could cause desiccation and associated cracking of compacted clay lining the bottom of a waste cell. Similarly, cracking or general deterioration of subsurface vertical barriers could result from more frequent or extreme wet-dry or freeze-thaw cycles or heat stress.

Climate-related hazards potentially affecting performance of compacted clay liners include desiccation, freeze-thaw, thermally induced moisture movement leading to desiccation, and subsidence.

Potential hazards also might concern the LFG management process required for waste containment cells constituting a landfill.[5] Associated equipment such as aboveground gas-transfer pipes as well as gas flares or gas-to-energy turbines are commonly exposed to weather on a year-round basis. Modifications to an LFG management process are typically made over time to accommodate the gradual decrease in LFG production due to bacterial decomposition of the waste's organic matter.

Other hazards at landfills could relate to the particular content of a cover. Conventional covers use layers of material with low hydraulic conductivity, such as geomembranes, to serve as a barrier that minimizes percolation of water through the waste. Precipitation- or wind-generated erosion or abrupt washout of soil above a geomembrane could result in its exposure to ultraviolet radiation, which is a major contributor to the degradation of geosynthetic materials. In contrast, evapotranspiration (ET) covers minimize percolation by relying on the capability of multiple soil layers to store water until it evaporates or is transpired through vegetation. Sustained changes in onsite precipitation or temperatures could reduce viability of the assorted long-rooted plant species originally selected on the basis of their expected survival under historic climate conditions.

Designs for site-specific stormwater management depend on accurately estimating peak stream flow within the local watershed, including contributions from snowmelt. Regions that historically accumulated seasonal snowpack are expected to experience a shift from snow- to rain-dominated 100-year precipitation events. This shift affects the rainfall intensity, duration, and frequency (IDF) curves typically used to model potential flooding.[6, 7]

At some sites, hazards may concern the system's original siting or potential lapses in the system's long-term stewardship. Landfills at or near sea level in coastal areas, for example, might be vulnerable to saltwater intrusion and increased groundwater salinity, which may increase permeability of a clay liner. Other potential hazards may concern onsite or offsite anthropogenic stressors, such as land development that removes natural protective barriers or causes infill subsidence in low-lying areas. Land cover changes also could increase a system's vulnerability to sinkholes triggered by intense rainstorms or floods.[8]

Waste containment systems rely on effective control of water entering or exiting the system. As a result, these systems are commonly vulnerable to flooding that could cause cover material erosion, side slope failure or contaminant washout. Damaging floods from extreme precipitation events may be exacerbated if preceded by severe heat and drought.

Final cover systems for contained waste are intended to remain in place and maintain their functions for periods of many decades to hundreds of years. As a result, a vulnerability assessment typically considers future use of a covered landfill or other type of containment area. For example, the U.S. EPA and other federal agencies are evaluating opportunities to install renewable energy facilities on current or formerly contaminated lands, landfills and mine sites.[9] Site managers are encouraged to work closely with future-use planning entities when assessing site-specific exposure to climate change hazards.

Dynamic information about climate and weather variabilities and trends across the United States is available from several federal agencies to help screen potential hazards in a given spatial area and identify those of concern. Web-based platforms and tools include:

- National Oceanic and Atmospheric Administration (NOAA) resources such as *Digital Coast* and *Sea Level Trends.*
- National Weather Service resources such as *National Storm Surge Hazard Maps* and *Sea, Lake, and Overland Surges from Hurricanes (SLOSH).*
- U.S. Geological Survey (USGS) resources such as the *National Climate Change Viewer* and *StreamStats.*

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 some sites, installation of a meteorological station may be warranted to monitor the need for response measures and to aid predictive modeling for targeted vulnerabilities.

A **climate change sensitivity assessment** for a planned or operating waste containment system evaluates the likelihood for the climate change hazards of concern to reduce the system's effectiveness. Potential direct effects of the hazards associated with an extreme weather event include power interruption, physical damage, water damage and reduced accessibility. Potential indirect effects include petroleum oil or chemical spills, accidental fire, explosions and ecosystem damage. System failures due to exposure to one or more hazards could result in:

- Washout of covered waste at or near surface grades.
- Migration of subsurface contaminants to areas that were previously uncontaminated.
- Leakage from various depths of the contained waste or from damaged leachate-control equipment, which could affect underlying groundwater or nearby surface water.
- Atmospheric release of untreated LFG, which typically comprises about 50 percent methane and 50 percent carbon dioxide.
- Unexpected and additional costs for repairing or replacing portions of the containment system or site infrastructure such as power lines, maintenance corridors and buildings.

Vulnerable points of a containment system due to extreme weather events may physically exist below, at or above surface grades or involve the site's general operations and infrastructure (Table 1). For example, reduced access to a site due to road washout could disrupt a critical activity such as scheduled inspection of a waste cover or sampling of leachate.

Table 1. Considerations for Sensitivity Assessment of a Waste Containment System

Examples of System Components		Potential Vulnerabilities Due to Extreme Weather			
		Physical Damage	Water Damage	Power Interruption	Reduced Access
Underground and At-Grade Components	Synthetic materials such as geomembrane in a composite liner or cover system, geonet for drainage, or geotextile for leachate filtration	◆	◆		
	Bottom layer of unlined waste		◆		
	Vegetative layer integral to an evapotranspiration cover or overlaying a conventional cover	◆	◆		
	Vertical and horizontal wells for LFG extraction	◆			◆
	Pipe networks for leachate and/or LFG collection	◆	◆		◆
	Wells for monitoring groundwater or LFG	◆			◆
	Vertical barriers	◆			◆
Aboveground Components	Electrical controls for leachate and LFG management systems	◆	◆	◆	◆
	Pipe systems for leachate treatment and disposal and for LFG collection and transfer	◆			◆
	Transfer pumps for leachate and LFG	◆	◆	◆	◆
	Flow-through units for leachate treatment processes such as coagulation/flocculation, chemical precipitation or ozonation	◆	◆	◆	◆
	Leachate treatment or evaporation pond	◆			◆
	LFG pre-treatment equipment such as blowers, coolers and condensers	◆	◆	◆	◆
	LFG flares	◆	◆	◆	◆
	LFG-to-energy turbines	◆	◆	◆	◆
	Chemical storage containers	◆	◆		◆
	Treatment residuals disposal system	◆	◆		◆
	Treated leachate discharge system	◆	◆	◆	◆
	Auxiliary equipment powered by electricity, natural gas or diesel fuel	◆	◆	◆	◆
	Monitoring equipment	◆	◆	◆	◆
Site Operations and Infrastructure	Buildings, sheds or housing	◆	◆	◆	◆
	Electricity and natural gas lines	◆	◆		◆
	Liquid fuel storage and transfer	◆	◆	◆	◆
	Water supplies	◆	◆	◆	◆
	Exposed machinery and vehicles	◆	◆		◆
	Surface water drainage systems	◆	◆		◆
	Fencing for access control and litter prevention	◆			◆

Techniques for assessing potential vulnerability of a waste containment system may include:

- Collecting qualitative information such as photographs of system components and current field conditions.
- Extrapolating quantitative data documented in resources such as NOAA or USGS mapping systems.
- Modeling that uses predictive weather and climate data, through use of conventional software or commercially available risk assessment software for engineered systems.
- Developing site-specific maps and matrices that can aid decision-making.

Detailed information about climate-related vulnerability assessment and access to associated tools is provided in resources such as the:

- *U.S. Climate Resilience Toolkit* for exploring hazards and assessing vulnerability and risks.
- *Climate Change 2014: Impacts, Adaptation and Vulnerability* report from the Intergovernmental Panel on Climate Change, which includes a chapter (19) on assessing emergent risks and key vulnerabilities.

More examples of relevant tools and other resources are described online at **Superfund Climate Resilience: Vulnerability Assessment**.

As an illustration, Figure 2 highlights results of a preliminary vulnerability assessment for a waste containment system currently deployed at a Superfund site. The illustration identifies potential disruptions to the system due to extreme weather events and provides a sample structure for documenting high-priority resilience measures that could be implemented in the near term. Planning tools such as this also may be used to build additional adaptive capacity over time.

This sample cleanup scenario involves a 30-acre Superfund site located on an island of an inland river. Contaminants remain from the site's past use for disposal of industrial waste, domestic trash and construction debris. The remedy components involve covering historic waste disposal trenches with a multi-layer cap; covering other areas with an erosion cap consisting of asphalt, concrete paving or a vegetative layer; installing a passive gas collection system; constructing a stormwater runoff and erosion control system that includes subsurface vertical barrier walls; and monitoring natural attenuation in the groundwater plume. Portions of the area covered with the multi-layer cap are anticipated for reuse supporting roadways, parking areas or other developed structures.

Public information sources indicate that potential hazards for this scenario include flooding, high winds, cold temperatures and an elevated water table. In combination with site-specific data existing in materials such as site investigation reports and the Superfund record of decision, professional judgment is used to identify and prioritize resilience measures for this remedy.

Potential Points of System Vulnerability		Potential System Disruption Due to Extreme Weather				Resilience Measures for High-Priority Vulnerabilities
		Power Interruption	Physical Damage	Water Damage	Reduced Access	
Underground and At-Grade Components	Geosynthetic layer(s) in cover system		●	●		Upgrade rock armor system Install dewatering system
	Vegetative layer of erosion caps		●	●		Install runoff channels Plant flood-resistant species
	Wells for LFG extraction or groundwater monitoring		○		○	
	Leachate collection pipes		○	○	○	
	Cement vertical barriers		●		○	Emplace supporting gabions
Aboveground Components	Leachate transfer pumps	○	●	◐		Build well-head housing
	LFG well vents		●	◐		Fortify concrete pad Enclose exposed piping
	Leachate evaporation pond		●		○	Increase holding capacity
	Groundwater monitoring equipment	○	●	◐	◐	Add remote access system
Site Operations and Infrastructure	Equipment housing	○	◐	◐	◐	
	Site fencing		○		○	
	Water supplies		○		○	
	Surface water drainage systems		●	●	◐	Construct vegetated swales

● *high priority* ◐ *medium priority* ○ *low priority*

Figure 2. Illustrative Superfund Site Scenario: Vulnerability Assessment Results and Prioritized Adaptation Measures

Evaluation of Potential Climate Resilience Measures

Results of a vulnerability assessment may be used to develop a strategy for increasing a waste containment system's resilience to a changing climate and extreme weather events. Development of the strategy entails:

- Identifying resilience measures potentially applying to the hazards of concern under various climate and weather scenarios.
- Prioritizing resilience measures for the given system.

Identification of potential resilience measures involves screening of steps that may be taken to physically secure the system, provide additional barriers to protect the system, safeguard access to the system or alert project personnel of system compromises (Table 2). Some of the measures may address more than one climate or weather scenario. For example, extending the geosynthetic layer of a waste cell's top liner outward to cover vulnerable sides of the cell may increase the containment system's resilience to intense rainfall or rapid snowmelt as well as high winds.

Effective mitigation of climate change hazards for a waste containment remediation system involves a site-specific analytical approach rather than a broad prescriptive plan.

Some of the measures also may be scaled up to increase the resilience of co-located remediation systems, such as a groundwater extraction and treatment system operating in conjunction with a subsurface containment barrier. Other measures may provide a degree of desired redundancy. For example, installation of a small-scale photovoltaic (PV) system could help assure a steady source of power for LFG or groundwater monitoring systems during disruptions to the local power grid.

For a new remediation system, selecting optimal measures during the design phase may maximize the system's resilience to climate change hazards throughout the project life and help avoid costly retrofits. Designs for a waste containment system could include specifications to meet particular vulnerabilities. For example, the design could involve surface drainage criteria that use a worst-case storm scenario based on most recent and longer-term climate predictions; integration of more sumps to handle potentially higher volumes of leachate accumulating above a liner due to a higher water table; or additional intermediate berms to prevent water- or wind-related erosion or landslides in steep areas bordering a waste cell. If an area is predicted to experience increasingly frequent flooding or storm surge activity or be subject to rising sea levels, disposal of contaminated soil offsite in an area not subject to these hazards may be an option.

Descriptions of engineered structures commonly used in climate resilience measures are available online at **Superfund Climate Resilience: Resilience Measures**.

The process of identifying and prioritizing potential measures for a waste containment system may consider:

- Size and age of an existing system's components and auxiliary equipment.
- Complexity of the waste containment system.
- Local or regional climate adaptation plans or ordnances affecting sites with landfills or other waste containment classifications.
- Status of infrastructure components such as power and water supplies.
- Existing and critical means of access.
- Relevant aspects of future land use or development.
- Anticipated effectiveness and longevity of the resilience measures.
- Capital cost and operations and maintenance cost of the measures, as well as costs associated with potential system repair or replacement due to climate-related damage in the future.

Prioritization of resilience measures also may necessitate professional judgements regarding other aspects such as:

- Critical versus non- or marginally-critical equipment, activities or infrastructure.
- Minimum performance thresholds for system or site operations.
- Levels of tolerance for operational disruptions.

Table 2. Examples of Climate Resilience Measures

	Climate Change Effects					Potential Climate Resilience Measures for System Components
	Temperature	Precipitation	Wind	Sea Level Rise	Wildfires	
Underground and At-Grade Components of the Containment System		◆				**Construction at grade** *Designing a new containment system to be built at, rather than below, ground surface in order to minimize potential contact between groundwater and targeted waste (or an engineered liner) due to consistent rising of the water table*
		◆				**Dewatering well system** *Installing extraction wells at critical locations and depths to prevent or minimize groundwater upwelling into the waste zone of an aged landfill, waste consolidation unit or lined engineered landfill*
		◆		◆		**Leachate extraction upgrades** *Installing additional wells (and aboveground pumps) for leachate extraction in vulnerable areas*
	◆	◆		◆		**Liner system reinforcement** *Selecting geomembranes with a maximum feasible thickness for new liner systems, using a secondary liner or geotextile, or extending geosynthetic materials to vulnerable sides of a waste cell*
		◆	◆			**Pipe burial** *Installing pipes below, rather than above, ground surface where feasible, particularly for LFG transfer*
		◆				**Run-on controls** *Building one or more earthen structures (such as vegetated berms, vegetated swales, or stormwater ponds) or installing fabricated drainage structures (such as culverts or French drains) at vulnerable locations to prevent stormwater accumulating at higher elevations from reaching a landfill/containment system*
	◆					**Thermal insulation** *Covering composite liners and barriers made of geosynthetics with a layer of insulating material such as chipped tires to prevent liner/barrier desiccation due to heating or freeze-thaw action, or wrapping pipes with insulating material*
Aboveground Components of the Containment System		◆		◆		**Armor** *Placing fixed structures on or along the shoreline of flowing inland water or ocean water to mitigate effects of erosion and protect site infrastructure; "soft" armor may comprise synthetic fabrics and/or deep-rooted vegetation while "hard" armor may consist of riprap, gabions and segmental retaining walls*
		◆	◆	◆		**Coastal hardening** *Installing structures to stabilize a shoreline and shield it from erosion through use of soft engineering techniques, such as replenishing sand and/or vegetation, or hard engineering techniques, such as building a seawall or emplacing riprap*
	◆	◆		◆		**Concrete pad fortification** *Repairing cracked pads or replacing pads of insufficient size or with insufficient anchorage, particularly those used for monitoring purposes, and integrating retaining walls along a concrete pad perimeter where feasible*
		◆	◆			**Containment fortification** *Emplacing riprap adjacent to a subsurface containment barrier located along moving surface water, to minimize bank scouring that could negatively affect barrier integrity; for soil/waste capping systems vulnerable to storm surge, installing a protective vertical wall or armored base to absorb energy of the surge and prevent cap erosion or destruction*
		◆	◆		◆	**Entombment** *Enclosing vulnerable equipment or control devices in a concrete structure*

	Climate Change Effects					Potential Climate Resilience Measures for System Components
	Temperature	Precipitation	Wind	Sea Level	Wildfires	
Aboveground Components of the Containment System	◆	◆				**Evapotranspiration cover modification** *Replacing existing vegetation with a plant mix more tolerant of long-term changes in precipitation or temperature, or adding soil to increase water storage capacity*
					◆	**Fire barriers** *Creating buffer areas (land free of dried vegetation and other flammable materials) around vulnerable remediation/monitoring components and installing manufactured systems, such as radiant energy shields and electrical raceway fire barriers, around heat-sensitive components*
		◆	◆	◆	◆	**Flare enclosure** *Add industrial-strength protective material around equipment used to ignite and combust excess LFG*
		◆				**Ground anchorage** *Installing one or more steel bars in cement-grouted boreholes (and in some cases accompanied by cables) to secure an apparatus on a ground surface or to reinforce a retaining wall against an earthen slope*
		◆	◆	◆		**Relocation** *Moving selected system components to positions more distant or protected from potential hazards; for flooding threats, this may involve elevations higher than specified in the community's flood insurance study*
		◆			◆	**Retaining wall** *Building a structure (commonly of concrete, steel sheet piles or timber) to support earth masses having a vertical or near-vertical slope and consequently hold back loose soil, rocks or debris*
		◆	◆			**Tie down systems** *Installing permanent mounts that allow rapid deployment of a cable system extending from the top of a unit to ground surface*
	◆	◆	◆			**Well-head housing** *Building insulated cover systems made of high density polyethylene or concrete for control devices and sensitive equipment situated aboveground for long periods*
Site Operations and Infrastructure	◆	◆	◆	◆	◆	**Alarm networks** *Integrating a series of sensors linked to electronic control devices that trigger shutdown of selected remediation/monitoring components, or linked to audible/visual alarms that alert workers of the need to manually shut down the components when specified operating or ambient parameters are exceeded*
	◆	◆			◆	**Building envelope upgrades** *Replacing highly flammable materials with (or adding) fire- and mold/mildew-resistant insulating materials in a building, shed or housing envelope*
		◆		◆		**Flood controls** *Building one or more earthen structures (such as vegetated berms, vegetated swales, stormwater ponds, levees or dams) or installing fabricated drainage structures (such as culverts or French drains) to retain or divert floodwater spreading from adjacent surface water or land surface depressions*
		◆	◆	◆		**Hurricane straps** *Integrating or adding heavy metal brackets that reinforce physical connection between the roof and walls of a building, shed or housing unit, including structures used for leachate and LFG management*
		◆				**Pervious pavement** *Replacing impervious pavement that has deteriorated or impeded stormwater management with permeable pavement (in the form of porous asphalt, rubberized asphalt, pervious concrete or brick/block pavers) to filter pollutants, recharge aquifers and reduce stormwater volume entering the storm drain system*

	Climate Change Effects					**Potential Climate Resilience Measures for System Components**
	Temperature	**Precipitation**	**Wind**	**Sea Level Rise**	**Wildfires**	
Site Operations and Infrastructure	◆	◆	◆	◆	◆	**Plantings** *Installing a mix of flood- and drought-resistant grasses, shrubs, trees and other deep-rooted plants to prevent erosion, provide wind breaks and reduce fire risk*
	◆	◆	◆	◆	◆	**Power from off-grid sources** *Constructing a permanent system or using portable equipment that provides power generated from onsite renewable resources, as a primary or redundant power supply that can operate independent of the utility grid when needed*
	◆	◆	◆	◆	◆	**Remote access** *Integrating electronic devices that enable workers to suspend pumping or selected activities during periods of impeded access or unexpected hydrologic conditions*
	◆	◆	◆	◆		**Renewable energy system safeguards** *Extending concrete footing for ground-mounted PV systems, adding bracing for roof-top PV or solar thermal systems, and adding masts for wind turbines or windmills*
	◆	◆	◆		◆	**Utility line burial** *Relocating electricity and communication lines from overhead to underground positions to prevent power outages during and often after extreme weather events*
	◆	◆	◆	◆	◆	**Weather alerts** *Subscribing to open-access electronic networks that actively inform subscribers of extreme weather events*

Assurance of Adaptive Capacity

Assuring the adaptive capacity of a waste containment system involves:

- Implementing new or modified measures to increase climate resilience of the system or site operations and infrastructure, as needed.
- Establishing plans for periodically reassessing the system and site vulnerabilities, to determine if additional capacity is needed as cleanup progresses and climate conditions change.

Adaptive Capacity: The ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.[2]

Climate resilience measures that are selected for implementation may be integrated into primary or secondary documentation supporting existing containment systems. Key documentation includes monitoring plans, optimization evaluations, five-year reviews and close-out planning materials. For new projects, the measures also may be integrated into the site's feasibility study and remedy design. Resilience planning also may involve incorporating specific requirements to be met in cleanup service contracts. In general, implementation of climate resilience measures during early, rather than late, stages of the cleanup process might expand the universe of feasible options, maximize integrity of certain measures and reduce implementation costs. Upfront planning also could enable the selected measures to benefit the site's anticipated reuse. For example, climate-resistant plantings above a waste cell cover could intercept precipitation while providing a suitable substrate for future recreational or ecological use.

Assurance of sufficient adaptive capacity is an iterative and flexible process. It involves periodically reassessing the system's vulnerability, monitoring the measures already taken and incorporating newly identified options or information. Periodic reassessments typically include verifying key data. Established plans for the timing of vulnerability reassessment may involve a predetermined schedule or use triggers such as an extreme weather event.

A regional wildfire event could trigger reassessment of a containment system's potential vulnerability associated with:

- Stormwater controls needing modification due to altered land cover.
- Invasive species moving into the system's vegetative layer.
- Changes in the system's hydrologic balance due to loss of nearby tree canopy.[10]

Resources to help understand climate resilience planning and implementation are available through online compendiums such as:

- *ARC-X* (EPA's Climate Change Adaptation Resource Center), which provides online access to tools that help communities anticipate, plan for and adapt to the changing climate.
- The NOAA *National Centers for Environmental Information*, which provide climate and weather data and monthly summaries of U.S. temperatures and precipitation.
- EPA's *Addressing Climate Change in the Water Sector* website, which provides access to the State Water Agency Practices for Climate Adaptation Database.

More tools to help assure adaptive capacity are described online at **Superfund Climate Resilience: Adaptive Capacity**.

The general concepts, tools and examples provided in such compendiums may be used to tailor climate resilience planning for a specific waste containment remediation system. Resources such as these also may serve as a guide in assuring that the measures align with climate adaptation actions taken by relevant state, regional or local agencies.

The **Malone Services Company Superfund Site** along Galveston Bay, Texas, borders open water and extensive wetlands and marshes. Remedial action at this site, which was formerly used for waste oil and chemical reclamation, storage and disposal, has involved placing the waste in two onsite cells and monitoring of groundwater. The remedy's vulnerability to flooding due to hurricane storm surge or sea level rise was addressed in the remedy's design and construction by:

- Using NOAA's SLOSH model and historical weather data to analyze storm surge and wave runup under various hurricane scenarios and sea level rise predictions, to establish design storm criteria.
- Armoring the bay-facing boundary of a levee surrounding the site.
- Installing riprap armor along vulnerable portions of the waste cells.

Following Hurricane Harvey in 2017, recently emplaced topsoil and hydromulch above one cell were replenished in areas that experienced erosion or washout.

Consolidated waste cells at the Malone Services Company Superfund Site in Texas City, Texas.

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[10] Current Forestry Reports; Assessing Landscape Vulnerability to Wildfire in the USA; Vaillant, Nicole M. et al.; 2:201–213 (2016); https://www.fs.fed.us/pnw/pubs/journals/pnw_2016_vaillant001.pdf

To learn more about climate resilience at Superfund sites and access new information and decision-making tools as they become available, visit:

www.epa.gov/superfund/superfund-climate-resilience

Contacts

Questions about climate resilience in EPA's Superfund Program may be forwarded to:
Carlos Pachon (pachon.carlos@epa.gov) or Hilary Thornton (thornton.hilary@epa.gov)

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