

Resilient remediation: Addressing extreme weather and climate change, creating community value

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Abstract

Recent devastating hurricanes demonstrated that extreme weather and climate change can jeopardize contaminated land remediation and harm public health and the environment. Since early 2016, the Sustainable Remediation Forum (SURF) has led research and organized knowledge exchanges to examine (1) the impacts of climate change and extreme weather events on hazardous waste sites, and (2) how we can mitigate these impacts and create value for communities. The SURF team found that climate change and extreme weather events can undermine the effectiveness of the approved site remediation, and can also affect contaminant toxicity, exposure, organism sensitivity, fate and transport, long-term operations, management, and stewardship of remediation sites. Further, failure to consider social vulnerability to climate change could compromise remediation and adaptation strategies. SURF's recommendations for resilient remediation build on resources and drivers from state, national, and international sources, and marry the practices of sustainable remediation and climate change adaptation. They outline both general principles and site-specific protocols and provide global examples of mitigation and adaptation strategies. Opportunities for synergy include vulnerability assessments that benefit and build on established hazardous waste management law, policy, and practices. SURF's recommendations can guide owners and project managers in developing a site resiliency strategy. Resilient remediation can help expedite cleanup and redevelopment, decrease public health risks, and create jobs, parks, wetlands, and resilient energy sources. Resilient remediation and redevelopment can also positively contribute to achieving international goals for sustainable land management, climate action, clean energy, and sustainable cities.

KEYWORDS

climate change, extreme weather events, remediation resiliency, sustainable remediation, sustainable remediation forum

1 | INTRODUCTION

After Hurricane Harvey made landfall in 2017, 13 Superfund sites in Houston, Texas, were flooded. At one site, the U.S. Environmental Protection Agency (U.S. EPA) measured dioxin at levels over 2,300 times the level requiring cleanup actions. Five weeks after Hurricane Maria hit in 2017, one in four Puerto Ricans lacked access to clean water. During Hurricane Florence, U.S. EPA and scientists from industry, universities, and civil organizations warned of the potential release of toxic chemicals from North Carolina and South Carolina Superfund sites. Post landfall, Florence led to extensive flooding that "... swept away

part of a retaining wall holding back a pond of coal ash – which contains mercury, arsenic and other toxic substances – and have also overrun several lagoons of pig waste in North Carolina" (Pierre-Louis, Popovich, & Tabuchi, 2018, p. 1).

In the United States, nearly two million people—the majority in low income communities—live within 1 mile of one of 327 Superfund sites in areas prone to flooding or vulnerable to sea-level rise caused by climate change (Dearen, Biesecker, & Kastanis, 2017). These 327 sites are part of a much larger universe of U.S. sites that need to be assessed. There are more than 650,000 contaminated commercial and industrial sites and more than 81,000 acres of

brownfields at 21,000 sites in 232 cities across the United States (Targ, 2017).

Globally, the number of contaminated sites is overwhelming and growing as a result of increasing urbanization especially in emerging economies. Estimates for Europe alone (excluding many diffuse land contamination problems) range from 2.5 to 4.5 million sites. In China, about 20% of farmland is contaminated by trace metals, pesticides, and hydrocarbons such as petrochemicals (Bardos, Bakker, Slenders, & Nathanail, 2011). Over one million contaminated sites may require cleanup (Hou & Li, 2017), nearly 60% of groundwater is not safe for drinking (Hou, Li, & Nathanail, 2018), and public health threats can exist even on contaminated land that has been remediated.

2 | RESEARCH FINDINGS

Decades of research, including the recent 2017 U.S. Climate Science Special Report (Wuebbles et al., 2017), document the global reality of more powerful and frequent storms, heavy rainfall, heat waves, wildfires, and more frequent and longer droughts. Rising sea levels, declining snowpack, long-term stress on water availability, dynamic groundwater levels, acidification, and rising temperatures represent further threats to ecosystems and communities.

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At hazardous sites, climate change and extreme weather events can undermine the effectiveness of the original site remediation design and can also impact contaminant toxicity, exposure, organism sensitivity, fate and transport, and long-term operations, management, and stewardship of remediation sites.

Higher temperature and lower pH can increase the availability of contaminants in the environment. For example, the speciation and availability of metals changes with environmental pH (Millero, Woosley, DiTrolio, & Waters, 2009), and the fate and transport of persistent organic pollutants changes with temperature and precipitation (Nadal, Marques, Mari, & Domingo, 2015).

Increasing temperatures can also change the water cycle influencing the local water budget. Warmer temperatures can result in altered precipitation, increased evaporation rates of surface water, increased rates of water uptake by vegetation, and reduced rates

of water recharge to soils and groundwater reservoirs (Famiglietti, 2014).

Increased temperatures and changes to the water cycle may also result in more frequent and severe weather events, such as the occurrence of the 100-year storm event, as well as, contribute to more frequent nuisance flooding due to the prevalence of supersaturated soils. Both events are exacerbated by sea level rise resulting in shoreline encroachment and increased nuisance flooding during high tide.

Additional vulnerabilities of water resources include, but are not limited to, changes to water supplies, subsidence, increased amounts of water pollution, erosion, and related risks to water and wastewater infrastructure and operations, degradation of watersheds, alteration of aquatic ecosystems and loss of habitat, creating multiple impacts in coastal areas (LARWQCB, 2015). These hydrological changes are happening at the same time as groundwater extraction is increasing as heat also increases demand for various water needs, including drinking, irrigation, and industrial uses (Famiglietti, 2014).

A recent study showed a potential impact of such climatic shifts on residual contaminants in soil and groundwater (Libera et al., 2018). The study found that the hydrological shifts influence contaminant concentrations in a complex manner, since increased infiltration, for example, could cause conflicting effects of both diluting and mobilizing contaminants. The study showed that, in general, higher infiltration events could mobilize vadose-zone residual contaminants, raising contaminant concentrations in groundwater for a prolonged period.

Similarly, the sensitivity of organisms and ecosystems can be affected by environmental change. Higher temperatures increase the metabolic rate of ectotherms (organisms that derive their heat and, therefore, maintain their metabolic activity from the environment around them), which can increase the rate at which they absorb or process contaminants (Noyes et al., 2009). Behavioral changes in response to environmental change may also alter exposure and sensitivity as organisms react to new stresses in ways that ameliorate or exacerbate other stresses.

The use of the chemicals that become environmental contaminants is also likely to change. For example, warming temperatures leads to expansion of agricultural pests, resulting in increased use of pesticides. Furthermore, more rain may require repeated application of pesticides and fertilizers. Both scenarios can result in agricultural land contaminated by intense application of chemicals as well as contributions to polluted runoff that impact nearby and downgradient waterbodies.

Climate change also poses challenges for selecting remediation techniques, including the feasibility of passive remediation technologies (O'Connell & Hou, 2015). Passive remediation carries an increased burden of proof, since contaminants stay longer in the subsurface—compared to conventional soil removal options—while degradation/treatment processes occur.

Thus, the efficacy of remediation efforts may be undermined if attention is not paid to climate change impacts throughout the remediation process. This can be thought of from two different perspectives: (1) how climatic change will affect remediation, and (2) how remediation techniques will be affected by climate change. Examples of each are presented in Exhibits 1 and 2.

EXHIBIT 1 Implications of climate change for remediation

Climate impact	Secondary effect	Relevant remediation effect
Altered precipitation pattern	Wetter: Flooding, storms, more runoff	Mobilization of contaminants (e.g., from vadose zone to groundwater) → Higher contaminant concentration/export, overpowering significant degradation rate in groundwater zone could remove natural protective barriers or cause infill subsidence in low-lying areas Dilution → Lower contaminant concentration/export Damage to capping systems
	Drier: Drought	Oxidation of soils Increased volatility Less dilution → Higher contaminant concentration/export Reduced mobilization → Higher contaminant persistence (higher contaminant concentration/export) Insufficient water for remediation; Overuse of groundwater Possible enhanced natural attenuation, expedited contaminant removal Altered degradation rates (physical, microbial)
Sea level rise	Erosion	Damage to site integrity
	Site inundation	Increased mobilization of contaminants, possible dilution, or compromised site with mixing or loss of contaminated materials, increased bioavailability of contaminants
	Mobilization of contaminants	Clean sediments transported on top of contaminated sediments
	Elevations increase	Changing footprint of flood plains, river boundaries, and coastal shoreline encroachment → Impact on regulations (e.g., dredging, cleanup levels, negotiation of water levels, monitoring)
Extreme weather	Scour (wind/wave action; surface water flow velocity)	Damage to site integrity, capping systems
	Flooding	Possible dilution (lower contaminant concentration/export), or compromised site with mixing or loss of contaminated materials, damage to capping systems
	Extreme heat	Increased volatility → Mobilization of contaminants from site through soil and air Changes in use of site by wildlife Melting permafrost → Mobilization of contaminants from site through water, soil, and air
	Freezing conditions	Damage to capping systems and in situ stabilization systems
Extreme weather: Fire	Increased use of fire retardants	Spread of contaminants
	Damage to site infrastructure	Loss of function of remediation systems
Decreasing pH		Increased availability, mobilization, toxicity Increased sensitivity of species due to pH stress Altered transformation rates
Increasing temperature	Altered transformation or degradation	Increased or decreased toxicity
	Decreased dissolved oxygen/anoxic conditions	Altered transformation, decreased species resilience
	Increased species heat stress and associated conditions	Increased sensitivity to contaminants
Human impact and responses	Vulnerable communities commonly comprised of low socioeconomic and minority populations	Cardio-pulmonary illness Food, water, and vector-borne diseases Loss of homes, drinking water, and livelihoods mental health consequences and stress
	Increased use of some chemicals Conflicting solutions, changing land use demands, shifting populations	Additional toxicity, additional remediation sites.

EXHIBIT 2 Impact of climate change on remediation techniques*

Remediation approach	Technique	Climate change impact
Soil treatment	Bioremediation	Degradation activity may change, unexpected intermediaries
	Landfarming/landspreading	Inundation of site by sea level rise or flooding
Groundwater treatment	Pump and treat	Altered rate of recharge and extraction
Removal of contaminated materials		Extreme weather, flooding, or sea level rise will complicate containment Groundwater level decline may support expedited removal
Engineered in situ solutions	Soil washing	Insufficient water would limit feasibility
	Soil extraction	Warmer temperatures may help
	Natural attenuation	Models do not include climate change which may alter resident time of contaminants in soil → Attenuation rates may vary
	Incineration	Emissions allowances may change due to temperature or greenhouse gases
	Capping systems	Climate change may degrade the cap (e.g., because of extreme precipitation events) → Much higher contaminant concentration/export and increased mobilization of contaminants in vadose zone

*Note. See also U.S. EPA fact sheets developed for contaminated sediments, groundwater remediation systems, and landfills and other containment remediation.

3 | SOCIETAL IMPACTS AND LEGAL IMPLICATIONS

The National Climate Assessment (NCA) provides an in-depth assessment of climate change impacts on the lives of Americans; the Fourth NCA noted that “extreme weather events have cost the United States \$1.1 trillion since 1980” (Hibbard, Dokken, Stewart, & Maycock, 2017); and The U.S. Government Accounting office warned that climate change “could increase flooding costs in coastal communities by \$23 billion per year by midcentury” (Plumer, 2017).

Communities adjacent to contaminated sites are often comprised of socioeconomically depressed and environmental justice (sensitive) populations that usually have little influence over the decision-making process, even when they are most impacted. North Carolina residents evacuated during Hurricane Florence shared the fate of New Orleans residents post Katrina “... the poor are always vulnerable- to the perceived values of their residences in good times and the ravages of Mother Nature when disaster hits” (Fausset, 2018, p. 1).

Parties liable under the U.S. Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) can face additional liability if global warming-related weather events exacerbate problems on contaminated properties. There is no minimum quantity of a hazardous substance needed to establish liability, and a generator or transporter is liable whether or not the hazardous substances they generated or transported are the primary contaminants of concern at the site. All of the parties (current and past owners and operators, generators, and transporters) are also liable if contaminants migrate from the original disposal area.

CERCLA contains an “Act of God” defense, defining an “Act of God” as “an unanticipated grave natural disaster or other natural phenomena of an exceptional, inevitable, and irresistible character, the effects of which could not have been prevented or avoided by the exercise of due care or foresight” (42 U.S.C. § 9601(1)(1980)).

CERCLA also specified three steps necessary to succeed with the Act of God defense. First, the defendant will have to prove that the Act of God was the “sole cause” of the hazardous substances release

(42 U.S.C. § 9607(b)(1)(1980)). Second, the defendant will have to prove the event was “unanticipated” (42 U.S.C. § 9601(1)(1980)). Third, the defendant will have to prove that the effects of the event “could not have been prevented or avoided by the exercise of due care or foresight” *Id.* The failure to date of the Act of God defense is illustrated by the results in the cases in which it has been unsuccessfully attempted (see, e.g., *U.S. v. Stringfellow*, 661 F.Supp. 1053 (C.D. CA 1987); *U.S. v. W.R. Grace & Co.-Conn.*, 280 F.Supp.2d 1135 (D. MT 2002); *U.S. v. Alcan Aluminum Corp.*, 892 F. Supp. 648 (M.D. Pa. 1995), *aff'd*, 96 F.3d 1434 (3d Cir. 1996); *U.S. v. Barrier Industries, Inc.*, 991 F. Supp. 678 (S.D. N.Y. 1998); *U.S. v. M/V Santa Clara I*, 887 F. Supp. 825, 843 (D.S.C. 1995)).

As part of a U.S. government-wide effort, the U.S. EPA began analyzing how climate change could impact the nation's most hazardous sites and developing best practices for the most vulnerable remediation techniques (<https://www.epa.gov/superfund/superfund-climate-change-adaptation>). U.S. EPA also reported on additional community benefits of climate change adaptation at “brownfields” and recommended land use, zoning, and building code changes and/or development incentives that could increase resiliency (<https://www.epa.gov/brownfields/climate-adaptation-and-brownfields>).

3.1 | Overarching resilient remediation principles

Sustainable Remediation Forum (SURF) recommendations to advance climate change resilience within contaminated lands rehabilitation build on these U.S. EPA initiatives, along with well-established climate change adaptation tenets, marrying them with sustainable remediation principles and practices. SURF's Sustainable Remediation Framework calls for “a systematic, process-based, iterative, holistic approach beginning with the site end use in mind” (Holland et al., 2011). This holistic approach can incorporate planning for uncertainty, reducing the rate and extent of local, regional, and global climate change impacts, and address social impacts, equity concerns, and opportunities. Setting criteria and indicators for measuring progress provide for more transparency and can gain stakeholder support.

While the toxicological literature includes a fair amount of understanding regarding how the parameters related to climate change (temperature, pH, salinity, dilution) affect contaminants, there is little application of these parameters in combination (as will often be the case with climate change). As a result, it will be necessary to develop approaches to remediation that can be adapted as new information is gathered in the treatment process.

To be most effective, adaptation should be an iterative and flexible process that involves periodically reevaluating the remediation system's vulnerability, monitoring the measures already taken, and incorporating newly identified options or information into the adaptation strategy. This involves consideration of short- and long-term availability of resources, such as energy and clean water, and ecosystem services as well as land uses of site or the surrounding area that may be critical aspects of the remediation system (U.S. EPA, 2015). As part of this iterative and flexible process site managers can use scenario planning that details future potential conditions in a manner that supports decision-making under conditions of uncertainty but does not predict future change that has an associated likelihood of occurrence (Glick, Stein, & Edelson, 2011).

Considering the role of remediation in greenhouse gases (GHGs) emissions is important. Energy-intensive remedies are often a significant source of GHGs. At one remediation project in New Jersey, it was estimated that the difference between two proposed remedies could be as high as 2% of the annual GHG emissions for the entire state (Ellis & Hadley, 2009). Further, a meta-analysis indicated that the cleanup of 1 kg of contaminants in groundwater may result in up to 130 tons of CO₂ emissions, with a geometric mean of 1.3 tons of CO₂ emissions (Hou & Al-Tabbaa, 2014).

As part of the sustainable remediation assessment, these GHGs determinations can support decisions that reduce the manifestations of climate change on the site. Best management practices can be found in the ASTM Greener Cleanups and Consideration Sustainability in Remediation Projects guidance documents.

Social vulnerability is an ability to cope with and adapt to any external stress placed on livelihoods and well-being (Adger & Kelly, 1999). Adaptation strategies need to identify stakeholder concerns and address risk perception barriers. These strategies can include localized investigation to find answers to the questions about whom and what are vulnerable, to what are they vulnerable, how vulnerable are they, what the causes of their vulnerability are, and what responses can lessen their vulnerability (U.S. National Oceanic and Atmospheric Administration [NOAA], 2016; NOAA Community Social Vulnerability Indicators [Coburn, Spence, & Pomonis, 1994]). For example, the local community, municipal planners, and office of emergency management representatives can inform site managers on areas in and within the vicinity of the site that experience frequent nuisance flooding and are vulnerable to severe weather events.

Strategies for resilient rehabilitation of contaminated sites should:

- Involve the community throughout the cleanup and redevelopment process.

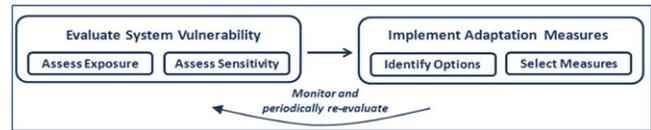


EXHIBIT 3 U.S. EPA climate vulnerability and adaptation model (U.S. EPA, 2013)

- Build partnerships by collaborating with community advocacy groups, academia, and/or professional organizations for outreach activities.
- Employ transdisciplinary processes that can help various stakeholders with different objectives and risk perceptions to reach consensus.
- Consider innovative measures such as social contracts that can link climate change and equity targets and measure progress in meeting community needs.
- Maximize opportunities to increase the well-being of vulnerable populations and creating value (direct and indirect) including public health benefits and jobs (part of the cleanup, long-term monitoring program, or through reuse of sites as parks or renewable energy deployment).
- Coordinate policies across sectors of transport, land use, health, and energy.

3.2 | Site-specific protocols

Aligned with these overarching principles are recommended site-specific protocols that begin with the U.S. EPA and ASTM guidance and recent Washington State guidance, Adaptation Strategies for Resilient Remedies (Washington State Department of Ecology [DOE], 2017). The Washington DOE guidance is intended to: (1) help understand site-specific vulnerabilities of cleanup sites to climate change impacts, and (2) provide recommendations to increase resilience of remedies at each phase of cleanup. The guidance focuses on four climate change impacts: sea-level rise, flooding, landslides, and wildfires. The Washington DOE guidance also includes examples of vulnerability analyses, a list of references, links to different technologies, adaptation plans, decision tools, case studies, and sustainable remediation resources.

Exhibit 3 depicts U.S. EPA's climate vulnerability and adaptation model, which evaluates the sensitivity, exposure, and adaptive capacity of the site, contaminant, or remediation technique to climate change.

An evaluation of a system's vulnerability to climate change involves identifying climate change hazards of concern (such as treatment or containment systems) in light of potential climate/weather and considering factors that may exacerbate the system's exposure and sensitivity, such as a long operating period.

For riverine and coastal sites, a vulnerability assessment may also encompass hydraulic and hydrological modeling or hydrodynamic modeling, respectively, to evaluate the role of precipitation projections, storm surge, surface water flow velocity, sea level rise, wave

**ASTM International Guidance
Climate Resiliency Planning and Strategy (E3032-15e1)
Climate Resiliency in Water Resources (ASTM WK55606)**

- addresses extreme weather,
- reflects general risks for certain regions of the country with its matrix approach
- Discusses impacts to ecosystems, global repercussions and vulnerable communities.
- Looks at effective scale of adaptation (site, town, watershed) and recommends setting priorities – e.g., drought and heat events, extreme runoff and flooding, storm damage to infrastructure, sea level rise.
- Offers a schematic flow chart with feedback loop for Selection, Monitoring, Measurement and Review of Resiliency Projects
- Generates reports describing the costs and benefits of risk reduction strategies for decision-makers and stakeholders (ASTM International, Inc., 2015)

EXHIBIT 4 ASTM international guidance for climate resiliency

action, and/or wind action under existing and future storm events (e.g., 100-year storm event). The results of the modeling aid in remedial design, such as armor stone specifications for cap enhancement, and periodic climate change vulnerability monitoring, such as continuous monitoring of water levels, wave action, and flow velocity.

To support these vulnerability assessments, practitioners should use best available guidance (e.g., see Exhibit 4) and confer with local/regional experts and affected communities. Dynamic geospatial data are available from several sources, including federal, state, regional, or local sources such as watershed and forestry management authorities, nonprofit groups, and academia.

The site vulnerability assessment process should involve local government and residents: Stakeholder engagement strategies can include focus group interviews, local workshops, and/or or public comment periods. This process can also increase local understanding of the risk of climate change and provide new perspectives on remediation options (Harclerode et al., 2015).

The vulnerability assessment should identify the need for adaptation strategies and long-term vulnerability monitoring protocols as part of operation and maintenance (O&M).

Adaptation strategies can also leverage existing regulatory tools such as the NCP long-term effectiveness and permanence (40 CFR 300.430(e)(9)(iii)(C)) and the Superfund Five-Year Reviews (Thun, 2017).

Five-Year Reviews should include the following elements (Thun, 2017):

- Evaluate remedy implementation/performance to determine protectiveness.
- Determine if the remedy functioning as intended. QUESTION C: Has any other information come to light that could call into question the protectiveness of the remedy?
- Address site changes or vulnerabilities that may be related to climate change impacts not apparent during remedy selection, rem-

edy implementation, or O&M (e.g., sea level rise, changes in precipitation, increasing risk of floods, changes in temperature, increasing intensity of hurricanes and increasing wildfires, melting permafrost in northern regions, etc.).

- Determine if the assumptions, data, and cleanup levels are still valid and, if there are issues, update O&M or remedy decision.

4 | ADAPTATION STRATEGIES CASE STUDIES

Adaptation strategies can be categorized as resistance, resilience, and response.

Resistance strategies maintain current conditions. They can include physical security, such as hardening covers, caps, and barriers to prevent flooding or erosion. Resistance strategies eventually will succumb to change or need to be increased at continuing cost.

Resilience strategies allow sites to experience the change but still manage contaminant mitigation successfully. For example, to improve protectiveness and long-term effectiveness against more frequent severe storms, damaged portions of an intertidal cap at the Port Gamble Bay and Mill Site in Kitsap County, Washington, were repaired and replaced with armor of rocks and other natural materials almost twice the original size (Washington DOE, 2017).

Resilience strategies also include backup power and remote and communication including automated data acquisition. An example developed by the Lawrence Berkeley Laboratory for the Department of Energy capitalizes on 21st century technology through a new streamlined real-time data processing and analysis and early warning system for the Savannah River Superfund Site F-Area with a 50% cost saving (Exhibit 5, Wainwright, 2016).

Resilience strategies can also include the use of recycled water, including treated groundwater, to respond to drought conditions or salt water intrusion.

Another example of resilience comes from Huangshi in south central China, where intensive mining and smelting have caused significant air and water pollution and the contamination of nearby agricultural lands. Strip mining resulted in over 100 man-made bluffs, which are susceptible to landslides. One of the Rockefeller Foundation 100 resilient cities, Huangshi helped stabilize the land at these abandoned sites to prevent flooding and protect resources and human health. These efforts included controlling water pollution through sewage collection, water treatment, and increasing vegetation with ecological restoration projects.

Response strategies range from pre- and post-site inspection to removal of some or all of the contamination. For example, the New Jersey Department of Environmental Protection (NJDEP) developed response strategy guidance targeted to site owners and persons responsible for conducting and overseeing cleanup (i.e., "Licensed Site Remediation Professionals"). After storms, all sites should be reevaluated to determine if any immediate environmental concerns needing action arose and whether site conditions changed requiring reassessment (NJDEP, 2016).

5 | CLIMATE RESILIENT REDEVELOPMENT: DRIVERS AND CASE STUDIES

Over the last decade U.S. and European Union (EU) initiatives have sought to advance remediation by assessing the benefits of rehabilitated land in strengthening community, economic, and ecosystem resilience.

A U.S. EPA 5-year study of brownfields found that residential property values increased from 5.1 to 12.8% after a nearby brownfield was assessed or cleaned up (Bartsch, 2015). The study also determined that brownfields cleanup can increase overall property values within a 1 mile radius by \$0.5 to \$1.5 million. In 2016, U.S. EPA also published guidance regarding brownfield Revitalization in Climate-Vulnerable Areas including ordinance regulation and development incentives (U.S. EPA, 2016).

Working for the City of San Francisco, Hou, Song, Hou, O'Connor, & Harclerode (2018) developed a method based on life cycle assessment of GHG emissions to compare brownfields to greenfield land development. The team examined three categories: (1) primary impact (associated with physical state of brownfield sites and greenfield sites), (2) secondary impact (associated with remediation activities at brownfield sites), and (3) tertiary impact (associated with post-remediation usage of the brownfield sites and avoided usage of greenfield land). Overall, the results show that the City's brownfield land redevelopment could lead to a net GHG reduction of 51.9 million metric tons (Mt) CO₂ eq. over a 70-year period, or 0.74 Mt CO₂ per yr, the equivalent of 14% of San Francisco's GHG emissions in 2010.

Overall, the results show that the City's brownfield land redevelopment could lead to a net GHG reduction of 51.9 million metric tons (Mt) CO₂ eq. over a 70-year period, or 0.74 Mt CO₂ per yr, the equivalent of 14% of San Francisco's GHG emissions in 2010.

The RE-Powering America's Land Initiative, where U.S. EPA supports renewable energy development on potentially contaminated land, landfills, and mine sites, tracks the economic and environmental benefits associated with completed sites. Common benefits reported from developers/public agencies include revenues from land leases and taxes, electricity cost savings, job creation, and reduced GHG emissions (U.S. EPA, 2018b).

A recently completed renewable energy project in the San Francisco Bay Area, the Marin Clean Energy (MCE) Solar One partnership, exemplifies the RE-Power America benefits.

MCE Solar One repurposed 60 acres of a remediated brownfields site leased by Chevron to MCE Solar One for \$1 per year. At 10.5 megawatts, MCE Solar One will eliminate 3,234 Mt of carbon dioxide in one year, equivalent to taking more than 680 cars off of the road annually. MCE Solar One provided community benefit by partnering with RichmondBUILD, a public-private partnership that focuses on training for skilled construction, hazardous waste removal, and renewable energy jobs. All RichmondBUILD participants come from low-income households. In addition, almost \$2 million dollars was spent on project materials purchased or rented locally. The project also includes an innovative procurement approach called "community choice energy," in which a public agency offers citizens and businesses an alternative to the utility for purchasing their electricity. As a result of the MCE Solar One project, homes and businesses now benefit from a more renewable electricity option that costs 2 to 5% less than the traditional Bay Area utility rates (<https://www.mcecleanenergy.org/news/press-releases/mce-solar-one-thinking-globally-building-locally/>).

6 | EU AND UK DRIVERS AND CASE STUDIES

There is presently a trend across Europe for densification as a planning approach for sustainable development to foster efficient use of resources, efficient transport systems, and a vibrant urban life (e.g., Haaland & van den Bosch, 2015). Development often takes place on areas that are often viewed as underutilized land (such as green space, marginal land) or through redevelopment on previous industrial estates (derelict, brownfield sites). However, this approach has also been challenged for its threat to urban green spaces (Haaland & van den Bosch, 2015) since together with urban Brownfields they potentially have an important role for offering climate change adaptation solutions.

This is strongly related to a much wider European debate about "Nature Based Solutions" (NBS), their importance in urban areas and how they might be managed and, if necessary, regenerated. The concept of NBS was introduced toward the end of the 2000s by the World Bank (MacKinnon, Sobrevila, & Hickey, 2008) and International Union for Conservation of Nature (IUCN, 2009) to highlight the importance of biodiversity conservation for climate change mitigation and adaptation. NBS were proposed by IUCN for inclusion in the climate change negotiations in Paris "as a way to mitigate and adapt to climate change, secure water, food and energy supplies, reduce poverty and drive economic growth" (IUCN, 2014). The IUCN proposed principles for NBS included cost efficiency, harnessing both public and private funding, ease of communication, and replicability of solutions (van Ham, 2014). Thus, NBS puts an explicit emphasis on linking biodiversity conservation with goals for sustainable and climate resilient development (Eggermont et al., 2015), and represent innovative, implementable "solutions."

The Holistic Management of Brownfield Regeneration (HOMBRE) was a major EU project completed in 2014 (www.zerobrownfields.eu), examining the enhanced transition of brownfields through to becoming once more a functional part of the land cycle. One of its areas of interest was in “soft,” that is, non-built reuse of brownfields, the services this might provide, and how those might be appreciated and valued. One of the outputs of this work is a simple Excel design aid to help developers and others involved in brownfields map the range of opportunities, the resulting value, and the initial default design considerations by identifying specific opportunities for synergies between different “services” such as risk management, water improvement, and renewable energy.

6.1 | Case study: Brownfields redevelopment as wetlands park and community management

Port Sunlight Riverside Park: Port Sunlight River Park is a 28-hectare park near Birkenhead in Wirral, Merseyside, UK, which opened in 2014. It is located on a former landfill capped and covered by the waste management company (Biffa Waste Management) and leachate and gas management systems were put in place. The site was passed over to the Land Trust on a 99-year lease and, after planning and design, was created as a riverside park in 2013. The waste management company remains responsible for ongoing management and monitoring of the capping, landfill gas, and leachate treatment.

The Land Trust secured a £3.4 million investment for a transformation project encompassing park creation, site of special protection and ongoing management, and established a partnership with the charity, Autism Together, which manages the park.

A retrospective qualitative sustainability assessment was performed by the University of Brighton in 2016. The aim of the sustainability assessment was to understand the economic, environmental, and social benefits/disbenefits of transforming the former landfill into a public open space, managed long term (Li, Bardos, & Cundy, 2017), using SURF-UK qualitative sustainability assessment guidance (www.claire.co.uk/surfuk) enhanced with the HOMBRE idea of conceptual site models of sustainability (Bardos et al., 2016). Climate change-related considerations were a significant part of the sustainability assessment, including emissions of carbon to atmosphere versus sequestration; and economic factors such as the project's future resilience. Unsurprisingly, the reuse of the capped landfill as a public park showed substantive sustainability improvement.

Anticipate Adsorb Reshape (“A2R”), a United Nations (2017) Climate Resilience Initiative can support sustainable, resilient cleanup and reuse of hazardous sites. A2R focuses on the capacity to reshape development pathways by: (1) transforming economies to reduce risks and root causes of vulnerabilities, and (2) supporting the sound management of physical infrastructure and ecosystems to foster climate resilience.

Complementing A2R is the World Bank vision of contaminated sites as “engines for economic development, sources of sustainable energy, food security & efficiency—all while assuring public health and environmental protection” (World Bank, 2009, p. 1).

7 | CONCLUSIONS

SURF's recommendations can guide owners and project managers in developing a site resiliency strategy. By following a systematic, holistic approach with the site end use in mind, and by meeting priority social and economic needs, climate-resilient sustainable remediation and redevelopment can reduce public health risks and create long-term value for communities. SURF plans to partner with the private and public sector to support pilot studies and conduct national and international capacity-building.

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