# Anticipating Environmental and Environmental-Health Implications of Extreme Storms: ARkStorm Scenario

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**Abstract:** The ARkStorm Scenario predicts that a prolonged winter storm event across California would cause extreme precipitation, flooding, winds, physical damages, and economic impacts. This study uses a literature review and geographic information system-based analysis of national and state databases to infer how and where ARkStorm could cause environmental damages, release contamination from diverse natural and anthropogenic sources, affect ecosystem and human health, and cause economic impacts from environmental-remediation, liability, and health-care costs. Examples of plausible ARkStorm environmental and health concerns include complex mixtures of contaminants such as petroleum, mercury, asbestos, persistent organic pollutants, molds, and pathogens; adverse physical and contamination impacts on riverine and coastal marine ecosystems; and increased incidences of mold-related health concerns, some vector-borne diseases, and valley fever. Coastal cities, the San Francisco Bay area, the Sacramento-San Joaquin River Delta, parts of the Central Valley, and some mountainous areas would likely be most affected. This type of screening analysis, coupled with follow-up local assessments, can help stakeholders in California and disaster-prone areas elsewhere better plan for, mitigate, and respond to future environmental disasters. **DOI: 10.1061/(ASCE)NH.1527-6996.0000188.** 

## Introduction

In the winter of 1861–1862, a series of extreme winter storms pummeled California for 45 days, causing severe flooding and damages (Dettinger et al. 2012). The ARkStorm Scenario was developed by the U.S. Geological Survey (USGS) Multi-Hazards Demonstration Project (MHDP) to model the physical and economic impacts that such a series of storms would have on modern-day California (Porter et al. 2011). The MHDP and its successor, the Scientific Applications for Risk Reduction (SAFRR) Project, use disaster scenarios such as ARkStorm to engage emergency planners, businesses, universities, government agencies, and the public in preparing for major natural disasters.

The meteorological model developed for the ARkStorm Scenario (Dettinger et al. 2012) indicated that the series of storms would produce extreme precipitation across mountainous parts of California and high winds on the lee sides of mountain ranges (Fig. 1). Except over the highest elevations, most of this precipitation would be rainfall. Hydrologists concluded that the resulting runoff would likely overwhelm the state's flood-protection system, cause levee failures, and flood much of the Central Valley and portions of Orange County, Los Angeles County, San Diego, the San Francisco Bay area, and other coastal communities (Fig. 1). Storm-related flooding, coastal storm surges, high winds, runoff, erosion, and tens of thousands of landslides and debris flows triggered by the storms (Fig. 1) would cause extensive damage to homes, buildings, highways, and other infrastructure (Wills et al. 2014; Porter et al. 2011). Repairs to water, power, sewer, and road lifelines would likely take months. There could also be storm-caused fires ignited by wind-downed power lines or ignition of petroleum products released into floodwaters. The economic costs of the storm are estimated to include \$350 billion in physical damages and \$58–\$290 billion in business interruption losses (Wing et al. 2015).

A review of the scientific literature and news media reports (e.g., Cozzani et al. 2010; Young et al. 2004; Gautam and van der Hoek 2003) provides significant insights into the types of environmental contamination that have resulted from past flood events and other disasters—results of this review are summarized in Table 1 and the Supplemental Data. There are also excellent summaries about the impacts of disasters on human health (e.g., Cook et al. 2008). However, there has not been a systematic assessment of the potential environmental damages, environmental contamination, and environmental-health threats to humans and ecosystems that could be caused by a geographically complex combination of extreme rainfall, flooding, landslides, winds, storm surges, and storm-caused fires.

The state of California and many of its counties and cities have developed hazard mitigation plans (Cal OES 2013b; URS Corp. 2005), emergency plans to help prepare for future disasters (Cal OES 2013a), and databases cataloging locations of environmentally significant facilities (e.g., Cal EPA CERS 2013). However, these efforts have not included a systematic assessment of potential environmental and environmental-health impacts of future extreme statewide disasters.

The ARkStorm Scenario thus provides a unique opportunity to assess for the first time the plausible environmental and environmental-health implications of a prolonged, catastrophic winter storm event across a large, geographically complex region such as California. This study uses knowledge gleaned from the literature review of disaster-related environmental contamination (Table 1) and a geographic information systems (GIS) analysis to

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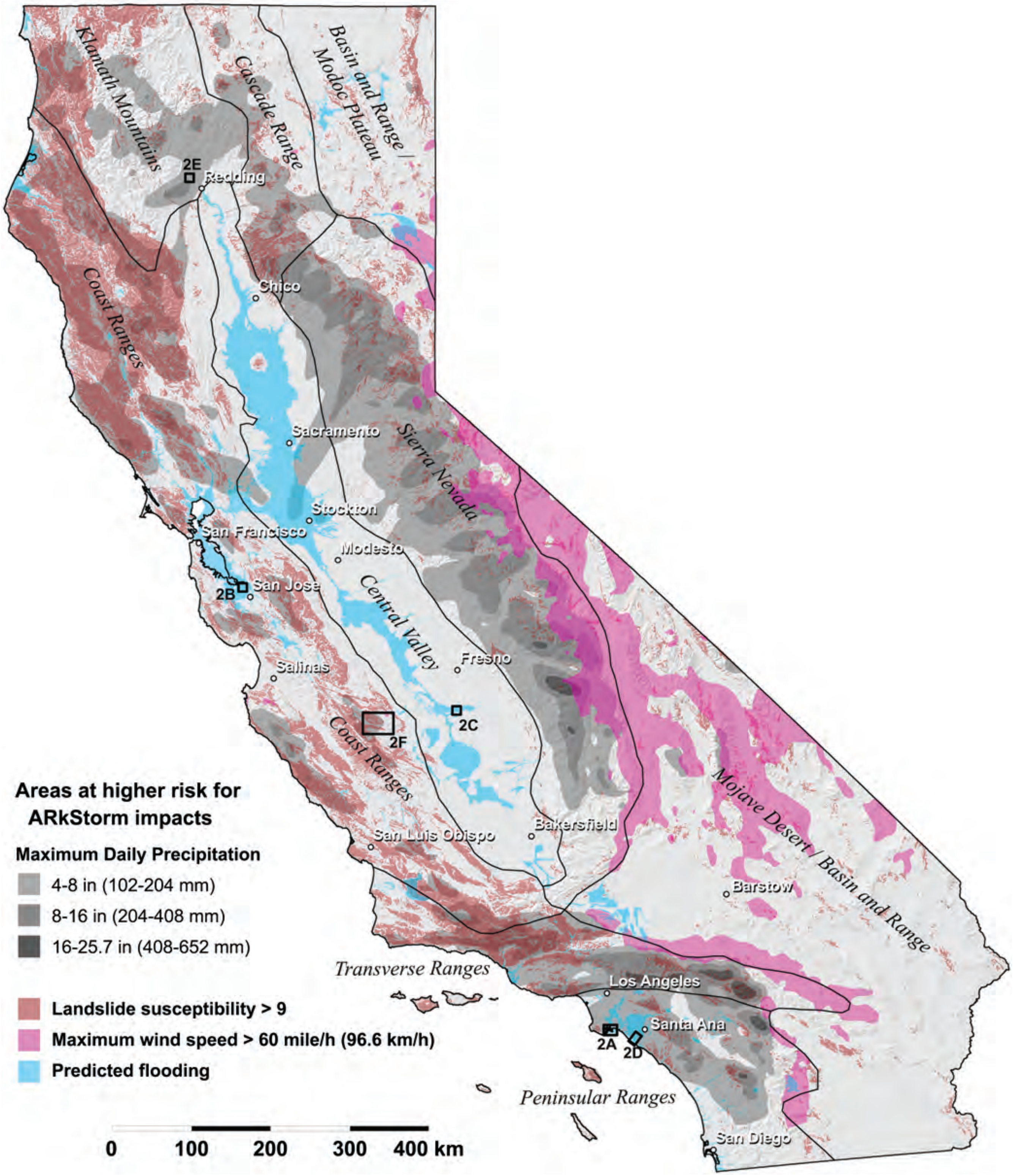


**Fig. 1.** (Color) Summary map showing ARkStorm predicted maximum daily precipitation map, plausible flooded areas, maximum winds, and landslide susceptibility; also shown are boundaries of generalized geomorphic provinces from CGS (2002) and boxes indicating locations of satellite images in Fig. 2 (used by permission, © 2015 Esri, DigitalGlobe, Earthstar Geographics, CNES/Airbus DS, GeoEye, USDA FSA, USGS, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community, all rights reserved)

infer areas where predicted ARkStorm precipitation, flooding, winds, landslides, and physical damages could cause environmental damages and contamination from a broad range of vulnerable natural and anthropogenic sources. By knowing the likely types and relative amounts of contaminants that could be released from these diverse sources, and by understanding the environmental processes that influence the transport and fate of these contaminants, it can be inferred how potential ARkStorm-related environmental contamination, environmental impacts, and environmental-health concerns could vary across California.

**Table 1.** Examples of Mineral, Metal, Organic, and Pathogen Contaminants Noted in Literature to Result from Floods and Other Disasters

| Potential sources | Examples of possible contaminants |
|---|---|
| Raw or partially treated sewage from combined sewer overflows, WWTPs, sewer lines, septic tanks | Pathogens: bacteria (e.g., *E. coli*, *Salmonella*, *Vibrio cholera*), protozoa (*Giardia lamblia, Cryptosporidium*), enteric viruses, parasitic worms. Some bacteria may have enhanced antibiotic resistance. Organics: human hormones, metabolic wastes, pharmaceuticals and personal care products (e.g., synthetic hormones, disinfectants), detergents, fire retardants, solvents. Inorganics: nitrates, ammonia, metals (copper, lead, zinc), organotin, fertilizer components. Solids: fecal solids, metal-bearing particles. Emulsions: paints, hair colorants |
| Industrial facility wastewater | Solvents, petroleum and petroleum products, pesticides, paints, cyanide compounds, cleaners, acids, and alkalis |
| Municipal water treatment facilities, WWTPs | Chemicals used to treat large volumes of water: disinfectants (chlorine gas), pH control chemicals (sodium hydroxide, acids, sulfur dioxide gas), oxidants (hydrogen peroxide), fluoridation chemicals (fluorosilicic acid) |
| Food processing plants | Refrigerants (anhydrous ammonia), sanitizers (chlorine, hypochlorite), detergents, solvents, acids |
| Untreated wastes from animal feeding operations | Pathogens: bacteria (*E. coli*, *B. Anthracis*, *Brucella*), protozoa (*Giardia lamblia*), viruses (bovine enterovirus, hepatitis E virus), parasitic worms (*Schistosoma*). Some bacteria may have enhanced antibiotic resistance. Organics: natural animal hormones, animal metabolic wastes, synthetic hormones, antibiotics. Inorganics: nitrates, ammonia, metal(loid)s (As, Co, Cu, Zn, Cd). Solids: suspended fecal particles, carcasses of drowned animals |
| Municipal waste landfills | Ammonium, solvents, organohalogens, pesticides, phenols, plasticizers, metal(loid)s (Hg, Pb, Cr), organometals (Hg, Sn), organic and inorganic acids, gases (hydrogen sulfide, volatile organic compounds) |
| Petroleum refineries, bulk petroleum facilities | Crude oil, petroleum and petroleum products, and their combustion products. Gaseous ammonia, hydrogen fluoride, hydrogen sulfide, liquefied petroleum, and propane. Metal(loid)s (As, Ni, V) in petroleum and in other process chemicals |
| Pesticide, chemical, fertilizer manufacturing plants | Bulk chemicals manufactured or used in chemical manufacturing: pesticides (chlorine gas, dimethylamine), fertilizers (anhydrous ammonia, ammonium nitrate), other industrial chemicals (polyvinyl chloride, many different metal(loid)s, organics) |
| Releases from metal mining or placer gold mining sites | Metal(loid)-rich (Fe, Al, Mn, Zn, Hg, Pb, Cu, As, Cd, Co, etc.), sulfide-rich, potentially acid-generating solids from historical mine-waste piles and tailings impoundments. Rainfall leachates or mine waters with high levels of acid and/or dissolved/particulate metals. Processing fluids from active sites (cyanide compounds, metals, surfactants) |
| Smoke, ash, and debris from burning buildings, oil fires | Smoke has high respirable ($<2.5\ \mu m$ in size) particulate matter. Inorganics: caustic alkali solids, metal(loid)s (Pb, As, Cr[VI], Sb, asbestos). Organics: PAHs, dioxins, formaldehydes, pesticides, fire retardants (PBDEs) |
| Contaminants in flooded houses, buildings | Mold (fungus) species (*Aspergillus*, *Stachybotrys*), and their metabolic byproducts (mycotoxins). Contaminated flood sediment deposits within buildings |
| Nonpoint runoff from urban, industrial, suburban areas and highways | Road salt, petroleum or petroleum products, lead (from leaded paint, legacy gasoline combustion, tire weights), zinc (from tires, tire weights), oxides or sulfides of various metals (metal sulfides in anoxic sewer sediments), organic petroleum combustion byproducts (PAHs, PCBs, dioxins, furans), surfactants, fertilizer compounds, pesticides |
| Nonpoint runoff from agricultural operations | High sediment loads, nutrients (nitrates, phosphates, potassium), pesticides, herbicides, fungicides, other chemicals applied to crops. Metal(loid)s (Cd, Cu, U, As) are associated with some phosphate fertilizers, legacy pesticides, or other crop treatments. Zinc in runoff from farmyard buildings with galvanized surfaces. Releases of stored solid, liquid, and gaseous fertilizers, pesticides, and herbicides |
| Buildings and other components of the built environment | Materials used for building and materials found in the built environment. Metal(loid)s: Pb, Cr[VI], As, Hg, Cd, Ni, Cu, Zn, Sb. Pesticides: dieldrin, aldrin, chlordane, many others. Organics: PCBs, PBDEs, formaldehyde, di(2-ethylhexyl) phthalate, PAHs. Minerals: asbestos, asbestos-contaminated vermiculite |
| Remobilization of contaminated sediments/ soils from cities, storm drains, river or harbor bottoms | Organics: persistent organic pollutants (aldrin, chlordane, DDT, dieldrin); PAHs; PBDEs; organometallic compounds (Sn, Hg). Metal(loid)s: Hg, Pb, Cu, Zn, As. Minerals: metal sulfides, asbestos. Materials from the urban, built environment: lead paint flakes, solder, tire weights |
| Asphalt pavement from damaged roads | Pulverized asphalt may provide an environmentally available source of some heavy metal(loids) (Ni, V), PAHs, and other organic toxicants |
| Natural sulfide-mineralized rocks | Runoff from, landslides in, or erosion of these rocks can carry metal-rich (Fe, Al, Mn, Zn, Pb, Cu, As, Cd), acid-drainage water and sulfide-bearing, acid-generating rock materials into nearby watercourses |
| Natural asbestos-containing rocks, soils | Ultramafic rocks (especially serpentinite), metamorphosed mafic volcanic and plutonic rocks, marbles, contact-metamorphosed dolomite rocks, soils developed on these rocks, and alluvial materials derived from these rocks can contain elevated levels of asbestos. Materials from ultramafic rocks can also contain elevated levels of Ni, Cr, and V |

Note: PAHs = polycyclic aromatic hydrocarbons; PBDEs = polybrominated diphenyl ethers; PCBs = polychlorinated biphenyls.

The analytical approach described here provides a first step in helping emergency managers, government officials, engineers, the public, and other stakeholders understand the potential spatial distribution and complexity of storm-related environmental and environmental-health impacts across California. More detailed investigations that can be done as follow-up are also described. This screening analysis using national-scale databases is readily transferable to other areas of the country and to other types of disasters such as tsunamis (e.g., Plumlee et al. 2013). A similar GIS approach could be taken in other countries or global regions with available geospatial data.

## GIS Coverages and Databases Used

Databases and GIS coverages used in this analysis of ARkstorm are discussed in detail in the Supplemental Data. Key coverages are mapped in the multiple-layer Supplementary Maps file—specific layers in that file are referred to in the following discussion as "SM-x," in which x is the appropriate layer number.

The ARkStorm Scenario impacts (Wills et al. 2014; Dettinger et al. 2012; Porter et al. 2011) considered include areas of predicted high maximum daily precipitation, flooding, winds, and landslide susceptibility (Fig. 1; Supplemental Data; SM-17–SM-24). Flooding impacts from other storm events can be evaluated using Federal Emergency Management Agency (FEMA) floodplain coverages for 0.01 annual flooding probability (FEMA DFIRM 2013; SM-19).

Possible natural contamination sources were assessed using databases listing the occurrences of environmentally or toxicologically significant minerals such as acid-generating iron sulfides (USGS MRDS 2010) or asbestos (Van Gosen and Clinkenbeard 2011). A digital geologic map of California (Ludington et al. 2007) was recast to show the distribution of rocks that are geologically favorable to contain these minerals, or that are known to host soil pathogens such as *Coccidioides*, the soil fungus that causes valley fever (Fisher et al. 2007).

Potential anthropogenic sources of contamination were assessed using, for example: (1) the U.S. Environmental Protection Agency (EPA) facilities registry service (FRS) database (EPA FRS 2015) that lists locations of and information on environmentally significant facilities (e.g., wastewater treatment plants, oil refineries, and Superfund sites); (2) USGS databases of active or historical mining operations and significant ore deposits (USGS MRDS 2010; Long et al. 1998); and (3) a state database showing the locations of animal feeding operations (AFOs) (California DWR 2010). Additional GIS coverages helped elucidate potential ARkStorm environmental implications for critical species habitats and environmentally or ecologically significant federal lands.

## Limitations of This Analysis

There are uncertainties in the ARkStorm Scenario's modeled precipitation and flooding results (Porter et al. 2011). As detailed in the Supplemental Data, there are also uncertainties in the national-scale databases used for the environmental analysis, and in the methods used to extract information from the databases. Examples include: (1) imprecise location data on environmentally significant facilities; (2) lack of detailed information on the specific contaminants and their volumes that are present at specific facilities; and (3) lack of information on the potential vulnerability of specific facilities to ARkStorm impacts and damages, such as presence or absence of engineered flood mitigation structures. These uncertainties preclude a detailed analysis of specific local areas or sites in this study, but nonetheless enable a statewide screening analysis that can be followed up with more detailed local or site-specific analyses.

## Mapping Potential Sources of ARkStorm-Related Contamination

Many plausible environmental contamination sources could be vulnerable to ARkStorm impacts, as illustrated by satellite imagery (Fig. 2), the Supplemental Data, and Supplementary Maps.

### *Point Anthropogenic Sources*

Numerous industrial or commercial facilities fall within predicted ARkStorm flooded areas and/or areas of high precipitation, whereas fewer plot in areas of likely landslides or high winds (compare SM-5 through 9 to SM-20 through 24). If flooded, damaged, or combusted, these facilities could become point sources for environmental contamination. Damages to large numbers of smaller facilities in a given area, or to smaller numbers of large facilities, could collectively release substantial volumes of contaminants with potential for extensive environmental impacts. Examples of small to intermediate size facilities in ARkStorm-affected areas include gas stations, dry cleaners, metal plating operations, and oil and natural gas wells. Examples of larger facilities include EPA Superfund sites; equipment or electronics manufacturing plants; chemical, fertilizer, or pesticide manufacturing plants; electric power generation plants; landfills (SM-6); food-processing plants; foundries, metal smelters, or metal refineries; agricultural operations (e.g., rice, wheat, and tree nut farms, and vineyards); water-treatment facilities; oil refineries, marine oil terminals, or bulk petroleum-storage facilities [Fig. 2(a); SM-5]; and wastewater-treatment plants (WWTPs) [Fig. 2(b); SM-4].

A number of dairy, livestock, and poultry feeding operations (California DWR 2010) occur within areas of predicted ARkStorm flooding in the Central Valley [Fig. 2(c); SM-10] and/or high precipitation (e.g., east of Los Angeles). These have the potential to release pathogens and chemical contaminants from flooded waste-storage lagoons or as runoff into local surface waters (Casteel et al. 2006).

### *Nonpoint Anthropogenic Contamination*

Complex mixtures of a wide range of contaminants could plausibly be produced from nonpoint sources (Table 1). Large urban areas {Sacramento, Stockton, San Jose, other San Francisco Bay area cities, Los Angeles and Orange County [Fig. 2(d)], and San Diego} and many smaller towns heavily affected by ARkStorm would serve as nonpoint sources for contaminated stormwater runoff, previously contaminated urban soils and sediments, and debris. Other plausible nonpoint-source contamination includes stormwater runoff from highways and agricultural operations [Fig. 2(c)]; pulverized asphalt and other debris from damaged highways and infrastructure; and previously contaminated sediment deposits redistributed from highway storm drains, rivers, deltas, harbors [Fig. 2(a)], and nearshore-marine areas.

Analysis of online parcel databases (www.zillow.com) and the FEMA Hazus (2013) database shows that many neighborhoods in areas of predicted flooding have large numbers of older residences and buildings that, if damaged, could release legacy asbestos, lead paint, metallic mercury, and legacy pesticides into the environment (Plumlee et al. 2012). Remobilization of contaminated, anoxic harbor sediments would enhance exposure of aquatic and terrestrial organisms to toxic legacy contaminants such as DDT, organotin (used in ship antifouling paints), lead from leaded paints or combustion of leaded gasoline (e.g., Weston Solutions, Inc. 2009), and acid-generating iron sulfides. Storm runoff from agricultural lands could contain particulate or dissolved fertilizers and pesticides.

Widespread debris deposits left behind by floodwaters can become nonpoint sources of contaminants such as hexavalent chromium and arsenic leached from pressure-treated wood. Debris piles also provide habitat for undesirable rodents and insects.

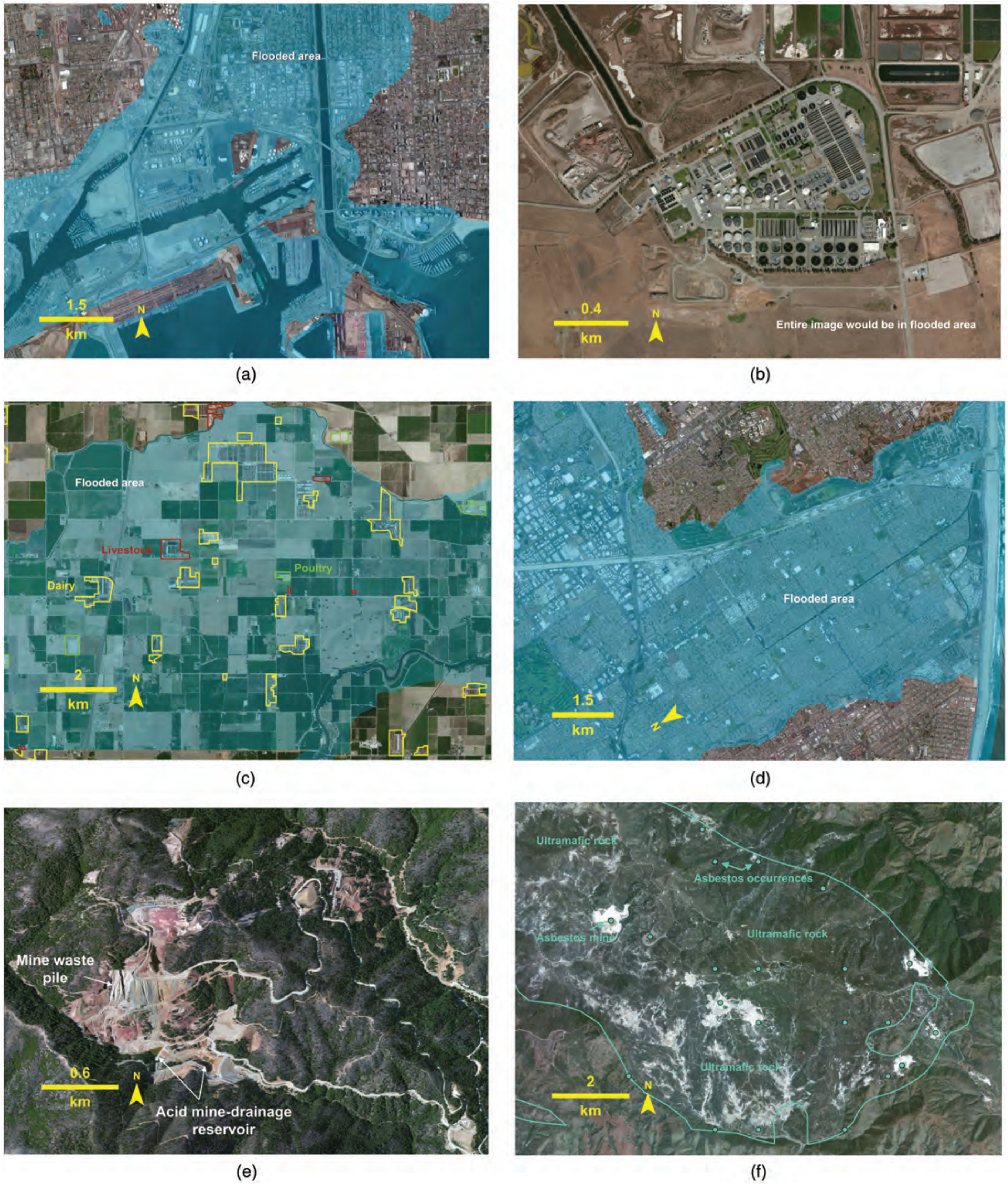


**Fig. 2.** (Color) Satellite images from Esri ArcGIS showing examples of potential contamination sources that could be vulnerable to ARkStorm precipitation, runoff, or flooding (predicted flooding in transparent blue) (used by permission, © 2015 Esri, DigitalGlobe, Earthstar Geographics, CNES/Airbus DS, GeoEye, USDA FSA, USGS, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community, all rights reserved): (a) ports of Los Angeles and Long Beach; (b) wastewater treatment plant in the South San Francisco Bay; (c) southern Central Valley, showing predicted flooding of AFOs and agricultural fields; (d) coastal Huntington Beach; (e) Iron Mountain Mine ~12 km northwest of Redding; (f) asbestos-containing ultramafic rocks, asbestos mines, and asbestos occurrences ~25 km northwest of Coalinga

### *Mixed Point/Nonpoint and Natural/Anthropogenic Contamination*

Historical hard-rock mining sites (EPA FRS 2015; USGS MRDS 2010; Long et al. 1998) fall within areas of predicted high daily ARkStorm precipitation (100 to > 400 mm per day) in the Klamath, Cascade, Sierra Nevada, and Coast Range mountains. These sites are at risk for runoff-related failure of mine-water holding ponds, mine-waste piles, and tailings impoundments. These failures would release acid mine waters and sulfidic, acid-generating solid mine wastes with elevated levels of toxic metal (loid)s such as zinc, copper, lead, mercury, and arsenic (SM-12; Plumlee et al. 2014). Even sites such as Iron Mountain near Redding [Fig. 2(e)] that have undergone environmental remediation may be vulnerable, and should be assessed for whether the engineered remedial actions could withstand ARkStorm's extreme but plausible predicted precipitation rates. Extensive outcrops of metamorphosed marine volcanic rocks that host many of California's hard rock zinc and copper mining sites, as well as sub-economic and noneconomic mineralization, could also serve as natural nonpoint sources of metal(loid)s and acid-generating sulfides [Fig. 2(e); SM-12]. Other rock types (e.g., metalliferous marine shales) may be nonpoint sources of metal(loid)s such as cadmium, selenium, and uranium.

Historical placer and lode gold-mining operations that used mercury amalgamation extraction, and historical mercury-mining operations that produced the mercury used in gold extraction (USGS MRDS 2010; Alpers et al. 2005; Long et al. 1998) provide many potential point sources of mercury contamination (SM-11). Contaminated sediment deposits downstream from historical mine sites (e.g., in Coast Range streams and the Sacramento River, its tributaries, and delta), are significant nonpoint sources of both elemental mercury and methylmercury (Alpers et al. 2008, 2005).

Historical asbestos mining sites (Van Gosen and Clinkenbeard 2011) and rock units that are geologically favorable for natural occurrences of asbestos are present in parts of the Coast Range, Klamath Mountains, and Sierra Nevada foothills that are predicted to receive high precipitation [Fig. 2(f)]. Storm-induced landslides and erosion of asbestos-containing rocks and mine wastes redistribute the asbestos into downstream sedimentary deposits, which can produce windborne dusts when dried. Storm-enhanced asbestos accumulations in downstream reservoir waters and sediments pose a water-quality issue, a dust-exposure issue during low water levels, and a sediment-disposal issue when the reservoirs are drained and cleared of sediments.

Valley fever is a relatively common illness in California residents and some animal populations. It is caused by inhalation of dusts bearing spores of the soil fungus *Coccidioides*, which is endemic in many parts of the Central Valley and southern California (Fisher et al. 2007). Some rock types that occur in portions of the Coast Ranges and Central Valley, in concert with high soil temperatures and other favorable soil characteristics, can develop soils conducive to the growth of the fungus (SM-14). Runoff-triggered erosion of soils from *Coccidioides* growth sites can redistribute the fungus to downstream flood-sediment deposits, from which the spores can become windborne during subsequent dry periods and cause valley fever outbreaks (Fisher et al. 2007).

## Environmental Behavior of ARkStorm-Generated Contaminants

Once released into the environment by disasters such as ARkStorm, contaminants are subjected to a wide range of environmental processes that modify their concentrations, forms, pathways of exposure to, and toxicity to humans and other organisms (Plumlee et al. 2014).

Many environmental processes (e.g., dilution, volatilization, biodegradation, photolytic degradation) help decrease contaminant concentrations in soils, sediments, and waters, and as a result can help diminish toxicological impacts from these media. Volatilization, however, can result in exposures of humans and terrestrial organisms to the volatilized toxicants in the air. Photolytic transformations and other oxidation or reduction processes may create more toxic intermediate compounds.

Other processes may help enhance toxicological impacts. For example, anhydrous ammonia gas generates caustic alkaline solutions when it comes into contact with water in the environment or water-based body fluids in humans or other organisms exposed to it. Microbial transformation of inorganic mercury into more toxic methylmercury typically occurs in poorly oxygenated, organic-rich riverine, lake, wetland, marsh, or marine sediments. Methylation substantially increases mercury bioavailability, bioaccumulation, and toxicity (Wiener and Suchanek 2008). Evaporation of ponded floodwaters could conceivably increase concentrations of some contaminants in the floodwaters to the point that they exceed toxicity thresholds.

Processes that sequester contaminants into sediments (such as sorption onto particulates, or bacterial sulfate reduction and resulting precipitation of metal sulfides in anoxic sediments) would help diminish some contaminant loads and toxicity of floodwaters (references in Plumlee et al. 2014). However, these processes would also concentrate the contaminants in the sediments, where they would be available for consumption by bottom-feeding aquatic organisms and subsequent uptake into the food chain.

Different contaminants released from multiple sources in the same area could interact geochemically when in the environment. For example, metals from a mining source could complex with anionic ligands, organic chemicals, or dissolved organic matter (DOM) from WWTPs, which could enhance their mobility. Similarly, complex contaminant mixtures may have complex toxicological impacts that are different from those expected from the individual chemicals. For example, copper complexation with DOM helps diminish its aquatic toxicity (Santore et al. 2001).

Many pathogens in releases from WWTPs or AFOs can persist in the environment for days to months (Rogers and Haines 2005). Various environmental factors will help reduce numbers of these pathogens, such as ultraviolet radiation in sunlight, elevated temperature, evaporation of waters, drying of sediments, predation by other microbes, or exposures to toxins produced by other microbes. Some bacterial or fungal pathogens deposited in soils or sediments can survive for even longer periods of time by encapsulating themselves in spore forms (Griffin et al. 2009).

## Results—Plausible ARkStorm Environmental Impacts

Based upon the GIS analysis and knowledge of contaminant fate and transport, it is possible to infer how the potential for various physical damages to the environment, environmental contamination, and resulting environmental and health concerns would vary across different geomorphic provinces and major urban areas of California as a result of the ARkStorm Scenario (Fig. 3; Supplementary Maps).

In Fig. 3, each concern in each area is constrained by a semi-quantitative, GIS-enabled assessment of the spatial extent of anticipated ARkstorm impacts and nonpoint contamination, coupled with the types and numbers of point contamination sources in areas

| | Klamath Mountains | Cascade Range | Coast Ranges | Sierra Nevada | Transverse Ranges | Peninsular Ranges | Central Valley | Western Mojave, Basin and Range | Sacramento / Stockton | San Francisco Bay urban areas | Los Angeles / Orange County / San Diego | Coast |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Physical damages to the environment** | | | | | | | | | | | | |
| From debris flows, landslides | ◆ | ◆ | ◆ | ◆ | ◆ | O | • | • | • | • | • | • |
| From erosion, sediment transport and deposition | ◆ | ◆ | ◆ | ◆ | ◆ | O | O | • | O | O | O | O |
| From coastal storm surges | | | | | | | | | | O | ◆ | ◆ |
| **Contamination** | | | | | | | | | | | | |
| From built environment | • | • | • | • | • | • | O | • | ◆ | ◆ | ◆ | O |
| Road debris, runoff | • | • | • | • | • | • | ◆ | • | ◆ | ◆ | ◆ | • |
| Mercury | O | • | ◆ | ◆ | O | • | O | O | O | O | • | • |
| Sulfides, metals from mines, mineralized rocks | ◆ | O | O | ◆ | O | O | O | • | | | • | • |
| Asbestos (natural, mining) | ◆ | O | ◆ | O | O | • | • | O | | • | | |
| Sewage contaminants | • | • | O | • | O | O | ◆ | • | ◆ | ◆ | ◆ | O |
| AFO contaminants | • | | | | | | ◆ | | • | • | O | O |
| Petroleum and related chemicals | | | | | O | • | ◆ | | ◆ | ◆ | ◆ | O |
| Fertilizers, pesticides, other industrial chemicals | | | O | | O | • | ◆ | • | ◆ | ◆ | ◆ | O |
| Agricultural runoff | | | O | | O | | ◆ | • | O | O | O | O |
| Combustion contaminants | • | • | • | • | • | • | O | O | O | O | O | • |
| **Health concerns** | | | | | | | | | | | | |
| Post-flood molds | • | • | • | • | • | O | ◆ | O | ◆ | ◆ | O | • |
| Valley fever | • | • | O | | O | O | ◆ | • | O | | ◆ | • |
| Gastrointestinal illnesses | • | • | • | • | • | O | ◆ | O | ◆ | ◆ | O | • |
| West Nile virus | • | • | • | • | • | O | ◆ | O | ◆ | ◆ | O | • |

[ ] Negligible potential  [•] Some potential  [O] Moderate potential  [◆] Higher potential

**Fig. 3.** Summary of potential ARkStorm-related environmental and health concerns in different geographic provinces and major urban areas of California

of high impacts. Areas defined as having negligible potential are those having minor extent of impacts and nonpoint contamination sources, and no point sources. Areas defined as having some potential are those with a limited spatial extent of impacts and nonpoint sources, and fewer than 10–15 point sources. Areas with moderate potential or locally higher potential have ~50% spatial extent of impacts and nonpoint sources, ~10 to 15 point sources, or a cluster of sources in one part of the area. Areas of higher potential have more than ~50% spatial extent of impacts and nonpoint sources, and more than ~10 to 15 point sources.

### *Physical Damages to the Environment*

ARkStorm runoff, erosion, landslides, debris flows, storm surges, and sediment deposition are expected to cause extensive physical damages to riverine, floodplain, lacustrine, and coastal environments across many parts of California (Fig. 3). The most intense physical damages will likely be in mountainous, landslide-prone areas receiving high precipitation, and coastal areas affected by storm surges.

Storm-related impacts are an integral component of healthy natural riverine and coastal ecosystems. For example, seasonal flooding and associated increases in suspended sediment loads and subsequent deposition of sediments in floodplains benefit some aquatic organisms and terrestrial plant species. The delta smelt, a fish inhabiting the Sacramento-San Joaquin River Delta, benefits during certain life stages from increased sediment loading and turbidity (Feyrer et al. 2007). However, ARkStorm's likely extreme physical impacts (e.g., extreme bank erosion, scouring of gravels from river channels, sediment deposition, and changes in river channels) may cause substantial damage to aquatic or terrestrial ecological habitat, as well as loss of life in some populations such as those of benthic aquatic insects, fishes, and burrowing rodents or snakes (Cook 2014; Pérez-Maqueo et al. 2007).

### *Environmental Impacts from Contamination*

For this ARkStorm analysis, it is not possible to determine in detail if and where concentrations of the many potential contaminants [e.g., metal(loid) or chemical toxicants, pathogens] in air, floodwaters, sediments, and soils would reach high enough levels to cause acute or chronic toxicity effects in exposed aquatic or terrestrial organisms. However, the greatest potential for adverse impacts will be (1) in general proximity downstream or downwind from large sources that release significant volumes of contaminants (e.g., WWTPs); (2) in very close proximity to smaller contamination sources; (3) in low-lying areas where floodwaters pond and their contained toxicants are concentrated by evaporation; (4) in reservoirs or floodplains where sediment-borne contaminants accumulate; and (5) associated with contaminants such as DDT and methylmercury that can cause toxicity effects at low concentrations.

Mountain or foothill watersheds with steep topography, high precipitation rates, environmentally significant facilities (e.g. historical gold, metal, mercury, and asbestos mines; WWTPs), roads, canyon towns, and/or areas that are underlain by environmentally significant rock types (asbestos-bearing or sulfide-bearing rocks) will have substantial potential for diverse anthropogenic and/or natural contaminants and debris in floodwaters and flood sediments. Water supply reservoirs in these watersheds would help limit downstream dispersal of coarse debris and coarser particulate-borne contaminants, but not aqueous, liquid, or suspended-particulate contaminants.

Flooding and flood-related environmental contamination impacts are expected to be most widespread and substantial in lowland areas of the Central Valley, the Sacramento-San Joaquin River Delta, the San Francisco Bay area, and portions of the greater Los Angeles metroplex. These lowland and/or coastal areas host a number of critical species habitats and wildlife refuges, and have high potential to receive and accumulate inorganic, organic, and pathogen contaminants released from many local sources (e.g., urban areas, AFOs, WWTPs) and upstream sources.

Coastal marine environments near river mouths and urban areas would be affected by contaminated terrestrial runoff. Runoff, erosion, and coastal storm surges would remobilize a variety of contaminants that had been sequestered in riverine, deltaic, harbor, and nearshore marine sediment deposits, with resulting adverse environmental impacts on riverine and marine ecosytems (e.g., Oetken et al. 2005).

The ArkStorm Scenario is expected to affect agricultural lands adversely within river floodplains across many parts of California, particularly in heavily flooded areas of the Central Valley (Wein et al. 2015). Erosion or flooding could lead to loss or contamination of arable soils (Casteel et al. 2006). Nutrients contained in agricultural land runoff or releases of stored fertilizers into floodwaters could lead to subsequent algal blooms and hypoxia in receiving lakes and lowland areas (Casteel et al. 2006). Conversely, contamination of agricultural fields by floodwaters and contaminated flood sediments, as well as leaching of key nutrients from agricultural fields, have been noted in past flood events (Casteel et al. 2006).

Based on studies from past flood events, it is inferred that environmentally persistent contaminants (some organic chemicals, metals, some pathogens, and asbestos) would accumulate in riverine, lakebed, nearshore marine, and flood-sediment deposits. Contaminated underwater sediment deposits would serve as long-term sources of toxicity for benthic aquatic organisms and organisms at successively higher levels in the food chain. Exposed and dried flood-sediment deposits would become sources of potential contaminant-bearing dusts.

Surface-water reservoirs and shallow groundwater supplies used for human consumption, livestock consumption, or agricultural irrigation could become contaminated and require remediation, which would incur treatment costs (Wing et al. 2002). There may be limited impacts from saltwater storm surges, such as soil salinization, contamination of shallow wells by seawater, and impacts on coastal vegetation in low-lying onshore areas along the coast.

## Results—Plausible ARkStorm Health Implications

### *Direct Impacts on Health and Safety*

It is well known that extreme storms and associated flooding can pose significant threats to human safety and public health (Alderman et al. 2012). Drowning in floodwaters is quite common, as are injuries or deaths caused by hypothermia; tornadoes (although tornadoes are rare in California); floodwater-borne debris; lightning strikes; rainfall-triggered landslides, rockfalls, or debris flows; avalanches; wind-related damages (such as falling trees or power lines); and fires.

There can be longer-term physical and psychological effects in those injured or affected by disasters such as floods or storms (Mason et al. 2010; Cook et al. 2008). Disasters can also exacerbate chronic diseases such as kidney failure and diabetes when patients lose access to medical care facilities.

A detailed analysis is needed of plausible types and rates of fatalities, injuries, and psychological or chronic disease effects that could result from the ARkStorm Scenario.

### *Environmental-Health Implications*

Significant human infectious-disease outbreaks related to pathogens in floodwaters (e.g., cholera, *E. coli* infections, cryptosporidiosis, nonspecific diarrhea, poliomyelitis, typhoid, leptospirosis) have been noted primarily in developing countries (Alderman et al. 2012; Cook et al. 2008), and so are not expected to be a significant concern for ARkStorm. Instead, infectious diseases may be limited primarily to less serious gastrointestinal illnesses (gastroenteritis and nonspecific diarrhea) and skin and wound infections due to exposures to pathogens in floodwaters or contaminated ground waters (Cook et al. 2008). Effective health hazard communication and preventive emergency response measures (e.g., warnings not to drink potentially contaminated water, providing access to uncontaminated water, mosquito control measures, dust mitigation measures) commonly prevent or substantially lessen the magnitude of many infectious disease outbreaks in most developed and some developing countries (Alderman et al. 2012).

Vector-borne illnesses that are transmitted by mosquitoes (e.g., West Nile virus) can be enhanced post-flooding where ponded stagnant floodwaters provide ideal breeding grounds (Alderman et al. 2012). However, it is possible that mosquito-transmitted diseases may not be an issue for winter storms such as ARkStorm unless stagnant floodwater accumulations persist into the spring and summer. The rodent-transmitted disease hantavirus pulmonary syndrome, which has been linked to flood events (Alderman et al. 2012), is known to occur in California. Leptospirosis, another rodent-transmitted disease linked to flooding, typically occurs in tropical climates and so at present may not be a concern in California.

Mold development is common in buildings that have been flooded as the waters recede. Exposures to mold-produced toxins are associated with increased incidences of respiratory problems such as asthma (Barbeau et al. 2010).

The extreme erosion and flooding from ARkStorm would likely increase the abundance of easily windborne flood-sediment deposits containing spores of *Coccidioides* in or adjacent to the Central Valley and geologically favorable areas across southern California. During post-ARkStorm dry periods, exposures to dust from these deposits could plausibly result in increased numbers of valley fever cases in humans and some animal species (Fisher et al. 2007).

The potential for human-health impacts linked to inorganic or organic toxicants released into the environment by ARkStorm is unclear. Such impacts have been widely speculated following other extreme storms, but specific case studies documenting such links are rare in the environmental-health literature. Alderman et al. (2012) and Young et al. (2004) cite limited examples of short-term illnesses (such as respiratory problems) and potentially increased cancer rates following specific flood events, but also note that much more work is needed to improve understanding of potential environmental-health implications of disasters in general.

Although much attention has focused on human-health impacts, there are also demonstrated effects of storm events on wildlife and livestock health. For example, flood events in parts of the United States have been linked to outbreaks of anthrax in livestock (Griffin et al. 2009). Although *B. anthracis*, the soil bacterium that causes anthrax, is present in California soils, public health data indicate that anthrax cases are rare in California. There could be outbreaks of mosquito-borne infectious diseases (such as West Nile virus) in birds and wildlife due to the likely abundance of stagnant floodwaters in lowland areas. There similarly could be outbreaks of other pathogen-related diseases in aquatic and terrestrial organisms exposed to pathogens in floodwaters and post-storm sediment accumulations.

## Implications for Assessing Economic Impacts of the ARkStorm Scenario

Given the qualitative nature of this analysis and the spatial complexity of potential environmental impacts, it is not possible to estimate the costs of environmental damages, environmental remediation, health care for environmental-health problems, and loss of economically important aspects of affected ecosystems. These costs have not been clearly articulated or substantially accounted for in published economic impacts of past disasters.

However, limited news accounts about environmental remediation costs from specific facilities or specific storms suggest that such costs could significantly add to the total economic costs tallied for the ARkStorm exercise by Wing et al. (2015). For example, the release in 2007 of some 42,000 gal. of crude oil from a flooded oil refinery at Coffeyville, Kansas, resulted in an insurance claim of $50 million to cover costs incurred to investigate and remediate the contamination, and resolve claims arising from the spill (TIRR 2010). News reports indicated that cleanup and repair of a single flooded wastewater treatment plant at Clarksville, Tennessee, in 2010 would be in the range of $20–30 million. As of April 2013, debris removal costs alone from the New York City area following Superstorm Sandy in 2012 had exceeded $177 million. Given the large numbers of significant facilities and cities that could be affected by ARkStorm, these anecdotal accounts suggest environmental-cleanup costs across the state could easily reach into the billions of dollars, a figure that does not include health-care treatment costs. This underscores that analysis of potential economic costs from the environmental impacts, remediation, and environmental-health care following disasters is an area of needed research.

## Next Steps

This GIS-based analysis is a foundation for additional analyses that can be done by government agencies (from local to state), individuals, and private industry to help enhance resilience to ARkStorm-like events, both in California and nationwide.

This screening approach is largely based on national-scale databases that, in part due to their scale, have limitations such as those described earlier and in the Supplemental Data. Other state or local databases such as the Cal EPA CERS (2013) database should provide more detailed and accurate information that can also be added to the national databases. Where more detailed information is lacking, the existing national-scale databases could benefit from substantial cleanup to remove duplicate entries, provide more accurate location information, and address other inaccuracies.

A logical way to organize more detailed follow-up assessments of potential flood impacts would be on a watershed basis, rather than on a county or municipality basis. This is because watersheds, which can extend well beyond human-defined county or city borders, ultimately control patterns of runoff, flooding, and downstream distribution of water-borne environmental contaminants.

The following process can be used to examine watersheds with substantial numbers of vulnerable contamination sources, large human populations, and ecologically significant areas:

1. Identify in the watershed all types of natural and anthropogenic contamination sources with greatest potential to affect the environment;
2. For each source type, identify specific sources with greatest vulnerability for flooding or other storm damage, and assess each source for storm-related vulnerabilities, potential contaminants, and quantities of contaminants that could be released; and
3. For each watershed, prioritize the sources that pose the biggest threat of significant contamination releases and develop for those sources a strategy for engineered vulnerability mitigation (e.g., constructing or strengthening flood protection berms or sediment retention ponds; covering open-air storage tanks or lagoons; enhancing site surface-water management). Ideally, these engineered solutions should be evaluated from a cost/benefit standpoint, accounting for construction costs versus the potential costs that would be incurred from environmental remediation, liability, ecosystem damages, and health care should damage and contaminant releases occur.

The same sort of analysis can also be done on a windshed basis to evaluate windborne contaminant sources and impacts.

Geologists at the California Geological Survey (CGS) are working at the regional-to-local scale to enhance existing databases and develop geology-based hazard maps that call attention to potential geologic and mining-related sources of heavy metals, acid-rock drainage, and asbestos into the environment (CGS 2013; Higgins et al. 2010). Their work is an excellent example of how the type of analysis presented in this study can be taken to a much more detailed and more quantifiable level.

All local governmental and quasi-governmental entities (such as municipal water districts) and businesses can benefit from analysis of their facilities' vulnerability to ARkStorm-level impacts. Although large, potentially vulnerable facilities undergo such assessments as part of their design and permitting process, it is plausible that these assessments may not have been done for a storm the magnitude of ARkStorm. For example, facilities may not have been designed to withstand ARkStorm floodwater depths expected to occur in many areas (e.g., Nafday 2014).

Individuals can access the information sources described by this study and the Cal EMA Hazards Portal (2013) to understand where their residence is located relative to potential storm-related hazards and to develop appropriate mitigative measures (e.g., in flood-prone areas, keeping only minimal amounts of pesticides and other toxic household chemicals in watertight, tethered containers to minimize releases). Residents returning to flood-damaged or storm-damaged homes should follow public health advisories and be aware of, prepare for, test for, and appropriately address potential environmental hazards (e.g., mold, contaminated flood sediments, and toxicant-bearing debris; CDC 2013).

## Summary

This statewide GIS analysis provides a qualitative overview of plausible environmental and environmental-health implications of the ARkStorm extreme winter storm scenario in California, and also identifies limitations and needs for further research. The results show that there is substantial potential for both physical environmental damages and complex environmental contamination from many natural and anthropogenic sources. The nature, magnitude, and spatial extent of damages and contamination will vary substantially across the state. Examples of likely ARkStorm-related environmental and health concerns include contaminants such as petroleum, mercury, asbestos, persistent organic pollutants, molds, and soil-borne or sewage-borne pathogens; physical, chemical, and pathogen impacts on aquatic ecosystems; and increased cases of vector-borne diseases and valley fever. Areas with likely substantial impacts include coastal cities, the San Francisco Bay area, the Sacramento-San Joaquin River Delta, parts of the Central Valley, and parts of the Coast Ranges, Klamath Mountains, and Sierra Nevada foothills. Economic impacts stemming from environmental remediation, liability, loss of ecosystem services, and health care could be substantial, but need much more study and quantification.

This screening analysis and more detailed assessments described as next steps will help stakeholders better plan for and prioritize solutions to mitigate environmental and health impacts of future extreme storms. Due to its emphasis on national-scale databases and GIS coverages, this screening analysis is readily transportable to other parts of the United States, to other countries where pertinent geospatial data are available, and to other types of disasters. This screening approach can also help rapidly anticipate potential environmental and environmental-health concerns from looming or active disasters.



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## Supplemental Data

GIS analysis used to map potential natural and anthropogenic sources of contamination, Table S1, and the Supplementary Maps are available online in the ASCE Library (www.ascelibrary.org).

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