

Flood Resilience Design for Drinking Water Infrastructure: Protecting Treatment Plants, Wellheads, and Distribution Systems Through Green Stormwater Engineering

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Abstract: Background: Flooding threatens drinking-water safety through raw-water contamination, wellhead inundation, treatment-plant damage, power and chemical interruption, pressure loss, backflow, cross-contamination, and delayed recovery.

Main body: This critical review translates flood-hardening and green stormwater engineering into a drinking-water infrastructure framework for treatment plants, wellfields, pump stations, storage, and distribution networks. The review combines hazard mapping, site grading, conveyance, detention, infiltration, perimeter protection, redundancy, and green infrastructure within a layered strategy. Green infrastructure reduces runoff volume and peak flow outside critical footprints, while floodproofing, elevation, backup power, isolation, and safe exceedance routing protect essential processes. A source-facility-network-consumer model, tiered design protocol, and service-based performance measures address resistance, continuity, recovery, and water-quality integrity.

Conclusions: Flood-resilient drinking-water design requires coordinated control of environmental loading, facility entry pathways, process dependencies, distribution pressure, and recovery. Combining green stormwater engineering with structural and operational safeguards reduces public-health consequences during compound events.

Keywords: drinking-water infrastructure; flood resilience; treatment plant; wellhead; distribution system; green infrastructure; low impact development; backflow

Background

Drinking-water systems depend on continuous separation between contaminated environmental water and treated water. Floods challenge that separation at every stage. Floodwater carries sediment, sewage, animal waste, fuels, pesticides, and industrial chemicals. It may submerge wells, overload intakes, enter treatment buildings, disable power and controls, isolate operators, damage pumps, and undermine buried pipe. Pressure loss then permits intrusion through cracks, joints, and cross-connections. FEMA, EPA, CDC, and state guidance consistently treat flooded wells and impaired systems as potential public-health emergencies (CDC, 2024a, 2024b; EPA, 2014; FEMA, 2021).

Risk increases because drinking-water facilities often occupy low ground near rivers, lakes, or wellfields. Their location reflects access to water, gravity, and historic development rather than modern flood projections. Climate change alters rainfall intensity, river behavior, storm surge, wildfire–flood sequences, and compound hazards. Aging infrastructure and constrained budgets further limit adaptive capacity (IPCC, 2022; National Academies, 2019; Pamidimukkala et al., 2021). A facility may meet a historic design elevation and still fail through an access road, drainage outfall, utility trench, sewer connection, or upstream power dependency.

Conventional flood protection focuses on structural exclusion through levees, walls, elevation, dry floodproofing, and equipment relocation. Green stormwater engineering adds distributed storage, infiltration where safe, evapotranspiration, conveyance slowing, floodplain restoration, and controlled release. These measures reduce the runoff reaching critical sites and create space for exceedance flows. Their value is highest when integrated with hard protection and operational continuity, not treated as a substitute for facility-specific floodproofing (EPA, 2014, 2024; World Bank, 2019).

This paper reviews drinking-water flood failure modes and proposes a design framework for treatment plants, wellheads, pump stations, storage, and distribution systems. The contribution is a direct translation of site-scale stormwater, grading, drainage, and GI/LID practice into public-health protection for water infrastructure. The framework asks where water enters, which process or separation barrier fails, how contamination reaches consumers, and which layered intervention limits consequence.

Review Method and Resilience Definition

The review draws on peer-reviewed water-infrastructure resilience literature, flood-risk assessment, stormwater engineering studies, and guidance from EPA, FEMA, CDC, USGS, and state drinking-water agencies. Evidence was classified by asset, entry pathway, failure mechanism, consequence, and intervention. Drinking-water relevance received priority over general flood-control benefit. Wastewater studies informed facility flood modeling and process exposure where engineering principles transfer, but the analysis distinguishes wastewater containment from potable-water safety.

Resilience has four measurable dimensions. Resistance is the ability to prevent damage or contamination during flooding. Continuity is the capacity to maintain minimum safe service. Recovery is the speed and reliability of restoration. Adaptation is the ability to reduce future risk after events and as hazard conditions change. Water-quality integrity cuts across all four. A system that maintains flow but loses microbial safety is not resilient. Likewise, a facility that survives structurally but lacks power, chemicals, staff access, communications, or laboratory support has not preserved its service function (Leštáková et al., 2023; Pamidimukkala et al., 2021).

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Source–Facility–Network–Consumer Failure Model



Figure 1. Flood failure pathways across a drinking-water system.

Source: Authors' original schematic. Arrows show the principal design or failure pathway; field conditions require site-specific verification.

Layer	Flood pathway	Primary consequence	Control focus
Source	Watershed wash-off, erosion, sewage and chemical mobilization	Turbidity, pathogens, nutrients, toxic contaminants	Upstream retention, monitoring, alternate intake
Facility	Overland flow, river rise, backwater, groundwater, roof and trench entry	Process, electrical, chemical, control, and access failure	Grading, barriers, elevation, drainage, redundancy
Network	Pipe exposure, pressure loss, backflow, cross-connections	Intrusion and contaminated distribution water	Pressure zones, isolation, backflow control, flushing
Consumer	Outage, boil advisory, unsafe private or public supply	Exposure, displacement, unequal recovery	Warnings, emergency water, sampling, priority restoration

The model traces a flood from environmental loading to human exposure. It avoids designing solely to a water-surface elevation. A treatment plant may remain dry while raw-water quality exceeds process capacity. A wellhead may sit above flood level while contaminated shallow water enters through an annular seal or nearby abandoned well. A distribution main may remain intact while a power outage causes pressure loss and intrusion. Design therefore needs a system boundary broad enough to include catchment, facility, dependencies, network, and public-health response.

Asset-Specific Flood Failure Modes and Controls

Watersheds and raw-water intakes

From a drinking-water perspective, Watersheds and raw-water intakes should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is distributed retention, floodplain storage, erosion control, vegetated conveyance, and real-time monitoring that reduce or reveal incoming contaminant pulses. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (Carpenter et al., 1998; EPA, 2014; Rauh et al., 2024). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is extreme-event bypass, upstream sewage or chemical releases, reservoir resuspension, and intake exposure outside the controlled drainage area. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer. Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (Carpenter et al., 1998; EPA, 2014; Rauh et al., 2024).

A practical acceptance framework links Watersheds and raw-water intakes to peak tributary flow, turbidity, microbial indicators, contaminant alerts, and time available for intake response. The utility and stormwater authority should agree on baseline conditions, a load-reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment. The resulting record makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (Carpenter et al., 1998; EPA, 2014; Rauh et al., 2024).

Treatment-plant site grading

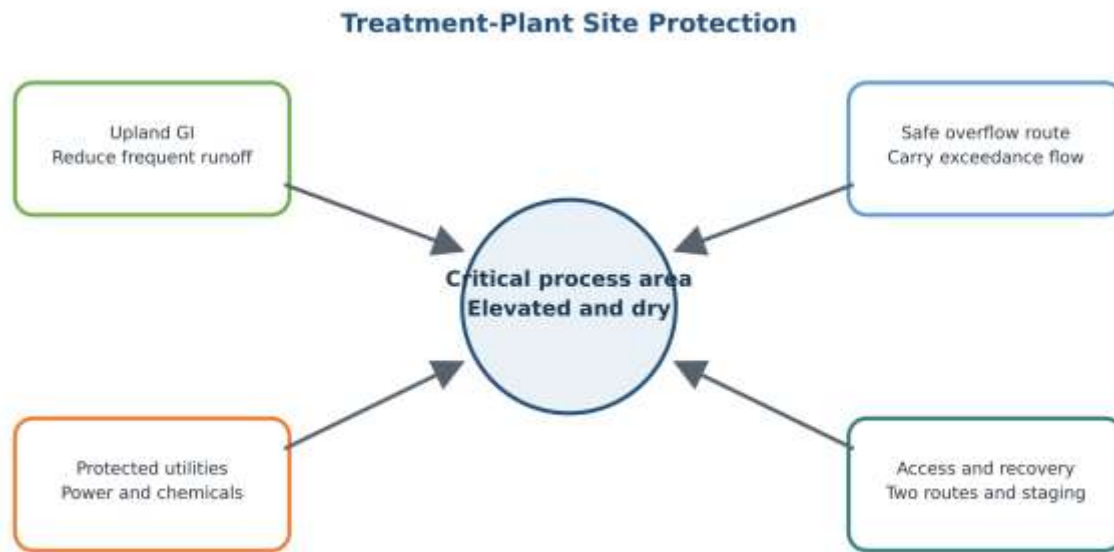


Figure 2. Green stormwater protection around a critical treatment facility.

Source: Authors' original schematic. Arrows show the principal design or failure pathway; field conditions require site-specific verification.

From a drinking-water perspective, Treatment-plant site grading should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is positive drainage away from buildings, separated clean and dirty drainage, stabilized slopes, and defined exceedance corridors. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (FEMA, 2021; EPA, 2014; Sun et al., 2021). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is blocked inlets, backwater through outfalls, settlement, poorly mapped utility penetrations, and flow routed toward doors or chemical areas. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer. Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (FEMA, 2021; EPA, 2014; Sun et al., 2021).

A practical acceptance framework links Treatment-plant site grading to freeboard, maximum depth and velocity, drainage recovery time, and number of vulnerable openings. The utility and stormwater authority should agree on baseline conditions, a load-reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment. The resulting record makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (FEMA, 2021; EPA, 2014; Sun et al., 2021).

Perimeter green infrastructure

From a drinking-water perspective, Perimeter green infrastructure should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is bioswales, bioretention, tree systems, wetlands, and detention that intercept runoff outside the critical process footprint. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (Ahiablame et al., 2012; Dietz, 2007; EPA, 2021). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is practice overtopping, saturated soils, high groundwater, erosion, maintenance failure, and attraction of floodwater toward sensitive structures. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer. Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (Ahiablame et al., 2012; Dietz, 2007; EPA, 2021).

A practical acceptance framework links Perimeter green infrastructure to runoff volume, peak reduction, overflow route, drawdown time, and separation from critical assets. The utility and stormwater authority should agree on baseline conditions, a load-reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment. The resulting record makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (Ahiablame et al., 2012; Dietz, 2007; EPA, 2021).

Floodwalls, berms, and deployable barriers

From a drinking-water perspective, Floodwalls, berms, and deployable barriers should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is physical exclusion of riverine or overland floodwater from process, electrical, and chemical areas. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (EPA, 2014; FEMA, 2021; World Bank, 2019). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is underseepage, gate failure, overtopping, trapped interior drainage, and delayed deployment. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer. Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (EPA, 2014; FEMA, 2021; World Bank, 2019).

A practical acceptance framework links Floodwalls, berms, and deployable barriers to design elevation, freeboard, seepage, closure time, interior pumping, and inspection status. The utility and stormwater authority should agree on baseline conditions, a load-reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment.

The resulting record makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (EPA, 2014; FEMA, 2021; World Bank, 2019).

Wellheads and wellfields



Figure 3. Flood-resilient wellhead protection section.

Source: Authors' original schematic. Arrows show the principal design or failure pathway; field conditions require site-specific verification.

From a drinking-water perspective, Wellheads and wellfields should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is elevated and sealed casings, graded pads, sanitary setbacks, protected vents, and diversion of runoff. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (CDC, 2024a, 2024b, 2024c; FEMA, 2021). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is submergence, damaged seals, contaminated shallow recharge, abandoned wells, and inaccessible sampling or disinfection points. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer. Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (CDC, 2024a, 2024b, 2024c; FEMA, 2021).

A practical acceptance framework links Wellheads and wellfields to flood elevation relative to casing, sanitary integrity, microbial results, turbidity, and recovery clearance. The utility and stormwater authority should agree on baseline conditions, a load-reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment. The resulting record

makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (CDC, 2024a, 2024b, 2024c; FEMA, 2021).

Intake, pumping, and pretreatment

From a drinking-water perspective, Intake, pumping, and pretreatment should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is redundant intake depths, debris control, protected pump drives, raw-water storage, and flexible pretreatment. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (EPA, 2014; FEMA, 2021; Mueller & Helsel, 1996). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is debris blockage, sediment abrasion, contaminant slug, power loss, and inability to isolate an intake. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer. Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (EPA, 2014; FEMA, 2021; Mueller & Helsel, 1996).

A practical acceptance framework links Intake, pumping, and pretreatment to raw-water envelope, pump availability, intake switching time, storage duration, and pretreatment capacity. The utility and stormwater authority should agree on baseline conditions, a load-reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment. The resulting record makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (EPA, 2014; FEMA, 2021; Mueller & Helsel, 1996).

Electrical, controls, and communications

From a drinking-water perspective, Electrical, controls, and communications should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is elevation, watertight enclosures, redundant feeds, protected generators, fuel security, and manual operation. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (EPA, 2014, 2024; Pamidimukkala et al., 2021). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is submerged switchgear, wet generators, fuel contamination, sensor loss, cyber-physical confusion, and staff access failure. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer. Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (EPA, 2014, 2024; Pamidimukkala et al., 2021).

A practical acceptance framework links Electrical, controls, and communications to elevation margin, backup runtime, failover test, spare inventory, and manual-control readiness. The utility and stormwater authority should agree on baseline conditions, a load-

reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment. The resulting record makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (EPA, 2014, 2024; Pamidimukkala et al., 2021).

Chemical storage and residuals

From a drinking-water perspective, Chemical storage and residuals should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is elevated or anchored tanks, secondary containment, protected feed systems, and separation of incompatible chemicals. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (EPA, 2014; FEMA, 2021; World Bank, 2019). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is tank flotation, line break, floodwater contamination, loss of dose control, and release to source water. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer. Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (EPA, 2014; FEMA, 2021; World Bank, 2019).

A practical acceptance framework links Chemical storage and residuals to anchor capacity, containment volume, inventory days, feed redundancy, and post-flood integrity. The utility and stormwater authority should agree on baseline conditions, a load-reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment. The resulting record makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (EPA, 2014; FEMA, 2021; World Bank, 2019).

Distribution pressure and intrusion

From a drinking-water perspective, Distribution pressure and intrusion should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is looping, elevated storage, backup pumping, pressure monitoring, district isolation, and backflow prevention. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (Leštáková et al., 2023; Pamidimukkala et al., 2021; Washington State Department of Health, 2024). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is main break, pump outage, negative pressure, cross-connection, hydrant entry, and contaminated trench water. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer. Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources

exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (Leštáková et al., 2023; Pamidimukkala et al., 2021; Washington State Department of Health, 2024).

A practical acceptance framework links Distribution pressure and intrusion to minimum pressure, low-pressure duration, alarm coverage, isolation time, and bacteriological clearance. The utility and stormwater authority should agree on baseline conditions, a load-reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment. The resulting record makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (Leštáková et al., 2023; Pamidimukkala et al., 2021; Washington State Department of Health, 2024).

Buried pipe crossings

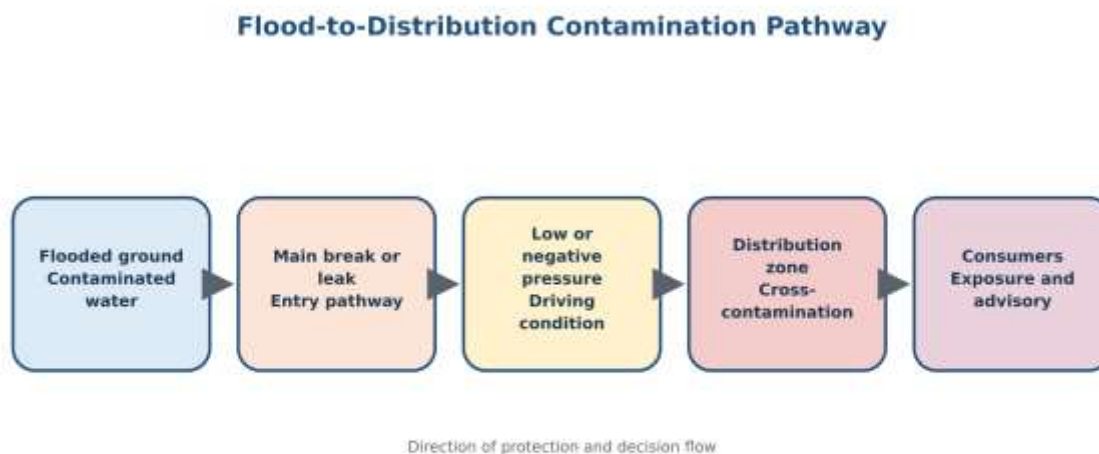


Figure 4. Distribution-system contamination pathway during flooding.

Source: Authors' original schematic. Arrows show the principal design or failure pathway; field conditions require site-specific verification.

From a drinking-water perspective, Buried pipe crossings should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is armoring, flexible joints, scour-resistant cover, restrained connections, shutoff access, and redundant routing. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (National Academies, 2019; World Bank, 2019; USGS, 1998). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is bank erosion, flotation, washout, debris impact, differential settlement, and inaccessible valves. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer. Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources

exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (National Academies, 2019; World Bank, 2019; USGS, 1998).

A practical acceptance framework links Buried pipe crossings to scour depth, cover, joint movement, valve operability, break isolation, and alternate supply. The utility and stormwater authority should agree on baseline conditions, a load-reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment. The resulting record makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (National Academies, 2019; World Bank, 2019; USGS, 1998).

Storage tanks and pressure zones

From a drinking-water perspective, Storage tanks and pressure zones should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is elevated vents, protected overflow and drain connections, anchorage, isolation, and operational reserve. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (EPA, 2014; FEMA, 2021; Lešťáková et al., 2023). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is contaminated vent or overflow entry, foundation erosion, power loss, and pressure-zone collapse. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer. Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (EPA, 2014; FEMA, 2021; Lešťáková et al., 2023).

A practical acceptance framework links Storage tanks and pressure zones to storage hours, vent elevation, water-quality residual, structural inspection, and zone pressure. The utility and stormwater authority should agree on baseline conditions, a load-reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment. The resulting record makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (EPA, 2014; FEMA, 2021; Lešťáková et al., 2023).

Access, staffing, and supply chains

From a drinking-water perspective, Access, staffing, and supply chains should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is all-weather access, remote operation, alternate routes, on-site spares, mutual aid, and protected communications. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (EPA, 2014, 2024; World Bank, 2019). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is road closure, staff displacement, laboratory loss, delayed fuel or chemical delivery, and unsafe work conditions. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer.

Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (EPA, 2014, 2024; World Bank, 2019).

A practical acceptance framework links Access, staffing, and supply chains to days of autonomy, access-route redundancy, staffing coverage, communication tests, and delivery lead time. The utility and stormwater authority should agree on baseline conditions, a load-reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment. The resulting record makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (EPA, 2014, 2024; World Bank, 2019).

Emergency water-quality response

From a drinking-water perspective, Emergency water-quality response should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is event detection, sample plans, boil-water protocols, flushing, disinfection, and public communication. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (CDC, 2024a; EPA, 2014; Washington State Department of Health, 2024). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is late detection, unclear authority, inadequate laboratories, inconsistent advisories, and premature return to service. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer. Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (CDC, 2024a; EPA, 2014; Washington State Department of Health, 2024).

A practical acceptance framework links Emergency water-quality response to notification time, sampling coverage, clearance criteria, flushing volume, and advisory duration. The utility and stormwater authority should agree on baseline conditions, a load-reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment. The resulting record makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (CDC, 2024a; EPA, 2014; Washington State Department of Health, 2024).

Compound and cascading hazards

From a drinking-water perspective, Compound and cascading hazards should be specified as a contaminant-control asset rather than as a drainage ornament. Its principal pathway is multi-hazard mapping, dependency analysis, redundancy, and scenario exercises. This pathway matters because source-water risk depends on both mass and timing. A lower annual load reduces the long-run burden on reservoirs and aquifers, while attenuation of short, high-concentration pulses gives intake operators more time to adjust withdrawal depth, coagulant dose, filtration rate, or source blending. Field evidence also shows substantial variation between events and sites, so a design claim should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime (IPCC, 2022; National Academies, 2019; Pamidimukkala et al., 2021). The most defensible performance statement is therefore conditional: the practice reduces exposure when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

The critical design boundary is flood plus outage, flood plus wildfire ash, flood plus sewer overflow, simultaneous facility and network damage. Ignoring this boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater, for example, may lower surface discharge while moving dissolved nitrate, chloride, or mobile organic contaminants toward an aquifer. Conversely, a lined or underdrained configuration may protect groundwater but return a larger treated volume to the surface-water system. Designers should document this tradeoff through a source-water conceptual model that connects the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake. Monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources exist. This evidence supports adaptive operation and prevents a generic percent-removal value from being applied outside its tested context (IPCC, 2022; National Academies, 2019; Pamidimukkala et al., 2021).

A practical acceptance framework links Compound and cascading hazards to minimum service under combined scenarios, dependency duration, and recovery sequence. The utility and stormwater authority should agree on baseline conditions, a load-reduction objective, a hydraulic service level, inspection frequency, and a trigger for corrective maintenance. Performance should be expressed through event mean concentration and mass load, because concentration alone may hide the benefit of volume reduction, while load alone may hide a high-concentration pulse at an intake. Where direct pathogen measurement is infeasible, indicator organisms, turbidity, antecedent land use, and sanitary survey data should form a multiple-line-of-evidence assessment. The resulting record makes upstream infrastructure legible to treatment-plant staff, supports source-water protection planning, and helps capital planners compare distributed controls with treatment expansion. Such integration is central to the preventive logic advanced in this paper (IPCC, 2022; National Academies, 2019; Pamidimukkala et al., 2021).

Green Stormwater Engineering as Layered Protection

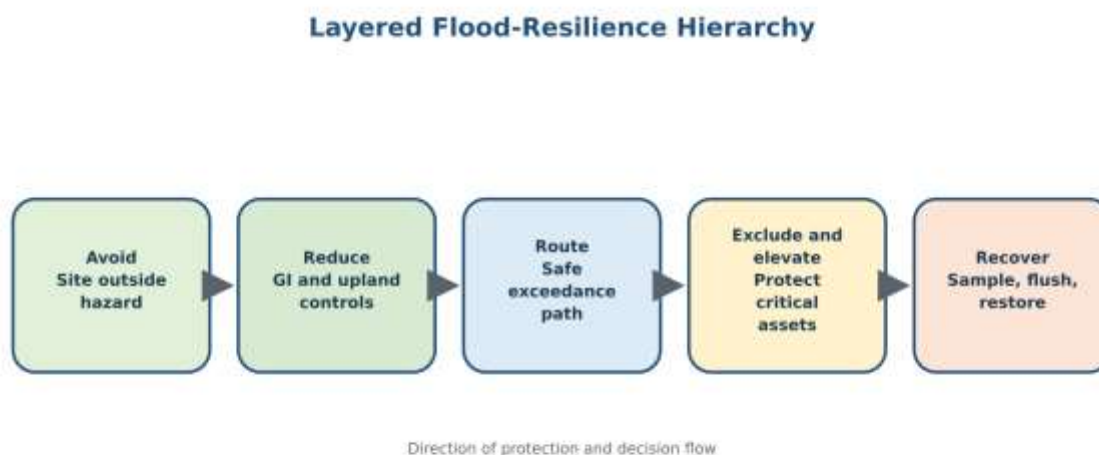


Figure 5. Layered resilience hierarchy for drinking-water facilities.

Source: Authors' original schematic. Arrows show the principal design or failure pathway; field conditions require site-specific verification.

Control runoff before the critical footprint

The strongest GI role is to intercept upland runoff before it reaches treatment buildings, wells, electrical yards, or chemical storage. Distributed bioretention, permeable pavement in low-risk areas, swales, trees, wetlands, and detention reduce and delay runoff. Designers should preserve a dry security zone around critical assets and route all GI overflow toward a mapped exceedance corridor. Infiltration should not occur where it raises groundwater against foundations, mobilizes contaminated soil, or threatens well capture zones.

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Designers must preserve a dry security zone around critical assets and route all GI overflow toward a mapped exceedance corridor. Infiltration must not occur where it raises groundwater against foundations, mobilizes contaminated soil, or threatens well capture zones.

Preserve safe conveyance and exceedance routes

Every control has a capacity. Once exceeded, water needs a safe route. Grading plans should show minor and major systems, blocked-inlet scenarios, backwater, culvert failure, and flow at doors, vents, electrical penetrations, tank pads, and access roads. Surface conveyance should remain visible and maintainable. Buried drainage needs backflow prevention and isolation because a storm sewer may become an inflow path during river rise.

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Combine green and structural measures

A defense-in-depth design uses GI for volume and peak reduction, detention for controlled storage, grading for direction, barriers for exclusion, elevation for consequence reduction, and redundancy for continuity. No single layer receives credit for the full service objective. The design basis should state which layer handles routine rainfall, the selected design event, residual risk, and events beyond design. Independent failure modes should receive priority over multiple controls that depend on the same outfall, power source, or maintenance crew.

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Protect water quality during recovery

Post-flood recovery is a designed process. Facilities need safe sample taps, disinfection connections, drain and flush routes, temporary power connections, spare pumps, accessible valves, and documented clearance criteria. A well that looks intact still needs sanitary assessment and testing after inundation. A distribution zone that lost pressure needs risk-based isolation, flushing, disinfectant restoration, and bacteriological confirmation before normal service resumes (CDC, 2024a; EPA, 2014).

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Figure 6. Preparedness, response, and verified recovery workflow.

Source: Authors' original schematic. Arrows show the principal design or failure pathway; field conditions require site-specific verification.

Tier	Required decision	Deliverable
1	Establish service objectives	Define minimum safe demand, maximum tolerable outage, priority customers, water-quality limits, and recovery targets.
2	Map present and future hazards	Analyze pluvial, riverine, coastal, groundwater, dam-release, and compound flooding across relevant time horizons.
3	Inventory assets and dependencies	Locate openings, elevations, process links, power, fuel, communications, roads, laboratories, chemicals, and workforce needs.
4	Trace contamination pathways	Follow floodwater from source through facilities and pressure zones to consumer exposure.
5	Apply the hierarchy	Avoid exposure, control upland runoff, route exceedance, exclude water, elevate sensitive equipment, isolate, and provide redundancy.
6	Test credible failures	Model blocked inlets, barrier nondeployment, power loss, contaminated raw water, main breaks, and simultaneous access loss.
7	Design recovery	Provide sampling, flushing, disinfection, temporary connections, spares, mutual aid, and clear return-to-service criteria.
8	Fund lifecycle performance	Budget inspection, sediment removal, vegetation, barrier tests, generator exercises, asset replacement, and updated hazard analysis.

Establish service objectives

Define minimum safe demand, maximum tolerable outage, priority customers, water-quality limits, and recovery targets. The owner should document responsible staff, verification frequency, decision thresholds, and evidence retained after each inspection or exercise. A design becomes operationally credible only when operators know which action to take, which valve or barrier to use, where equipment is stored, and how long each dependency remains available.

The analysis should include uncertainty and residual risk. Flood maps, rainfall estimates, terrain, pipe records, and asset elevations all contain error. Freeboard provides one response, but uncertainty also calls for conservative opening protection, independent backup systems, monitoring, and an emergency plan for events beyond design. The final record should distinguish assumed protection from field-verified protection.

Map present and future hazards

Analyze pluvial, riverine, coastal, groundwater, dam-release, and compound flooding across relevant time horizons. The owner should document responsible staff, verification frequency, decision thresholds, and evidence retained after each inspection or exercise. A design becomes operationally credible only when operators know which action to take, which valve or barrier to use, where equipment is stored, and how long each dependency remains available.

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Inventory assets and dependencies

Locate openings, elevations, process links, power, fuel, communications, roads, laboratories, chemicals, and workforce needs. The owner should document responsible staff, verification frequency, decision thresholds, and evidence retained after each inspection or exercise. A design becomes operationally credible only when operators know which action to take, which valve or barrier to use, where equipment is stored, and how long each dependency remains available.

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Trace contamination pathways

Follow floodwater from source through facilities and pressure zones to consumer exposure. The owner should document responsible staff, verification frequency, decision thresholds, and evidence retained after each inspection or exercise. A design becomes operationally credible only when operators know which action to take, which valve or barrier to use, where equipment is stored, and how long each dependency remains available.

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Apply the hierarchy

Avoid exposure, control upland runoff, route exceedance, exclude water, elevate sensitive equipment, isolate, and provide redundancy. The owner should document responsible staff, verification frequency, decision thresholds, and evidence retained after each inspection or exercise. A design becomes operationally credible only when operators know which action to take, which valve or barrier to use, where equipment is stored, and how long each dependency remains available.

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Test credible failures

Model blocked inlets, barrier nondeployment, power loss, contaminated raw water, main breaks, and simultaneous access loss. The owner should document responsible staff, verification frequency, decision thresholds, and evidence retained after each inspection or exercise. A design becomes operationally credible only when operators know which action to take, which valve or barrier to use, where equipment is stored, and how long each dependency remains available.

The analysis should include uncertainty and residual risk. Flood maps, rainfall estimates, terrain, pipe records, and asset elevations all contain error. Freeboard provides one response, but uncertainty also calls for conservative opening protection, independent

backup systems, monitoring, and an emergency plan for events beyond design. The final record should distinguish assumed protection from field-verified protection.

Design recovery

Provide sampling, flushing, disinfection, temporary connections, spares, mutual aid, and clear return-to-service criteria. The owner should document responsible staff, verification frequency, decision thresholds, and evidence retained after each inspection or exercise. A design becomes operationally credible only when operators know which action to take, which valve or barrier to use, where equipment is stored, and how long each dependency remains available.

The analysis should include uncertainty and residual risk. Flood maps, rainfall estimates, terrain, pipe records, and asset elevations all contain error. Freeboard provides one response, but uncertainty also calls for conservative opening protection, independent backup systems, monitoring, and an emergency plan for events beyond design. The final record should distinguish assumed protection from field-verified protection.

Fund lifecycle performance

Budget inspection, sediment removal, vegetation, barrier tests, generator exercises, asset replacement, and updated hazard analysis. The owner should document responsible staff, verification frequency, decision thresholds, and evidence retained after each inspection or exercise. A design becomes operationally credible only when operators know which action to take, which valve or barrier to use, where equipment is stored, and how long each dependency remains available.

The analysis should include uncertainty and residual risk. Flood maps, rainfall estimates, terrain, pipe records, and asset elevations all contain error. Freeboard provides one response, but uncertainty also calls for conservative opening protection, independent backup systems, monitoring, and an emergency plan for events beyond design. The final record should distinguish assumed protection from field-verified protection.

Integrated Evidence for Flood-Resilience Design

The following synthesis connects hydrologic modeling, subsurface pathway analysis, geographic information systems, remote sensing, early warning, data integration, and urban-resilience research with specific drinking-water assets and decisions.

Continuity planning for water facilities shares core features with resilience planning for other public-health infrastructure: critical-function mapping, dependency analysis, protected access, redundant utilities, inventory control, and staged recovery. Drinking-water application adds source isolation, treatment integrity, pressure maintenance, and water-quality clearance. This transfer supports a service-centered design basis instead of treating an undamaged building as proof of resilience (Aminu-Ibrahim et al., 2025; Dagodzo & Ahiaeké Patrick, 2021a; Falegan & Aniebonam, 2024; Ike et al., 2025).

Decentralized water-treatment research offers relevant lessons for emergency and remote operations. Modular processes, simplified maintenance, local storage, performance monitoring, and defined residual handling reduce dependence on a single large facility. Drinking-water utilities may apply those principles to emergency treatment skids, alternate wells, satellite disinfection, and temporary interconnections, subject to drinking-water standards and validated operating procedures (Falegan & Aniebonam, 2022, 2023, 2024, 2026).

Post-flood recovery should treat contaminated water, damaged equipment, and accumulated residuals as connected lifecycle risks. Sampling establishes influent and distribution conditions; treatment and flushing remove contaminants; waste management prevents captured material from returning to the site or source. A performance record should connect event conditions, process response, waste disposition, and verified restoration of service (Falegan & Aniebonam, 2022, 2023, 2025, 2026).

A digital facility record improves preparedness when it combines geospatial assets, elevations, dependencies, maintenance status, emergency inventory, and live observations. Operators then see which access route, electrical room, chemical system, well, or valve approaches its threshold. Environmental-compliance and infrastructure-resilience frameworks support traceable decisions, while utility GIS supports field deployment and post-event documentation (Aminu-Ibrahim et al., 2025; Dagodzo & Ahiaeké Patrick, 2021a; Ike et al., 2025; Falegan & Aniebonam, 2026).

Facility flood design should start with a terrain-connected model that includes the surrounding watershed, not only the parcel boundary. Climate-sensitive hydrologic analysis identifies changing inflow, while LiDAR and GIS reveal low points, flow convergence, access constraints, and off-site dependencies. Remote observations also help detect land-cover change that invalidates earlier runoff assumptions (Badmus & Olamide, 2019; Badmus, 2025; Dagodzo & Ahiaeké Patrick, 2021b; Nwafor et al., 2019).

Floodwater entry often follows small and poorly documented pathways. Utility trenches, abandoned connections, subsided pavement, blocked swales, and altered rights-of-way may bypass a nominal perimeter barrier. Corridor mapping and encroachment

detection help identify these pathways before an event. Field verification then confirms elevations, connections, and operability (Dagodzo & Ahiaeke Patrick, 2021b; Dagodzo & Ahiaeke Patrick, 2022; Badmus, 2025; Azeez & Badmus, 2018).

Wellhead protection requires both surface and subsurface reasoning. Diversion and elevation reduce direct inundation, while subsurface pathway analysis tests whether contaminated recharge may reach the screened interval through preferential flow, damaged seals, or nearby abandoned wells. Spatial risk models help position monitoring and define post-flood sampling zones (Azeez & Badmus, 2018; Lamidi & Olamide, 2018; Azeez & Badmus, 2024b; Badmus & Olamide, 2019).

Remote sensing supports preparedness when linked to facility thresholds. Rainfall estimates, surface-water extent, vegetation loss, disturbed soil, and access-route condition may provide early evidence of rising exposure. Operators still need defined triggers for barrier deployment, generator checks, chemical delivery, intake changes, and staff mobilization. Data without an action protocol does not create resilience (Badmus, 2025; Azeez & Badmus, 2024a; Dagodzo & Ahiaeke Patrick, 2021b; Ahiaeke Patrick et al., 2021).

Treatment-plant site plans should preserve independent surface routes for routine drainage and flood exceedance. Green controls handle frequent runoff, while protected channels and grading carry larger flows away from process and electrical areas. Urban flood-resilience research supports combining landscape measures with building and network interventions rather than relying on a single barrier (Nwafor et al., 2019; Badmus & Olamide, 2019; Badmus, 2025; Dagodzo & Ahiaeke Patrick, 2021b).

A high-resolution terrain model should be treated as a starting point, not final truth. Curbs, temporary materials, vegetation, sediment, gates, and construction changes alter local flow. UAV, LiDAR, and inspection records should be reconciled after major works and significant events. This practice reduces the risk of basing floodproofing on obsolete surface conditions (Dagodzo & Ahiaeke Patrick, 2021b; Dagodzo & Ahiaeke Patrick, 2022; Badmus, 2025; Ahiaeke Patrick et al., 2021).

Compound flooding requires connected models. Intense rainfall may fill site storage while a receiving river creates backwater and high groundwater limits infiltration. A power outage may then disable pumps and monitoring. Hydrologic vulnerability analysis should test coincident conditions and report the sequence of threshold crossings, not only a final inundation map (Badmus & Olamide, 2019; Azeez & Badmus, 2018; Nwafor et al., 2019; Badmus, 2025).

Redevelopment around a treatment plant or wellfield may change flood and contaminant risk simultaneously. New impervious surfaces increase runoff, excavation alters drainage, and infiltration may mobilize legacy pollution. Review should combine flood routing, subsurface contamination, and vapor-pathway evidence where occupied buildings exist. This integrated assessment prevents one risk-control project from worsening another pathway (Azeez & Badmus, 2018; Azeez & Badmus, 2024b; Lamidi & Olamide, 2018; Badmus & Olamide, 2019).

Asset prioritization should account for consequence and network position. A modestly exposed pump, control cabinet, road segment, or valve may govern service for a large pressure zone. Geospatial decision models help rank such dependencies by exposure, criticality, redundancy, restoration time, and data confidence. The ranking should be reviewed with operators who understand undocumented field dependencies (Ahiaeke Patrick et al., 2021; Dagodzo & Ahiaeke Patrick, 2021b; Badmus, 2025; Nwafor et al., 2019).

Flood recovery needs pre-event spatial data. Teams require verified coordinates and access routes for valves, hydrants, sample stations, generators, barriers, chemical connections, and temporary pumps. Corridor imagery and GIS records support routing when landmarks and roads are inundated. Offline copies and field-readable formats protect access when communications fail (Dagodzo & Ahiaeke Patrick, 2021b; Dagodzo & Ahiaeke Patrick, 2022; Ahiaeke Patrick et al., 2021; Badmus, 2025).

Data integration should preserve the timing of observations. Rainfall, river stage, facility depth, pressure loss, power state, turbidity, disinfectant residual, and sampling results operate on different time scales. A shared timeline helps distinguish initial contamination, operational interruption, intrusion, and recovery. Quality flags and provenance prevent uncertain observations from driving premature return to service (Azeez & Badmus, 2024a; Badmus, 2025; Badmus & Olamide, 2019; Azeez & Badmus, 2018).

Scenario design should include barrier failure and route obstruction. A deployable wall may arrive late, an access road may close earlier than expected, and sediment may block drainage. Spatial and hydrologic models should test these failures and identify alternate routes or independent layers. Resilience comes from preserving service after credible component failure (Badmus & Olamide, 2019; Nwafor et al., 2019; Dagodzo & Ahiaeke Patrick, 2022; Badmus, 2025).

Post-flood investigation should update the model. Recorded high-water marks, sensor data, drone imagery, operator observations, damage, and water-quality results provide evidence about actual pathways. Comparing observed and predicted conditions supports calibration and directs retrofits. The updated record should identify both successful controls and near failures (Badmus, 2025; Dagodzo & Ahiaeke Patrick, 2021b; Azeez & Badmus, 2018; Ahiaeke Patrick et al., 2021).

Environmental compliance and drinking-water resilience share a need for traceable data. Design assumptions, inspection findings, sensor calibration, barrier tests, maintenance, and response decisions should remain linked to asset identity and time. Integrated records strengthen audits and help utilities show that protective measures remain operational between major floods (Azeez & Badmus, 2024a; Badmus, 2025; Dagodzo & Ahiaeke Patrick, 2021b; Ahiaeke Patrick et al., 2021).

Community-scale resilience affects facility recovery. Flooded roads, housing, power, telecommunications, and drainage systems shape staff access and supply delivery. Urban resilience measures outside the plant may therefore protect drinking-water continuity. Utility planning should coordinate with municipal flood, transportation, emergency, and land-use programs (Nwafor et al., 2019; Badmus & Olamide, 2019; Badmus, 2025; Dagodzo & Ahiaeke Patrick, 2022).

The combined evidence supports an adaptive design cycle: model watershed and subsurface pathways, map assets and corridors, monitor changing conditions, connect alerts to operational thresholds, and recalibrate after events. Applied to drinking-water systems, this cycle links green stormwater engineering with floodproofing, continuity planning, and verified recovery (Azeez & Badmus, 2018; Badmus & Olamide, 2019; Dagodzo & Ahiaeke Patrick, 2021b; Badmus, 2025).

The author's urban-water and drainage studies give the flood framework a direct planning basis. Water-security risk assessment connects aquifer pressure, unequal access, and land-use decisions, while the sediment-driven open-drain index links maintenance condition to hydraulic failure. Together they support facility screening that includes source dependence, drainage capacity, sediment blockage, and distributional consequences (Aniebonam et al., 2023b; Aniebonam & Ihwughwavwe, 2025b).

Nature-based flood-management research supports layered runoff reduction outside critical drinking-water footprints. Predictive environmental-risk modeling adds a repeatable hazard–pathway–receptor structure for testing future conditions and uncertainty. Neither replaces floodproofing, but both improve where green controls are placed and how residual risk is documented (Aniebonam, 2025; Ihwughwavwe & Aniebonam, 2025).

Flood operations increasingly depend on digital systems. Work on explainable anomaly detection, smart-city planning, sustainability risks of digitalization, and cyber-physical vulnerabilities shows the need for interpretable alarms, trustworthy data, manual fallback, segmented controls, and tested recovery. These requirements apply to pumps, gates, power systems, pressure sensors, and SCADA-supported response (Aniebonam, 2024; Aniebonam et al., 2024; Aniebonam et al., 2025b; Aniebonam & Aniebonam, 2025).

Contamination during and after flooding is a mixture problem. Heavy-metal and microplastic research underscores particle transport and interacting stressors, while low-cost adsorption and decentralized treatment research provides transferable concepts for modular treatment, media management, and remote operation. Drinking-water use still requires validated processes, sampling, and regulatory clearance (Aniebonam & Aniebonam, 2023; Falegan & Aniebonam, 2021, 2022, 2023, 2024, 2026).

Circular-economy and resource-recovery studies contribute lifecycle discipline to flood recovery. Temporary treatment, flushing, sediment removal, damaged media, and contaminated residuals need defined destinations and verification, not displacement into the source watershed. The reuse hierarchy remains subordinate to potable-water safety and environmental controls (Falegan & Aniebonam, 2020, 2025).

Community education, youth engagement, and equity-oriented policy assessment support response plans that reach affected users and preserve procedural fairness. Warning design, emergency-water distribution, sampling priorities, and capital sequencing should reflect different exposure, mobility, language, and recovery constraints (Ihwughwavwe & Aniebonam, 2024; Aniebonam & Ihwughwavwe, 2025a; Aniebonam et al., 2025a).

Cross-infrastructure studies expand the compound-hazard boundary. Renewable-energy transition risk analysis highlights social and environmental tradeoffs, and wildfire risk to electric networks illustrates cascading power loss, access disruption, and debris-related consequences. Flood-resilient drinking-water design should test shared dependencies and sequences such as wildfire, outage, intense rainfall, and treatment interruption (Aniebonam et al., 2023a; Aniebonam, P. C., et al., 2025).

Flood resilience requires operational supplies and lifecycle visibility as well as physical protection. Critical-infrastructure supply-chain, predictive-procurement, asset-management, and performance-metric studies support inventories tied to failure consequence, minimum stock levels, supplier alternatives, and service-based replacement priorities. Water utilities can apply these principles to pumps, motors, controls, barriers, generators, treatment chemicals, repair clamps, laboratory supplies, and communication equipment (Ogunwole et al., 2021; Okonkwo et al., 2023, 2024; Aminu-Ibrahim et al., 2025).

Emergency management benefits from preassigned actions and live evidence. Emergency-readiness, digital hazard-identification, continuous-monitoring, and real-time indicator frameworks offer transferable structures for thresholds, escalation, and learning after an event. Applied to drinking-water facilities, the monitored variables include flood depth, access, power state, pump condition, raw-water quality, tank level, network pressure, and sampling clearance (Arumosoye & Obriki, 2023; Obriki & Arumosoye, 2023; Obriki et al., 2023; Tonoyan et al., 2024).

Geospatial and aerial monitoring strengthens post-event assessment when access is constrained. Utility GIS and UAV corridor research supports rapid inspection of pipelines, rights-of-way, erosion, debris, access roads, and remote structures. Utilities should link imagery to asset identifiers, inspection dates, confidence ratings, and field verification so remote observations inform repair priorities without replacing engineering judgment (Dagodzo & Ahiaeke Patrick, 2020, 2023).

Floodwater accelerates mechanical and electrical failure pathways. Digital-twin, non-destructive testing, corrosion-prediction, environmental-risk, early-failure, and resilient-microgrid studies contribute transferable methods for condition tracking, dependency analysis, backup-power control, and intervention planning. Their use in drinking-water systems should remain tied to validated equipment data, operator review, and conservative safety thresholds (Ogunnowo et al., 2024a, 2024b, 2024c; Arumosoye et al., 2025; Komi & Adamolekun, 2021; Komi & Ganiu, 2023).

Performance Metrics and Decision Support

Dimension	Illustrative metric	Management use
Resistance	Critical assets above design flood plus freeboard	Capital design and retrofit acceptance
Continuity	Hours or days of minimum safe service	Storage, power, chemical, and staffing planning
Water quality	Time within raw and finished-water limits	Treatment envelope and advisory decisions
Network integrity	Customers and pressure zones below minimum pressure	Isolation, flushing, and backflow response
Recovery	Time to verified return of safe service	Emergency planning and mutual aid
Adaptation	Risk reduction after lessons and updated hazards	Asset management and capital programming

Metrics should reflect service, not merely asset survival. A pump station that stays dry but lacks power does not provide continuity. A treatment plant that produces water outside microbial or chemical limits has failed its core function. A distribution system that restores pressure without bacteriological clearance has not completed recovery. System-level measures should therefore join hydraulic, structural, operational, and water-quality evidence.

Scenario analysis should report both expected performance and threshold behavior. Useful thresholds include the water level at which an access road closes, an outfall backflows, a well casing submerges, switchgear becomes exposed, a barrier must deploy, or a pressure zone loses residual head. These thresholds translate models into operator action. Sensors and forecasts then support staged response rather than a single alarm at failure.

Benefit–cost analysis should include avoided outage, emergency water, public-health response, equipment loss, environmental release, business interruption, and reputational harm. GI co-benefits matter, but capital comparisons should preserve the drinking-water service objective. A lower-cost runoff practice that lacks safe overflow may create unacceptable residual risk near a wellhead or treatment building.

Application to Facility Retrofits and New Design

Existing facilities need a walkdown before modeling. Survey door thresholds, louvers, vents, cable penetrations, trenches, floor drains, chemical connections, tank anchors, generator elevation, fuel access, sample taps, and barrier storage. Interview operators about past ponding, inaccessible routes, nuisance alarms, and undocumented modifications. Small elevation differences often control entry, so survey accuracy should match the decision.

Retrofits should prioritize low-cost pathway closures and high-consequence assets. Regrading, curb changes, backflow valves, sealed penetrations, raised controls, protected vents, portable pump connections, and barrier anchor points often precede major walls or relocation. GI fits where contributing runoff is controllable and failure routes remain safe. The retrofit sequence should avoid transferring water toward neighbors, sanitary systems, or another critical asset.

New facilities should use risk-informed siting. Avoidance produces stronger protection than permanent dependence on barriers and pumping. Where proximity to the source is unavoidable, designers should preserve elevation, multiple access routes, independent utilities, space for future barriers, and a protected green drainage network outside the critical footprint. Future rainfall and flood conditions should inform site reserve, not only current code minima.

Small and rural systems require scaled solutions. Raised wellheads, sealed caps and vents, simple diversion swales, protected generators, accessible chlorination points, sampling plans, mutual aid, and clear advisories may provide large risk reduction. Funding and technical assistance should support maintenance and exercises because an untested barrier or generator offers uncertain protection.

Research and Policy Priorities

Research should connect flood depth and duration with actual drinking-water process failure, low-pressure intrusion, contaminant occurrence, and recovery time. Many studies map exposure without measuring service consequences. Standardized event reports would support fragility functions for wells, electrical systems, treatment processes, storage, and distribution assets.

GI studies near critical facilities should test performance during saturated and extreme conditions, including backwater and high groundwater. Routine-storm monitoring does not establish flood protection. Researchers should quantify overflow direction, erosion, debris blockage, maintenance condition, and interaction with structural barriers. Compound events deserve special attention.

Policy should align hazard mitigation, drinking-water revolving funds, stormwater programs, source-water protection, and capital asset management. Design reviews should include utility operators, public health, emergency management, stormwater engineers, electrical and process engineers, and distribution staff. Shared criteria would reduce gaps between site drainage approval and drinking-water resilience.

Conclusions

Flood resilience for drinking-water infrastructure requires protection of water quality and service across sources, treatment facilities, wellheads, storage, and distribution networks. Floodwater creates direct contamination, physical damage, power and process interruption, pressure loss, backflow, and difficult recovery. Green stormwater engineering reduces runoff and creates safe space for water, especially outside critical footprints. Structural exclusion, elevation, isolation, redundancy, monitoring, and recovery planning remain indispensable. The proposed source–facility–network–consumer model keeps design focused on public-health consequences. It also provides a disciplined path for transferring proven stormwater, GI/LID, grading, and flood-hardening expertise to treatment plants and water systems whose continuity carries national public-health and infrastructure significance.

List of abbreviations

CDC: Centers for Disease Control and Prevention

EPA: United States Environmental Protection Agency

FEMA: Federal Emergency Management Agency

GI: Green infrastructure

GIS: Geographic information system

LID: Low impact development

LiDAR: Light detection and ranging

SCADA: Supervisory control and data acquisition

USGS: United States Geological Survey

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Consent for publication

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Oreoluwa Adedapo conceived the review and developed the analytical framework. Nwakamma Ninduwezuor-Ehiobu and Henry Chukwuemeka Olisakwe contributed to the literature synthesis, engineering interpretation, and critical revision of the manuscript. All authors contributed to the figures, reviewed the complete manuscript, approved the final version, and accept responsibility for the work.

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