

Modern Trends in Engineering Science

ISSN 3143-6773

DAC Insight Publishers

<https://journals.dacinsightpublishers.com/MTES>



## LOW IMPACT DEVELOPMENT AND GREEN INFRASTRUCTURE AS SOURCE WATER PROTECTION: MITIGATING NONPOINT-SOURCE CONTAMINATION OF MUNICIPAL DRINKING WATER SUPPLIES

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### ABSTRACT

*Municipal drinking-water protection often begins after contaminants have entered a reservoir, river intake, or aquifer. This review examines low-impact development and green infrastructure as preventive source-water controls, synthesizing evidence on bioretention, permeable pavement, vegetated buffers, and treatment trains, with emphasis on sediment, nitrogen, phosphorus, fecal indicators, and contaminant mobilisation. A source–pathway–receptor framework connects runoff-generating land, distributed controls, groundwater recharge zones, surface-water intakes, and treatment processes. Evidence supports consistent reductions in suspended solids and many particle-associated pollutants, while performance for dissolved nutrients, chloride, and pathogens depends more strongly on media characteristics, hydraulic residence time, temperature, antecedent moisture, bypass, and maintenance. Infiltration also creates an obligation to protect groundwater from mobile contaminants. The framework therefore incorporates intake sensitivity, aquifer vulnerability, treatment consequences, lifecycle maintenance, and mass-load monitoring into routine stormwater design. Green infrastructure can serve as an upstream barrier within a multiple-barrier drinking-water system when each practice is appropriately matched to a contaminant source, transport pathway, and municipal receptor. Performance-based siting, treatment trains, conservative pathogen controls, and shared governance can strengthen public-health protection before conventional treatment.*

**Keywords:** *source water protection; low impact development; green infrastructure; bioretention; permeable pavement; vegetated buffer; nonpoint-source pollution; drinking water*

*Received 1 July 2026; Received in revised form 20 July 2026; Accepted 22 July 2026, Available online 30 July 2026*

## 1. INTRODUCTION

### 1.1 Background

Safe drinking water depends on more than treatment-plant performance. It depends on the quality and variability of the water arriving at the intake or production well. Urban and peri-urban runoff transports sediment, nutrients, microorganisms, metals, hydrocarbons, pesticides, road salts, and organic matter from diffuse surfaces. Impervious cover shortens travel time and increases runoff volume, producing contaminant pulses that conventional monitoring may miss. The resulting burden affects coagulation, filtration, disinfection, residuals management, taste and odor control, harmful algal bloom risk, and operating cost (Arnold & Gibbons, 1996; Brown & Peake, 2006; McGrane, 2016; National Research Council, 2009).

Source-water protection follows a preventive public-health logic. Avoiding contaminant entry often costs less and creates fewer treatment by-products than removing pollution after arrival. The economic literature links degraded source water with higher treatment expenditure, while national studies show persistent nitrate violations and unequal exposure across communities (Pennino *et al.*, 2017, 2020; Price & Heberling, 2018, 2020; Switzer & Teodoro, 2018). Yet stormwater planning and drinking-water planning often operate under separate budgets, performance measures, and institutional mandates. This separation obscures the value of distributed runoff controls to water suppliers.

Low impact development and green infrastructure restore interception, infiltration, evapotranspiration, storage, filtration, sorption, and biological processing within developed landscapes. Their literature usually emphasizes peak-flow reduction, channel protection, or sewer-overflow control. Those outcomes matter, but a drinking-water frame asks a different question: how much contaminant mass and short-duration exposure do these practices prevent from reaching a municipal reservoir, river intake, or recharge zone? The answer depends on pollutant form, local hydrogeology, system design, and maintenance (Ahiablame *et al.*, 2012; Dietz, 2007; Fletcher *et al.*, 2015).

This paper reviews the evidence through a source-water lens and proposes an operational design framework. It does not claim that green infrastructure replaces treatment. Instead, it positions distributed controls as the upstream barrier in a multiple-barrier system. The contribution lies in connecting stormwater performance metrics to drinking-water outcomes, identifying conditions where infiltration may create groundwater risk, and defining a governance and monitoring structure through which utilities can treat green infrastructure as part of their source-water portfolio.

## 2. REVIEW SCOPE AND ANALYTICAL METHOD

The review integrates peer-reviewed field, laboratory, synthesis, and modeling studies with U.S. government guidance on source-water protection, groundwater, flood resilience, and green infrastructure. Evidence was organized around a causal chain: contaminant source, runoff mobilization, control mechanism, residual pathway, receiving source water, and treatment consequence. Greater weight was given to field studies reporting paired influent and effluent data, flow volumes, or long-term hydraulic performance. Reviews and meta-analyses supported cross-site interpretation. Government documents defined regulatory and operational context. Because

study designs differ, the paper uses bounded qualitative synthesis rather than a pooled removal estimate.

Four questions structure the analysis. First, which pollutants threaten drinking-water sources through urban and peri-urban runoff? Second, which LID or GI mechanisms interrupt their transport? Third, under what conditions does treatment fail, bypass, or transfer risk to groundwater? Fourth, how should stormwater and drinking-water agencies design, monitor, and finance a shared upstream barrier? These questions distinguish hydrologic performance from public-health performance and keep the analysis within the documented engineering domain of runoff control, filtration, infiltration, and site design.

A generative large language model assisted with language editing and manuscript organization. The author reviewed the technical analysis, verified source attribution, revised the text, and accepts full responsibility for the manuscript.

### 3. THE SOURCE–PATHWAY–RECEPTOR FRAMEWORK

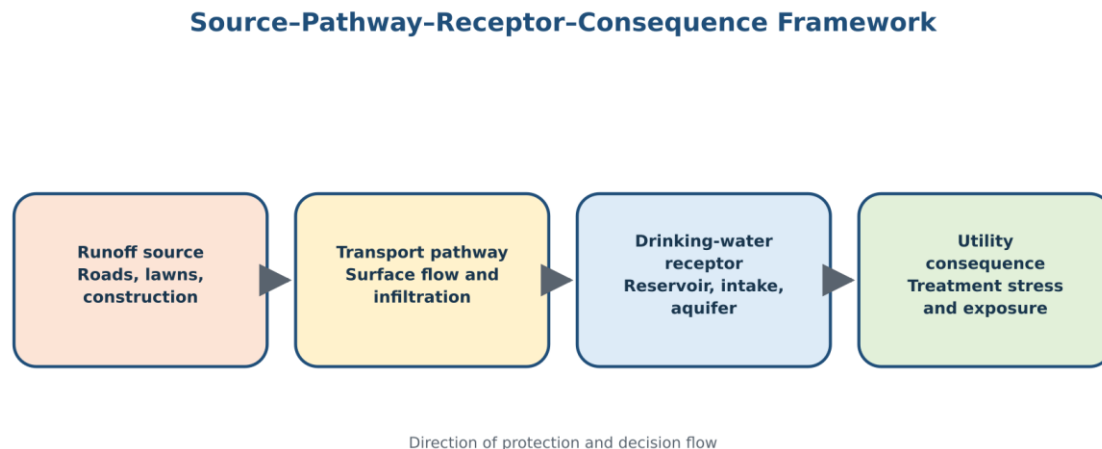


**Figure 1:** Source to pathway to drinking-water receptor.

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

The proposed framework starts with the source, not the device. A transportation corridor produces sediment, metals, hydrocarbons, tire particles, and chloride. A residential catchment contributes nutrients, pet-waste microorganisms, lawn chemicals, and organic matter. Construction sites create high suspended-solids loads. Agricultural edges add sediment, nitrogen, phosphorus, pesticides, and fecal matter. The pathway includes overland flow, storm drains, shallow subsurface movement, stream transport, reservoir mixing, and aquifer recharge. The receptor is an intake, wellfield, or protected recharge zone, together with the treatment processes and consumers dependent on it. Figure 1 illustrates this source-to-receptor chain, and Table 1 summarizes the corresponding design question and evidence type for each framework element.

**Table 1:** Source-pathway-receptor framework summary.

| Framework element | Design question                                                      | Evidence                                          |
|-------------------|----------------------------------------------------------------------|---------------------------------------------------|
| Source            | What land use, activity, and season generate the pollutant?          | Inventory, sanitary survey, monitoring            |
| Pathway           | Does the pollutant move dissolved, particulate, or microbially?      | Speciation, runoff routing, hydrogeology          |
| Control           | Which physical, chemical, or biological process interrupts movement? | Media tests, residence time, field performance    |
| Receptor          | Which intake, reservoir layer, well, or recharge zone is exposed?    | Source-water assessment, capture zone             |
| Consequence       | How does the pulse affect treatment and health protection?           | Turbidity, dose, filter run, disinfection, alerts |

This chain prevents a common category error. A practice that retains runoff is not automatically protective of drinking water. Protection exists only when retention breaks the relevant pathway without creating another. Particle filtration may protect a reservoir from turbidity and attached phosphorus. The same practice may pass nitrate or chloride to groundwater. A saturated zone may improve denitrification but requires hydraulic and media conditions that sustain anoxic processing. The source-water objective therefore changes siting, lining, underdrain, media, overflow, and monitoring decisions (Clark & Pitt, 2007; Pitt *et al.*, 1999; Zinger *et al.*, 2013).

#### 4. PERFORMANCE OF CORE LID AND GI PRACTICES

Each practice below should be specified as a contaminant-control asset rather than as a drainage ornament, because source-water risk depends on both the mass and the timing of what a practice retains. 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. Because field evidence shows substantial variation between events and sites, a design claim for any of these practices should state the target pollutant, tributary area, design storm, antecedent condition, and expected maintenance regime; the most defensible performance statement is therefore conditional, since a practice reduces exposure only when its hydraulic capacity, media, vegetation, and outlet configuration match the contaminant pathway.

For each practice, ignoring its critical design boundary converts apparent capture into pollutant transfer. Infiltration near vulnerable groundwater 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 connecting the contributing surface, the practice, the vadose zone, the aquifer or reservoir, and the municipal intake, and monitoring should include influent and effluent concentration, flow volume, bypass frequency, seasonal groundwater level, and at least one microbial indicator when fecal sources exist.

A practical acceptance framework should then link each practice to the variables identified for it below. 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, an integration central to the preventive logic advanced in this paper.

#### 4.1 Bioretention for sediment and turbidity control

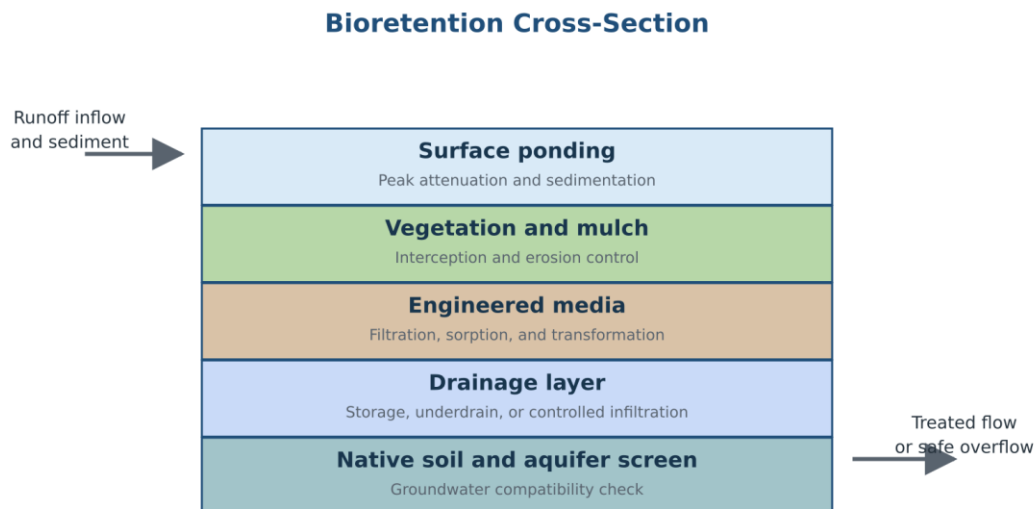


**Figure 2:** Bioretention cross-section and contaminant-control mechanisms.

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

Figure 2 shows its cross-section and contaminant-control mechanisms. Its principal pathway is settling at the surface, straining through mulch and media, and retention of eroded particles within

the cell. The critical design boundary is surface clogging, erosion at the inlet, short-circuiting, and bypass during storms larger than the design event. A practical acceptance framework links this practice to event-scale suspended-solids mass, turbidity distribution, and bypass volume (Davis, 2007; Hatt *et al.*, 2009; Liu *et al.*, 2014).

#### 4.2 Bioretention for nitrogen management

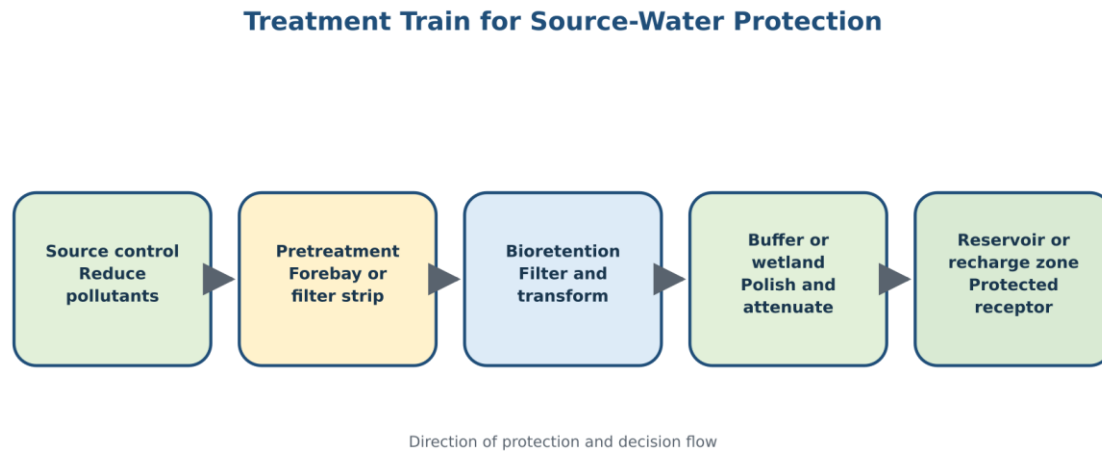


**Figure 3:** Low impact development treatment train protecting a municipal source.

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

Figure 3 depicts how this mechanism functions within a broader treatment train protecting a municipal source. Its principal pathway is plant uptake, microbial transformation, adsorption of ammonium, and denitrification where a saturated zone provides carbon and anoxic residence time. The critical design boundary is nitrate export from oxidizing media, insufficient carbon, cold-weather kinetics, and underdrain short-circuiting. A practical acceptance framework links this practice to total nitrogen load, nitrate and ammonium speciation, residence time, and seasonal performance (Davis *et al.*, 2006; Hunt *et al.*, 2006; Zinger *et al.*, 2013).

#### 4.3 Bioretention for phosphorus control

Its principal pathway is capture of particulate phosphorus and sorption of dissolved phosphate onto iron-, aluminum-, or calcium-bearing media. The critical design boundary is media saturation, organic matter release, and dissolved phosphorus export from unsuitable compost-rich mixes. A practical acceptance framework links this practice to particulate and dissolved phosphorus loads, media sorption capacity, and replacement threshold (Erickson *et al.*, 2007, 2012; Shrestha *et al.*, 2018).

#### 4.4 Bioretention for microbial risk reduction

Its principal pathway is filtration, adsorption to media, predation, desiccation, and longer subsurface contact. The critical design boundary is high-flow breakthrough, remobilization, warm wet antecedent conditions, and wildlife or pet inputs within the practice. A practical acceptance framework links this practice to flow-weighted fecal indicator load, first-flush concentration, bypass, and post-maintenance response (Hathaway *et al.*, 2009; Hatt *et al.*, 2007; Zhang *et al.*, 2014).

#### 4.5 Permeable pavement as pretreatment

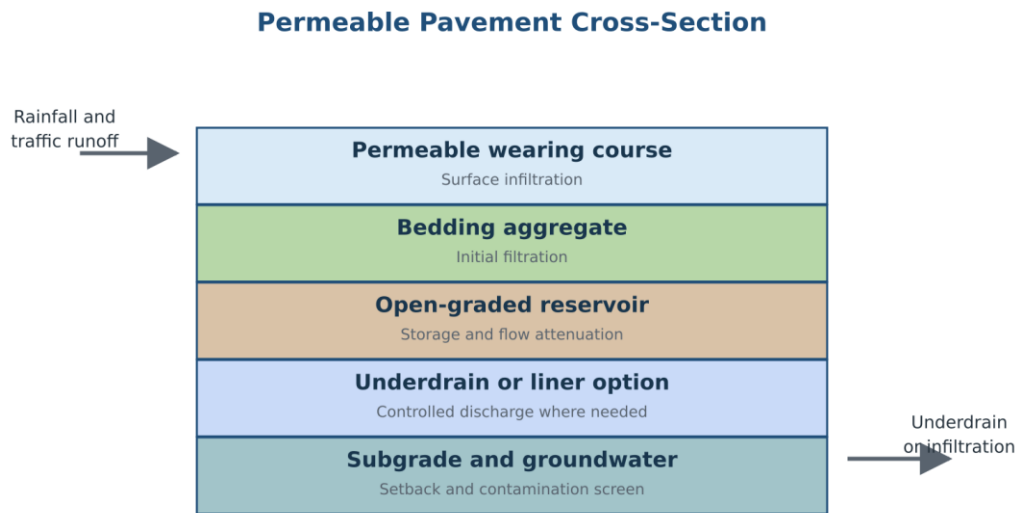


**Figure 4:** Permeable pavement cross-section and groundwater safeguards.

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

Figure 4 shows its cross-section and the groundwater safeguards described below. Its principal pathway is surface interception, filtration in bedding and aggregate, sedimentation in storage layers, and runoff-volume reduction (Brattebo & Booth, 2003; Barrett, 2005). The critical design boundary is surface clogging, winter salt loading, hydrocarbon spills, groundwater sensitivity, and neglected vacuum maintenance: field surveys report infiltration rates falling markedly with pavement age once vacuum sweeping lapses (Bean *et al.*, 2007; Boogaard *et al.*, 2014), and restoration methods recover only part of that lost capacity once fine sediment has bound the surface (Drake & Bradford, 2013). A practical acceptance framework links this practice to surface infiltration rate, effluent event mean concentration, overflow frequency, chloride, and sediment accumulation, following the constituent-concentration and clogging methods used in highway and parking-lot studies (Kayhanian *et al.*, 2007, 2012; Sansalone *et al.*, 2008, 2012) and confirmed by long-term maintenance monitoring (Winston *et al.*, 2016; Kuruppu *et al.*, 2019; Winston *et al.*, 2020).

#### 4.6 Permeable pavement in cold climates

Its principal pathway is temporary storage, delayed drainage, and filtration during rainfall and snowmelt. The critical design boundary is frozen layers, deicing salt, sand application, freeze-thaw damage, and seasonal maintenance constraints; porous pavement retains measurable drainage capacity through freezing provided sub-base ground temperature stays above the frost line (Bäckström, 2000; Bäckström & Bergström, 2000). A practical acceptance framework links this practice to winter infiltration, chloride mass, freeze-thaw condition, and spring maintenance recovery (Borst & Brown, 2014; Roseen *et al.*, 2009).

#### 4.7 Vegetated buffers for sediment interception

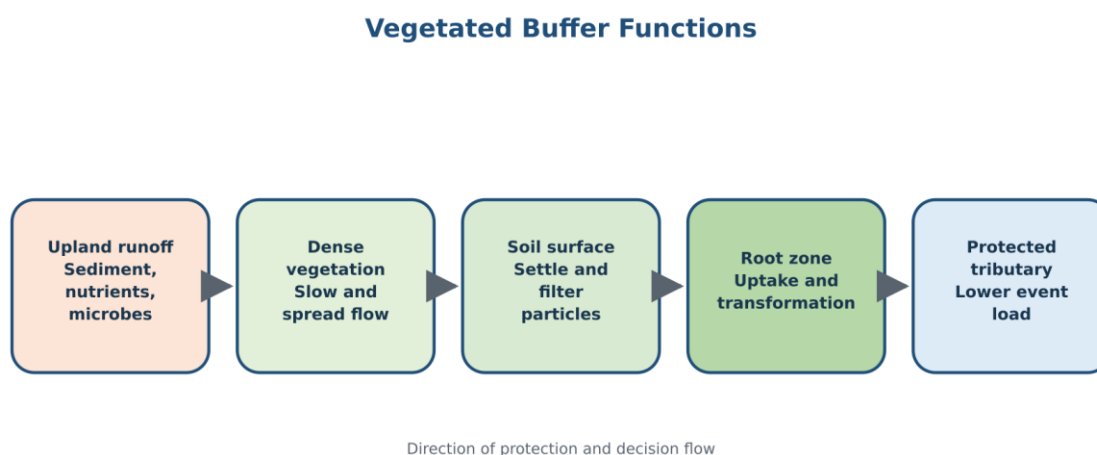


**Figure 5:** Vegetated buffer pollutant-removal pathways.

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

Figure 5 shows its pollutant-removal pathways. Its principal pathway is roughness-induced slowing, deposition, infiltration, root stabilization, and reduced bank erosion. The critical design boundary is concentrated flow, insufficient width, steep slopes, vegetation gaps, and channelized bypass. A practical acceptance framework links this practice to sediment delivery ratio, buffer width, slope, vegetation density, and runoff convergence (Liu *et al.*, 2008; Dunn *et al.*, 2022; Yuan *et al.*, 2009).

#### 4.8 Vegetated buffers for nutrients and pathogens

Its principal pathway is particulate capture, plant uptake, soil processing, denitrification, and increased travel time. The critical design boundary is dissolved nutrient passage, seasonal senescence, subsurface bypass, and direct fecal deposition near the water. A practical acceptance framework links this practice to nitrogen and phosphorus forms, indicator organisms, groundwater flow path, and buffer continuity (Mayer *et al.*, 2007; Prosser *et al.*, 2020; King *et al.*, 2016).

#### 4.9 Distributed treatment trains

Its principal pathway is sequencing source control, conveyance slowing, filtration, sorption, infiltration, and controlled overflow. The critical design boundary is correlated failure, undersized downstream controls, maintenance gaps, and unmonitored interconnections. A practical acceptance framework links this practice to cumulative load reduction, component bypass, whole-train residence time, and reliability (Brown *et al.*, 2012; Scholes *et al.*, 2008; Loperfido *et al.*, 2014).

#### 4.10 GI in groundwater recharge zones

Its principal pathway is vadose-zone filtration, sorption, biodegradation, and controlled recharge. The critical design boundary is mobile nitrate, chloride, solvents, PFAS, shallow groundwater, karst, and contaminated soils. A practical acceptance framework links this practice to recharge quality, groundwater travel time, capture-zone contribution, and sentinel-well trends (Clark & Pitt, 2007; U.S. Environmental Protection Agency, 2018; Shapiro *et al.*, 2022).

#### 4.11 GI upstream of reservoirs

Its principal pathway is reduction of sediment, particulate nutrients, organic matter, and microbial pulses before tributary entry. The critical design boundary is large untreated catchment fractions, legacy nutrients, resuspension, extreme storms, and internal reservoir loading. A practical acceptance framework links this practice to tributary loads, turbidity, chlorophyll-a, cyanotoxin indicators, and intake-depth conditions (Carpenter *et al.*, 1998; Paerl & Paul, 2012; Rauh *et al.*, 2024).

#### 4.12 Construction-phase source control

Its principal pathway is erosion prevention, sediment retention, stabilized access, and rapid revegetation before permanent GI is commissioned. The critical design boundary is bare soil exposure, failed perimeter controls, incomplete sequencing, and high-intensity rainfall. A practical acceptance framework links this practice to turbidity, suspended-solids load, inspection closure time, and stabilization percentage (National Research Council, 2009; Walsh *et al.*, 2012; Yuan *et al.*, 2009).

### 5. CONTAMINANT-SPECIFIC INTERPRETATION

#### 5.1 Sediment and turbidity

Sediment is both a contaminant and a carrier. Fine particles transport phosphorus, metals, hydrophobic organics, and microorganisms. High turbidity complicates coagulation and filtration and may interfere with disinfection. GI practices often show their strongest and most consistent performance for suspended solids because settling and straining are robust mechanisms. Source-water design should still distinguish coarse sediment retained at inlets from fine colloids that remain mobile. Maintenance records should quantify removed sediment, since accumulated material represents stored contaminant mass that may re-enter runoff if erosion or bypass occurs.

#### 5.2 Nitrogen and phosphorus

Nutrient performance is less uniform. Particulate phosphorus follows sediment, while dissolved phosphate needs sorptive media or biological uptake. Nitrate remains mobile in oxygenated systems and needs plant assimilation or denitrification with suitable carbon and residence time. Nutrient control should connect catchment fertilizer and waste sources with media chemistry, vegetation, and hydrology. The drinking-water value includes reduced nitrate exposure, lower

harmful algal bloom pressure, less organic loading, and fewer treatment disruptions (Pennino *et al.*, 2017; Ward *et al.*, 2018; Paerl & Paul, 2012).

### 5.3 Pathogens and microbial indicators

Pathogen control requires conservative claims. Fecal indicator reductions vary with organism, particle association, sunlight, temperature, moisture, and hydraulic loading. Practices also host wildlife and may become sources when poorly drained. A multiple-barrier approach uses source exclusion, pretreatment, filtration, detention, controlled infiltration, and disinfection at the plant. GI performance should never serve as the sole microbial barrier. Sanitary surveys and event-based monitoring should identify high-risk sources, including pet waste, sanitary cross-connections, livestock, failing septic systems, and flood mobilization.

### 5.4 Organic matter, metals, hydrocarbons, and salts

Many particle-associated metals and hydrocarbons respond well to filtration and sorption, but dissolved fractions may pass through or leach from media. Dissolved organic carbon deserves attention because it affects disinfectant demand and disinfection by-product formation. Chloride is highly mobile and poorly controlled by standard infiltration practices. Spill-prone areas require pretreatment, isolation valves, liners, or exclusion from infiltration. Designers should screen industrial and transportation catchments before directing runoff toward drinking-water aquifers.

## 6. PROPOSED DRINKING-WATER SOURCE PROTECTION DESIGN PROTOCOL

The eight steps below convert the source-pathway-receptor framework into a design and operating sequence; Figure 6 summarizes the decision framework for selecting among source-water controls, and Table 2 sets out the eight steps with their drinking-water purpose. For each step, the project record should state assumptions, evidence, uncertainty, and the person responsible for approving the design basis. This documentation allows later operators to understand why the control was selected and which condition signals loss of protection, and it supports benefit-cost analysis by connecting an upstream intervention with avoided contaminant load, treatment response, and service reliability.

Implementation should proceed at both site and watershed scales. Site design controls local loading and failure pathways, while watershed planning identifies cumulative coverage, untreated gaps, equity priorities, and the spatial relationship between controls and drinking-water receptors; a practice close to a high-contribution tributary or vulnerable well may therefore produce more source-water value than a larger practice sited elsewhere, and capital ranking should reflect this receptor-weighted benefit rather than treating every retained gallon as equivalent. The subsections below add design-specific detail for each step beyond the summary in Table 2.

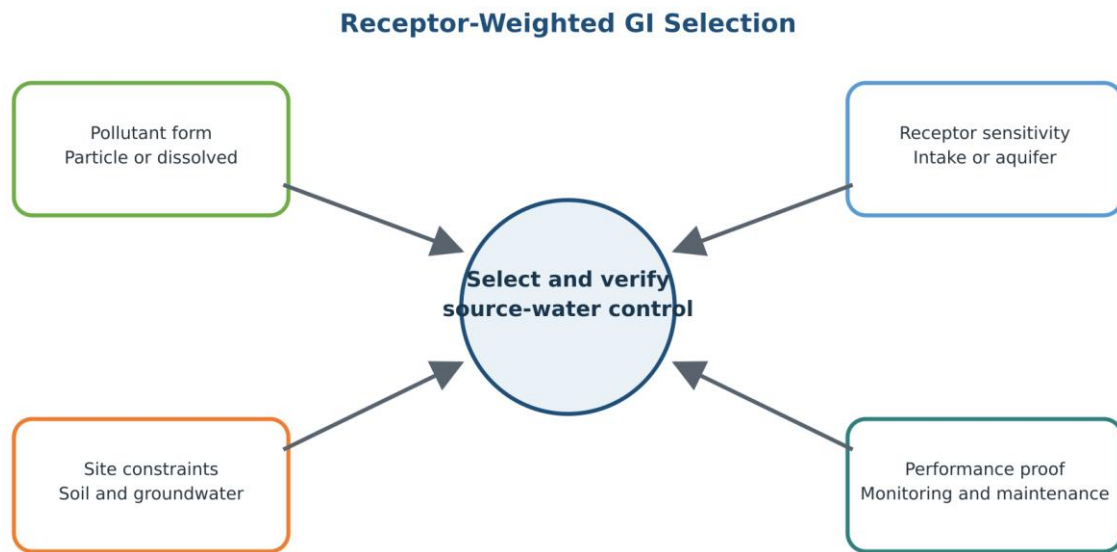


**Figure 6:** Decision framework for selecting source-water green infrastructure.

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

**Table 2:** Proposed drinking-water source protection design protocol.

| Step | Action                         | Drinking-water purpose                                                                                                                      |
|------|--------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| 1    | Map the receptor               | Delineate reservoir tributaries, intake protection areas, wellhead zones, recharge areas, groundwater capture zones, and emergency sources. |
| 2    | Characterize the source        | Inventory land use, spills, septic systems, construction, roads, fertilizer use, animal waste, and legacy contamination.                    |
| 3    | Define pollutant form          | Separate dissolved, particulate, colloidal, and microbial transport because each requires a different control mechanism.                    |
| 4    | Select and sequence controls   | Use source reduction first, then pretreatment, filtration or sorption, infiltration where safe, and a controlled overflow.                  |
| 5    | Test groundwater compatibility | Compare expected infiltrate quality, vadose-zone capacity, seasonal water table, aquifer vulnerability, and travel time to wells.           |
| 6    | Set measurable outcomes        | Specify load, concentration, bypass, infiltration, maintenance, and receiving-water indicators tied to utility decisions.                   |
| 7    | Plan failure safely            | Route exceedance flows away from wellheads and critical zones, preserve access, and prevent erosion or resuspension.                        |

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|   |                        |    |                                                                                                                 |
|---|------------------------|----|-----------------------------------------------------------------------------------------------------------------|
| 8 | Operate infrastructure | as | Assign inspection ownership, maintenance funding, data custody, corrective triggers, and lifecycle replacement. |
|---|------------------------|----|-----------------------------------------------------------------------------------------------------------------|

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### 6.1 Map the receptor

Delineate reservoir tributaries, intake protection areas, wellhead zones, recharge areas, groundwater capture zones, and emergency sources, using state source-water assessment program delineations and wellhead-protection-area travel-time analysis where available. Because capture-zone boundaries carry real uncertainty, particularly in karst or fractured-rock settings, the delineation should state its confidence level and assign a combined utility and stormwater GIS team as the responsible owner.

### 6.2 Characterize the source

Inventory land use, spills, septic systems, construction, roads, fertilizer use, animal waste, and legacy contamination, drawing on parcel and zoning records, environmental site assessments, NPDES industrial permit data, and historical land-use records that predate current zoning. Utility corridors and easements deserve separate attention because they may redirect flow or carry a contaminant source not visible on a current land-use map.

### 6.3 Define pollutant form

Separate dissolved, particulate, colloidal, and microbial transport because each requires a different control mechanism. Particle-size fractionation, typically by filtration through a 0.45-micrometer membrane, distinguishes dissolved from particulate metal and phosphorus fractions, while microbial risk should combine culturable indicator methods with molecular methods; documented detection limits matter because they constrain how a non-detect result may be interpreted.

### 6.4 Select and sequence controls

Use source reduction first, then pretreatment, filtration or sorption, infiltration where safe, and a controlled overflow, mirroring the multiple-barrier logic already used at the treatment plant so that coarse solids are removed before fine filtration and biological or sorptive polishing. A bypass or high-flow route should be an engineered design element rather than an unplanned failure mode.

### 6.5 Test groundwater compatibility

Compare expected infiltrate quality, vadose-zone capacity, seasonal water table, aquifer vulnerability, and travel time to wells, applying a groundwater vulnerability index or state vulnerability mapping where it exists and testing infiltrate against groundwater standards for chloride, nitrate, and any contaminant of concern identified in the source characterization step. Where travel time to a well is short or vulnerability is high, a lined or underdrained configuration should be preferred over open infiltration, consistent with the practice-specific design boundaries described above.

### 6.6 Set measurable outcomes

Specify load, concentration, bypass, infiltration, maintenance, and receiving-water indicators tied to utility decisions, expressed as both event mean concentration and mass load consistent with the acceptance-framework approach applied to each practice above. Outcomes should be tied to a specific utility action, such as a coagulant-dose adjustment, a filter-run-length target, or an intake-

relocation trigger, so a distributed control's value appears in treatment-plant operating records rather than only in stormwater compliance reports.

### **6.7 Plan failure safely**

Route exceedance flows away from wellheads and critical zones, preserve access, and prevent erosion or resuspension. Failure planning should identify the storm return period at which each practice is expected to bypass, the flow path that bypass will follow, and whether that path crosses a wellhead or intake protection area; an emergency isolation valve or diversion structure should be specified wherever a bypass path could otherwise connect a contamination source to a sensitive receptor.

### **6.8 Operate as infrastructure**

Assign inspection ownership, maintenance funding, data custody, corrective triggers, and lifecycle replacement, converting the preceding seven steps into a budgeted asset consistent with the asset-management practices discussed later in this review. Each practice should have a named owner, media replacement and sediment removal funded on a lifecycle schedule rather than deferred, and inspection and water-quality records held in the same asset register used for other utility infrastructure so its protective value remains auditable over its service life.

## **7. GOVERNANCE, FINANCE, AND EQUITY**

Joint governance is essential because the stormwater agency often owns the assets while the drinking-water utility receives part of the benefit. A memorandum of understanding should define shared objectives, data exchange, design review, emergency notification, inspection standards, and funding. Source-water assessments should guide municipal capital improvement plans, zoning, redevelopment review, and transportation projects. Utility participation also adds operational knowledge about intake sensitivity, seasonal treatment constraints, and contaminant thresholds (Rauh *et al.*, 2024).

Funding decisions should compare distributed prevention with added treatment capacity, recognizing that the two options often work together. Avoided cost categories include chemical use, residuals production, filter backwash, advanced treatment, emergency supply, monitoring, and service interruption. Benefits also include flood reduction, heat mitigation, habitat, recreation, and property value, but source-water claims should remain traceable to pollutant and pathway evidence (Montalto *et al.*, 2007; Price & Heberling, 2018; Weiss *et al.*, 2007).

Equity analysis should examine who bears upstream pollution, who receives GI investment, who pays utility rates, and who faces the greatest consequence of failure. Small systems often lack staff and financing for advanced treatment, while communities with historic disinvestment experience higher compliance burdens. Targeted GI near vulnerable sources may reduce risk, but it must not substitute for required treatment or defer correction of failing water infrastructure (McDonald & Jones, 2018; McFarlane & Harris, 2018; Switzer & Teodoro, 2018).

## **8 INTEGRATED EVIDENCE FOR SOURCE-WATER DESIGN**

The following synthesis connects spatial modeling, monitoring, early warning, treatment-system management, and subsurface-risk research with the drinking-water framework. The evidence supports risk-based siting and verification while the LID performance literature establishes pollutant-removal boundaries.

Treatment-train design benefits from evidence outside conventional stormwater practice when the transfer is explicit. Produced-water research emphasizes matching physicochemical and biological processes to influent variability, residuals, and reuse objectives. Applied upstream of drinking-water sources, this reinforces a sequence of characterization, pretreatment, filtration or sorption, biological polishing where suitable, and verification at the receptor. The analogy informs process selection but does not convert produced-water results into drinking-water performance claims (Falegan & Aniebonam, 2022, 2023).

Distributed treatment assets require lifecycle management. Remote installations face variable loading, limited operator access, spare-parts constraints, and delayed failure detection. A source-water GI portfolio faces similar operational risks across dispersed bioretention cells, permeable surfaces, buffers, and monitoring stations. Asset registers, condition ratings, remote alarms, inspection routes, and planned media replacement therefore belong in the source-protection program (Dagodzo & Ahiaeke Patrick, 2021a; Ike *et al.*, 2025).

Water reuse literature also sharpens the distinction between pollutant removal and safe end use. Captured runoff or treated industrial water may support irrigation, process needs, or aquifer recharge only after managers define fit-for-purpose quality, exposure controls, monitoring, and residual management. For municipal recharge zones, the receiving aquifer and drinking-water well remain the controlling receptors, so beneficial reuse does not remove the need for conservative contaminant screening (Falegan & Aniebonam, 2025).

Digital monitoring should support regulatory evidence and maintenance decisions rather than operate as an isolated dashboard. A useful system links each asset to location, design capacity, inspection history, sensor quality, overflow events, corrective work, and downstream water-quality response. Utility-asset GIS supplies the spatial backbone, while performance modeling and environmental-compliance records support trend review and auditability (Dagodzo & Ahiaeke Patrick, 2021a; Ike *et al.*, 2025).

A source-water assessment gains precision when it combines hydrologic response with spatial evidence. Watershed vulnerability modeling identifies runoff concentration zones and changing rainfall stress, while subsurface pathway models identify where infiltration may transmit contaminants toward a receptor. Remote sensing then provides repeatable observations of land-cover change, disturbed soil, vegetation condition, and drainage alteration. Together, these approaches support receptor-weighted placement of GI rather than uniform distribution by available space (Badmus & Olamide, 2019; Azeez & Badmus, 2018).

The contributing area should be treated as dynamic. Redevelopment changes grading, imperviousness, soil compaction, utility corridors, and potential contaminant sources. A static drainage map may therefore understate both surface and subsurface pathways. Periodic GIS and remote-sensing updates help detect encroachment, altered conveyance, and new exposure before those changes appear in routine intake data (Azeez & Badmus, 2024b; Dagodzo & Ahiaeke Patrick, 2022).

Groundwater-protective design needs a three-dimensional conceptual model. Surface capture does not prove risk reduction when dissolved pollutants remain mobile through fill, fractures, preferential flow, or utility trenches. Screening should combine contaminant properties, depth to groundwater, vadose-zone materials, hydraulic gradient, well capture zones, and uncertainty. This

approach supports decisions on lining, underdrains, media amendments, pretreatment, and infiltration exclusion areas (Azeez & Badmus, 2018; Lamidi & Olamide, 2018).

Monitoring networks should cover both expected performance and early evidence of failure. Surface sensors document rainfall, ponding, bypass, turbidity, and outlet flow. Sentinel wells document groundwater level and water-quality change. Aerial or satellite data document land disturbance and vegetation loss. Integrating these streams in one spatial record strengthens causal interpretation and supports timely maintenance (Badmus, 2025; Dagodzo & Ahiaeke Patrick, 2021b).

Climate adjustment should affect design storms, antecedent conditions, drawdown expectations, and overflow routing. A practice sized from historical rainfall may bypass more often as short-duration intensity rises. Watershed models help identify sensitivity, while remote sensing helps test whether modeled land-cover assumptions still hold. The design record should preserve both baseline and future scenarios for later asset review (Badmus & Olamide, 2019; Nwafor *et al.*, 2019).

Urban redevelopment requires explicit screening for legacy contamination. Infiltration placed over contaminated fill or near volatile compounds may mobilize dissolved contaminants or alter vapor pathways. GI planning should therefore review site history, environmental investigations, utility corridors, groundwater direction, and adjacent receptors before infiltration approval. Where uncertainty stays high, lined filtration and controlled discharge provide a safer configuration (Azeez & Badmus, 2024b; Lamidi & Olamide, 2018).

Vegetation condition is an operational variable. Sparse cover, plant mortality, exposed media, and invasive growth alter erosion resistance, infiltration, nutrient uptake, and flow distribution. Remote sensing supports broad screening, but field inspection confirms inlet blockage, preferential flow, sediment accumulation, and outlet condition. Combining both scales improves inspection targeting without replacing direct observation (Badmus, 2025; Dagodzo & Ahiaeke Patrick, 2022).

A drinking-water utility needs a defensible ranking method for distributed projects. Suitable criteria include expected contaminant load reduction, proximity and travel time to the receptor, aquifer vulnerability, bypass risk, maintenance access, data quality, and community burden. Geospatial decision models make tradeoffs visible and allow weights to be tested. They also document why one project receives priority over another (Ahiaeke Patrick *et al.*, 2021; Badmus & Olamide, 2019).

Early warning should connect observations to action. A land-disturbance alert, rapid turbidity rise, abnormal ponding, or sentinel-well change has limited value without a response threshold and responsible owner. The response may include inspection, source tracing, intake adjustment, temporary isolation, sampling, or maintenance. A documented chain from detection to decision makes remote monitoring part of source-water protection rather than a separate technology project (Badmus, 2025; Dagodzo & Ahiaeke Patrick, 2021b).

Data quality needs the same attention as hydraulic design. Inconsistent coordinate systems, missing maintenance dates, uncalibrated sensors, changing laboratory limits, and incomplete catchment boundaries weaken conclusions. An integrated data model should retain provenance, quality flags, temporal resolution, and asset identity. These controls support credible trend analysis

and prevent apparent performance from reflecting changes in measurement practice (Azeez & Badmus, 2024a; Badmus, 2025).

Source-water design should distinguish predictive screening from proof of treatment. Models and imagery identify where risk is likely and where monitoring should intensify. Field flow and water-quality measurements establish whether a practice delivers the expected reduction. Using both forms of evidence supports efficient sampling while preventing model outputs from being treated as observed removal (Badmus & Olamide, 2019; Lamidi & Olamide, 2018).

Utility corridors deserve attention because trenches, disturbed soils, and rights-of-way may redirect water across nominal drainage divides. Encroachment or unrecorded works may damage controls and create rapid pathways. GIS, LiDAR, and field survey should reconcile surface flow, buried infrastructure, and asset access before final siting. The resulting map also supports emergency isolation and maintenance logistics (Dagodzo & Ahiaeké Patrick, 2021b; Dagodzo & Ahiaeké Patrick, 2022).

Equity analysis benefits from spatial specificity. Communities nearest impaired tributaries, shallow groundwater, industrial redevelopment, or recurring flood routes may experience greater source-water risk and slower infrastructure response. Mapping exposure, service dependence, and project distribution helps utilities direct protection toward measurable burdens. Public reporting should state the criteria and uncertainty behind those priorities (Nwafor *et al.*, 2019; Badmus & Olamide, 2019).

Maintenance planning should respond to risk rather than a calendar alone. Practices close to high-contribution drainage areas or vulnerable wells need shorter inspection intervals and stronger redundancy. Remote observations identify broad changes, while field records establish clogging, erosion, media loss, and outlet function. A risk-based schedule directs limited crews toward failures with the greatest drinking-water consequence (Badmus, 2025; Dagodzo & Ahiaeké Patrick, 2022).

Scenario testing should include model and data uncertainty. Rainfall estimates, terrain, soil properties, groundwater elevation, contaminant loading, and asset condition each affect predicted performance. Sensitivity analysis reveals which assumptions control the result and which additional measurement has the highest decision value. This discipline supports transparent design margins and monitoring priorities (Badmus & Olamide, 2019; Azeez & Badmus, 2018).

The combined literature supports a preventive systems view. Hydrologic models describe changing watershed stress, contaminant-pathway models trace subsurface exposure, geospatial systems organize assets and corridors, and remote sensing supports early warning. Their combined value lies in directing physical GI controls, verifying continuing protection, and identifying conditions that require treatment, isolation, or redesign (Badmus & Olamide, 2019; Badmus, 2025).

The author's broader water portfolio supports a receptor-centered source-water strategy. Work on urban water security identifies scarcity, inequitable access, aquifer stress, and planning as connected risks, while the open-drain hydraulic index shows how sediment accumulation changes conveyance and exposure. For LID/GI programs, these perspectives support prioritizing controls by intake or well vulnerability, sediment delivery, and consequences for communities served, rather than by runoff volume alone (Aniebonam *et al.*, 2023b; Aniebonam & Ihwughwavwe, 2025b).

Nature-based flood-management research and predictive environmental-risk modeling strengthen the case for distributed prevention. Their transferable contribution is a structured link among hazard, pathway, receptor, uncertainty, and adaptive action. Applied here, that logic places bioretention, permeable pavement, and buffers where they interrupt documented source-water pathways and pairs them with monitoring and maintenance thresholds (Aniebonam, 2025; Ihwughwavwe & Aniebonam, 2025).

Emerging contaminants require conservative design. Research on combined heavy-metal and microplastic threats illustrates that mixtures, particle association, and changing environmental conditions complicate single-contaminant removal claims. Source-water GI should therefore monitor both dissolved and particulate fractions, manage captured sediment as a residual, and avoid infiltration where mobilization toward wells remains plausible (Aniebonam & Aniebonam, 2023).

Digitalization and smart-city studies add governance cautions as well as technical opportunities. AI-assisted planning, anomaly detection, and integrated data platforms can improve asset targeting and early warning, but accountability, data quality, cybersecurity, and human override remain design requirements. These safeguards are particularly important when sensor results influence intake operation, maintenance dispatch, or public-health decisions (Aniebonam, 2024; Aniebonam & Aniebonam, 2025).

Low-cost adsorption, circular water reuse, and produced-water treatment studies expand the treatment-train perspective without supplying direct potable-water validation. Their useful transfer is the discipline of influent characterization, fit-for-purpose media selection, residual management, decentralized operation, resource recovery, and lifecycle verification. Those principles support amended bioretention media and pretreatment only after source-water-specific testing (Falegan & Aniebonam, 2020, 2021).

Implementation depends on public legitimacy and durable stewardship. Community environmental education and youth engagement research supports co-produced monitoring, locally intelligible risk communication, and maintenance participation. Equity assessment in climate and infrastructure policy further indicates that benefits, burdens, and access to protection should be measured explicitly rather than assumed from aggregate investment (Ihwughwavwe & Aniebonam, 2024; Aniebonam *et al.*, 2025a).

Cross-sector resilience studies reinforce attention to dependencies and compound hazards. Renewable-energy transition analysis highlights socio-environmental tradeoffs, while wildfire risk to electric networks shows how loss of power and cascading infrastructure failure can undermine water protection. Source-water plans should therefore include backup energy, communications, access, and post-fire sediment and contaminant scenarios (Aniebonam *et al.*, 2023a; Aniebonam *et al.*, 2025c).

Source-water programs depend on reliable distributed assets, supplies, and maintenance. Cross-sector studies of critical-infrastructure supply chains, asset lifecycle management, predictive procurement, and long-term infrastructure metrics support four transferable practices: identify critical spares, maintain condition-linked inventories, forecast replacement needs, and connect spending to service outcomes. For GI portfolios, those practices apply to media, plants, underdrains, sensors, sampling equipment, and sediment-removal capacity (Ogunwole *et al.*, 2021; Okonkwo *et al.*, 2023).

Risk detection should combine field inspection with continuous and spatially referenced evidence. Digital hazard streams, continuous-monitoring frameworks, real-time performance indicators, utility GIS, and aerial corridor inspection offer transferable methods for locating anomalies and directing crews. Within a drinking-water source area, such methods support detection of blocked inlets, damaged buffers, eroded channels, unauthorized disturbance, and sensor deviations, but field confirmation remains necessary before operational action (Dagodzo & Ahiaeke Patrick, 2020; Obriki & Arumosoye, 2023).

Mechanical integrity also affects source-water protection. Failure-analysis and digital-twin research on mechanical systems provides transferable approaches for organizing inspection results, degradation mechanisms, operating conditions, and intervention thresholds, including for the corrosion mechanisms that affect buried and submerged components. These approaches fit underdrains, outlet structures, culverts, valves, monitoring stations, and other components whose failure causes bypass or uncontrolled discharge (Ogunnowo *et al.*, 2024a, 2024b).

Emergency readiness and environmental discipline close the gap between routine performance and unusual events. Cross-sector models emphasize defined roles, staged response, waste handling, and early failure prediction. For source-water systems, the corresponding actions include isolating spill-affected drainage, protecting monitoring continuity, managing contaminated sediment, deploying backup power, and documenting return-to-service criteria (Arumosoye & Obriki, 2023; Arumosoye *et al.*, 2025).

## 9. RESEARCH AGENDA

Research should report paired flow and water-quality data, distinguish concentration from load, document bypass, and follow performance across seasons and maintenance cycles. Studies need stronger links between stormwater effluent and actual source-water receptors. Tracers, groundwater monitoring, tributary models, and reservoir models can quantify how local controls change exposure at wells and intakes.

Pathogen studies should move beyond single indicator concentrations toward event loads, organism-specific behavior, resuspension, and risk-based interpretation. Nutrient studies should report chemical forms and media aging. Groundwater studies should evaluate mixtures, especially chloride, nitrate, mobile organic contaminants, and contaminants released from construction materials. Long-term field sites should publish negative results and failure histories.

Decision research should quantify how upstream load reduction changes treatment-plant operations, cost, energy, residuals, and reliability. A shared national reporting structure could connect GI asset condition, catchment load, source-water monitoring, and utility response. Such evidence would permit drinking-water agencies to credit distributed controls without overstating uncertain removal percentages.

## 10. CONCLUSIONS

Low impact development and green infrastructure provide a defensible first line of source-water protection when designers connect each practice to a contaminant source, transport pathway, drinking-water receptor, and measurable treatment consequence. Bioretention, permeable pavement, vegetated buffers, and treatment trains often reduce sediment and particle-associated loads. Dissolved nutrients, salts, and pathogens demand more careful media, residence-time, groundwater, and maintenance controls. The central design shift is from managing runoff volume

in the abstract to managing exposure at a reservoir, intake, aquifer, or wellfield. This shift supports public health, treatment reliability, and accountable infrastructure investment while keeping conventional drinking-water treatment as the final regulated barrier.

## LIST OF ABBREVIATIONS

**GI:** Green infrastructure

**LID:** Low impact development

**EPA:** United States Environmental Protection Agency

**GIS:** Geographic information system

**LiDAR:** Light detection and ranging

**PFAS:** Per- and polyfluoroalkyl substances

**UAV:** Uncrewed aerial vehicle

**USGS:** United States Geological Survey

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