Supporting Information

for

Evaluation of Life Cycle Assessment (LCA) for Roadway Drainage Systems

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36 pages, 28 tables, 11 figures

S1. Overview of Roadway Drainage Components (Page S2)

S2. Sample Projects (Pages S3-S6)

S3. Life Cycle Inventory and Impact Assessment Assumptions (Pages S7-S12)
- S3.1 Representative Cross Sections
- S3.2 Required Materials and Equipment for Activities and Constituent Elements
- S3.3 ecoinvent Material Processes
- S3.4 Maintenance Schedule
- S3.5 Concrete Mix Design
- S3.6 Productivity and Costs for Construction and Maintenance Activities
- S3.7 NONROADS Equipment Emissions Calculations
- S3.8 BTEX Calculations for Removed BOD

S4. Uncertainty and Sensitivity Analyses (Pages S13-S19)
- S4.1 Uncertainty Ranges
- S4.2 Initial Concentrations of Pollutants
- S4.3 Removal Efficacy for Grass Swales, Bioswales, and Basins

S5. Additional Results (Pages S20-S35)
- S5.1 Full Results for Life Cycle Phases
- S5.2 Sensitivity Analysis Results
- S5.3 Cut-off Criteria Results
- S5.4 Conveyance Element Comparison

S1. Overview of Roadway Drainage Components

This research considers six different components of roadway drainage systems (**Figure S1**): grass swales, bioswales, storm sewers, basins (detention or retention), pipe underdrains, and culverts (box or pipe). Grass swales, bioswales, and storm sewers are linear conveyance elements that are used as the primary drainage system for a stretch of roadway. Grass swales are excavated, grass-lined open channels along the side of the road. Runoff enters the grass swales directly from the road and either infiltrates or discharges to surface water. Bioswales are similar to grass swales but include denser vegetation as well as a permeable subsurface layer in order to filter pollutants and promote infiltration. As with grass swales, roadway runoff enters bioswales directly from the road and either infiltrates or discharges to surface water. Storm sewers are closed, circular, underground pipes that run along the edge of the road. Runoff enters the storm sewer system through inlets that take the runoff into catch basins connecting to storm sewer pipes that ultimately discharge to surface water.

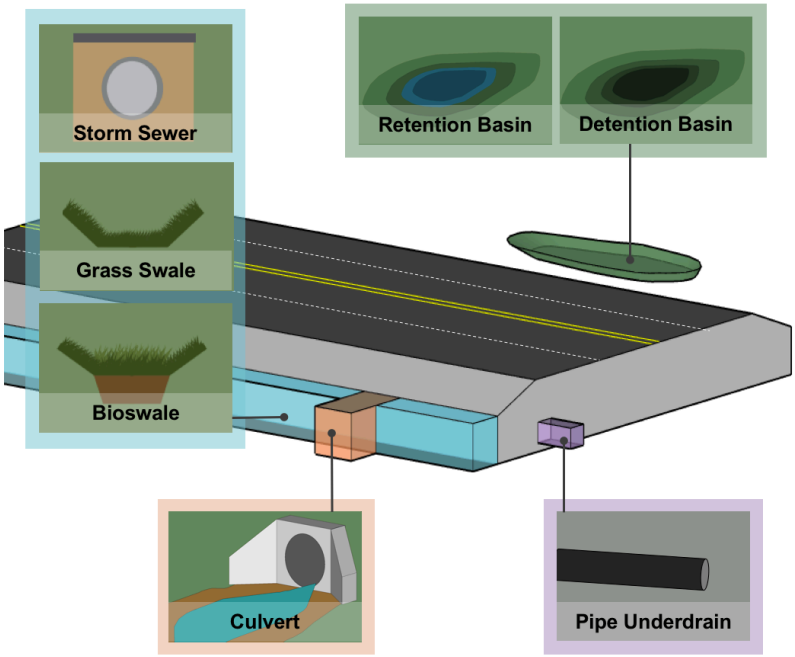

Figure S1: Overview of Drainage Components

In addition to these three major conveyance elements, roadway drainage systems can also include basins, pipe underdrains, and culverts. Basins are excavated ponds that can either store water only during a storm event (i.e., detention basin) or constantly maintain a permanent pool (i.e., retention basin). Basins are usually used when the volume of roadway runoff is large enough that having the runoff discharge directly to the natural water body would cause an undesirable increase in the flow to that receiving water; therefore, basins are used to store the runoff and slowly release it over time. Basins can also provide water quality benefits, particularly through settling of sediment. Pipe underdrains are small-perforated pipes, usually 6 or 8 inches in diameter, located beneath the road surface to capture water that infiltrates through the pavement. Underdrains help keep the pavement surface clear of water and also protect the pavement from deterioration caused by prolonged exposure to water. Finally, culverts are used to allow water to travel under the road surface in order to prevent the disruption of streams and other natural water bodies by roadway systems. Depending upon the flow of water, culverts can either be pipes or box culverts and typically require a headwall for structural stability and erosion prevention.

S2. Sample Projects

The following describes the drainage components and their associated design parameters that were extracted for the 10 sample projects. Projects which contain a given drainage component multiple times are cases in which that drainage component changed in size within the project boundary (i.e., dimensions changed along its length). These dimensions were used to create the life cycle inventory for each drainage component (e.g., volume of materials)

Project 1; annual average daily traffic (AADT) = 33,500

- *Grass Swale:* length = 100 ft, no erosion blanket, bottom width = 4 ft, top width = 46 ft, foreslope = 4:1, backslope = 2.5:1
- *Storm Sewer:* curb/gutter included, inner diameter = 24 in, length = 200 ft, backfilled with sand, manhole spacing = 0, catch basin spacing = 200 ft
- *Storm Sewer:* curb/gutter included, inner diameter = 30 in, length = 400 ft, backfilled with sand, manhole spacing = 0, catch basin spacing = 133 ft
- *Pipe Underdrain:* length = 200 ft, inner diameter = 6 in, backfilled with sand, outlet spacing = 500 ft

Project 2; annual average daily traffic (AADT) = 33,500

- *Grass Swale:* length = 650 ft, no erosion blanket, bottom width = 4 ft, top width = 60 ft, foreslope = 4:1, backslope = 2.5:1
- *Storm Sewer:* curb/gutter included, inner diameter = 30 in, length = 650 ft, backfilled with sand, manhole spacing = 323 ft, catch basin spacing = 0
- *Pipe Underdrain:* length = 1,300 ft, inner diameter = 6 in, backfilled with sand, outlet spacing = 500 ft

Project 3; annual average daily traffic (AADT) = 23,220

- *Bioswale:* length = 120 ft, erosion blanket, bottom width = 4 ft, top width = 30 ft, foreslope = 4:1, backslope = 4:1, sand side slope = 1:2, sand depth = 30 in
- *Grass Swale:* length = 780 ft, no erosion blanket, bottom width = 4 ft, top width = 30 ft, foreslope = 4:1, backslope = 4:1
- *Grass Swale:* length = 300 ft, no erosion blanket, bottom width = 4 ft, top width = 50 ft, foreslope = 4:1, backslope = 4:1
- *Pipe Underdrain:* length = 1,200 ft, inner diameter = 6 in, backfilled with sand, outlet spacing = 500 ft

Project 4; annual average daily traffic (AADT) = 23,220

- *Culvert (Box):* box height = 6 ft, box width = 7 ft, 1 headwall, length = 60 ft
- *Grass Swale:* length = 1,100 ft, no erosion blanket, bottom width = 4 ft, top width = 60 ft, foreslope = 4:1, backslope = 2.5:1
- *Grass Swale:* length = 300 ft, no erosion blanket, bottom width = 20 ft, top width = 40 ft, foreslope = 4:1, backslope = 4:1
- *Pipe Underdrain:* length = 1,400 ft, inner diameter = 6 in, backfilled with sand, outlet spacing = 250 ft

Project 5; annual average daily traffic (AADT) = 23,220

- *Culvert (Box):* box height = 12 ft, box width = 9 ft, 1 headwall, length = 70 ft
- *Grass Swale:* length = 550 ft, no erosion blanket, bottom width = 12 ft, top width = 70 ft, foreslope = 4:1, backslope = 4:1

- *Grass Swale:* length = 650 ft, no erosion blanket, bottom width = 6 ft, top width = 65 ft, foreslope = 4:1, backslope = 4:1
- *Pipe Underdrain:* length = 1,200 ft, inner diameter = 6 in, backfilled with sand, outlet spacing = 250 ft

Project 6; annual average daily traffic (AADT) = 26,520

- *Culvert (Box):* box height = 12 ft, box width = 7 ft, 1 headwall, length = 88 ft
- *Grass Swale:* length = 300 ft, no erosion blanket, bottom width = 10 ft, top width = 70 ft, foreslope = 3:1, backslope = 2.5:1
- *Grass Swale:* length = 100 ft, no erosion blanket, bottom width = 20 ft, top width = 70 ft, foreslope = 3:1, backslope = 2.5:1
- *Grass Swale:* length = 200 ft, no erosion blanket, bottom width = 25 ft, top width = 70 ft, foreslope = 3:1, backslope = 2.5:1
- *Grass Swale:* length = 200 ft, no erosion blanket, bottom width = 4 ft, top width = 50 ft, foreslope = 4:1, backslope = 3:1
- *Grass Swale:* length = 100 ft, no erosion blanket, bottom width = 4 ft, top width = 40 ft, foreslope = 6:1, backslope = 3:1
- *Grass Swale:* length = 100 ft, no erosion blanket, bottom width = 4 ft, top width = 30 ft, foreslope = 7.2:1, backslope = 3:1
- *Pipe Underdrain:* length = 1,000 ft, inner diameter = 6 in, backfilled with sand, outlet spacing = 200 ft

Project 7; annual average daily traffic (AADT) = 45,350

- *Basin:* top area = 175,500 sf, bottom area = 80,000 sf, depth = 27 ft, outlet inner diameter = 24 in, outlet pipe length = 100 ft, no erosion blanket
- *Storm Sewer:* curb/gutter included, inner diameter = 24 in, length = 100 ft, backfilled with sand, manhole spacing = 0, catch basin spacing = 100 ft
- *Storm Sewer:* curb/gutter included, inner diameter = 30 in, length = 300 ft, backfilled with sand, manhole spacing = 0, catch basin spacing = 150 ft
- *Storm Sewer:* curb/gutter included, inner diameter = 15 in, length = 600 ft, backfilled with sand, manhole spacing = 0, catch basin spacing = 150 ft
- *Pipe Underdrain:* length = 1,000 ft, inner diameter = 6 in, backfilled with sand, outlet spacing = 500 ft

Project 8; annual average daily traffic (AADT) = 33,500

- *Culvert (Pipe):* inner diameter = 84 in, 1 headwall, length = 100 ft
- *Bioswale:* length = 200 ft, erosion blanket, bottom width = 4 ft, top width = 40 ft, foreslope = 3:1, backslope = 3:1, sand side slope = 1:2, sand depth = 30 in
- *Bioswale:* length = 100 ft, erosion blanket, bottom width = 10 ft, top width = 50 ft, foreslope = 3:1, backslope = 3:1, sand side slope = 1:2, sand depth = 30 in
- *Grass Swale:* length = 500 ft, no erosion blanket, bottom width = 4 ft, top width = 40 ft, foreslope = 3:1, backslope = 3:1
- *Grass Swale:* length = 500 ft, no erosion blanket, bottom width = 18 ft, top width = 50 ft, foreslope = 4:1, backslope = 3:1
- *Pipe Underdrain:* length = 1,300 ft, inner diameter = 6 in, backfilled with sand, outlet spacing = 500 ft

Project 9; annual average daily traffic (AADT) = 26,520

- *Grass Swale:* length = 1,200 ft, no erosion blanket, bottom width = 4 ft, top width = 50 ft, foreslope = 3:1, backslope = 4:1
- *Storm Sewer:* curb/gutter included, inner diameter = 15 in, length = 100 ft, backfilled with sand, manhole spacing = 0, catch basin spacing = 33 ft
- *Pipe Underdrain:* length = 1,200 ft, inner diameter = 6 in, backfilled with sand, outlet spacing = 250 ft

Project 10; annual average daily traffic (AADT) = 23,220

- *Basin:* top area = 75,000 sf, bottom area = 1,750 sf, depth = 4 ft, outlet inner diameter = 12 in, outlet pipe length = 50 ft, no erosion blanket
- *Culvert (Pipe):* inner diameter = 60 in, 1 headwall, length = 130 ft
- *Pipe Underdrain:* length = 1,400 ft, inner diameter = 6 in, backfilled with sand, outlet spacing = 333 ft

The calculated flow capacities or storage of each project's drainage components used for normalization in Figure 2B of the manuscript are presented in **Table S1**. Flow capacities for grass swales, bioswales, storm sewers, and pipe underdrains were calculated using Manning's equation and the dimensions listed above. Flow capacities for culverts were calculated using established roadway stormwater design relationships for pipe diameter or box height and headwater depth assuming inlet control.[1]

Table S1. Flow Capacities or Storage of Each Project's Drainage Components

Project	Basin (ft^3)	Bioswale (cfs)	Culvert (cfs)	Grass Swale (cfs)	Storm Sewer (cfs)	Pipe Underdrain (cfs)
1	-	-	-	399	8.6	0.39
2	-	-	-	340	13.1	0.30
3	-	10.4	-	36	-	0.39
4	-	-	259	230	-	0.30
5	-	-	396	249	-	0.39
6	-	-	396	874	-	0.40
7	365,904	-	-	-	5.5	0.77
8	-	8.6	155	325	-	0.34
9	-	-	-	1146	2.8	0.39
10	99,404	-	125	-	-	0.39

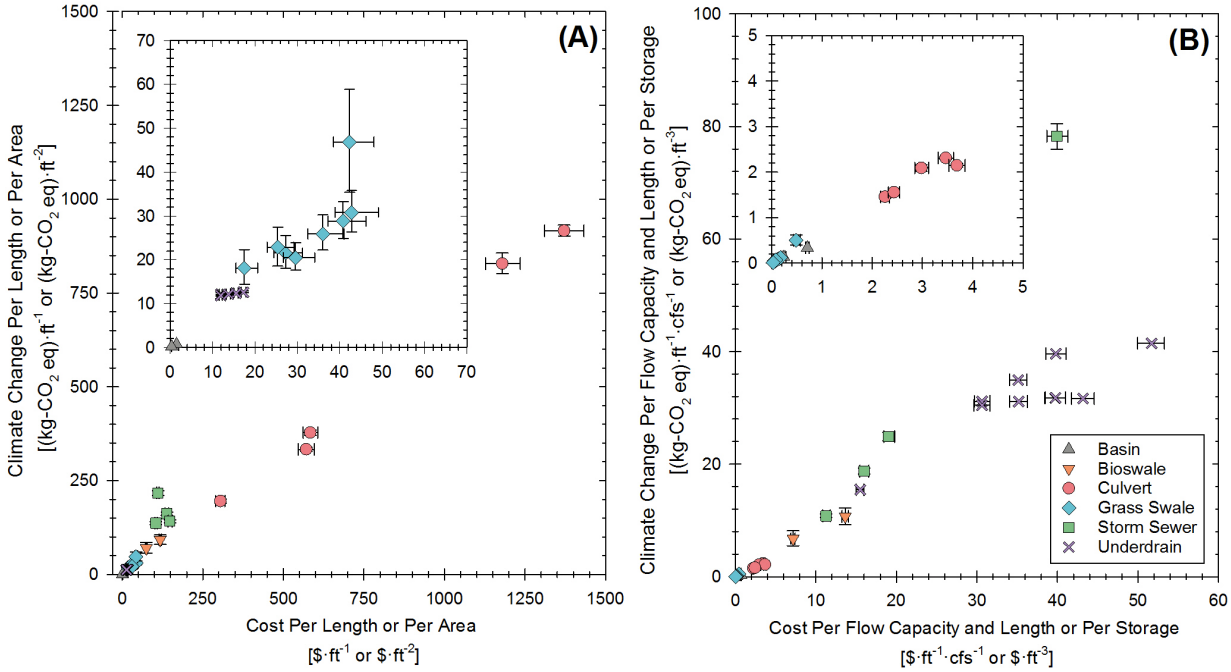

Figure S2. Comparison of normalized climate change and normalized cost for 10 sample projects (Figure 2 of main paper) in U.S. units. (A) Values are normalized to length (ft) for bioswales, culverts, grass swales, storm sewers, and underdrains, and normalized to area (ft^2) for basins. (B) Values are normalized to length and flow (ft·cfs) for bioswales, culverts, grass swales, storm sewers, and underdrains, and normalized to storage volume (ft^3) for basins. Whole project results stem from construction, maintenance, and end of life (use phase was not included in this figure as its impacts cannot be attributed to individual drainage components), with points indicating medians and error bars extending to 10th and 90th percentiles from uncertainty analysis.

S3. Life Cycle Inventory and Impact Assessment Assumptions

S3.1 Representative Cross Sections

Representative cross sections used for bioswale and basin design can be found online at the following link[2]: https://www.illinoistollway.com/documents/20184/238069/00+M-DRN-600+Drainage+%2528DRN%2529+%2528pdf%2529/dc05ab1f-009e-4fff-ac09-ae5de0aea601?version=1.7

- Representative bioswale cross section: Bioswale, Type 2; Page 6
- Representative basin outlet structure cross section: Profile View; Page 4

S3.2 Required Materials and Equipment for Activities and Constituent Elements

Table S2 provides the required materials and equipment for each construction or maintenance activity (e.g., grading) or constituent element (e.g., catch basin) as well as the applicable drainage component(s).

Table S2. Required Materials and Equipment for Activities and Constituent Elements

Activity or Constituent Element	Required Materials	Required Equipment	Basin	Bioswale	Culvert	Grass Swale	Storm Sewer	Underdrain
backfilling	sand	excavator		x			x	x
box culvert	concrete, steel	excavator, wheel loader			x			
catch basin	concrete, steel, iron	excavator					x	
compaction	-	compactor	x		x	x	x	x
curb and gutter	concrete, steel	slipform paver, concrete mixer					x	
erosion blanket	polypropylene, straw	skid steer loader	x	x		x		
excavation	-	excavator	x	x	x	x	x	
fertilizing	NPK fertilizer	hydroseed sprayer		x		x		
grading	-	grader	x	x		x		
grate	iron	-						x
HDPE pipe	HDPE	-						x
headwall	concrete, steel	excavator	x		x			x
herbicide	herbicide	hydroseed sprayer		x		x		
manhole	concrete, steel, iron	excavator	x				x	
mowing	-	mower	x	x		x		
pipe cleaning	-	vactor truck					x	
plug plants	plug plants	-		x				
reinforced concrete pipe	concrete, steel	excavator	x		x		x	
riprap	riprap	skid steer loader	x					
seeding	grass seed	hydroseed sprayer	x	x		x		
topsoil placement	topsoil	wheel loader		x				
trench liner	polyester	-						x
trenching	-	trencher						x

S3.3 ecoinvent Material Processes

Table S3 includes the applicable ecoinvent processes for each material inventory item.[3] All material processes also include a transport process to account for transportation during material extraction and processing: *Transport, truck >20t, EURO1, 50%LF, default/GLO Mass*

Table S3. Material Processes Used from ecoinvent Database[3]

Inventory Item	Applicable ecoinvent Process(es)
Bioswale Plugs	Tree seedling {GLO}| market for | Alloc Def, U
Cast Iron	Cast iron {GLO}| market for | Alloc Def, U Metal working, average for metal product manufacturing {GLO}| market for | Conseq, U
Concrete	See Section S3.5
Crushed Limestone	Limestone, crushed, for mill {GLO}| market for | Alloc Def, U
HDPE Pipe	Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U Extrusion, plastic pipes {GLO}| market for | Alloc Def, U
Herbicide	Pesticide, unspecified {GLO}| dichloropropene to generic market for | Alloc Def, U
Polyester Cable	Polyester resin, unsaturated {GLO}| market for | Alloc Def, U Stretch blow moulding {GLO}| market for | Alloc Def, U
Polyester Fabric	Polyester resin, unsaturated {GLO}| market for | Alloc Def, U Stretch blow moulding {GLO}| market for | Alloc Def, U
Polypropylene Fiber	Polypropylene, granulate {GLO}| market for | Alloc Def, U Stretch blow moulding {GLO}| market for | Alloc Def, U
Prepared Topsoil	Compost {GLO}| market for | Alloc Rec, U Sand {GLO}| market for | Alloc Def, U
PVC Pipe	Polyvinylchloride, suspension polymerised {GLO}| market for | Alloc Def, U Extrusion, plastic pipes {GLO}| market for | Alloc Def, U
Reinforcing Steel	Reinforcing steel {GLO}| market for | Alloc Def, U
Riprap	Limestone, crushed, for mill {GLO}| market for | Alloc Def, U
Sand	Sand {GLO}| market for | Alloc Def, U
Seed	Grass seed, organic, for sowing {GLO}| market for | Alloc Def, U
Fertilizer	Nitrogen fertiliser, as N {GLO}| market for | Alloc Def, U Potassium fertiliser, as K2O {GLO}| market for | Alloc Def, U Phosphate fertiliser, as P2O5 {GLO}| market for | Alloc Def, U
Steel	Steel, low-alloyed {GLO}| market for | Alloc Def, U Metal working, average for steel product manufacturing {GLO}| market for | Alloc Def, U
Steel Wire	Steel, low-alloyed {GLO}| market for | Alloc Def, U Wire drawing, steel {GLO}| market for | Alloc Def, U
Straw	Straw {GLO}| market for | Alloc Def, U

S3.4 Maintenance Schedule

The maintenance schedule for each drainage component was based on Illinois Tollway standards of practice[4] and includes:

- Mowing of grass swales and the area around basins: 3 times a year
- Mowing of bioswales: 1 time a year
- Herbicide application for grass swales and bioswales; 1 time a year
- Seeding for grass swales, bioswales, and basins: every 15 years
- Fertilizing of grass swales and bioswales: every 15 years
- Cleaning of storm sewers: every 15 years
- Grading of grass swales and bioswales: every 15 years
- Compacting of grass swales: every 15 years

S3.5 Concrete Mix Design

Due to the large volume of concrete required for certain drainage components, a concrete process within the ecoinvent database was modified to reflect the mix design specifications of the Illinois Department of Transportation.[5]

The ecoinvent process *Concrete, normal {RoW}| production | Alloc Def, U* within the ecoinvent process *Concrete, normal {GLO}| market for | Alloc Def, U*[3] was modified in accordance with the Illinois Department of Transportation's Standard Specifications for Road and Bridge Construction.[5] Process modifications included changes to the amount of cement, percent fly ash, and amount of water:

Cement: Included in uncertainty analysis as a triangular distribution (minimum = 335.2 kg/m^3, most probable = 376.7 kg/m^3, maximum = 418.3 kg/m^3)
Percent Fly Ash: Included in uncertainty analysis as a triangular distribution (minimum = 20%, most probable = 25%, maximum = 30%)
Water: 145.65 kg/m^3, according to the average water/cement ratio of 0.38 lb/lb

S3.6 Productivity and Costs for Construction and Maintenance Activities

Table S4 includes the reference for productivity rates and costs obtained from RSMeans – 2015 Heavy Construction Cost Data (HC),[6] 2015 Site Work & Landscape Cost Data (SWL),[7] 2015 Building Construction Cost Data (BC)[8] – for all construction and maintenance activities or constituent elements.

Table S4. Productivity and Costs for Construction and Maintenance Activities

Activity or Constituent Element	RSMeans Reference
Sewer trench excavation	HC: Excavating, trench (p. 220)
Riprap	SWL: Riprap and rock lining (p. 332)
Basin grading	SWL: Finish grading (p. 284)
Swales grading	SWL: Finish grading (p. 284)
Herbicide	HC: Fertilizer (p. 295)
Mowing bioswale	SWL: Mowing (p. 360)
Seeding and fertilizing	SWL: Mechanical seeding (p. 393)
Erosion blanket	SWL: Rolled erosion control mats and blankets (p. 325)
Excavation	HC: Excavating, bulk bank measure (p. 228)
Underdrain trench excavation	BC: Excavate drainage trench (p. 615)
Backfilling with sand	HC: Excavating, trench (p. 221) and SWL: Borrow (p. 280)
Vibrating plate compacting	HC: Compaction (p. 259)
Geotextile fabric	SWL: Geotextile soil stabilization (p. 327)
Topsoil placement	SWL: Topsoil placement and grading (p. 393)
Curb and gutter	HC: Cast-in-place concrete curbs and gutters (p. 307)
Underdrain headwall placement	HC: Precast concrete channel slabs (p. 81)
Bioswale plug plants	SWL: Ornamental grasses (p. 402)
Catch basin	HC: Catch basins (p. 363)
Manhole	HC: Storm drainage manholes, frames & covers (p. 365)
Manhole top	HC: Storm drainage manholes, frames & covers (p. 366)
Mowing grass	SWL: Mowing (p. 360)
Backfilling with excavated material	HC: Excavating, trench (p. 220)
HDPE pipe	HC: Piping, drainage & sewage, corrugated HDPE Type S (p. 359)
Headwalls	HC: Sewage/drainage collection, concrete pipe (p. 360); Headwalls (p. 502)
Storm sewer cleaning	HC: TV inspection of sewer pipelines (p. 337)
Reinforced concrete pipe	HC: Sewage/drainage collection, concrete pipe (p. 361)
Landfilling tipping fees	HC: Selective demolition, dump charges (p. 42)

S3.7 NONROADS Equipment Emissions Calculations

The US-EI process *Diesel, burned in building machine/GLO US-EI U* was modified using the U.S. EPA's NONROADS model[9] to obtain equipment-specific impacts for the following equipment types:

Table S5. Equipment Choices in NONROADS Model[9]

Equipment Type	Corresponding Type in NONROADS Model
Excavator	Diesel Excavators (HP=300)
Skid Steer Loader	Diesel Skid Steer Loaders (HP=100)
Wheel Loader	Diesel Rubber Tire Loaders (HP=175)
Hydroseed Sprayer	Diesel Sprayers (HP=100)
Grader	Diesel Graders (HP=175)
Compactor	Diesel Plate Compactors (HP=16)
Slipform Paver	Diesel Pavers (HP=100)
Concrete Mixer	Diesel Cement & Mortar Mixers (HP=100)
Herbicide Sprayer	Diesel Sprayers (HP=100)
Mower	Diesel Front Mowers (Commercial) (HP=100)
Vactor Truck	Diesel Other General Industrial Equipment (HP=100)
Trencher	Diesel Trenchers (HP=300)

The following emissions from the US-EI process were substituted with emissions from the NONROADS model*:*

> *Substituted Emissions:* Carbon dioxide, fossil; Carbon monoxide, fossil; Methane, fossil; Nitrogen oxides; Non-methane volatile organic compounds (NMVOC); Particulates < 2.5 µm; Particulates, > 2.5 µm, < 10 µm; Sulfur dioxide

NONROADS emissions were converted to emissions that were included within TRACI using U.S. EPA conversion factors.[10,11] The US-EI process *Diesel, at regional storage/US- US-EI U* was also used to account for the diesel itself. Energy demand for equipment operation was calculated assuming a conversion factor of 146.5 MJ per gallon of diesel consumed.

Table S6. Conversion Factors for NONROADS Emissions[10,11]

NONROADS Emission	Conversion Factor	TRACI Emission
Total hydrocarbons (THC) - exhaust	0.016 0.984 * 1.053	Methane Non-methane volatile organic compounds (NMVOC)
Total hydrocarbons (THC) - crankcase	1.053	Non-methane volatile organic compounds (NMVOC)
Carbon monoxide (CO)	1	Carbon monoxide
Nitrogen oxides (NO_x)	1	Nitrogen oxides
Carbon dioxide (CO_2)	1	Carbon dioxide
Sulfur dioxide (SO_2)	1	Sulfur dioxide
Particulate matter (PM) - exhaust	0.97 0.03	Particulates < 2.5 µm Particulates > 2.5 µm, < 10 µm

S3.8 BTEX Calculations for Removed BOD

The characterization factor for converting degraded biochemical oxygen demand (BOD) to fugitive CO_2 emissions was calculated by averaging the ratio of kg CO_2 to kg BOD for benzene, toluene, ethylbenzene, and xylene (BTEX):

Benzene:

$$C_6H_6 + 7.5O_2 \rightarrow 6CO_2 + 3H_2O$$

$$\frac{1 \text{ mole } O_2}{32 \times 10^{-3} \text{ kg } O_2} \times \frac{6 \text{ mole } CO_2}{7.5 \text{ mole } O_2} \times \frac{44 \times 10^{-3} \text{ kg } CO_2}{1 \text{ mole } CO_2} = 1.10 \frac{\text{kg } CO_2}{\text{kg BOD}}$$

Toluene:

$$C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_2O$$

$$\frac{1 \text{ mole } O_2}{32 \times 10^{-3} \text{ kg } O_2} \times \frac{7 \text{ mole } CO_2}{9 \text{ mole } O_2} \times \frac{44 \times 10^{-3} \text{ kg } CO_2}{1 \text{ mole } CO_2} = 1.07 \frac{\text{kg } CO_2}{\text{kg BOD}}$$

Ethylbenzene:

$$C_6H_5CH_2CH_3 + 10.5O_2 \rightarrow 8CO_2 + 5H_2O$$

$$\frac{1 \text{ mole } O_2}{32 \times 10^{-3} \text{ kg } O_2} \times \frac{8 \text{ mole } CO_2}{10.5 \text{ mole } O_2} \times \frac{44 \times 10^{-3} \text{ kg } CO_2}{1 \text{ mole } CO_2} = 1.05 \frac{\text{kg } CO_2}{\text{kg BOD}}$$

Xylene:

$$C_8H_{10} + 10.5O_2 \rightarrow 8CO_2 + 5H_2O$$

$$\frac{1 \text{ mole } O_2}{32 \times 10^{-3} \text{ kg } O_2} \times \frac{8 \text{ mole } CO_2}{10.5 \text{ mole } O_2} \times \frac{44 \times 10^{-3} \text{ kg } CO_2}{1 \text{ mole } CO_2} = 1.05 \frac{\text{kg } CO_2}{\text{kg BOD}}$$

Average: $1.07 \frac{\text{kg } CO_2}{\text{kg BOD}}$

S4. Uncertainty and Sensitivity Analysis

S4.1 Uncertainty Ranges

Table S7 provides a list of the parameters included in the uncertainty analysis along with their type of probability distribution (triangular, empirical, or uniform), values, and citations for the sources of information.

Table S7. Probability Distributions for Uncertainty Analysis

	Parameter	Units	Distribution	Values	Citation
Use Phase	Imperviousness coefficient for road	N/A	Triangular	0.7, 0.9, 1.0	[12]
	Removal efficacy of swales and basins	%	Triangular	see S3.3	[13]
Transportation	Transportation distance	miles	Triangular	2, 10, 20	a
	Weight of equipment	ton	Triangular	varies by type	a,b
Life Cycle Costing	Interest rate	%	Triangular	3, 6, 8	a
	Cost of construction and maintenance activities	$	Triangular	see S3.6	[6–8],b
Concrete Mix Design	Amount of cement per cubic meter of concrete	$kg \cdot m^{-3}$	Triangular	335.2, 376.7, 418.3	[5]
	Percent fly ash replacement	%	Triangular	20, 25, 30	[5]
Maintenance	Seeding, fertilizing, grading/compacting, pipe cleaning	years	Uniform	10-25	[4]
Component Specific Parameters	Width of area around basin to be seeded	ft	Uniform	0-5	a
	Percent area of basins and swales to be reseeded	%	Uniform	0-100	a
	Fertilizer application rate for swales	$kg \cdot ha^{-1}$	Triangular	250, 300, 350	[5]
	Herbicide application rate for swales	$kg \cdot ha^{-1}$	Triangular	2, 3.5, 5	a
	Percent of swales to be sprayed with herbicide	%	Uniform	0-100	a
	Volume of concrete in one manhole	yd^3	Triangular	1.69, 1.88, 2.07	[14],b
	Volume of rebar in one manhole	ft^3	Triangular	0.029, 0.033, 0.036	[14],b
	Volume of concrete in one catch basin	yd^3	Triangular	2.25, 2.5, 2.75	[14],b
	Mass of rebar in one catch basin	lb	Triangular	189, 210, 231	[14],b
	Volume of iron in one grate	yd^3	Triangular	0.106, 0.118, 0.130	[14],b

	Volume of concrete in one foot of curb	yd^3	Triangular	0.0032, 0.0035, 0.0039	[15],[b]
	Volume of concrete in one foot of gutter	yd^3	Triangular	0.032, 0.036, 0.040	[15],[b]
	Mass of rebar in one foot of curb	kg	Triangular	0.55, 0.61, 0.67	[15],[b]
	Mass of rebar in one foot of gutter	kg	Triangular	0.55, 0.61, 0.67	[15],[b]

Uniform distribution characterized as: minimum-maximum.
Triangular distribution characterized as: minimum, most probable, maximum.
[a] Assumed value.
[b] Minimum and maximum values calculated as plus/minus 10% of expected value.

S4.2 Initial Concentrations of Pollutants

Figure S3 provides box plots for National Stormwater Quality Database (NSQD) data for initial concentrations (measured in mg/L) or ratios of initial concentrations of pollutants after outliers were removed.[16] Outliers were identified following an approach modified from Devore;[17] if the distance between a data point and its closest limit (25th or 75th percentile) was greater than 5 times the spread (the distance between the 25th and 75th percentiles), it was identified as an outlier and removed from the dataset. Additionally, erroneous entries for Dulaney Valley Road and Pindell School Road in Maryland were removed from the dataset.[18] The remaining data were used in the uncertainty analysis as empirical distributions. In order to account for the correlations among concentration of metals (i.e., higher concentrations of zinc may indicate a higher concentration of copper), uncertainty analysis was conducted first for the concentration of zinc and then for the ratios of the concentration of each other metal to the concentration of zinc. These ratios were then used to calculate the concentration of each other metal.

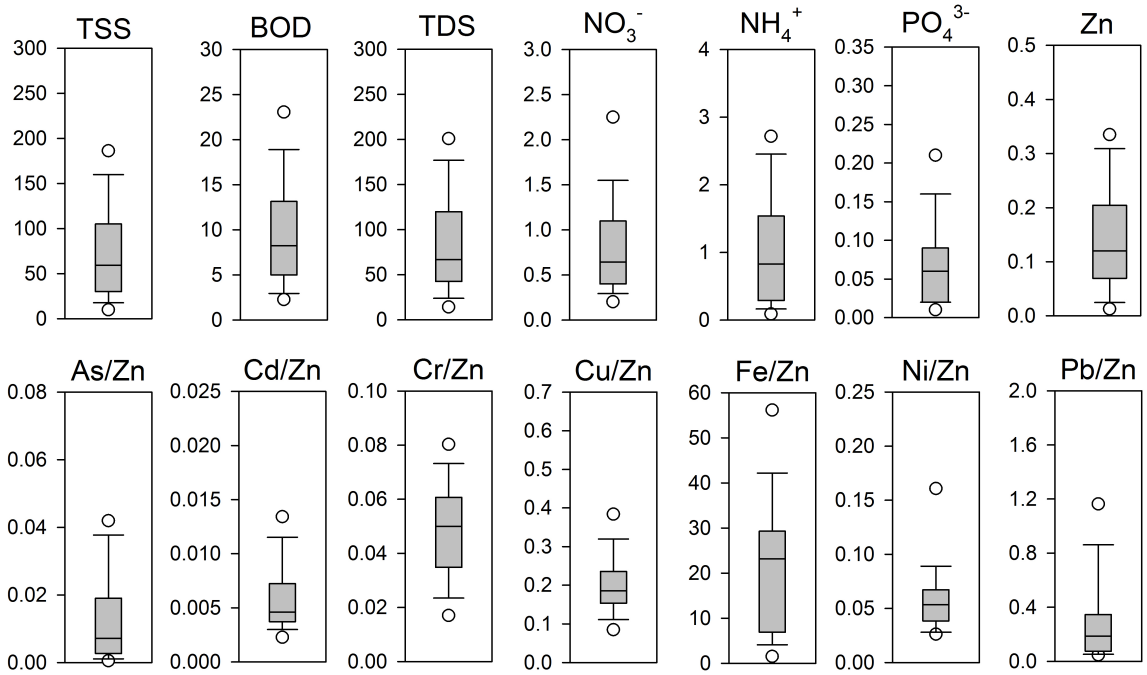

Figure S3. Box Plots for Empirical Distributions of Initial Concentrations (measured in mg/L) or Ratios of Initial Concentrations of Pollutants (derived from data in [16]).

S4.3 Removal Efficacy for Grass Swales, Bioswales, and Basins

Using the National Pollutant Removal Performance Database,[13] grass swales were considered to be open channels, bioswales were considered to be bioretention, and basins were considered to be dry ponds or wet ponds depending on whether or not they retained water. The removal efficacies for grass swales, bioswales, and basins (both dry and wet) were included in the uncertainty analysis according to probability distributions derived from quartile data provided by the National Pollutant Removal Performance Database.[13] Probability distributions were characterized by:

- *Minimum* = minimum value (negative values replaced by zero)
- *Most Probable* = average of endpoint values for the section of the cumulative distribution plot that had the steepest slope (excluding the first section); in cases where the slopes did not significantly vary from each other (less than 30% variation), a uniform distribution was used instead of a triangular distribution (probable value not applicable)
- *Maximum* = maximum value

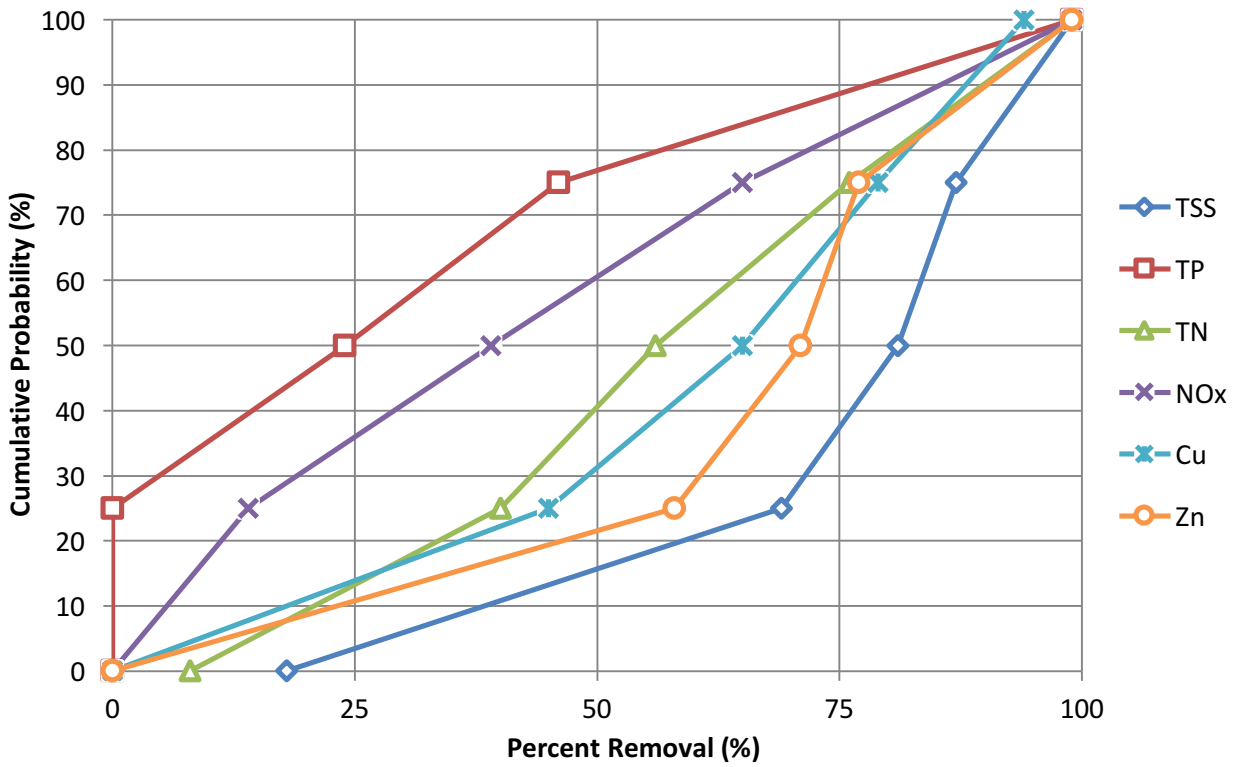

Figure S4. Cumulative Probability for Removal Efficacy of Grass Swales (Open Channels, derived from data in [13])

Table S8. Distributions for Grass Swale Removal Efficacies

	TSS	TP	TN	NOx	Cu	Zn
Distribution	Triangular	Triangular	Triangular	Triangular	Triangular	Triangular
Min	18	0	8	0	0	0
Probable	84	35	48	26.5	72	74
Max	99	99	99	99	94	99

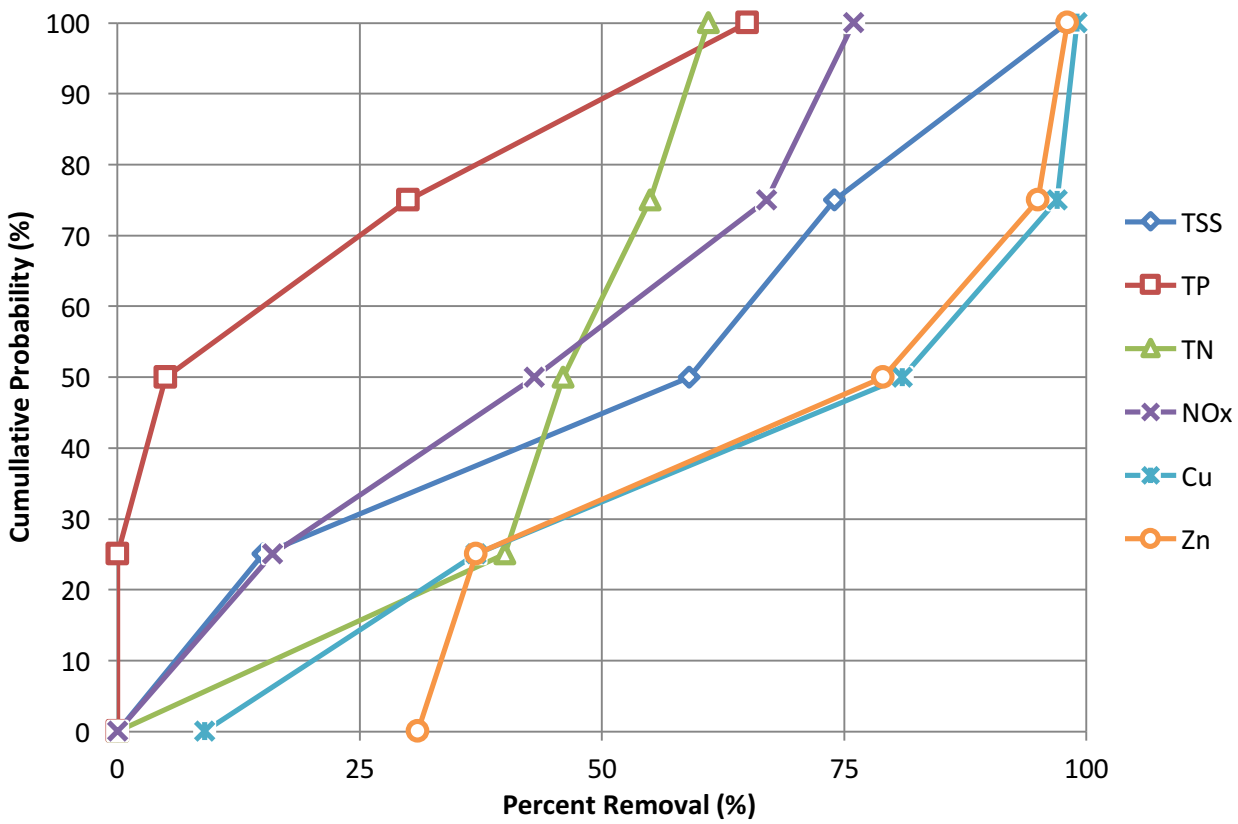

Figure S5. Cumulative Probability for Removal Efficacy of Bioswales (Bioretention, derived from data in [13])

Table S9. Distributions for Bioswale Removal Efficacies

	TSS	TP	TN	NOx	Cu	Zn
Distribution	Triangular	Triangular	Triangular	Triangular	Triangular	Triangular
Min	0	0	0	0	9	31
Probable	66.5	17.5	46	71.5	98	96.5
Max	98	65	61	76	99	98

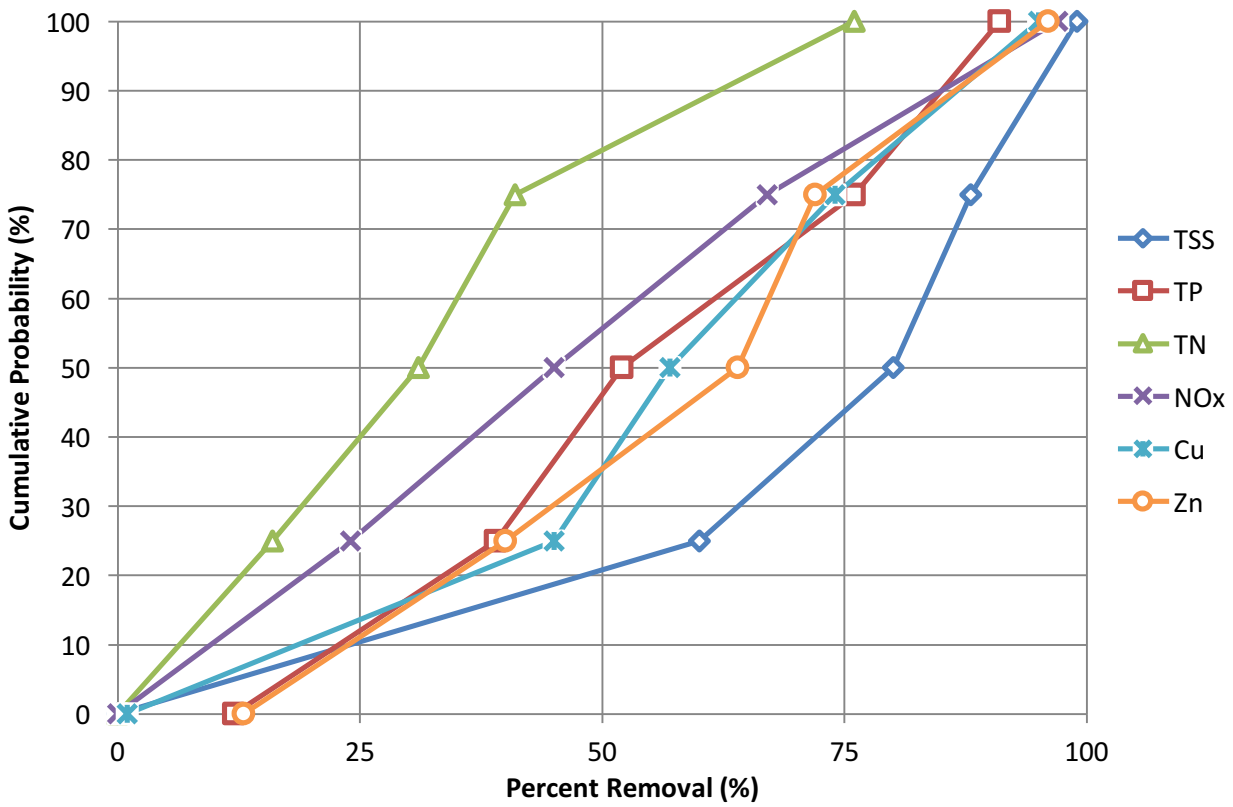

Figure S6. Cumulative Probability for Removal Efficacy of Retention/Wet Basins (Wet Basin, derived from data in [13])

Table S10. Distributions for Retention/Wet Basin Removal Efficacies

	TSS	TP	TN	NOx	Cu	Zn
Distribution	Triangular	Triangular	Triangular	Uniform	Triangular	Triangular
Min	0	12	0	0	1	13
Probable	84	45.5	36	N/A	51	68
Max	99	91	76	97	95	96

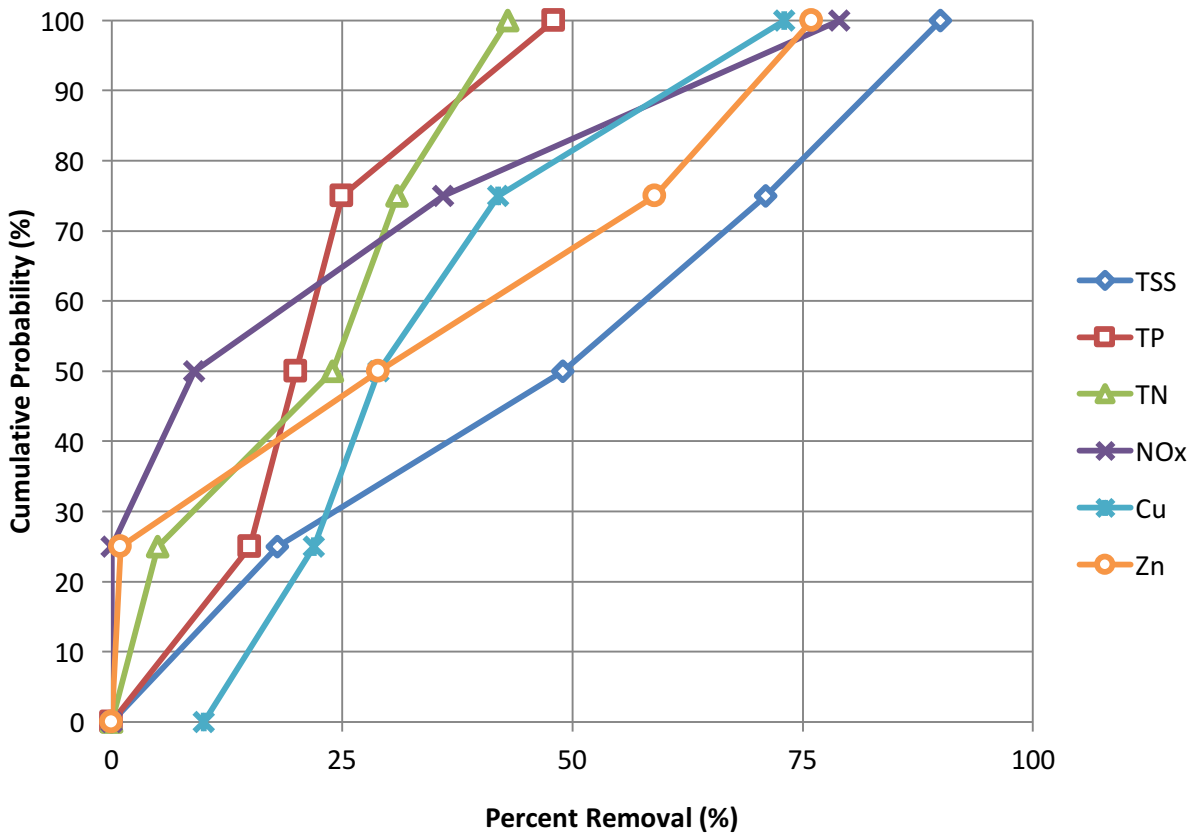

Figure S7. Cumulative Probability for Removal Efficacy of Detention/Dry Basins (Dry Basin, derived from data in [13])

Table S11. Distributions for Detention/Dry Basin Removal Efficacies

	TSS	TP	TN	NOx	Cu	Zn
Distribution	Uniform	Triangular	Triangular	Triangular	Triangular	Triangular
Min	0	0	0	0	10	0
Probable	N/A	20	27.5	4.5	25.5	67.5
Max	90	48	43	79	73	76

S5. Additional Results

S5.1 Full Results for Life Cycle Phases

Table S12 through **Table S18** provide the full results for the percent contributions of each life cycle phase for each drainage component (summarized in **Figure 3** of the manuscript). Results are presented as median percent contributions with the 10th and 90th percentile results provided in parenthesis.

Table S12. Full Results for Life Cycle Phase Contributions – Basin

	Con Mat	Con Equip	Con Trans	Main Mat	Main Equip	Main Trans	Use	End of Life
Ozone Depletion	3.9 (3.8 ,4.1)	94.3 (93.6, 95)	0 (0, 0)	0 (0, 0)	0.9 (0.2, 1.5)	0 (0, 0.1)	0 (0, 0)	0.8 (0.8, 0.9)
Climate Change	10.9 (10.3 ,11.5)	83.8 (82, 85.7)	0.6 (0.3, 0.9)	0 (0, 0)	0.8 (0.2, 1.4)	3.2 (1.8, 4.7)	2 (0.3, 5.8)	0.6 (0.6, 0.7)
Smog	11.8 (9.6 ,13.9)	75.7 (71.4, 80.2)	2 (1.2, 3)	0 (0, 0)	0.6 (0.1, 1.1)	7.7 (4.5, 11.1)	0 (0, 0)	2 (1.7, 2.4)
Acidification	12.7 (11.3 ,14.1)	78.5 (75.4, 81.6)	1.3 (0.7, 1.9)	0.1 (0, 0.2)	0.7 (0.1, 1.2)	5.1 (2.9, 7.4)	0 (0, 0)	1.6 (1.4, 1.8)
Eutrophication	27.7 (27.1 ,28.3)	68.6 (67.3, 69.8)	0.3 (0.2, 0.5)	0.2 (0, 0.6)	0.6 (0.1, 1.1)	1.3 (0.7, 2)	-616.7 (-1175.4, -273.4)	1.2 (1.2, 1.3)
Carcinogenics	96.9 (96.8 ,97)	1.8 (1.8, 1.8)	0 (0, 0.1)	0 (0, 0.1)	0 (0, 0)	0.2 (0.1, 0.2)	-111.6 (-470.8, -5.1)	1.1 (1.1, 1.1)
Non-carcinogenics	64.6 (62.1 ,65.8)	29.6 (28.1, 30.6)	0.3 (0.2, 0.5)	1.7 (0.2, 5.9)	0.3 (0.1, 0.5)	1.4 (0.8, 2)	-358.4 (-1075.9, -62.7)	1.9 (1.8, 2)
Respiratory Effects	1.3 (1.2 ,1.5)	97.7 (96.9, 98.5)	0 (0, 0)	0 (0, 0)	0.8 (0.2, 1.5)	0.1 (0, 0.1)	0 (0, 0)	0.1 (0.1, 0.1)
Ecotoxicity	82.8 (81.8 ,83.7)	12.1 (11.9, 12.3)	0.4 (0.2, 0.6)	0.1 (0, 0.3)	0.1 (0, 0.2)	1.7 (1, 2.6)	-597.1 (-1710.6, -111.5)	2.7 (2.7, 2.8)
Fossil Fuel Depletion	3.4 (2.9 ,3.9)	91.7 (90, 93.5)	0.5 (0.3, 0.7)	0 (0, 0)	0.8 (0.2, 1.5)	2.7 (1.5, 4)	0 (0, 0)	0.8 (0.7, 0.9)
Cumulative Energy Demand	5.8 (5.2 ,6.3)	88.7 (86.8, 90.7)	0.6 (0.3, 0.9)	0 (0, 0)	0.8 (0.2, 1.4)	3.1 (1.8, 4.6)	0 (0, 0)	0.9 (0.9, 1)

Table S13. Full Results for Life Cycle Phase Contributions – Bioswale

	Con Mat	Con Equip	Con Trans	Main Mat	Main Equip	Main Trans	Use	End of Life
Ozone Depletion	39.9 (37.1 ,43.1)	37.7 (35.1, 40.8)	0.3 (0.1, 0.4)	5.3 (2.2, 8.4)	15.7 (12.3, 19)	0.9 (0.5, 1.4)	0 (0, 0)	0 (0, 0)
Climate Change	47.9 (40.9 ,56.5)	11.3 (9.6, 13.3)	7.4 (4.8, 9.5)	1.7 (0.7, 3)	4.7 (3.4, 6.2)	26.7 (17.4, 34.5)	0.8 (0.1, 2.6)	0 (0, 0)
Smog	57.1 (48.1 ,68.4)	4.5 (3.8, 5.4)	11.4 (7.5, 14.4)	0.5 (0.2, 0.9)	1.5 (1.1, 2.1)	24.9 (16.3, 31.9)	0 (0, 0)	0 (0, 0)
Acidification	57.2 (49.2 ,66.8)	6.1 (5.3, 7.1)	9.8 (6.3, 12.6)	1.7 (0.7, 3.1)	2.3 (1.7, 3.1)	22.5 (14.5, 29.3)	0 (0, 0)	0 (0, 0)
Eutrophication	63.7 (49.7 ,79.1)	3.3 (2.5, 4.1)	1.7 (0.9, 2.6)	26.3 (8.5, 42.6)	1.3 (1, 1.6)	3.7 (2, 5.8)	-77.7 (-148.7, -32)	0 (0, 0)
Carcinogenics	88.4 (83.3 ,92.7)	0.4 (0.4, 0.4)	0.8 (0.5, 1.3)	7.8 (3.7, 12.9)	0.2 (0.1, 0.2)	2.2 (1.2, 3.3)	-187.3 (-538.4, -32.5)	0 (0, 0)
Non-carcinogenics	70.8 (61 ,79.8)	2.4 (2.1, 2.7)	2.7 (1.5, 4)	16.3 (6.4, 27.2)	1 (0.8, 1.2)	6.8 (3.8, 10)	-144.7 (-392.8, -29.9)	0 (0, 0)
Respiratory Effects	14.7 (13.7 ,15.9)	57.3 (53.2, 61.8)	1 (0.5, 1.4)	0.9 (0.4, 1.5)	23.6 (18, 28.6)	2.5 (1.4, 3.7)	0 (0, 0)	0 (0, 0)
Ecotoxicity	79.0 (73.1 ,85)	0.8 (0.8, 0.9)	2.9 (1.7, 4.2)	8.9 (4.1, 14.8)	0.4 (0.3, 0.4)	7.5 (4.3, 10.8)	-204.8 (-530, -43.7)	0 (0, 0)
Fossil Fuel Depletion	46.2 (39.8 ,54.2)	13.9 (11.9, 16.3)	7.1 (4.6, 9.1)	1.4 (0.6, 2.4)	5.7 (4.2, 7.6)	25.4 (16.4, 33)	0 (0, 0)	0 (0, 0)
Cumulative Energy Demand	49.1 (42.1 ,57.6)	11.6 (10, 13.6)	7.1 (4.6, 9.1)	1.7 (0.7, 2.8)	4.8 (3.5, 6.4)	25.5 (16.5, 33.2)	0 (0, 0)	0 (0, 0)

Table S14. Full Results for Life Cycle Phase Contributions – Box Culvert

	Con Mat	Con Equip	Con Trans	Main Mat	Main Equip	Main Trans	Use	End of Life
Ozone Depletion	71.0 (70.4 ,71.5)	15.3 (15, 15.6)	0 (0, 0.1)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	13.7 (13.4, 13.9)
Climate Change	87.3 (86 ,88.7)	6.2 (6, 6.4)	1.6 (0.9, 2.4)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	4.8 (4.1, 5.4)
Smog	72.5 (67.9 ,77.1)	5.6 (5.2, 5.9)	6.8 (4, 9.5)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	15.2 (13.1, 17.3)
Acidification	81.2 (78.4 ,83.9)	5 (4.9, 5.2)	3.7 (2.1, 5.3)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	10.1 (8.8, 11.4)
Eutrophication	94.4 (94.1 ,94.8)	1.9 (1.8, 1.9)	0.4 (0.2, 0.6)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	3.3 (3.1, 3.5)
Carcinogenics	99.3 (99.3 ,99.3)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0.7 (0.7, 0.7)
Non-carcinogenics	97.3 (97.2 ,97.4)	0.3 (0.3, 0.4)	0.2 (0.1, 0.2)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	2.2 (2.1, 2.3)
Respiratory Effects	59.5 (59.3 ,59.8)	37 (36.7, 37.3)	0.2 (0.1, 0.4)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	3.2 (3.1, 3.3)
Ecotoxicity	97.4 (97.2 ,97.5)	0.1 (0.1, 0.1)	0.1 (0.1, 0.2)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	2.4 (2.3, 2.4)
Fossil Fuel Depletion	62.6 (60.4 ,64.7)	18.3 (17.6, 18.9)	3.7 (2.1, 5.3)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	15.4 (14.3, 16.5)
Cumulative Energy Demand	74.7 (72.8 ,76.5)	11 (10.7, 11.3)	2.7 (1.5, 3.9)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	11.6 (10.7, 12.5)

Table S15. Full Results for Life Cycle Phase Contributions – Pipe Culvert

	Con Mat	Con Equip	Con Trans	Main Mat	Main Equip	Main Trans	Use	End of Life
Ozone Depletion	30.2 (29.4 ,31)	61.4 (60.6, 62.1)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	8.4 (8.3, 8.5)
Climate Change	54.9 (53.3 ,56.3)	38.8 (37.7, 40)	1.7 (1, 2.6)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	4.6 (4, 5.2)
Smog	45.4 (42.6 ,48.3)	33.8 (31.7, 35.8)	6.7 (3.9, 9.4)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	14.2 (12.1, 16.1)
Acidification	50.2 (48.1 ,52.3)	34.9 (33.5, 36.3)	4.2 (2.4, 6)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	10.8 (9.4, 12.1)
Eutrophication	68.8 (67.7 ,69.7)	23.8 (23.2, 24.5)	0.9 (0.5, 1.3)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	6.5 (6.2, 6.9)
Carcinogenics	94.1 (94 ,94.2)	0.6 (0.6, 0.6)	0.1 (0, 0.1)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	5.2 (5.1, 5.4)
Non-carcinogenics	86.8 (86.3 ,87.3)	6.4 (6.2, 6.6)	0.5 (0.3, 0.7)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	6.2 (6, 6.5)
Respiratory Effects	7.3 (7.1 ,7.6)	91.4 (91.1, 91.6)	0.1 (0.1, 0.2)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	1.2 (1.2, 1.3)
Ecotoxicity	89.7 (89.2 ,90.2)	2.2 (2.1, 2.3)	0.5 (0.3, 0.8)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	7.6 (7.3, 7.9)
Fossil Fuel Depletion	23.6 (22.7 ,24.5)	65.6 (64.2, 66.9)	2.2 (1.3, 3.3)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	8.5 (7.8, 9.2)
Cumulative Energy Demand	33.2 (32.1 ,34.4)	55.5 (54.2, 56.7)	2.3 (1.3, 3.3)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	9 (8.3, 9.7)

Table S16. Full Results for Life Cycle Phase Contributions – Grass Swale

	Con Mat	Con Equip	Con Trans	Main Mat	Main Equip	Main Trans	Use	End of Life
Ozone Depletion	2.1 (1.8 ,2.4)	36.3 (31.3, 42.2)	0 (0, 0)	10.2 (4.5, 15.1)	50.8 (48.7, 53.6)	0.5 (0.3, 0.7)	0 (0, 0)	0 (0, 0)
Climate Change	3.5 (2.9 ,4.3)	24 (20.1, 28.6)	0.8 (0.5, 1.1)	7.6 (3.5, 12.8)	34 (29, 39.9)	29.9 (18.6, 39.1)	2.6 (0.5, 8.5)	0 (0, 0)
Smog	2.3 (1.8 ,3)	15.9 (12.5, 21.3)	1.4 (1, 1.7)	4.5 (2, 8.5)	22.3 (17.4, 30.1)	53.2 (38.2, 63)	0 (0, 0)	0 (0, 0)
Acidification	8.2 (6.6 ,10.4)	16.8 (13.5, 21.3)	1 (0.6, 1.2)	14 (5.8, 24.6)	23.9 (20, 29)	35.5 (22.3, 46)	0 (0, 0)	0 (0, 0)
Eutrophication	37.0 (23.4 ,61.9)	3.2 (2, 5.4)	0.1 (0, 0.1)	53 (22, 70.2)	4.5 (3.2, 7)	2 (0.9, 3.7)	-143 (-342.9, -59.5)	0 (0, 0)
Carcinogenics	28.5 (18.7 ,45.3)	1.5 (1, 2.4)	0.1 (0.1, 0.2)	63.3 (42.4, 75.8)	2.1 (1.6, 3)	4.3 (2.1, 7.6)	-602.1 (-2593.7, -39.4)	0 (0, 0)
Non-carcinogenics	37.2 (23.3 ,63.2)	1.8 (1.1, 3.1)	0.1 (0, 0.1)	55.2 (25.2, 72)	2.5 (1.8, 4)	2.8 (1.3, 5)	-108.7 (-375.8, -8.6)	0 (0, 0)
Respiratory Effects	0.8 (0.7 ,0.9)	41.5 (37, 46.2)	0 (0, 0)	1.6 (0.7, 2.7)	55.3 (51, 59.1)	0.9 (0.5, 1.4)	0 (0, 0)	0 (0, 0)
Ecotoxicity	26.3 (17.9 ,39.9)	2.5 (1.7, 3.8)	0.3 (0.2, 0.5)	55.5 (34.3, 70.2)	3.4 (2.7, 4.7)	11.6 (5.8, 19.1)	-597.6 (-1897.7, -71.8)	0 (0, 0)
Fossil Fuel Depletion	1.3 (1.1 ,1.6)	27.4 (23.3, 32.3)	0.7 (0.4, 0.9)	5.6 (2.5, 8.7)	38.6 (33.4, 44.7)	26.2 (16.1, 34.8)	0 (0, 0)	0 (0, 0)
Cumulative Energy Demand	1.8 (1.5 ,2.2)	25.3 (21.2, 30.2)	0.8 (0.5, 1)	7.4 (3.4, 11.6)	35.5 (30.5, 41.5)	29.1 (18, 38)	0 (0, 0)	0 (0, 0)

Table S17. Full Results for Life Cycle Phase Contributions – Storm Sewer

	Con Mat	Con Equip	Con Trans	Main Mat	Main Equip	Main Trans	Use	End of Life
Ozone Depletion	30.8 (30 ,31.5)	61.5 (60.1, 62.4)	0 (0, 0.1)	0 (0, 0)	4.1 (2.7, 5.6)	0 (0, 0)	0 (0, 0)	3.8 (3.7, 3.9)
Climate Change	54.6 (53.2 ,55.8)	37.5 (36.6, 38.5)	2.8 (1.5, 4.1)	0 (0, 0)	3.1 (2.1, 4.4)	0 (0, 0)	0 (0, 0)	2 (1.7, 2.3)
Smog	58.3 (55.3 ,61.4)	23.5 (22.2, 24.7)	8 (4.6, 11.4)	0 (0, 0)	5.7 (3.8, 8.2)	0 (0, 0)	0 (0, 0)	4.4 (3.7, 5.1)
Acidification	63.0 (60.8 ,65.1)	24.4 (23.5, 25.3)	5 (2.8, 7.2)	0 (0, 0)	4.2 (2.8, 5.9)	0 (0, 0)	0 (0, 0)	3.4 (2.9, 3.8)
Eutrophication	88.4 (87.8 ,89)	9 (8.7, 9.4)	0.6 (0.3, 0.8)	0 (0, 0)	0.9 (0.6, 1.3)	0 (0, 0)	0 (0, 0)	1.1 (1, 1.2)
Carcinogenics	99.5 (99.5 ,99.5)	0.1 (0.1, 0.1)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0.4 (0.4, 0.4)
Non-carcinogenics	97.8 (97.6 ,97.9)	1.4 (1.3, 1.4)	0.2 (0.1, 0.3)	0 (0, 0)	0.1 (0.1, 0.1)	0 (0, 0)	0 (0, 0)	0.6 (0.6, 0.6)
Respiratory Effects	13.8 (13.4 ,14.2)	84.7 (84.2, 85.1)	0.2 (0.1, 0.2)	0 (0, 0)	0.9 (0.6, 1.2)	0 (0, 0)	0 (0, 0)	0.5 (0.5, 0.5)
Ecotoxicity	98.5 (98.4 ,98.7)	0.5 (0.5, 0.5)	0.2 (0.1, 0.3)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0.7 (0.7, 0.8)
Fossil Fuel Depletion	32.0 (31.1 ,32.7)	57.6 (56.1, 59)	3.3 (1.8, 4.8)	0 (0, 0)	3.8 (2.6, 5.3)	0 (0, 0)	0 (0, 0)	3.3 (3, 3.6)
Cumulative Energy Demand	43.0 (41.9 ,44)	47.2 (46.1, 48.4)	3.2 (1.8, 4.7)	0 (0, 0)	3.1 (2.1, 4.3)	0 (0, 0)	0 (0, 0)	3.4 (3.1, 3.7)

Table S18. Full Results for Life Cycle Phase Contributions – Pipe Underdrain

	Con Mat	Con Equip	Con Trans	Main Mat	Main Equip	Main Trans	Use	End of Life
Ozone Depletion	77.2 (77.1 ,77.2)	20.1 (20, 20.1)	0.1 (0, 0.1)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	2.7 (2.7, 2.7)
Climate Change	90.2 (89.4 ,90.9)	7.5 (7.4, 7.6)	1.6 (0.9, 2.4)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0.7 (0.6, 0.8)
Smog	76.2 (73.9 ,78.4)	16.4 (15.9, 16.9)	5.5 (3.1, 7.9)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	1.9 (1.6, 2.2)
Acidification	86.0 (84.6 ,87.2)	10 (9.8, 10.1)	2.8 (1.6, 4.2)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	1.2 (1, 1.4)
Eutrophication	96.7 (96.5 ,96.9)	2.5 (2.5, 2.5)	0.4 (0.2, 0.5)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0.4 (0.4, 0.5)
Carcinogenics	99.4 (99.4 ,99.5)	0.1 (0.1, 0.1)	0 (0, 0.1)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0.5 (0.5, 0.5)
Non-carcinogenics	98.0 (97.8 ,98.2)	0.8 (0.8, 0.8)	0.4 (0.2, 0.6)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0.8 (0.8, 0.8)
Respiratory Effects	89.0 (88.8 ,89.3)	9.4 (9.4, 9.5)	0.5 (0.3, 0.8)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	1 (1, 1.1)
Ecotoxicity	98.9 (98.8 ,99)	0.2 (0.2, 0.2)	0.3 (0.1, 0.4)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0.6 (0.6, 0.7)
Fossil Fuel Depletion	92.9 (92.4 ,93.5)	5.3 (5.3, 5.3)	1.1 (0.6, 1.6)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0.7 (0.6, 0.7)
Cumulative Energy Demand	94.2 (93.7 ,94.7)	4.1 (4.1, 4.1)	1 (0.6, 1.5)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)	0.7 (0.6, 0.7)

S5.2 Sensitivity Analysis Results

Sensitivity analysis results (as Spearman's rank correlation coefficients) are provided for the 3 design parameters that had the largest absolute value of correlation coefficient. Results are provided for cost (to represent economic impacts; **Figure S8**), climate change (to represent global environmental impacts; **Figure S9**), and eutrophication (to represent local environmental impacts; **Figure S10**).

In general, across all drainage components, climate change, eutrophication, and total cost were most affected by design parameters that affect size, which include areas, lengths, widths, and diameters. Outside of dimensional parameters, the number of headwalls had large implications for culverts (Spearman's rank correlation: ρ = 0.29 to 0.49) due to the large quantity of concrete and steel required for headwall construction. When comparing conveyance element options, storm sewers were most affected by length (ρ = 0.59 to 0.85), diameter (ρ = 0.04 to 0.40), and catch basin spacing (ρ = -0.20 to -0.76), all of which affect the amount of concrete (for pipe), steel (for pipe), sand (for backfill), and cast iron (for catch basin grates) required. Grass swales were most affected by length and top width; however, an increasing length decreases eutrophication impacts (ρ = -0.19) because a longer length causes more runoff to enter the swale, which results in greater use phase offsets due to water quality benefits. For bioswales, increasing length increases eutrophication impacts (ρ = 0.15) due to a larger quantity of materials required (e.g., sand and topsoil) compared to grass swales; however, eutrophication impacts are less correlated with length than climate change (ρ = 0.70) or total cost (ρ = 0.75), reflecting the favorable impacts of length on water quality offsets provided by bioswales. Additionally for bioswales, all impacts increased with increasing bottom width (ρ = 0.24 to 0.56) due to additional material requirements.

Eutrophication results were also found to be sensitive to use phase data including initial concentrations (ρ = -0.12 to -0.43) as well as the removal efficacy of bioswales (ρ = -0.12 to -0.29), grass swales (ρ = -0.15 to -0.25), and basins (ρ = -0.05 to -0.20). In addition to specific design parameters, designers could consider alternative materials to replace concrete (the most common material used) or leverage supplementary cementitious materials for partial replacement of clinker in cement or cement in concrete.[19,20]

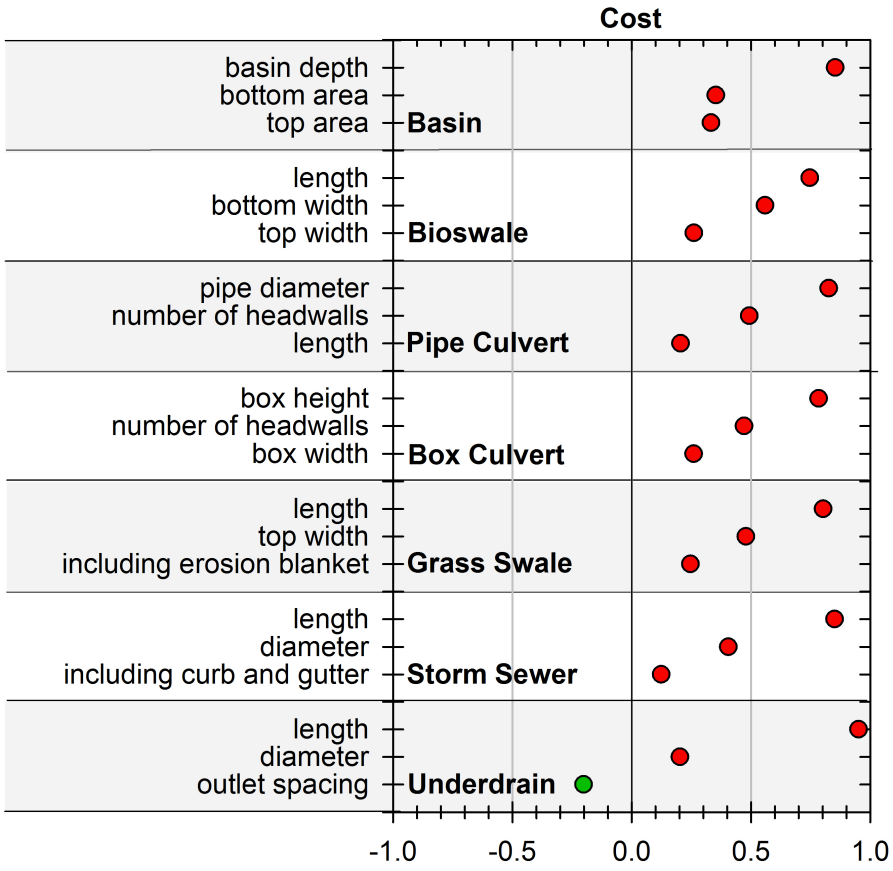

Figure S8. Cost Sensitivity Analysis Results for Top 3 Most Sensitive Design Parameters for Each Drainage Component

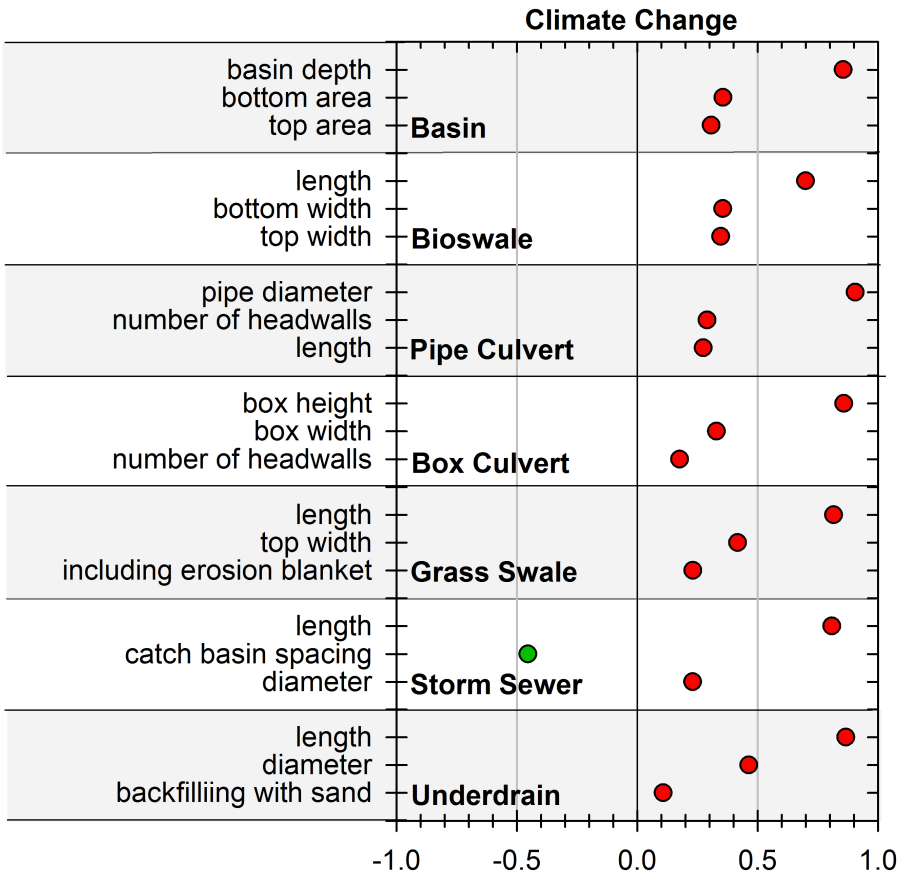

Figure S9. Climate Change Sensitivity Analysis Results for Top 3 Most Sensitive Design Parameters for Each Drainage Component

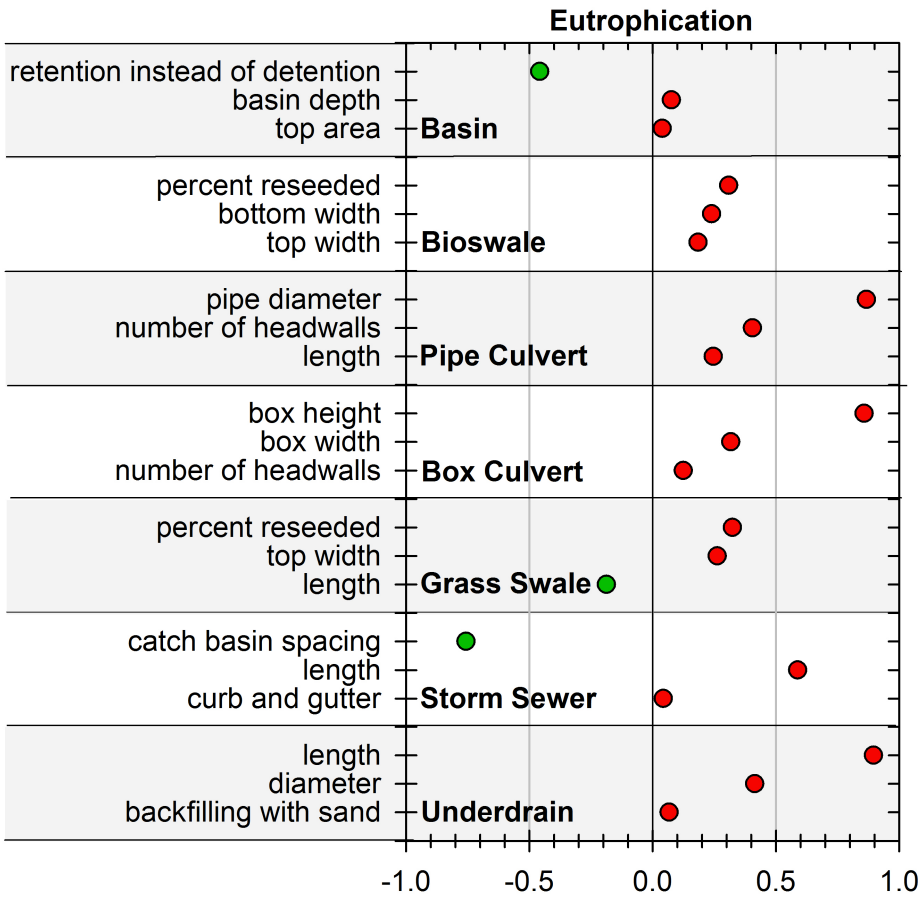

Figure S10. Eutrophication Sensitivity Analysis Results for Top 3 Most Sensitive Design Parameters for Each Drainage Component

S5.3 Cut-off Criteria Results

Table S19 through **Table S28** provide the top 5 contributors to climate change impacts for each of the 10 projects, along with their associated percent contributions to cost, mass, and energy.

Table S19. Cut-off Criteria Results for Project 1

Activity or Constituent Element	Climate Change (%)	Cost (%)	Mass (%)	Energy (%)
Reinforced concrete pipe	33.4	48.7	15.3	31.6
Sand backfill	16.6	12.0	73.2	18.5
Catch basin	16.4	5.2	3.5	13.6
Curb and gutter	10.0	7.1	6.9	7.5
Mowing grass	4.2	4.8	0.2	4.8

Table S20. Cut-off Criteria Results for Project 2

Activity or Constituent Element	Climate Change (%)	Cost (%)	Mass (%)	Energy (%)
Reinforced concrete pipe	35.9	45.1	15.6	30.8
Sand backfill	18.4	11.1	75.2	18.6
Curb and gutter	9.8	5.8	6.3	6.7
HDPE pipe	6.2	5.6	0.4	13.8
Excavation	4.4	8.7	0.2	4.7

Table S21. Cut-off Criteria Results for Project 3

Activity or Constituent Element	Climate Change (%)	Cost (%)	Mass (%)	Energy (%)
Herbicide	18.6	2.2	0.2	16.2
HDPE pipe	17.3	17.1	1.7	31.3
Mowing grass	16.3	14.0	0.7	13.9
Geotextile fabric	7.8	2.4	0.2	6.2
Sand backfill	7.6	4.8	42.7	6.2

Table S22. Cut-off Criteria Results for Project 4

Activity or Constituent Element	Climate Change (%)	Cost (%)	Mass (%)	Energy (%)
Box culvert	24.5	22.2	45.4	13.6
Mowing grass	14.2	11.3	1.7	14.6
Excavation	13.3	20.7	2.2	14.1
HDPE pipe	11.1	7.8	2.2	24.1
Herbicide	9.3	1.7	0.4	10.3

Table S23. Cut-off Criteria Results for Project 5

Activity or Constituent Element	Climate Change (%)	Cost (%)	Mass (%)	Energy (%)
Box culvert	48.8	44.2	72.4	32.0
Mowing grass	9.5	7.5	0.9	11.6
Excavation	9.0	13.9	1.1	11.2
Herbicide	6.3	1.1	0.2	8.2
HDPE pipe	6.3	4.3	0.9	16.0

Table S24. Cut-off Criteria Results for Project 6

Activity or Constituent Element	Climate Change (%)	Cost (%)	Mass (%)	Energy (%)
Box culvert	49.5	51.6	77.7	33.4
Mowing grass	11.5	5.6	0.6	14.0
Herbicide	11.0	0.9	0.2	13.7
Excavation	7.2	12.7	0.9	9.3
HDPE pipe	4.6	3.6	0.7	12.0

Table S25. Cut-off Criteria Results for Project 7

Activity or Constituent Element	Climate Change (%)	Cost (%)	Mass (%)	Energy (%)
Excavation	37.6	60.1	3.3	41.5
Reinforced concrete pipe	18.1	16.9	11.3	16.3
Catch basin	12.7	2.5	3.8	9.9
Sand backfill	9.5	4.5	61.6	9.7
Curb and gutter	7.0	3.3	7.2	4.9

Table S26. Cut-off Criteria Results for Project 8

Activity or Constituent Element	Climate Change (%)	Cost (%)	Mass (%)	Energy (%)
Reinforced concrete pipe	28.7	34.2	16.9	20.4
Topsoil	10.7	7.3	49.8	10.6
Herbicide	10.7	1.0	0.1	11.0
Sand backfill	8.0	3.8	28.7	7.8
HDPE pipe	7.9	5.8	0.5	17.1

Table S27. Cut-off Criteria Results for Project 9

Activity or Constituent Element	Climate Change (%)	Cost (%)	Mass (%)	Energy (%)
Catch basin	22.0	6.3	12.2	15.0
Mowing grass	12.3	14.3	1.5	12.0
HDPE pipe	11.9	11.0	2.2	24.4
Excavation	10.7	22.0	1.6	10.8
Herbicide	7.2	2.1	0.4	7.7

Table S28. Cut-off Criteria Results for Project 10

Activity or Constituent Element	Climate Change (%)	Cost (%)	Mass (%)	Energy (%)
Reinforced concrete pipe	41.6	41.2	36.8	30.3
HDPE pipe	15.1	10.1	1.5	31.4
Excavation	7.1	9.9	0.6	7.2
Geotextile fabric	6.8	1.4	0.2	6.3
Excavation	4.6	1.6	4.1	2.8

S5.4 Conveyance Element Comparison

Figure S11 provides the results for the analysis presented in Figure 5 of the manuscript using a roadway length of 100 ft, confirming the same trends discussed for a length of 1,000 ft (1,000 ft was used to generate Figure 5 in the manuscript). Impacts incurred from construction, maintenance, and end of life are above zero and offsets from the benefits of pollutant removal are below zero; both positive and negative impacts are normalized to the total impacts (before offsets) of grass swales. Conveyance elements were sized for a design flow of 1 cfs.

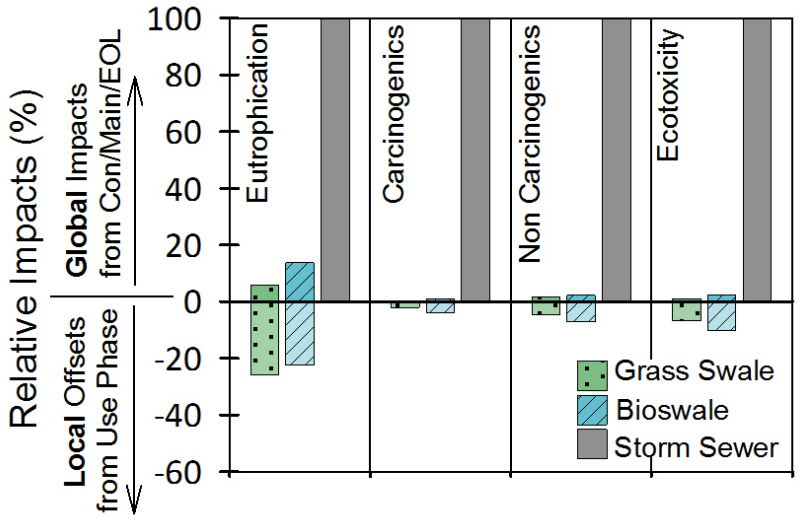

Figure S11. Comparison of Conveyance Elements for a Length of 100 ft

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