FEATURE

Impervious growth outpaces stormwater control measures in the Charles River watershed

MAX ROME, PhD, City of Boston, Massachusetts
JEREMY GREEN, Charles River Conservancy, Cambridge, Massachusetts
ALFREDO CON, Charles River Water Association, Boston, Massachusetts
SAM DOWNES, PE, Town of Brookline, Massachusetts

ABSTRACT | In the Charles River watershed, stormwater pollution is the major driver of degraded water quality. Decades of advocacy have resulted in strong local regulations that mandate a 50 percent reduction in phosphorus loading from municipal storm sewer systems by 2038. This study summarizes self-reported municipal progress and updated land use land cover mapping. The intent is to understand changes in baseline and current (2005–2021) phosphorus loading and to track progress toward nutrient reduction goals. We find that over 15 years, 14.5 mi² (37.5 km²) of new impervious surfaces were created on previously undeveloped, or pervious, sites. This is equivalent to nearly 5 percent of the total watershed area or a 21 percent growth in impervious area. Additional phosphorus loading from these new impervious surfaces is estimated to be greater than 17,000 lb (7,800 kg) per year. Stormwater control measures, as tracked by municipalities, have offset less than 20 percent of this new load. We aggregate data from municipal phosphorus control planning to present current trends and anticipated costs.

KEYWORDS | Stormwater, impervious cover, phosphorus, land use land cover, cost

Impervious cover as a percentage of watershed area (IC) is a key predictor of aquatic health. Increases in IC alter hydrology by increasing stormwater runoff, leading to higher levels of erosion and wet-weather pollution with IC levels above 10–15 percent being strongly associated with aquatic degradation (T. Schueler, 1995; T. R. Schueler et al., 2009). In the United States total impervious area more than doubled between 1985 and 2018 (Gong et al., 2020) and has increased in growing urban areas as well as in small towns with declining populations (Sahraei et al., 2025).

For urban waters, stormwater runoff is widely understood to be a key source of bacterial and nutrient pollution. Phosphorus from stormwater runoff is a driver of eutrophication for freshwater, fueling growth of invasive plants and harmful algal blooms. Because of the close relationship between impervious surfaces and stormwater pollution, IC is closely tracked by researchers and used by both regulators and municipalities to estimate nutrient loading, regulate stormwater pollution, and assess stormwater fees.

In Massachusetts, the 300 mi² (777 km²) Charles River watershed is among the most urbanized watersheds in New England and has a long history of impaired water quality. Decades of advocacy and regulatory action have resulted in improving water quality and declining phosphorus concentrations (Determan et al., 2021). These positive changes and progress likely reflect stricter effluent standards for wastewater treatment plants and reductions in combined sewage overflow (Wong et al., 2018). Today, while some stretches of the river meet water quality standards, others experience elevated bacterial concentrations during wet weather and regular summer cyanobacterial blooms (Rome et al., 2021).

To address remaining sources of pollution, municipalities within the Charles River watershed are subject to stringent nutrient reduction requirements under the Massachusetts Municipal Separate Storm Sewer System (MS4) permit. Municipalities

within the watershed must reduce phosphorus loading from regulated stormwater discharges by 50 percent by 2038, with interim milestones including a 25 percent reduction over the first 10-year permit cycle. To comply with these requirements, municipalities have developed phosphorus control plans (PCPs) that inventory best management practices (BMPs), identify implementation opportunities, and estimate costs and load reductions.

While these regulatory frameworks aim to drive measurable improvements in water quality, ongoing land development presents a challenge. Under current state regulations, new developments larger than 1 ac (0.4 ha) must implement BMPs to mitigate 60 percent of additional phosphorus loading, with no structural controls required for smaller projects. This results in potential net increases in loading associated with developments of all sizes. Understanding the magnitude of impervious surface growth and its relationship to implemented and planned BMPs is therefore critical for evaluating progress toward watershed-wide nutrient reduction goals.

This study aims to quantify changes in impervious cover and associated phosphorus loading in the Charles River watershed between 2005 and 2021 and to assess municipal progress toward phosphorus reduction targets under the MS4 permit. By integrating updated land use land cover (LULC) mapping with a systematic review of municipal PCPs, this analysis evaluates the balance between new phosphorus loading from development and load reductions achieved through structural and non-structural stormwater controls. The results provide insight into the effectiveness of current implementation strategies and highlight opportunities to improve regulatory and planning approaches for managing stormwater nutrient loads in highly developed watersheds.

METHODS

For this study, analysis was conducted in three phases:

1. Updated LULC data was created from the most recent available data for all municipalities with land within the Charles River watershed. This task was performed by the University of Vermont's Spatial Analysis Laboratory and overseen by the Charles River Watershed Association (CRWA) and a technical advisory committee. The committee included municipal staff, consulting engineers, EPA, and the Massachusetts Department of Environmental Protection.
2. Phosphorus loading from land use was calculated by merging the LULC with soils data and following the method specified in state stormwater regulations (MS4, attachment 3, appendix f).
3. A manual review of Phase I PCPs aggregated both quantitative and qualitative data.

Updated mapping of land use land cover

Seven land cover classes (e.g., tree canopy, water, bare-earth, buildings) were mapped using object-based image analysis techniques (OBIA) run on the best available remotely sensed and vector GIS datasets, including 2021 LiDAR data, 2021 orthoimagery, 2021 National Agriculture Imagery Program (NAIP) imagery, and municipal planometric data. OBIA works by grouping pixels into meaningful objects based on spectral and spatial properties while considering boundaries imposed by existing vector datasets.

Following the automated OBIA mapping, a detailed manual review of the dataset was carried out, and all observable errors were corrected. To account for impervious area not visible from aerial imagery, the seven-class land cover was converted to non-impervious and impervious features by adding two new classes (tree canopy over roads and tree canopy over buildings) and re-classifying the (now nine) features/classes. The resulting rasters (land cover and impervious layer) achieved a spatial resolution of 0.02 m² (0.22 ft²) per pixel.

Ten land use classes were mapped, including the nine land cover classes identified in the MS4 permit and water: agriculture, commercial, forest, high-density residential, highway, industrial, low-density residential, medium-density residential, and open land. This 10-class LULC was created based on data from the assessors database with manual data consolidation and wrangling up front, followed by a fully automated implementation using commercial geospatial object-based image analysis software and server tools. The technical advisory committee was consulted to ensure that the resulting land cover classes were consistent with decisions made during the 2005 mapping and the original calibration of phosphorus load export rates (PLERs) constrained in the 2016 MS4 permit.

Calculating current phosphorus loading and change in loading from land use

The impervious layer (binary classification) was combined with the 10 land cover classes and the 2021 Soils Soil Survey Geographic Database (SSURGO)-Certified Natural Resources Conservation Service layer from Massachusetts Bureau of Geographic Information to create a "master-raster" containing all data necessary to calculate PLERs for any given polygon (e.g., land use, pervious, imperviousness, and soil type). Current (2021) and baseline (2005) LULC characteristics were calculated for both the entirety of town boundaries and the area within the watershed without exclusions for Department of Conservation and Recreation, Department of Transportation, or other MS4 jurisdictions.

As part of their PCPs, many municipalities calculated their own updated phosphorus loads due to

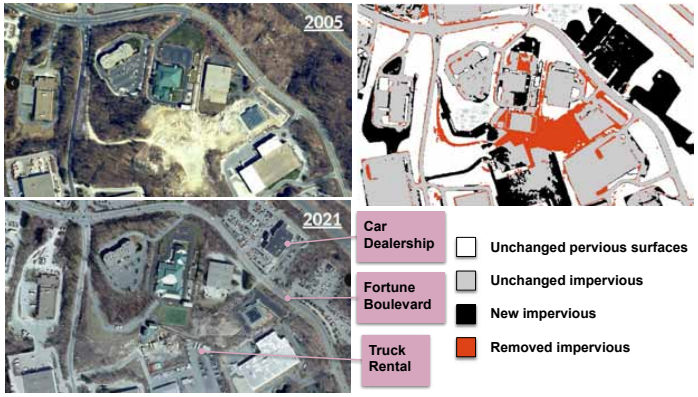


Figure 1. Changes in land cover as they appear in aerial imagery (left) and in mapped impervious-cover change (2005–2021)

changes in land use. Municipalities used various data sources and methods for this exercise; some of these re-calculations included detailed exclusions of non-town-owned properties that resulted in large P-load reductions; others used 2016 LULC data or appeared to include calculation errors. For this analysis, phosphorus load change 2005–2021 was calculated using an identical methodology for the 2005 LULC map and the updated 2021 LULC map. Across the watershed this methodology closely reproduced EPA's "whole community" baseline loading with a 1 percent relative percentage difference (RPD) and a standard deviation of 5 percent, across all communities. These discrepancies can mainly be attributed to the use of the updated soil data (SSURGO 2021) that was not available when the baseline loads were calculated.

Retrospective mapping of change in impervious cover

Key differences between classification of bare land in 2005 and subsequent LULC mappings make an equivalent comparison of phosphorus loading and change in impervious cover challenging. In 2005, areas of "man-made compacted soil or material such as mining or unpaved parking lots (no vegetation present)" were classified as impervious. In updated mapping, these areas are classified as bare ground. These discrepancies are illustrated in Figure 1.

New developments on previously undeveloped parcels show up clearly (e.g., car dealership and expanded parking areas), while development that occurs on land that had been cleared for construction in 2005 shows up as unchanged impervious (e.g., northern portions of truck rental lot). Removed impervious areas, therefore, rarely reflect elimination of pavement but, instead, most often represent conversion of bare earth to planted area, reclassification of bare ground, and more accurate mapping of pervious area around roadways and buildings.

For this reason, we define "unchanged impervious surfaces" as areas classified as impervious in both the 2005 and 2021 LULC. Unchanged impervious surfaces are tracked for each municipality and used as the baseline for understanding unambiguous conversion of previously undeveloped or pervious land. In this study, gross growth of impervious is defined as (New Impervious) / (New Impervious + Unchanged Impervious).

Review of Phase 1 PCPs

Thirty-five cities and towns have land within the Charles River watershed. Phase 1 PCPs were acquired for 25 of these municipalities. Of the 10 remaining municipalities, at the time of review, eight were still in development, with Boston covered under an individual permit. Foxborough has little area in the watershed and virtually no required load reduction.

An initial review was completed by personnel from CRWA and the University of New Hampshire Stormwater Center. Reviewers responded to 35 standardized prompts, which were refined during the first weeks of the review. These prompts included both qualitative metrics (e.g., how PCP addresses operations and maintenance) and quantitative metrics (e.g., number of structural BMPs). Following the initial review, the project team identified priorities for further analysis. These included performance and cost summaries of existing and proposed BMPs. For consistency, BMPs were sorted into categories, including existing or future implementation, structural or non-structural controls, and public or private development.

RESULTS

Changes in land use and changes in loading

Within the Charles River watershed, conversion of previously undeveloped land has resulted in 9,282 ac (3,756 ha) of new impervious area. New impervious surfaces account for 4.8 percent of total watershed land area and represent a 22 percent increase compared to unchanged impervious surfaces. This should be considered an underestimate of impervious surface growth as it fails to capture paving and building construction in areas previously classified as bare ground.

During the same period, some conversion of impervious to pervious surfaces has also occurred. True conversion (i.e., a parcel dominated by surface parking is replaced by a smaller building with more vegetated and open area) is difficult to estimate but most of the removed impervious surfaces (7,214 ac [2,919 ha]) appear to reflect conversion (80 percent) or reclassification (20 percent) of human-made compacted soils. In 2021, 67 percent (5,353 ac [2,166 ha]) of removed impervious surfaces are now classified as residential lawn and 13.4 percent (965 ac [390 ha]) are classified as forest. The remaining acres of removed impervious are now classified as commercial or industrial bare ground, which includes gravel or compacted bare-earth parking and storage areas as well as unpaved roadways. For consistency in understanding changes in phosphorus loading, these unchanged industrial and commercial areas are excluded from estimations of load reduction from removed impervious areas.

Loading from new impervious area, calculated using Sutherland equation conversion factors for directly connected impervious area, is 17,250 lb-P (7,824 kg-P) per year. The load reduction where impervious area was removed is 10,107 lb-P (4,584 kg-P) per year. This calculation of load reduction is an over-estimate as it assumes conversion of impervious to pervious surfaces, and at least 20 percent of conversions represent reclassification of unchanged surfaces.

BMP implementation strategy and cost

As of 2023, the 25 municipalities with completed PCPs tracked over 1,487 individual BMPs, mitigating approximately 2,400 lb-P (1,089 kg-P). Tracked load reductions include approximately one-third each from implementation of non-structural controls (e.g., street sweeping) (740 lb-P [336 kg-P]), structural controls on private land as required by regulation of development or redevelopment (820 lb-P [372 kg-P]), and projects on public property (778 lb-P [353 kg-P]).

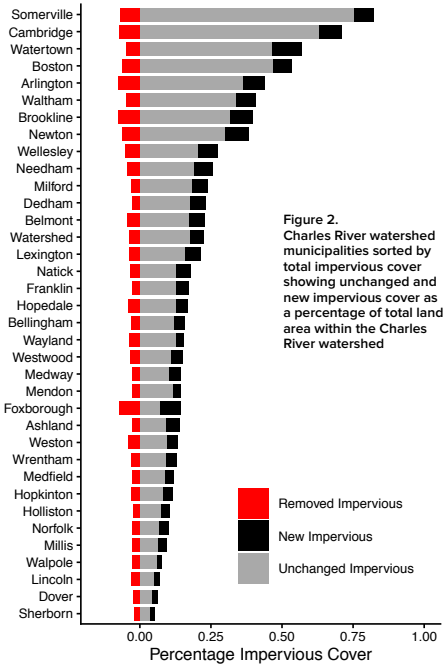


Figure 2. Charles River watershed municipalities sorted by total impervious cover showing unchanged and new impervious cover as a percentage of total land area within the Charles River watershed

BMPs on public property are roughly split between large projects removing >5 lb-P/year (>2.3 kg-P/year) amounting to 308 lb-P (140 kg-P) and smaller projects removing <5 lb-P/year (<2.3 kg-P/year) amounting to 470 lb-P (213 kg-P) (Figure 2).

In contrast to the pattern found for existing implementation, municipal BMP planning focuses mostly on public implementation (2,180 lb-P [991 kg-P]) with less than a 10 percent contribution coming from BMPs on private property or additional non-structural practices (Figure 3 *next page*). In their PCPs, communities provided detailed sizing and cost estimation for 140 planned projects. These projects ranged from small (<1 lb-P/year [<0.45 kg-P/year]) biofiltration or porous pavement projects to capture surface runoff to very large wet ponds or subsurface infiltration chamber projects (>20 lb-P/year [>9 kg-P/year]) for intercepting flows from drainage networks. The median phosphorus reduction for planned projects was 4.8 lb (2.2 kg) and the median implementation cost for all planned projects was $51,439.

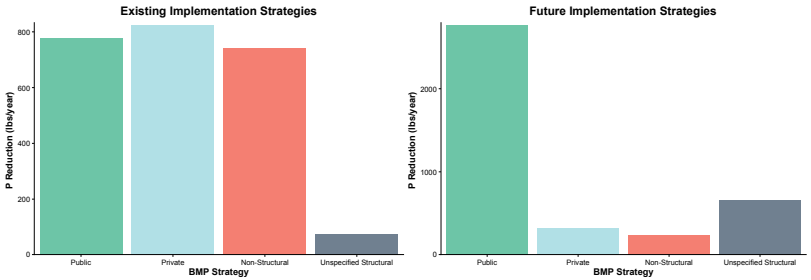


Figure 3. Aggregated phosphorus removal from public, private, and non-structural practices among existing and planned BMPs

On aggregate, larger planned projects (>5 lb/year [>2.3 kg/year]) are less expensive than smaller ones (<5 lb/year [<2.3 kg/year]), with a median cost per pound of phosphorus removal of $43,696 and $65,082 ($96,131 and $143,180 per kg), respectively (Figure 4). Among the reviewed projects, the most commonly proposed practice was subsurface infiltration chambers. A second common focus was on opportunities to rehabilitate or retrofit detention ponds for stormwater treatment. Fifty-seven such opportunities were identified across seven municipalities. These were among the most cost-effective projects identified in reviewed PCPs with median per unit costs of less than $30,000 per lb-P ($66,000 per kg-P) removal. Table 1 summarizes all structural and non-structural BMP costs.

Table 1. Summary of existing BMP and planned implementations and reported costs

BMP Type	Existing (lb-P/year)	Planned (lb-P/year)	Median cost ($/lb-P)
Non-structural	740	232	$7,413
Private*	822	329	$2,270
Structural < 5 lb	470	637	$65,082
Structural >5 lb	308	2121	$43,696

*Municipal cost associated with tracking and certification

Municipal progress

Watershed municipalities are at various stages of progress toward the MS4 10-year 25 percent load reduction target. We tracked existing structural and non-structural implementation and categorized planned projects as either "short-term implementation," projects in design with timelines and specified locations, or as "long-term planning," projects in conceptual design or general strategies for which municipalities included planning-level P-load reductions but did not include project specifics.

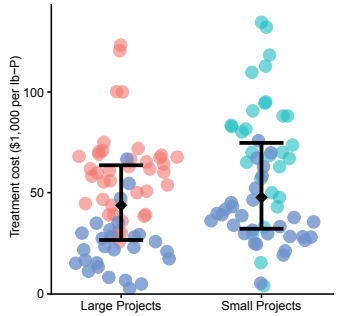


Figure 4. Distribution of treatment cost for large projects (>5 lb-P removal) and small projects (<5 lb-P removal). Rehabilitation of wet ponds and retrofits to detention basins are highlighted in blue. Outlying projects with very high unit costs are excluded from this figure for legibility.

Among the 25 municipalities with completed PCPs, approximately 2,400 lb-P (1,090 kg-P) are mitigated by existing BMPs with an additional 330 lb-P (140 kg-P) planned for short-term implementation. Approximately 3,700 lb (1,682 kg) of load reduction are identified from projects categorized as long-term planning. On the basis of existing implementation, seven towns are already halfway to their 10-year reduction targets, five have achieved between 25–50 percent of their 10-year targets, and 13 have achieved less than 25 percent of the 10-year target.

Municipalities with strong existing implementation generally also identified planning pathways to the 10-year reduction requirement while many municipalities lagging in implementation progress failed to identify clear pathways toward these goals. This assessment does not account for towns that reported large reductions in baseline loading (e.g., Millis & Norfolk reported 39 percent and 22 percent reductions in loading from land use) and may be skewed by towns still taking inventory and tracking existing BMPs.

DISCUSSION

Impervious growth and implications for phosphorus loading

This study indicates that impervious surface growth in the Charles River watershed between 2005 and 2021 has been substantial and has materially increased phosphorus loading. The addition of approximately 9,282 ac (3,757 ha) of new impervious surface is more than a 20 percent increase relative to unchanged impervious area and nearly 5 percent of total watershed land area. Phosphorus loading associated with this growth is estimated at over 17,000 lb-P (7,700 kg-P) per year, a magnitude that significantly exceeds reductions achieved through documented stormwater controls.

Although some impervious surfaces were removed or reclassified during the study, much of the apparent reduction reflects changes in classification of bare or compacted soils rather than true conversion to pervious cover. As a result, estimated load reductions from impervious removal likely overstate actual gains. These findings highlight a persistent challenge for urbanized watersheds: Incremental increases in impervious cover, when aggregated over time, can erode or exceed the benefits of retrofit-focused stormwater programs.

BMP implementation patterns and cost

Review of Phase 1 PCPs shows that phosphorus reductions have been achieved through a balanced mix of non-structural controls, private development requirements, and public projects. Non-structural practices, particularly enhanced street sweeping, account for a large share of reductions and represent low-cost, near-term opportunities for load reduction.

In contrast, planned future reductions are dominated by structural BMPs on public land, with limited reliance on additional non-structural measures or private-site controls. While this approach reflects practical constraints related to municipal authority and land ownership, it concentrates future reductions in a limited set of opportunities. Cost data indicate that larger projects generally achieve lower unit costs per pound of phosphorus removed than smaller installations, consistent with economies of scale. Notably, retrofits and rehabilitation of existing detention and wet ponds emerged as among the most cost-effective strategies across municipalities, suggesting that systematic inventories of existing stormwater infrastructure may yield additional opportunities.

Regulatory and planning implications

The imbalance between phosphorus loading from new impervious development and reductions achieved through BMP implementation raises concerns about the adequacy of current regulatory frameworks. Development and redevelopment of private parcels smaller than 1 ac (0.4 ha) often fall outside stormwater regulations, despite their cumulative contribution to watershed-scale loading. Addressing these diffuse sources is likely necessary to achieve long-term nutrient reduction goals.

In addition, variability in municipal approaches to estimating land use change and phosphorus loading complicates watershed-wide assessment of progress. Differences in data sources, assumptions, and exclusions limit comparability across PCPs. Greater consistency in load tracking methods and reporting would improve transparency and support more effective coordination among municipalities working toward shared watershed objectives.

CONCLUSIONS

Analysis of land use change in the Charles River watershed between 2005 and 2021 shows that growth in impervious cover has substantially increased phosphorus loading, outpacing reductions achieved through stormwater controls. Approximately 9,282 ac (3,757 ha) of new impervious surface were added during this period, contributing an estimated 17,250 lb-P (7,824 kg-P) per year of additional loading. Municipal best management practices documented in Phase 1 PCPs offset less than 20 percent of this new load, indicating that continued development is a barrier to achieving watershed-wide nutrient reduction targets.

Review of municipal implementation strategies indicates that early progress has relied on a mix of non-structural controls, private development requirements, and public projects, while future planning is dominated by structural BMPs on public land. Retrofits of detention and wet ponds and other large public projects offer cost-effective opportunities that can help to meet interim load reduction targets. However, these alone are unlikely to close the gap created by ongoing impervious growth. Achieving long-term phosphorus reduction goals will require expanded use of cost-effective retrofit strategies and improved regulatory mechanisms that better address incremental impervious development, especially on small private parcels. Critically, diverse approaches to land use classification and tracking changes in impervious area obscure real trends. A consistent regional approach is needed for assessing loading from current land use.

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ABOUT THE AUTHORS

- Max Rome is the director of green infrastructure for the City of Boston where he works to implement stormwater control measures that enhance the built environment and make it greener. He previously worked as CRWA's senior stormwater program manager after completing doctoral research on the restoration of urban water bodies.
- Alfredo Con is CRWA's stormwater associate performing technical analysis and community engagement for green stormwater infrastructure. Alfredo earned a Bachelor of Science in Earth and Atmospheric Sciences with a concentration in Climate Science from Cornell University.
- Jeremy Green is the land stewardship coordinator at the Charles River Conservancy and previously served as a watershed and stormwater co-op at CRWA. He is a graduate of Northeastern University and completed an undergraduate thesis on 'Wetlands' Effect on Nutrients in the Charles River watershed.
- Sam Downes is the deputy director of engineering for the Town of Brookline. Sam is a professional engineer and holds a Master of Science in Environmental Engineering from the University of Massachusetts Amherst where he worked as a research assistant examining biological treatment processes for wastewater systems.

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