Stronger Infrastructure Technical Report:

And Recommendations for Stormwater Strategies for Flood Mitigation

RESILIENT CAMBRIDGE

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Produced by Kleinfelder for the City of Cambridge

Stormwater Strategies for Flood Mitigation [Extreme Precipitation]

1.0 Overview

This technical memorandum reports the key findings and recommendations for a citywide technical analysis of flood mitigation solutions to address the increasing frequency and magnitude of precipitation-based flooding in Cambridge (the City). This analysis was undertaken to build upon previous climate change preparedness and resiliency (CCPR) assessments of flood impacts and mitigation alternatives in the two CCPR pilot areas (Alewife and The Port). In this citywide analysis, quantitative methods and GIS-based spatial mapping were used to assessestimated flood mitigation volumes of green and gray infrastructure stormwater strategies to address flooding and improve potential co-benefits. Co-benefits include metrics such as water quality improvements, urban heat island mitigation, air quality benefits, climate change mitigation, and ecosystem and habitat improvement.

Analyses in this memorandum was based on mitigating the increase in projected flood impacts between the present day 10% annual storm (or 10-year 24-hour storm event) and the 2070 10% annual (or 10-year) storm (the flood impacts determined from priormodeling efforts). For Resilient Cambridge, “present-day” describes the observed statistics for the time horizon 1971- 2000, and “2070” describes the best available projected statistics for the time horizon 2055-2084. Flood impacts were assessed in terms of subcatchments flood volumes.

For the purposes of this analysis, catchments are defined as large drainage areas within the City’s separate stormwater or combined sewer collection system that drain to the same outfall or drain over land to the same surface water). Within these larger catchments (or drainage areas), subcatchments are defined here as smaller drainage areas (approximately ~20 acres in total area) that were delineated using both topography and major piped infrastructure.

Green infrastructure strategies in this report constitute the natural ecosystem, such as increased tree canopy and other engineered solutions that use plants to mimic the soil ecosystem, such as bioretention basins, rain gardens, and green roofs. Gray infrastructure strategies for drainage systems to manage stormwater can include new pipes, pumps and/or underground storage tanks. Gray infrastructure projects mitigate flooding by holding water, such as large storage tanks, and/or by draining floodwaters away from areas as quickly as possible, such as larger pipes and pump stations.

This technical analysis applied a novel flood impact characterization approach that considered both localized flooding within a single subcatchment, as well as cumulative flooding at the catchment-scale. Based on this characterization and quantitative analysis, it was determined that the efficacy of flood mitigation strategies (using both gray and green infrastructure solutions) varied citywide between individual subcatchments, and could be mapped spatially as four (4) unique conditions (summarized below) that provide strategic spatial context to inform future project planning and design:

I. **Green infrastructure focus** - These catchments are likely to have significant flood reduction benefits from green infrastructure implementation.

II. **Mixed green/gray infrastructure** – These catchments are like to have significant flood reduction benefits from strategic implementation of both gray and green infrastructure on a case-by-case basis.

III. **Gray infrastructure focus** – These catchments have a high magnitude of modeled flood volumes such that gray infrastructure is necessary to manage stormwater flooding. For a subset of this group, future strategies to mitigate flooding may integrate a mix of gray and green infrastructure elements, and not necessarily gray infrastructure alone.

IV. **Co-benefits focus** – These subcatchments do not have significant flood risks in the present or the future. As such, gray infrastructure may not be necessary for these subcatchments, and green infrastructure implementation can provide co-benefits, such as urban heat island reduction and water quality improvements.

Based on the above classification, for at least two of the four conditions, greenstormwater infrastructure can be used for flood mitigation to complement (or even replace) gray infrastructure strategies to mitigate flood impacts between present day and 2070 flooding.

In areas focused on gray infrastructure implementation, green infrastructure solutions may still contribute water quality benefits or improve other co-benefits, such as urban heat island reduction or increased green space. This analysis found that flood mitigation benefits of distributed green infrastructure are of greater flood reduction potential in subcatchments located in upstream areas (e.g., higher elevation areas within Alewife or Neighborhood Nine).

2.0 Problem statement

The frequency and volume of precipitation during sizeable storm events that are relatively infrequent today (i.e., 10-, 25-, and 100-year storm events) are projected to increase both in intensity and frequency, with heavier precipitation resulting in more frequent and severe flooding impacts in the future. As shown in Figure 1, it is projected that today's 25-year, 24-hour event (4% probability in any given year) will likely be the 10-year, 24-hour event (10% probability in any given year) by 2070. Also, the 10% annual (or the 10-year) 24- hour storm in Cambridge that corresponds to 4.9 inches of rain today will correspond to 6.4 inches in the future (by 2070). Figure 2 illustrates the flood extents and flood depth results of a 2070 10% annual (or 10-year) 24-hour storm event using the City's hydrologic/hydraulic (H/H) model.

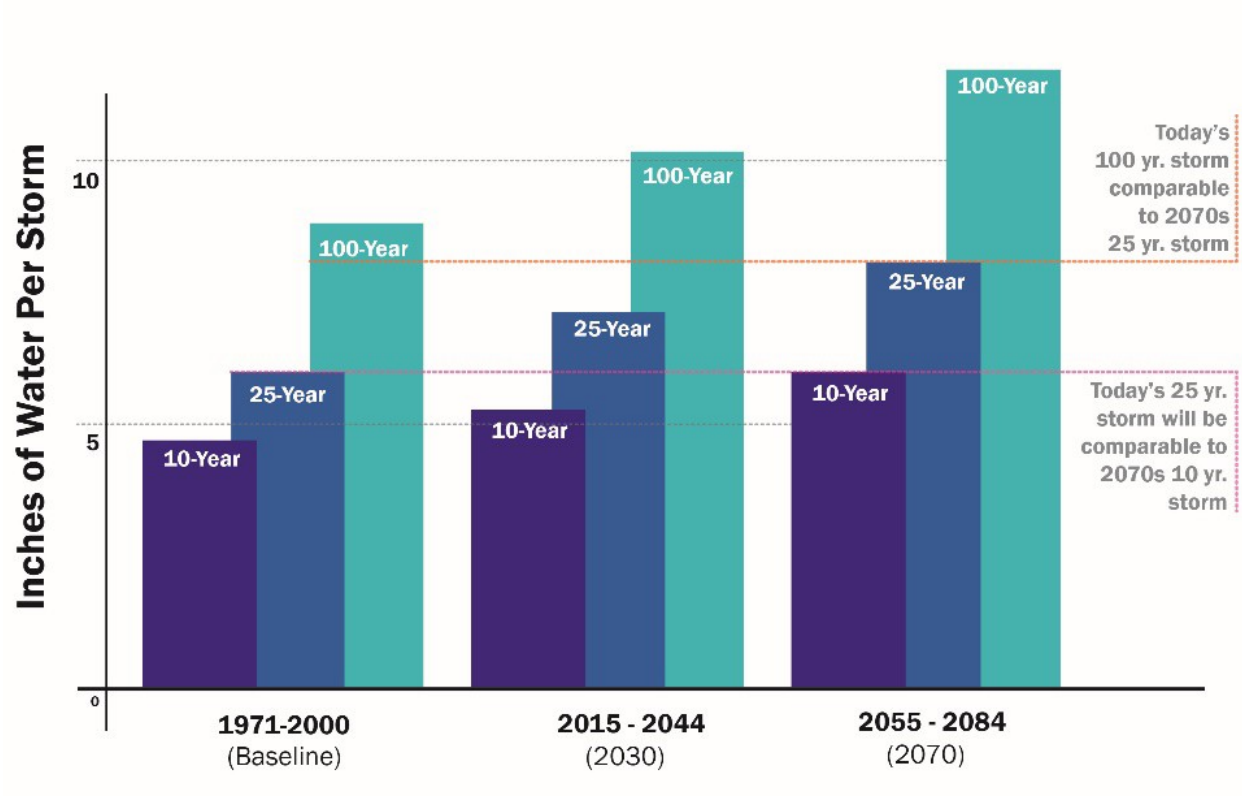


Figure 1 - Projected increases in precipitation volume and frequency between present day and 2070 climate conditions

Heavy Precipitation

Design to **2070 10-year storm**

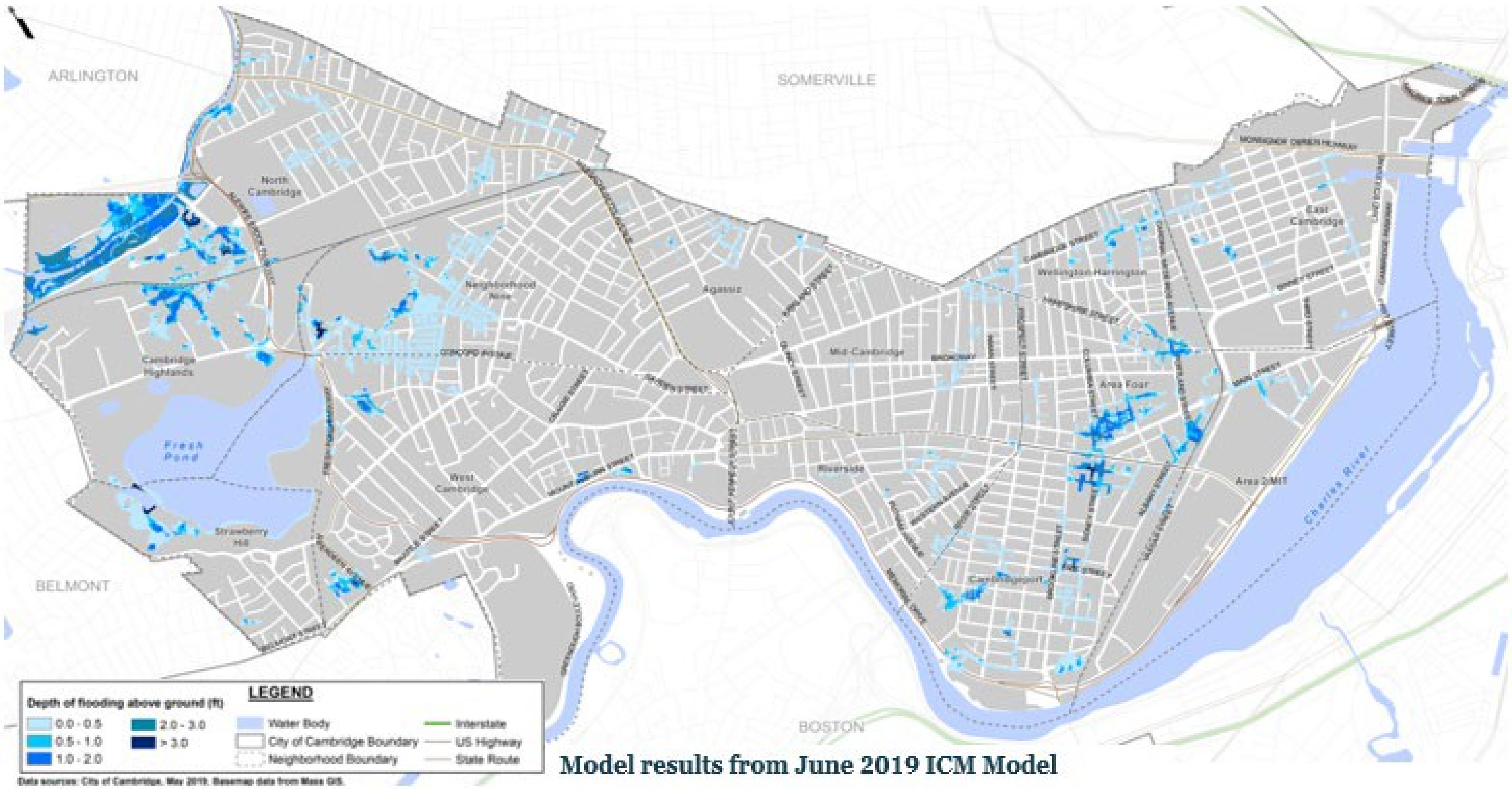


Figure 2 – 2070 flood conditions under a 10% annual (or 10-year) 24-hour storm event

3.0 Analysis methodology

This analysis is a programmatic assessment that builds off previous modeling efforts that the City has conducted and lessons learned from CCPR The Port Preparedness Plan pilot study area, which demonstrated that the difference in flood volume increase between the present day and 2070 10% annual (or 10-year), 24-hour storm event could be significantly mitigated using a combination of gray and green infrastructure strategies. For this Resilient Cambridge analysis, similar flood mitigation targets (i.e., mitigating the difference in present day and 2070 10% annual, 24-hour storm event) are hypothesized with varying implementation levels of gray and green infrastructure strategies.

In this section, the methodology used to conduct this citywide analysis is described by:

- Process for the integration of previous analyses
- Clarification of the baseline conditions
- Identification of targets for identifying successful strategies
- Scope of analysis
- Identification data sources

3.1 Process for Integration of Previous Analyses and Current Citywide Analysis

Prior scenario modeling analyses, performed using the City's ICM-2D hydrologic and hydraulic (H/H) model, identified spatially where flooding hotspots occur citywide under storm events of different recurrence probabilities (i.e., 10-yr and 100-yr recurrence) and at different points in time (i.e. present day, 2030, and 2070). The CCPR Alewife and The Port Preparedness plans utilized the same model to investigate the effectiveness of a toolkit of flood mitigation solutions, comprised of green and gray infrastructure interventions. This citywide analysis built upon the prior gray and green infrastructure technical analyses that were performed in those two pilot areas, as well as green infrastructure modeling analysisthat was performed citywide for areas within the public right-of-way.

Each of the prior analyses identified that the causal drivers of flooding vary spatially by neighborhood, which include (but are not limited to):

- piped infrastructure capacity and conditions;
- catch basin inlet and conveyance restrictions;
- imperviousness and drainage system connectivity in terms of directly connected impervious areas (DCIA);
- topography (i.e., contribution of upstream drainage to downstream flooding);
- soil and groundwater conditions, and
- land use.

To perform the same level of detailed citywide modeling analysis as in The Port and Alewife Preparedness Plan would require significant time and resources beyond the scope of Resilient Cambridge. Inplace of additional H/H modeling, the City determined that alternative quantitative methods, utilizing GIS spatial analyses and data from a previous citywide modeling study[1] (referred as the CRWA 2018

[1] Assessment of Hydraulic and Flood Impacts of City-Wide Green Infrastructure Implementation on Residential Streets, produced by Charles River Watershed Association and Stantec in 2018.

study in this analysis), would be most useful in expanding future climate flood analysis beyond The Port and Alewife neighborhoods to now include the entire City.

3.2 Clarification of baseline condition

The baseline (infrastructure condition in 2020) condition for this flood mitigation analysis is the Cambridge FloodViewer [2] model outputs for extreme precipitation 10% annual(i.e., total flood volume andspatial extents of flooding) that result under 2070 climate conditions, assuming 2020 infrastructure conditions. Modeled 2020 infrastructure conditions reflect infrastructure projects that are currently under construction or will begin construction in 2020[3] (these infrastructure conditions are consistent with those that are modeled within the City's ICM-2D hydrologic and hydraulic (H+H) model.

3.3 Identification of targets for identifying successful strategies

Citywide flood impacts for the present-day 10% annual (or 10-year), 24-hour storm event remain a priority for the City to address. The City has identified the present-day 10% annual storm flooding condition manageable, since flood impacts are mostly contained within public rights-of-way and a limited number of properties are affected.

A building block of this analysis are lessons learned from The Port Preparedness Plan, that the difference in flood volume between the present day 10% annual 24-hour storm and the 2070 10% annual storm event could be significantly mitigated using a combination of gray and green infrastructure solutions. This citywide analysis built upon the findings from The Port Preparedness Plan, that an appropriate goal for The Port was to ensure that flood impacts experienced in 2070 are no greater than flood impacts in the present-day condition for the 10% annual 24-hour recurrence event.

- Citywide target – No net increase in total stormwater volume (MG) as measured by thedifference between the present day and 2070 10% annual 24-hour storm events and the present-day 10% annual 24-hour event. (i.e, the delta (Δ) Flood Volume $_{\text{10\% annual, 24 hr. event}}$).

3.4 Scope of analysis

In place of additional modeling analysis (similar to what was conducted for neighborhood-specific modeling of infrastructure alternatives in CCPR Alewife - Appendix B, CCPR The Port - Appendix 1, and The Port – Short Duration Storm Analysis), the scope of this technical analysis is limited to a programmatic GIS-based assessment. To conduct the assessment, the following qualitative and quantitative methods were used to characterize flood impacts and assess the effectiveness of potential green and gray infrastructure strategies:

- Categorization of flood impacts at the subcatchment scale by establishing high-level correlation between (1) drivers of flooding and (2) where flood impacts are experienced.

    A high-level mapping analysis of flood volumes (and change in flood volume between present day and 2070 conditions) is performed by delineating subcatchments at ~20-acre scale, based on topography and piped infrastructure network (see Figure 3).

[2] Cambridge FloodViewer - https://cambridgegis.maps.arcgis.com/apps/webappviewer/index.html?id=1d30c73456d246f48daf8489405c6629

[3] *Section 1.2, The Port Preparedness Plan Appendix 1, https://www.cambridgema.gov/CDD/Projects/Climate/~/media/B6A47B26D46B4125AA785541BCE63455.ashx*

- Compilation of gray and green infrastructure strategies from CCPR Alewife Preparedness Handbook, CCPR The Port (Appendix 1), including:
    - Gray infrastructure strategies:
        - flow re-routing or optimization (new or upsized pipes, reducing piped network constrictions);
        - subsurface infiltration or detention tanks;
    - Green infrastructure strategies:
        - Rain gardens, bioretention basins or swales;
        - Porous pavement, outside of public roadways;
        - Green/blue roofs;
        - Enhanced tree box filter and/or leaching catch basins

- Assessment of most appropriate strategies for flood reduction per subcatchment:
    - Using a set of flood impact and opportunity matrices, high-level recommendations are provided for the appropriate mix/composition of the gray and green infrastructure strategies at the subcatchment scale, as informed by:
        - flood impacts characterization mapping;
        - availability of opportunity spaces, per land-use and ownership including:
            - public right-of-way (roadway and sidewalk space);
            - land use (defined, for the purpose of this study, as available footprint of rooftops, parking lots, and private open space);
            - Publicly owned parcel open spaces (i.e., Public Open Space);
        - co-benefit with identified opportunities in plans or capital planning, including:
            - overlap with priority spatial locations identified as part of technical analyses in support of the City's Long-Term Control Plan for combined sewer overflow, inflow and infiltration programming and water quality improvements in separated areas; and
            - overlap with priority spatial locations identified within the City's Urban Forest Master Plan (tree canopy and urban heat island).
            - upcoming Capital Improvement earth-disturbing projects (as identified in Cambridge's 10-year Sewer and Drain Infrastructure Plan and 5-year Sidewalk and Street Reconstruction Plan);

The following are the six key tasks that comprise the full scope of this technical analysis.

<u>Key Tasks</u>

1. Delineate the City of Cambridge watersheds into subcatchments at approximately 20-acre resolution

2. Determine increases in flood volume between present-day 10% annual, 24-hour storm and 2070 forthe 10% annual, 24-hour storm)

3. Determine the upstream tributary areas and the associated tributary run off volumes for each subcatchment generated in Task 1, using the ICM model
4. Develop flood matrix to categorize flood impacts and potential for gray and green infrastructure implementation in subcatchments
5. Assign categorization to each of the generated subcatchments in Task 1
6. Overlay categorized catchments with various strategies in the Resilient Cambridge Handbook, to identifypotential early actions

3.5 Data sources

The following datasets and sources were used in this technical analysis:

- GIS layer data
    - Topography – from Digital Elevation Model (DEM) [source: City GIS, 2014 Pictometry]
    - Piped infrastructure network – including storm drain network, combined and sanitary sewer network, catch basins, manholes, pump structures, and other storm conveyance assets [source: Cambridge DPW, 2019]
    - Storm system large catchment and subcatchment boundaries [source: City of Cambridge ICM-2D model, 2019]

- The following previous reports and technical analyses/memoranda were used in the quantitative analysis of benefits of Flood Mitigation Solutions:
    - Cambridge Climate Change Preparedness and Resiliency Plan (CCPR)
        - CCPR – Alewife Preparedness Handbook
        - CCPR – Alewife Preparedness Plan Appendix B: Green Infrastructure Analysis & Urban Heat Island Modeling
        - The Port Preparedness Plan Appendix 1 (Gray and GreenInfrastructure Analyses for The Port)
    - Cambridge DPW mapping, technical analyses/memoranda
        - FloodViewer 2.1 (webmap resource)
        - The Port – Short Duration Storm Analysis (Kleinfelder)
        - Assessment of Hydraulic and Flood Impacts of City-Wide Green Infrastructure Implementation on Residential Streets (Stantec/CRWA)

4.0 Categorizing flood impacts

This section will describe how the methodology explained in Section 3.0 was executed at the citywide scale. The goal is to delineate drainage areas in the City of Cambridge into subcatchments with a 20-acre resolution, and then categorize each subcatchment into a flood impact type. Using the 20-acre categorized subcatchements as the basis, potential to implement gray and green infrastructure can be identified by referencing opportunities to yield the most flood reduction benefit. Opportunities can include open space, future development, Inflow & Infiltration removal projects, etc.

Resolution of assessment: Subcatchments are delineated at approximately 20-acre in size, totaling about ~180 subcatchments for the City of Cambridge. Figure 3 illustrates the delineated subcatchments based on:

1) Topography from LiDAR digital elevation model (Black/white gradients)
2) City GIS stormwater and combined sewer pipes (see inset map in lower left corner)

Figure 3 – Delineation of subactchment for Resilient Cambridge analysis, totaling approximately ~180 subcatchments

Detailed Procedure:

- Calculate the difference (delta) in flood volume between the present day and 2070 10% annual,24-hour storm events within each subcatchment, and cumulative difference (delta) for all subcatchments situated 'downstream';
- Based on flood volumes, perform a high-level characterization (per subcatchment) of the dominant flood impact regime, as shown in Table 1, i.e.:
    - ***Impact Type A:*** considerable change in flood volume (Δ2070-present day) is experienced in downstream subcatchment(s), but not within the subcatchment

of interest (*for example, due to topography and upstream runoff contribution of downstream flooding*)

- **Impact Type B:** considerable change in flood volume (Δ2070-present day) is experienced both in the downstream subcatchment(s), as well as within the subcatchment of interest

- **Impact Type C:** considerable change in flood volume (Δ2070-present day) is experienced within subcatchment of interest, but not within downstream subcatchment(s) (*for example, due to infrastructure constriction that limits subsurface flow to downstream subcatchment(s)*

- **Impact Type D:** no considerable change in flood volume (Δ2070-present day) is experienced within subcatchment of interest, or within downstream subcatchments

Greater flood impact downstream→

Impact Type A **within sub-catchment: Low (Δ) flood impacts** **d/s sub: High cumulative flood volumes**	**Impact Type B** **within sub-catchment: High (Δ) flood impacts** **d/s sub: High cumulative flood volumes** or **former wetland area**
Impact Type D **within sub-catchment: Low (Δ) flood impacts** **d/s sub: Low cumulative flood volumes**	**Impact Type C** **within sub-catchment: High (Δ) flood impacts** **d/s sub: Low cumulative flood volumes**

Greater flood impact within sub-catchment →

where
Δ = {Change in sub-catchment flood volume between present day and 2070}, as per ICM2D model

Table 1 – Description of flood impacts matrix to categorize subcatchments

As one of the objectives of this citywide analysis is set to minimize the net increase in flood volume for the 10% annual storm between present-day and 2070 climate conditions, the first criterion is to determine the delta (Δ), or changes in flood volumes within each delineated subcatchment. Figure 4 though Figure6 provide a visualization of the changes in flood impacts. Figure 6, showing the difference between theflood volumes in Figure 4 and Figure 5, highlights the subcatchments that may experience the most drastic changes in flood volume for the 10% annual 24 hour storm due to changing climate conditions

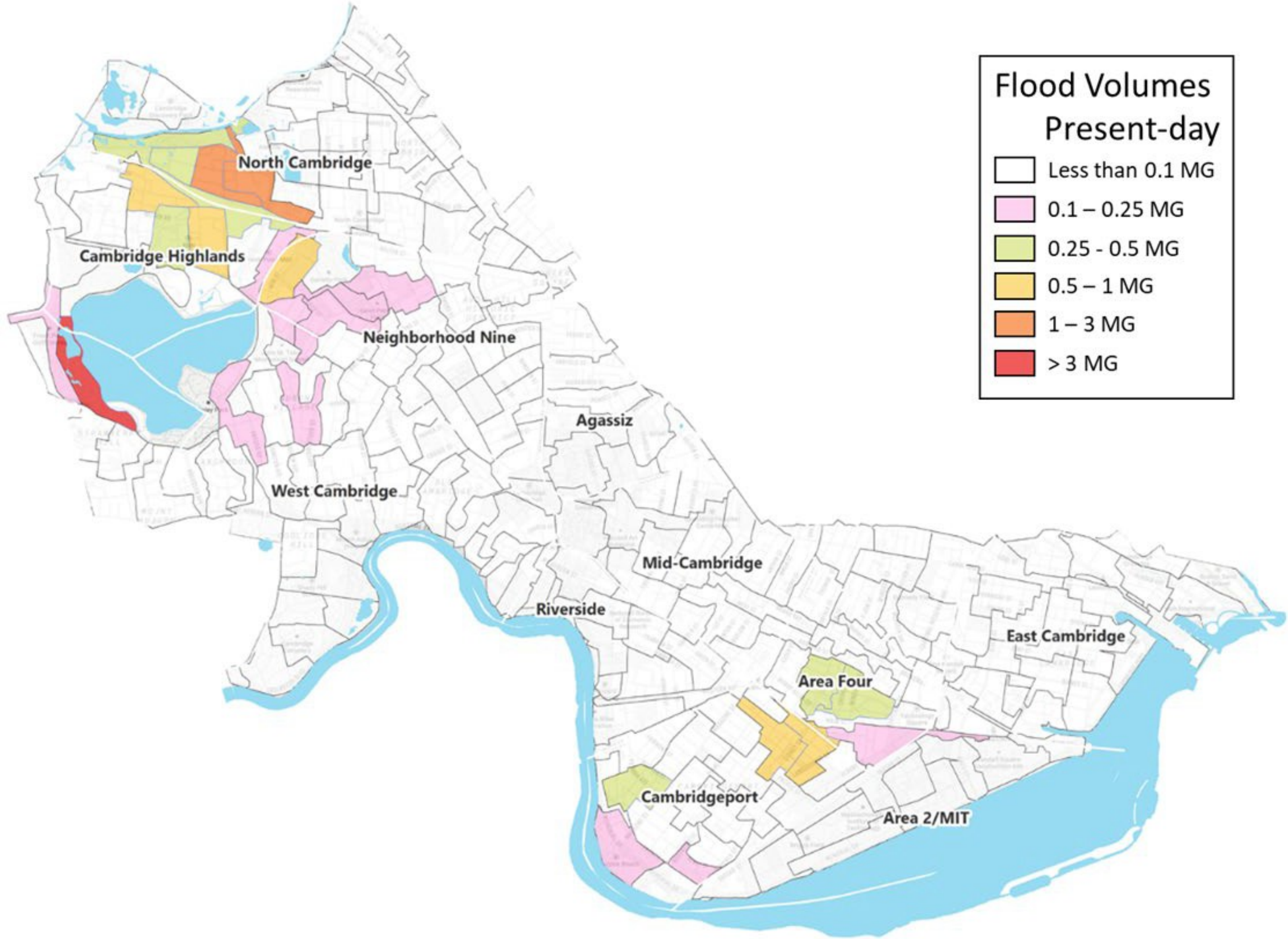


Figure 4 - Flood volumes by subcatchments under a present-day 10% annual 24-hour storm

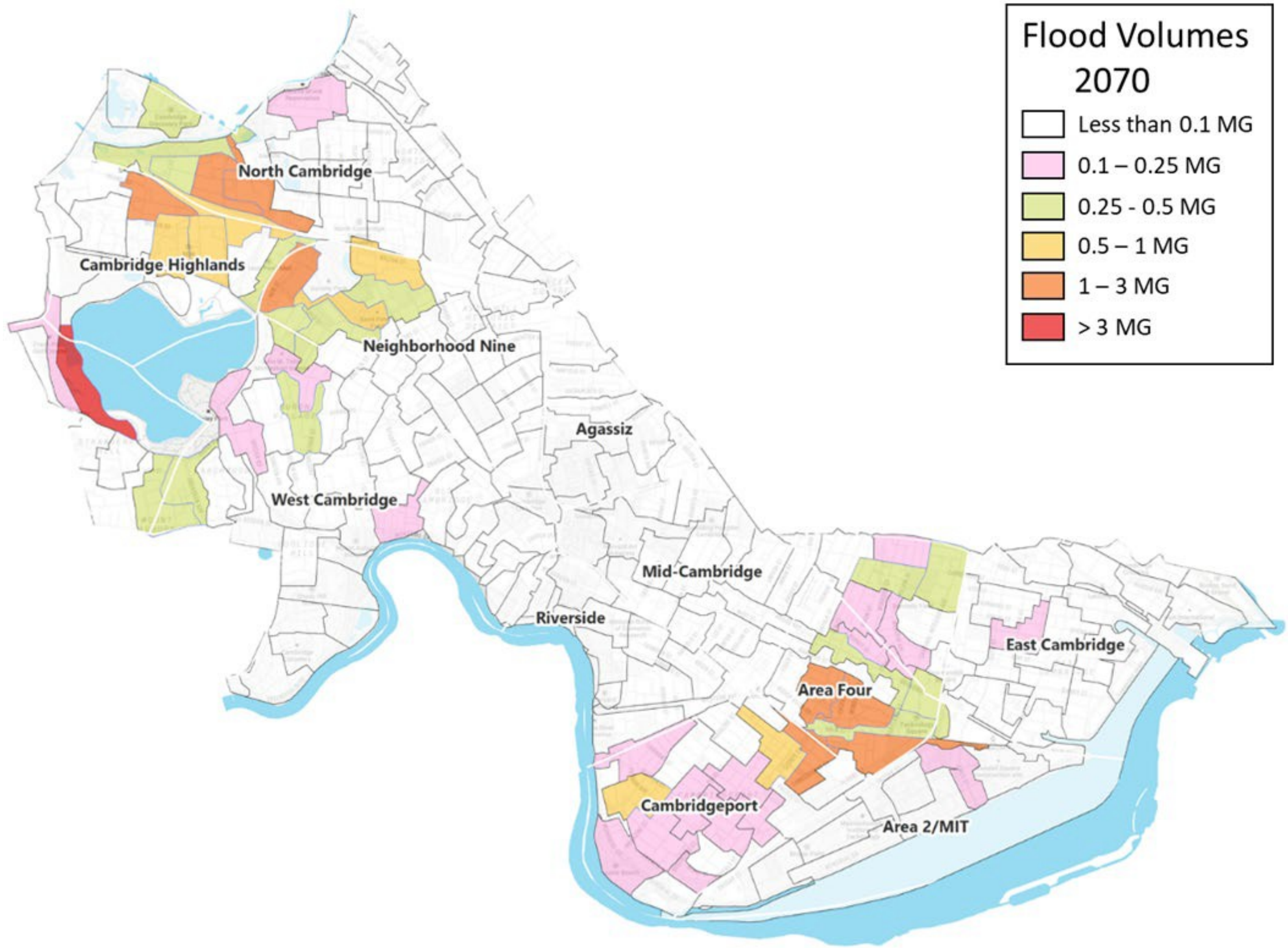


Figure 5 - Flood volumes by subcatchments under a 2070 10% annual 24-hour storm

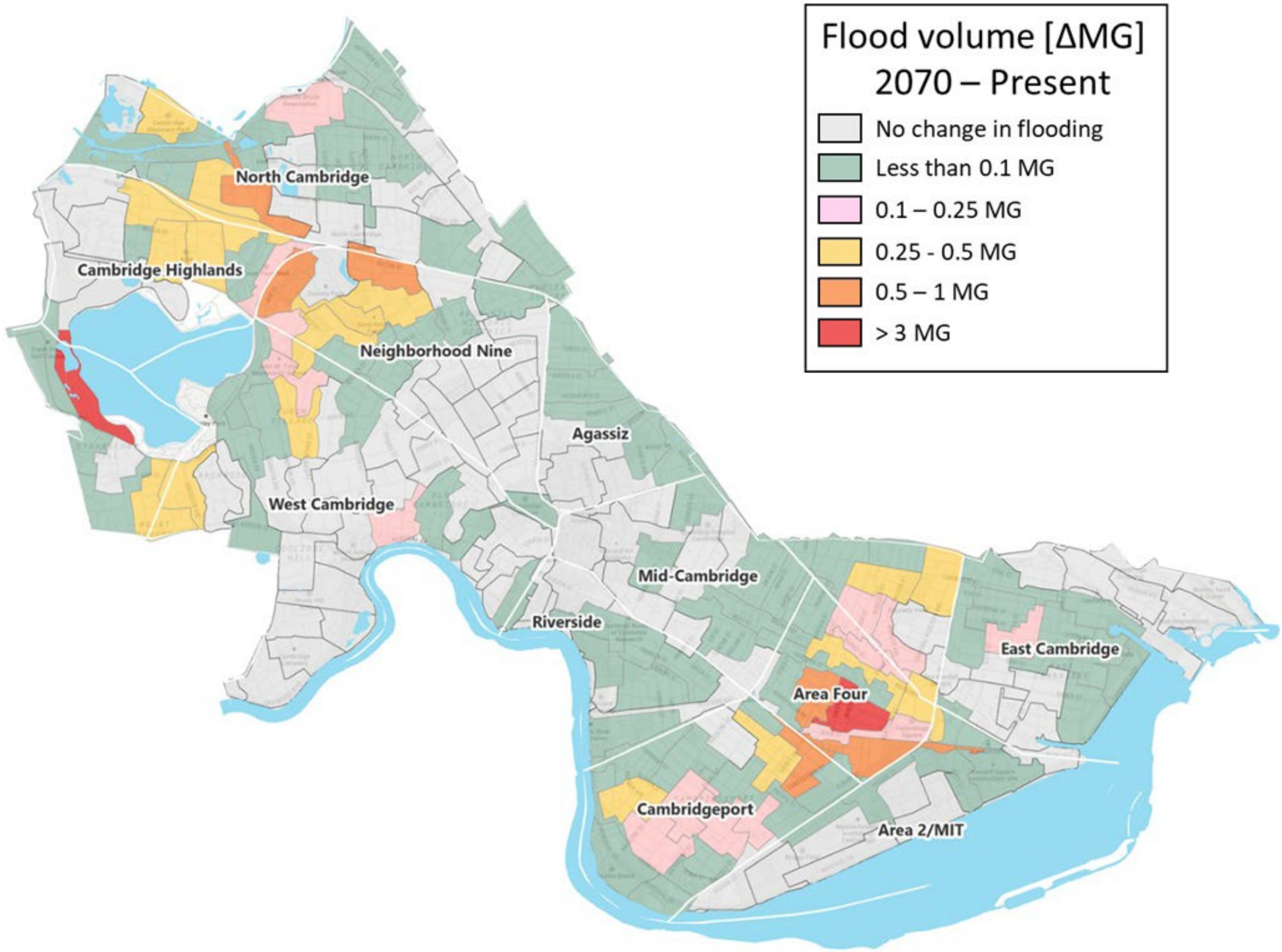


Figure 6 – Change(Δ) in flood volumes between present day and 2070 climate conditions

The second criterion serves as a proxy to qualitatively estimate the flood reduction benefits gray/green infrastructure would bring to each catchment. This criterion calculates the cumulative downstream total flood volumes per subcatchment. Figure 7 provides an explanation on how this works, showing subcatchments (highlighted in gray) that share the same downstream outfall (red triangle). The surface runoff following a routing highlighted in yellow, flowing from left (upstream) to right (downstream). For the most upstream catchment on the left, the flood volume in a 2070 10% annual 24-hour storm is 0.3 MG. The cumulative 2070 flood volumes are estimated by summing up the flood volumes for all subcatchments that are part of the highlighted route, until it reaches the outfall. From this, the second criterion, the cumulative total of year 2070 flood volume in the downstream subcatchments is estimated to be 0.3 + 1.2 + 0.1 + 0.5 = 2.1 MG.

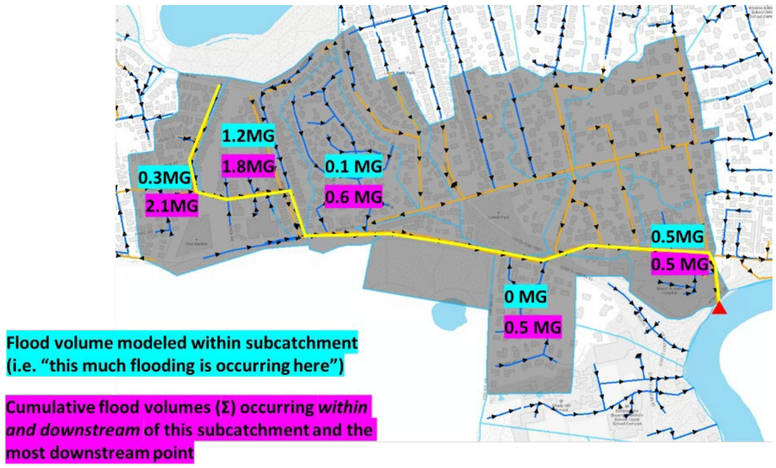
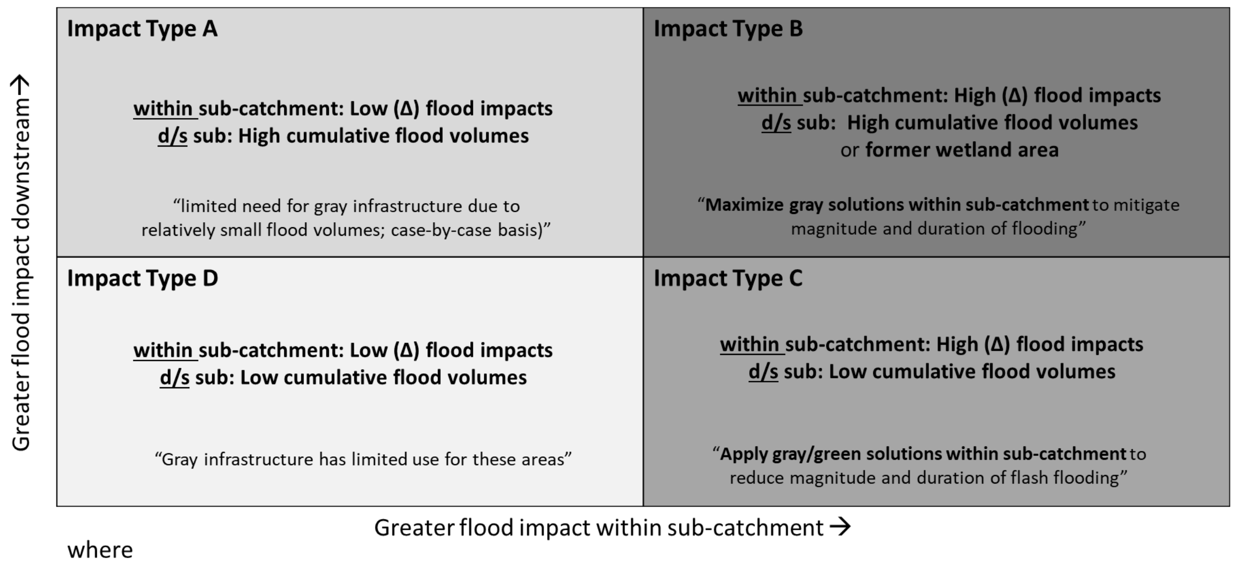


Figure 7 – Example to estimate the downstream subcatchments cumulative flood volumes. Criterion 1 is highlighted in cyan and criterion 2 is highlighted in magenta

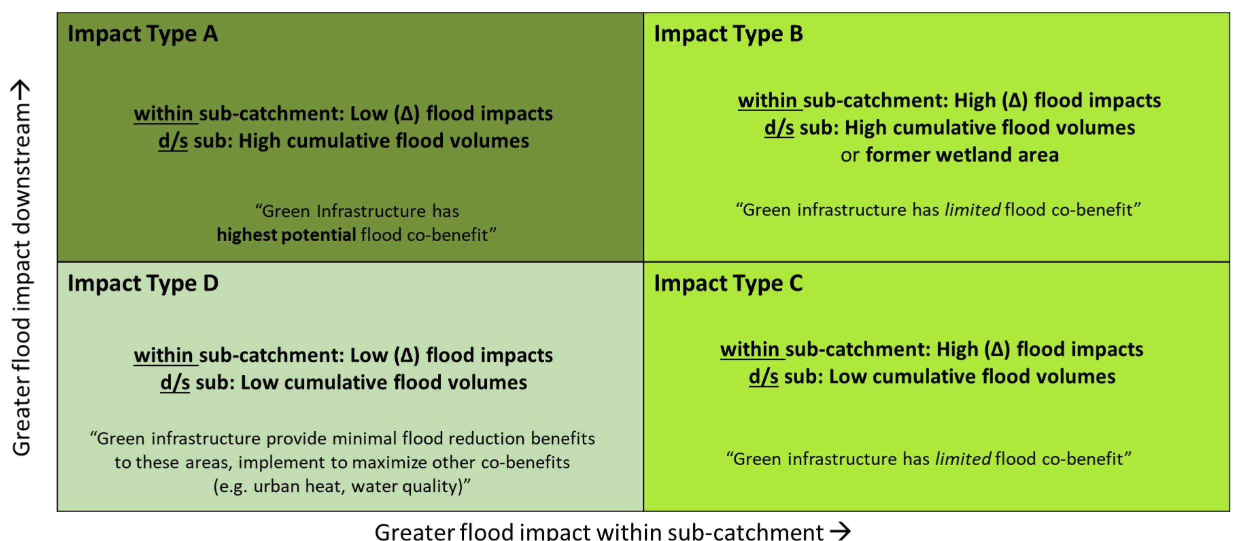
For gray and green infrastructure, the two criteria have different implications:

Gray infrastructure implementation such as pipe upsizing, flow rerouting and storage tank installation are usually effective to reduce flood volume within the same subcatchment, or in other words, in areas where flow converges. On the other hand, green infrastructure implementation, such as green roof, rain garden and porous pavement in an urban setting usually needs to be at a more distributed scale and can be effective in reducing cumulative flood volumes in downstream subcatchments. Figure 8 and Figure 9 summarize how each flood impact type proximate the implementation of gray and green infrastructure.



where
Δ = {Change in sub-catchment flood volume between present day and 2070}, as per ICM2D model

Figure 8 – Subcatchment categorization for gray infrastructure implementation



where
Δ = {Change in sub-catchment flood volume between present day and 2070}, as per ICM2D model

Figure 9 - Subcatchment categorization for green infrastructure implementation

5.0 Results: GIS assessment of flood mitigation strategies

In section 4, each subcatchment was categorized into one of the four flood impact types. This section will summarize the results and present various assessments to identify potential gray and green infrastructure implementation, matching up the flood impact types to the following potential opportunities for implementation:

1. Open green space
2. Combined sewer and drainage catchment areas
3. Capital plan projects for the next 10 years

Figure 10 shows the flood impact type categorization for green infrastructure implementation. The dark green subcatchments are categorized as flood impact Type A, (e.g. areas south of North Cambridge, north of Neighborhood Nine, east of Mid-Cambridge, etc.) where it is expected that green infrastructure implemented in these subcatchments can potentially provide significant flood reduction benefits. These subcatchments have relatively low increase in flood volumes within them between present and future but contribute to downstream areas that experience significant flooding increase in the future.

Subcatchments categorized as impact types B and C have high increase in flood volumes within the subcatchment boundary between present and future. Distributed forms of green infrastructure, such as rain gardens and green roofs will have limited flood reduction benefits in theseareas. Subcatchments in these two impact types will need to have a combination of both green and gray implemented strategically to effectively reduce flood impacts.

Figure 11 shows the flood impact type categorization for gray infrastructure implementation. The dark gray subcatchments are categorized as flood impact Type B, with high increase in flood volumes within the subcatchment between present and future and are also connected to downstream subcatchments that have significant flooding increase in the future. To effectively manage the large quantity of surface runoff, gray infrastructure such as storage tanks, pipe up-sizing, flow diversion is necessary to provide flow attenuation benefits.

Gray infrastructure is also recommended for subcatchments categorized as impact Type C. These subcatchments experience high flood volume increase within the subcatchment between present and futurebut are connected to downstream subcatchments that have relatively low flood volume increase in the future. These characteristics also match the description of areas that are more prone to flooding from short-duration, high-intensity storms, which would need an effective combination of gray and green infrastructure to address both conveyance capacity and inlet capacity issues.

Figure 12 compares the green infrastructure implementation map with current open green spaces in the City. When feasible, maximum implementation of green infrastructure is recommended for the areas where the open green space coincides with the impact Type A subcatchments to yield the most flood reduction benefits.

Figure 13 overlays some key areas in the City's 10-year Sewer and Drain Infrastructure Plan on the gray infrastructure implementation map. For subcatchments with flood impact Type B or C, it is recommended to focus on gray infrastructure implementation for future flood reduction projects. Eligible project examples include I&I Removal projects, sewer separation projects, Chapter 90 roadway projects, pilot "Cool Corridor" concepts, private site development review and stormwater system retrofits.

Figure 14 shows the combined sewer and separated drainage areas overlaid on flood impact types for green infrastructure implementation. Combined sewer areas that overlap with flood impact Type D (e.g.

Agassiz) are areas where green infrastructure is likely to provide limited benefits in terms of flood reduction. However, there are co-benefits for implementing green infrastructure that can be gained in flood impact Type D areas, such as reduction in urban heat-island effect, enhancing urban livability, urban beautification, water qualityimprovement, along with potential combined sewer overflow (CSOs) reduction. These opportunitiesshould be considered for individual City projects as part of ongoing capital improvement planning/prioritization for CSO mitigation programs and MS4 permit compliance.

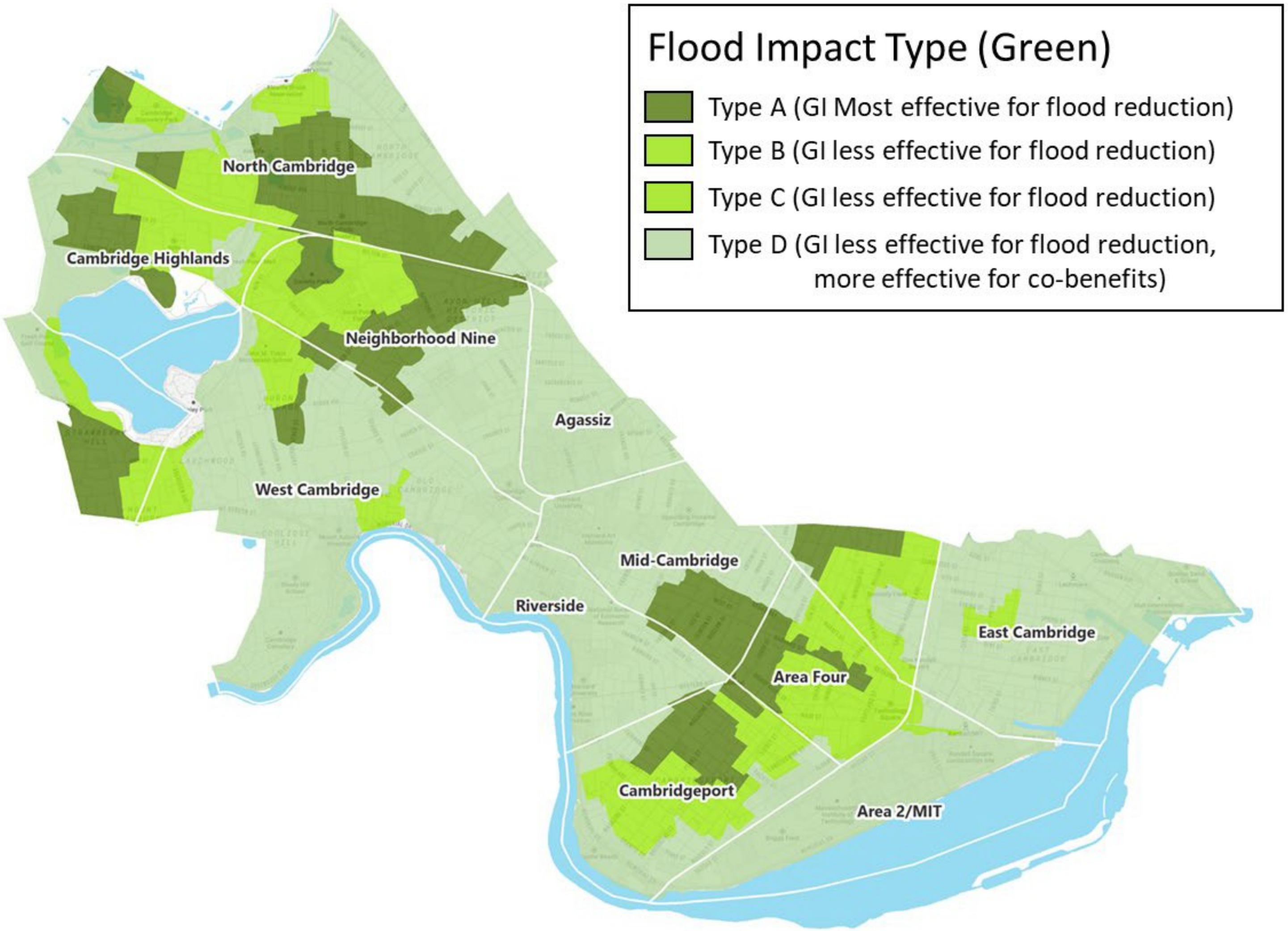


Figure 10 – Green Infrastructure flood benefits in Open Space areas

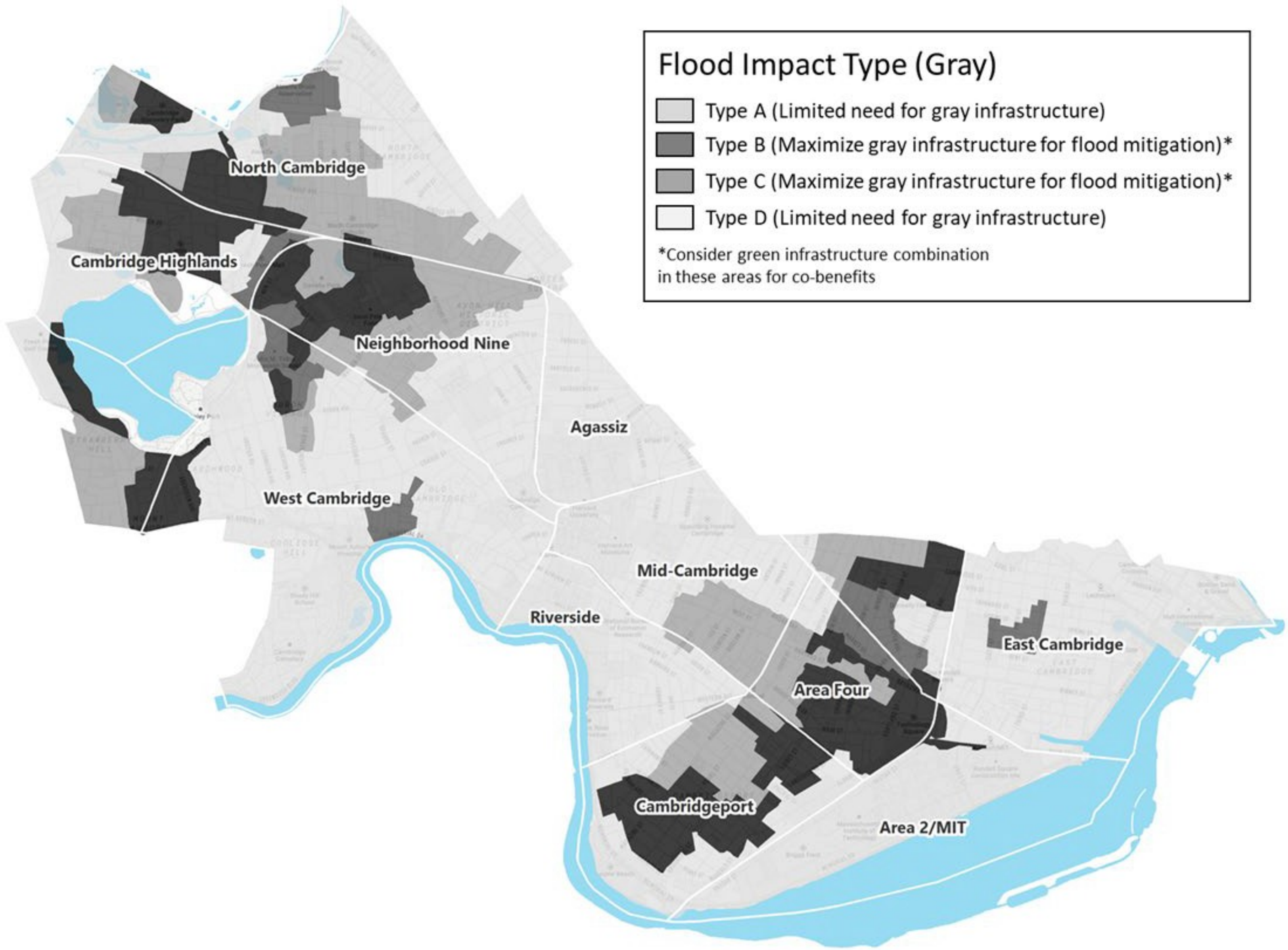


Figure 11 – Gray infrastructure implementation map

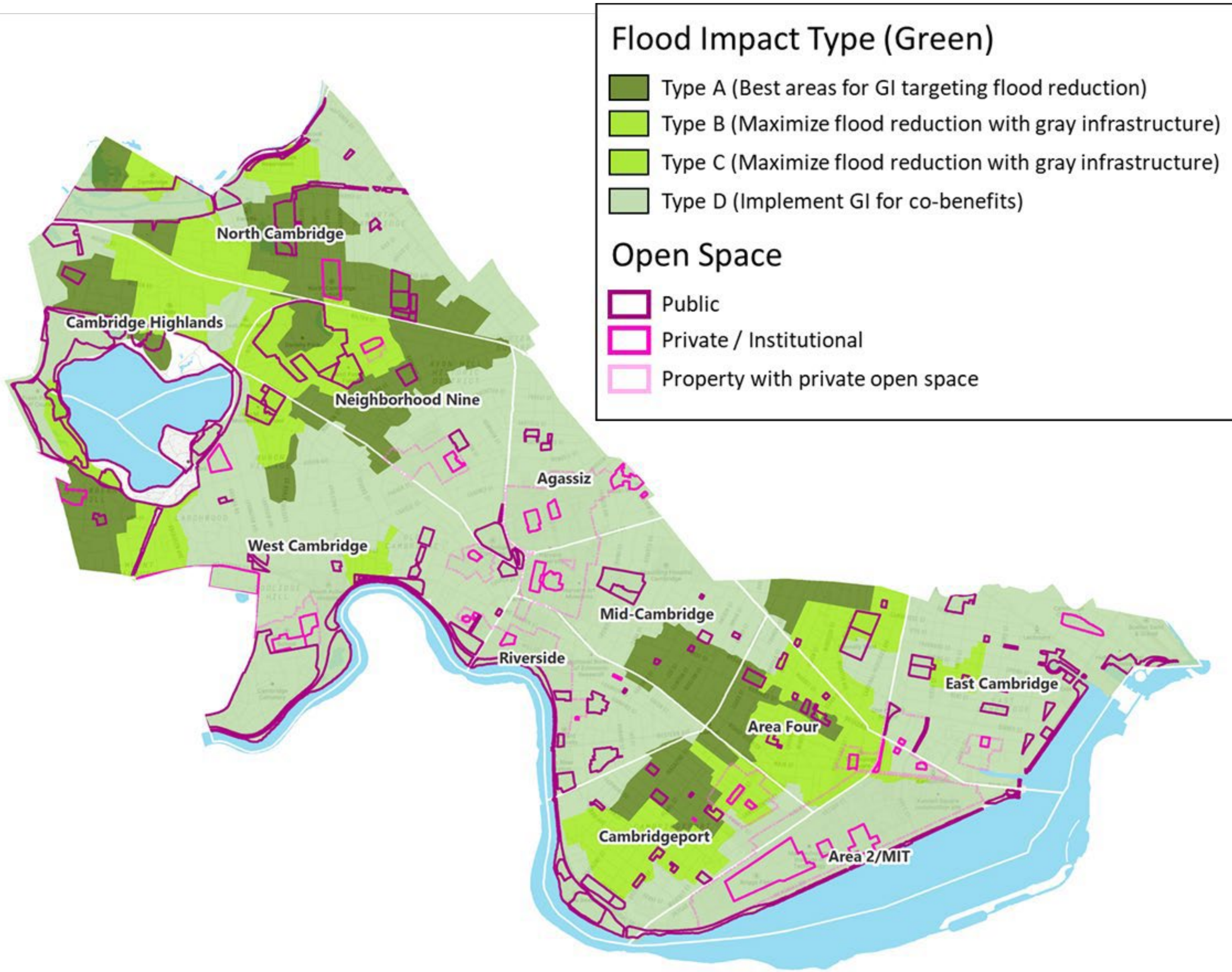


Figure 12 – Open space opportunities for green infrastructure implementation

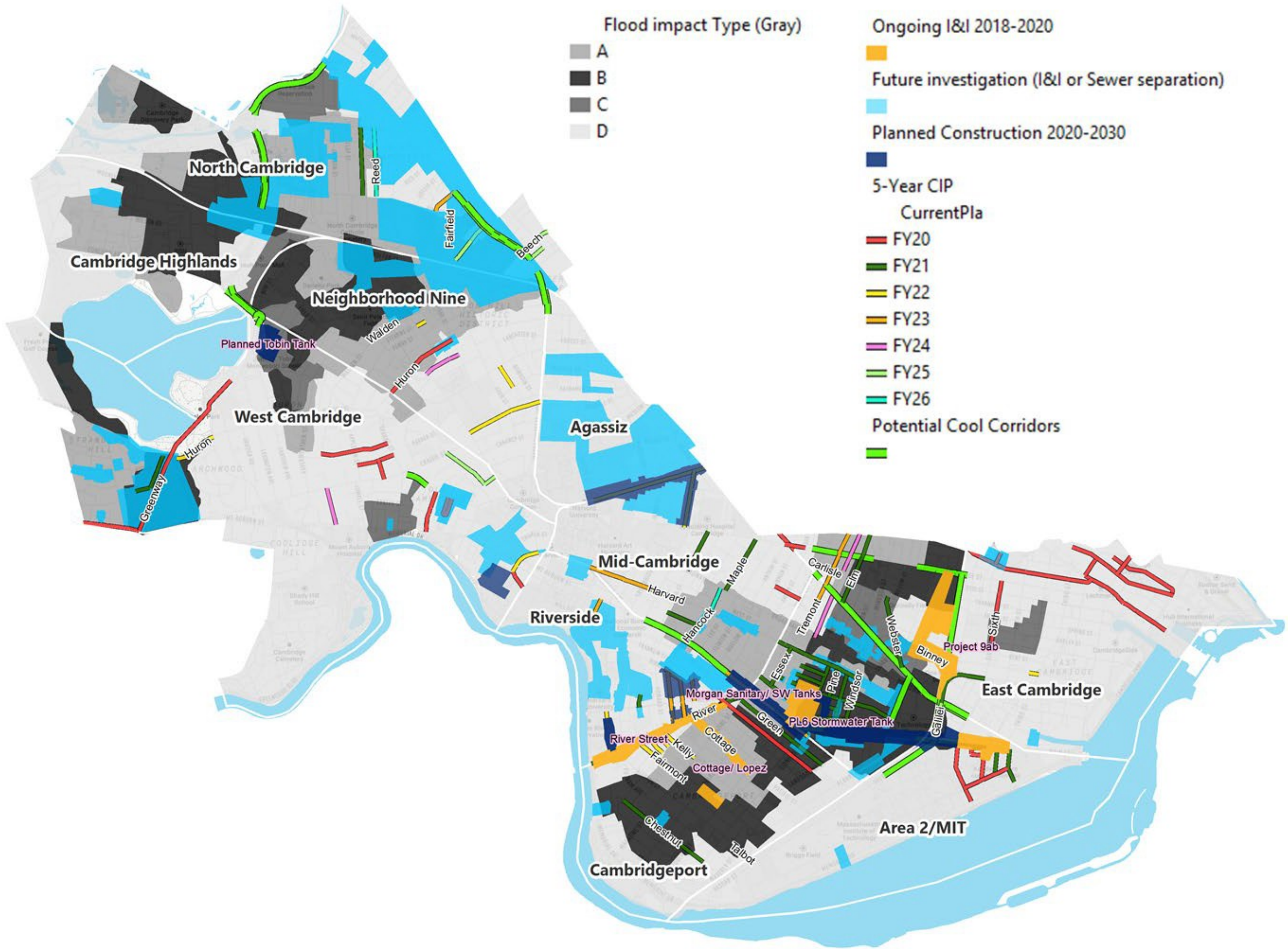


Figure 13 – Capital investment projects opportunities for gray infrastructure

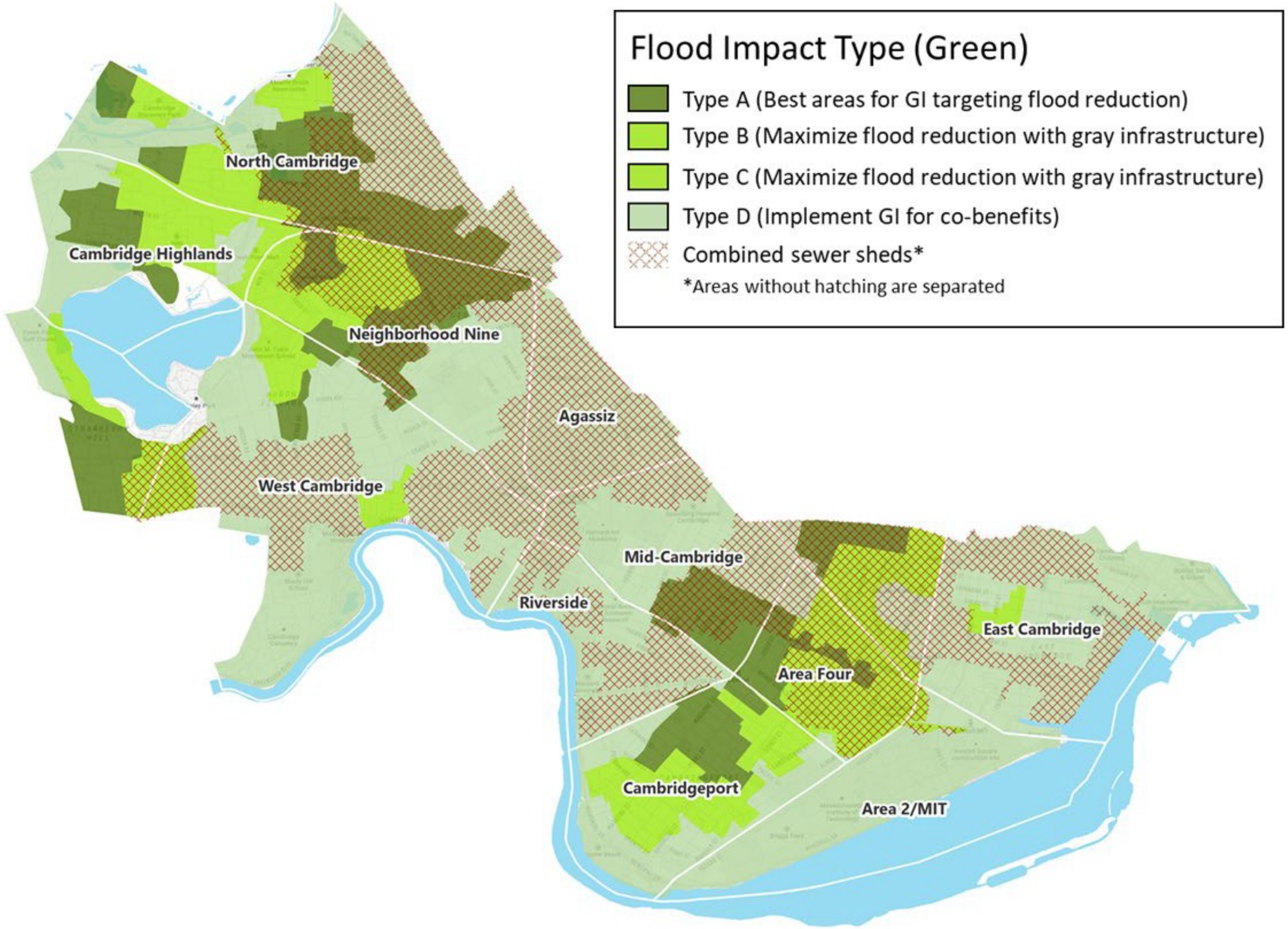


Figure 14 – Potential green infrastructure in combined sewer areas for co-benefit

6.0 Further studies – Short duration storms (SDS) in The Port

In addition to the 24-hour design storms that are covered in this memo, the City also investigated the impacts of short duration high-intensity storms on the drainage system in The Port area of the City. For detailed explanation on theshort-duration storm model results, please refer to Appendix A attached to this memorandum.

Short duration high-intensity storms (SDS) are extreme rainstorm patterns that are common in coastal areas of New England. Compared to traditional 24-hour design storms, the short duration high-intensity storms statistically have much higher peak intensity that precipitates a large amount of rainwater over a short period of time, typically ranging from 5 to 15 minutes. The high peak-intensity of these extreme storms can overwhelm the drainage system and cause local flash floods at locations where traditional 24-hour storms would show no impacts.

In Task 2 of the SDS study, simulates indicate that significant portion of The Port experience severe flood impacts under SDS conditions. Results indicate that insufficient inlet capacity induces surface flooding at multiple locations within The Port area. Hydraulic profiles in the model also show that there is limited conveyance capacity in the drainage system under SDS conditions, as the peak Hydraulic Grade Line in the drainage system is well above ground surface.

Task 3 in the SDS study explored flood mitigation options for SDS conditions using various combinations of gray and green infrastructure. In this analysis, most of The Port is categorized as Impact Type B and C for green infrastructure implementation. Model results in the SDS study reinforced our findings based on the flood impact types for this area. For green infrastructure to be effective in this area, it requires improved conveyance conditions to lower the peak hydraulic grade line in the drainage system, in which gray infrastructure investment is a prerequisite to green infrastructure implementation. This SDS study, together with the 24-hour design storm simulations the City had done for the neighborhood plans, suggest that a combination of both gray and green infrastructure can effectively reduce flood impacts in future climate conditions.

7.0 Co-benefits

Flood mitigation via the implementation of green and gray infrastructure strategies provides an opportunity to achieve multiple co-benefits via integrated planning and design. There is a potential for flood mitigation strategies to address additional positive outcomes, including water quality improvement and combined sewer mitigation. For example, many of the green and gray infrastructure strategies that aim to maximize flood volume capture, can also be designed in ways to promote treatment of stormwater runoff via detention, retention, filtration, and/or infiltration (see Green and Gray Infrastructure Strategies Toolkit; Appendix B) Such processes can be beneficial in reducing nutrient loading to surface water bodies, improving water quality outcomes in Alewife Brook, Fresh Pond, and the Charles River. The benefits of green and gray flood mitigation strategies, such as volume removal and/or peak flow attenuation, can also contribute toward the mitigation or reduction of CSOs in the combined sewersheds within the City.

Water Quantity and Quality (Sewershed co-benefits)

Runoff quantity co-benefits

Green and gray infrastructure strategies for flood mitigation can include concentrated or collective benefits, improving the performance of the City's sewer network.

Neighborhood- or site-scale stormwater management strategies, such as diversion of runoff toa subsurface infiltration or detention system installed below a public open space, parking lot, or ballfield – can be paired with outlet controls to manage the rate of any stormwater flow returning to the sewer network. These practices can include either green or gray infrastructure strategies or combine elements of both. When such systems are installed to mitigate flood outcomes, the stormwater quantity outcomes (i.e. volume detention or removal, peak flow attenuation, peak flow/rate mitigation) may result in concentrated, localized benefit to system performance.

In terms of collective benefits, distributed green infrastructure can act as a strategic patchwork of filtering practices, supplementing catch basins sumps and other structures which remove materials that collect over time and can reduce system efficiency and potentially clog key nodes in the drainage system.

Depending on the size of any installed system, as well as localized system factors (topography, sewer type, and existing conveyance capacity among others) the benefits of these strategies may extend beyond flood mitigation, such as peak flow/rate reduction that help mitigate CSOs, even in precipitation events that do not produce flooding (reduced activation frequency or total discharge volume).

Near-term priority combined sewersheds: CAM401A, CAM401B, CAM005, CAM017, Cottage Farm Inflow

Water quality co-benefits

By providing additional storage space for stormwater runoff, green and gray infrastructure strategies may also be advantageous for water quality treatment purposes. This is a particularly important co-benefit to consider for flood mitigation strategies implemented in municipal separate sewer systems (MS4) which discharge directly to surface water bodies. Green infrastructure strategies, such as vegetated systems with filter media can be effective in removing surface pollutants and excess nutrients. Where conditions allow, filtering practices – such as raingardens, bioswales/bioretention, and subsurface infiltration systems – can be effective in reducing pollutants typically conveyed during the "first flush," or early stages of storm events. Gray infrastructure strategies can also remove pollutants (solids) but are less effective for removing soluble pollutants, such as nutrients, given the absence of filter media and biological and chemical processes.

When designing system for flood mitigation purposes, systems are often sized to maximize storage space (to the extent feasible), for volumes larger than typical water quality sizing. For example, in the case of a subsurface infiltration or detention system sited below a ballfield, the space allocated for flood storage may far exceed the Water Quality Volume (WQV) of a system designed for other purposes. While the primary purpose of the system may be for flood mitigation, the system would also capture the runoff associated with smaller, more frequent storm events, thus resulting in water quality benefits.

Previous studies have demonstrated that green infrastructure and other stormwater retrofits can yield additional water quality benefits beyond the first inch of runoff. While a 1" WQV standard is a common requirement in many jurisdictions (e.g., Massachusetts Stormwater Handbook, 1996[4]; BWSC Stormwater Best Management Practices: Guidance Document, 2013[5]; City of Cambridge's Wastewater and Stormwater Management Guidance, 2008[6]), a growing number of jurisdictions in the Northeast and Mid-Atlantic have implemented WQV standards of 1.2" or greater in recent updates (e.g., City of Philadelphia, State of Rhode Island, Washington, D.C.). While observed impacts of climate change on precipitation indicate more rainfall is occurring during larger and more-intense storm events[7], the Chesapeake Bay Stormwater Working Group's Recommendations of the Expert Panel to Define Removal Rates for Urban Stormwater Retrofit Projects[8] (2012) reports diminishing treatment benefits beyond 1.5" of runoff capture for phosphorus, nitrogen, and suspended solids removal shown in Figure 15.

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4 https://www.mass.gov/guides/massachusetts-stormwater-handbook-and-stormwater-standards

5 http://www.bwsc.org/sites/default/files/2019-01/stormwater_bmp_guidance_2013.pdf

6 https://www.cambridgema.gov/-/media/Files/publicworksdepartment/stormwatermanagement/wastewaterandstormwaterguidance/draft_version1guidancedocument_may_2008_sect_1_through_5.pdf

7 National Climate Assessment report (2014) Key Message #6: Heavy Downpours Increasing https://nca2014.globalchange.gov/report/our-changing-climate/heavy-downpours-increasing

8 https://www.chesapeakebay.net/documents/Final_CBP_Approved_Expert_Panel_Report_on_Stormwater_Retrofits--_short.pdf

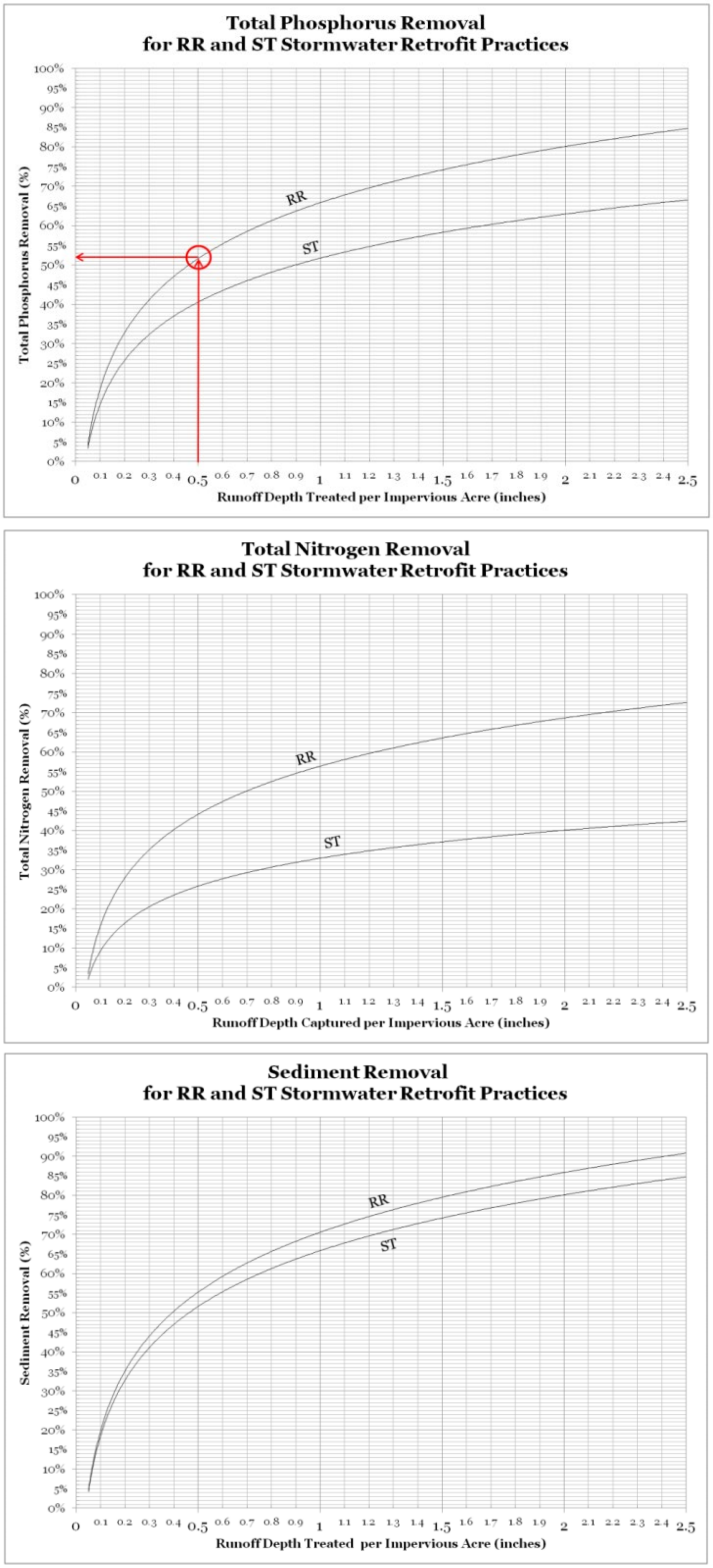

Figure 15 – Retrofit practices findings from the Chesapeake Bay Stormwater Working Group's Recommendations of the Expert Panel to Define Removal Rates for Urban Stormwater Retrofit Projects

Private development activities, including green or gray infrastructure retrofits or stormwater strategies for new construction to achieve the City's "25:2 requirement"[9] and water quality requirements, also provide water quality treatment. When achieved using green infrastructure strategies, such private parcel strategies may also be advantageous in achieving desired outcomes described in Resilient Cambridge Greener City strategies.

Near-term priority **<u>separate sewersheds where green infrastructure implementation may have flood mitigation and water quality co-benefits:</u>** Sparks St. catchment (Neighborhood Nine/West Cambridge), DeWolfe St. catchment (Mid-Cambridge)

Greener City co-benefits

In addition to the stormwater management outcomes, the implementation of green infrastructure can be beneficial in achieving several desired outcomes outlined in the Resilient Cambridge Greener City strategies. These outcomes include (among others): expansion of tree canopy, improving quality of urban green spaces, mitigation of urban heat island (UHI) effects, and enhancing urban livability. These co-benefits share significant overlap with desired outcomes in the City's Urban Forest Master Plan (UFMP), as well as Climate Resiliency Zoning Task Force recommendations.

Green infrastructure strategies for flood mitigation directly overlap with the Resilient Cambridge strategies for a Greener City, which help improve the performance of urban green spaces. In the public right-of-way, theimplementation of new or retrofit tree pits, and tree trenches - will (in time) improve local tree canopy, helping achieve desired outcomes of the City's UFMP. Parcel-based green infrastructure strategies (e.g., rain gardens, vegetated swales, subsurface infiltration systems, green roofs, downspout planter boxes, porous pavements, and rain barrels/cisterns) also contribute towards tree canopy expansion, infiltrationand groundwater recharge, and stormwater reuse. Each of these strategies can also contribute to UHI mitigation by improving canopy coverage and shading, reducing albedo of paved surfaces and rooftops, and restoring perviousness.

Spatial analysis of flood mitigation opportunities and priority co-benefit opportunities

As part of a citywide modeling study that investigated the efficacy of distributed green infrastructure strategies to mitigate flooding (CRWA 2018 study), a base conditions scenario and three scenarios for green infrastructure implementation were represented within the City's hydraulic model. The analysis varied the implementation level of distributed green infrastructure (i.e. 0%, 10%, 25%, and 50% of surface-level impervious surfaces routed through green infrastructure) within and modeled both total volume and peak flow outcomes (measure in MG and MGD, respectively). Each of these implementation levels constitute a significant amount of green infrastructure investment and are a significant challenge to achieve within a densely urban built environment.

[9] The City's 25:2 stormwater requirement is based on new construction and redevelopment projects demonstrating that the 25-year peak flow under post-construction conditions will be less than the 2-year peak flow under pre-construction conditions. The City is considering revising this requirement to use the 2070 storm conditions for both the 2- and the 25-year storms.

While the analysis performed for the CRWA 2018 has its limitations[10], this scenario-based modeling effort represents another quantitative resource assessing (spatially) where the implementation of green infrastructure strategies may be most efficient in terms flood mitigation. The results of the 2018 study, while simplified to the sewershed level (i.e., 22 of the City's major storm and combined sewer catchments), provide a good basis for comparison and validation to Figures 10 and 11 in that it quantitatively assesses the sensitivity of key flood parameters (stormwater volume and peak flow rate) within the City's hydraulic model.

Although neither the 2018 study nor the current citywide analysis presents a comprehensive understanding of where and how green and gray infrastructure strategies need to be effectively combined (refined analysis is required for individual projects and areas of interest), there are some shared observations between the two approaches that coincide with the City's priorities, including ongoing CSO mitigation efforts, water quality objectives, MS4 compliance, and Greener City strategies.

The following areas, for which the analyses suggest green infrastructure implementation may be best suited to achieve flood mitigation outcomes, are identified as priorities for follow-up analyses or near-term projects:

- **The Port:** As documented in The Port Preparedness Plan and Short Duration Storm analysis, this neighborhood experiences flooding as a result of both short-duration ("flash flood") events and longer duration, higher-volume events (e.g., a 24-hour storm event). Figure 10 highlights a portion of this neighborhood (dark green area corresponding to flood impact Type A south of Broadway, east of Prospect St, and west of Columbia St.) where clustered implementation of GI may help mitigate stormwater flows contributing to flooding experienced in downstream subcatchment areas near Bishop Richard Allen Dr. and Columbia St. The Port Short Duration Storm analysis modeling indicates that implementation of GI strategies may also help reduce flooding seen in short duration-type storms*, such as flooding experienced near Ashburton Pl*. The Port neighborhood also ranks among the highest priority by three Greener City metrics, with low pervious area, tree canopy cover, and vegetated condition per NDVI (see Greener City; Table 2).

- **Wellington-Harrington**: Figure 10 highlights a portion of this neighborhood (dark green area north of Cambridge St, east of Prospect St, and west of Harding St.) as an area where clustered implementation of GI may help reduce flooding near King Open School. This area is part of the CAM017 combined sewershed, which is the City's largest sewershed, and also ranks highest by imperviousness (as percentage of total area, compared to other sewersheds), and by CSO discharge to Charles River (discharge volume, as modeled at CAM017 outfall). The Residential Streets GI modeling[11] analysis suggests that GI implementation (managing upwards of 10% of impervious surface) could have significant outcomes for total volume and peak flow reduction, as compared to other sewersheds. This neighborhood also ranks among the highest priority by

[10] Note: a more detailed assessment of localized hydraulic conditions should be performed to address flooding at any particular location

[11]CCPR Alewife Preparedness Plan Appendix B : https://www.cambridgema.gov/-/media/Files/CDD/Climate/CCPR/ccpralewifeappendixbgianalysisanduhimodeling_processed.pdf

three Greener City metrics, with low pervious area, tree canopy cover, and vegetated condition per NDVI (see Greener City; Table 2).

- **Cambridgeport:** Figure 10 highlights portions of this neighborhood - particularly those west of Pleasant Street or north of Erie Street (near Dana Park) - as an area where clustered implementation of GI may help reduce future flooding in areas that experience little or no flooding today. Cambridgeport is the City's 2nd most impervious sewershed (by total impervious area) and ranks alongside The Port as the highest by percentage (as compared to other sewersheds). The FloodViewer maps indicate that changes in precipitation-based flooding (changes in surface extent and depth between present day conditions and 2070) in this neighborhood are among the most significant (in terms of projected change) in the City. This neighborhood is also part of a separated sewer system that drains to the Charles River, adding to the potential cobenefit case for GI, as there may be water quality benefits that accrue during smaller storm events (including those that do not produce flooding). The Cambridgeport neighborhood also ranks among the higher priority neighborhoods for green infrastructure implementation by several Greener City metrics, including low pervious area and tree canopy cover (see Greener City; Table 2).

- **Mid-Cambridge:** Figure 10 highlights portions of this neighborhood - particularly those in the southeast near The Port (i.e., south of Broadway, east of Hancock Street) – as potential "upstream" drainage areas where implementation of GI can help mitigate downstream subcatchment flooding experienced in The Port. These drainage areas include parts of the Western/Flagg St. separated sewershed (draining to the Charles River), as well as parts of the CAM017 combined sewershed. In addition to flood mitigation, implementation of GI in these areas may have greater water quality benefits (in separate sewer areas), and potentially help mitigate total volume and peak flow contribution to CSOs at CAM017.

- **Neighborhood Nine**: Figure 10 highlights elevated portions of this neighborhood draining to Alewife watershed (high elevation areas along topographic drainage divide, between Alewife and Charles River basins; refer to Figure 3), which are "upstream" areas of interest in mitigating downstream flooding in Alewife watershed subcatchments. Despite relatively low total imperviousness (54%), as compared to other sewersheds, the higher elevation portions of this neighborhood (just west of the drainage ridgeline) are important in terms of runoff generation and timing, given overlandand piped slope to areas that experience flooding. Neighborhood Nine includes most areas within the CAM401A combined sewershed, which currently ranks highest among Cambridge's outfalls in the Alewife watershed in terms CSOs (based on activations and total volume).

In addition to the neighborhoods identified above, green infrastructure strategies may also overlap additional City goals in the neighborhoods below. In these areas, the flood mitigation benefit of green infrastructure strategies is less significant (light green areas in Figure 10), and additional analysis may be needed to better assess and quantify potential co-benefits:

- **West Cambridge:** Most flooding in West Cambridge is concentrated, locally (between Huron Ave, Aberdeen Ave, and Mount Auburn St near commercial areas and the Cambridge Public Library – Collins Branch). Figure 11 indicates that gray infrastructure solutions may be needed to address flooding of this magnitude in these areas (Impact Type A lighter gray areas). However, green infrastructure solutions can be considered to supplement gray strategies. This area is part of the CAM005 combined sewershed, which ranks alongside CAM017 for most CSO activations and volume for Cambridge's remaining combined sewer outfalls to the Charles River.

- **North Cambridge:** Neighborhood Nine includes most areas within the CAM401B combined sewershed, which currently ranks highest among Cambridge's outfalls in the Alewife watershed in terms CSOs (based on activations and total volume) along with CAM401A. The Residential Streets GI modeling analysis[12] suggests that implementation of GI in this area may not be as efficient (in terms of total flow volume and peak flow mitigation) as in other parts of the City. However, more analysis may be required to investigate opportunities in higher elevation areas, similar to Neighborhood Nine / CAM401A.

- Additional separated sewer areas in **Neighborhood Nine**, **West Cambridge**, and **Mid-Cambridge**: The Residential Streets GI modeling analysis suggests that implementation of GI in the Sparks St. and DeWolfe St separate sewer catchments **may be a strategic consideration for water quality outcomes in the Charles River**.

  Both of the catchments are below in the middle tier of the 22 sewer catchments for imperviousness(by total area and percentage), with the GI modeling indicating that total volume removal and peak flow reduction benefits in these areas may be more efficient than GI implemented in othercatchments of similar size and imperviousness:
  - The Sparks St. sewer catchment includes areas in both **Neighborhood Nine** (north of Concord Ave, west of Linnean St.) and **West Cambridge** (south of Concord Ave, between Lowell St. and Sparks St.).
  - The DeWolfe St. sewer catchment is located southeast of the Agassiz neighborhood in **Mid-Cambridge** (south of Cambridge St, east of Harvard Yard, and west of Dana St). *Mid-Cambridge areas ranks among the higher priority neighborhoods for green*

[12]CCPR Alewife Preparedness Plan Appendix B : https://www.cambridgema.gov/-/media/Files/CDD/Climate/CCPR/ccpralewifeappendixbgianalysisanduhimodeling_processed.pdf

infrastructure implementation by several Greener City metrics, including low pervious area and tree canopy cover (see Greener City; Table 2).

8.0 Key findings and recommended actions

The City has already implemented (or is in the process of implementing) numerous green and gray infrastructure improvements to improve stormwater management and reduce flooding. However, additional strategies will be needed to address citywide flooding, which is projected to increase with climate change. In addition to high-volume precipitation events, a key finding of The Port Short Duration Storm analysis is that effective combination of green and gray infrastructure strategies for addressing high-intensity short-duration-type storms (i.e., cloudburst or "flash flood" events) may vary by location, as flooding can be a function of several factors (e.g., surface storage capacity, inlet sizing and conveyance, or storm system capacity).

The following recommendations specify both early actions and long-term opportunities for the City to consider addressing stormwater flooding:

1. Integrate findings from the citywide analysis that highlight areas where green, and/or gray infrastructure strategies can be effectively implemented into **planning and design of near-term priority projects.** These include the City's ongoing infrastructure improvements projects, upcoming capital improvement projects included in the City's 10-year Sewer and Drain Infrastructure Plan, the 5-year Sidewalk and Street Reconstruction Plan, future long-term combined sewer overflow (CSO) management plans, and the Open Space Plan update.

2. On an ongoing basis, consider the potential flood mitigation benefit, and related co-benefit opportunities (water quality improvements and UHI mitigation) of individual projects as part of ongoing **capital improvement planning/prioritization for CSO mitigation programs and MS4 permit compliance.**

3. Integrate green and gray infrastructure recommendations into the **identification, planning, and design for future projects** (e.g., priority I&I Removal projects, sewer separation projects, Chapter 90 roadway projects, pilot Cool Corridor concepts, private site development review, municipal stormwater retrofits).

   Where previous analysis has not been already conducted, **a targeted modeling analysis of flood mitigation alternatives should be conducted in neighborhoods** where green and gray infrastructure have been identified to be most effective for flood reduction (i.e., mapped areas in the darkest green & gray colors in Figures 10 and 11). Similar to prior analyses performed for The Port, Alewife, and Kendall Square areas, these studies should consider: specific project alternatives, land use and cover types, parcel ownership, topography, sewer type and piped infrastructure, density of critical underground infrastructure, available space for BMPs, soil and groundwater conditions, past site use/environmental limitations, and co-benefit opportunities.

4. The City should consider a **targeted program to retrofit catch basins** within the highest green infrastructure opportunity areas (i.e., those in dark green on the map, where green infrastructure is likely to have the highest flood mitigation benefit) and replace these with leaching catch basins connected to tree box filters (as recommended in The Port Preparedness Plan) or infiltration trenches, where feasible.

5. For new constructions and redevelopments, that City should consider a new requirement for new rooftops to maximize implementing green/blue roof, or a combination with other sustainable energy and UHI mitigation strategies (similar to New York City's Sustainable Roof Laws, which require green roofs or solar panels on all new construction or buildings undertaking major roof renovations). For large commercial, industrial, or institutional buildings in neighborhoods that experience flooding (and where relatively fewer near- or long-term capital projects are identified), the City should consider a **targeted program for green roof/blue roof retrofits.** Such a program can be limited to existing rooftops where the Resilient Cambridge Better Buildings analysis indicates high feasibility potential for retrofits

6. In conjunction with Greener City recommendation #4: "*Coordinate with study committee focusing on green infrastructure improvements in public right of way as an* ***initial planning phase of Cambridge Cool Corridors Initiative****",* including **screening/suitability assessment of stormwater management retrofit opportunities** in areas identified as "UHI hot spots" within the public realm.

7. In coordination with implementation of resiliency improvements in The Port, **develop citywide guidance materials for private property owners** interested in implementation of green/gray infrastructure in dense urban setting on private property. Provide private property owners guidance for non-structural BMPs (i.e., street sweeping, leaf collection, and other strategies to support compliance with MS4 requirements).

8. **Revisit the City's stormwater policies for new private development and major retrofits,** such as using the 2070 climate conditions as part of "25:2" requirement and updating the water quality volume capture criterion to be more than 1-inch (possibly using 1.5-inch), where feasible.
9. **City to map out soil conditions, ground water and soil contamination conditions to help identify locations where infiltration systems are suitable.**

10. **Add a statement about: The need and value of proper and regular operation and maintenance of any green or gray infrastructure installation. Annual O&M requirements for projects should be through the provisions found in the Stormwater Control Permit or through an annual self-certification by the property owner**