Executive summary

This report documents the Minnehaha Creek Watershed District, Weather: Extreme Trends project, including objectives, methods, results, and synthesis of findings. The project significantly increased awareness at local, municipal and regional scales, of the vulnerability of stormwater management systems to already-intensified precipitation and projected mid-21st century extreme precipitation. The project identified specific components in existing systems that are vulnerable for current and future climates, and components that remain adequate even under extreme precipitation conditions. Estimated costs were developed for several adaptation tactics, and the ability of Low Impact Development methods to mitigate flooding was investigated. An extensive stakeholder outreach program incorporated stakeholder concerns into project goals. The program provided stakeholders with forums to: identify the strengths and challenges of local stormwater management governance; understand the project's technical results; and derive plans to act on results. These forums expedited the translation of technical results into awareness of the need for, and specific requirements of, a program to adapt stormwater drainage.

A number of communities in the region have already incorporated sustainable drainage methods into their stormwater management strategies. This capacity to adopt better methods, combined with the increased awareness of stormwater vulnerability, should enable many communities in the region to respond sooner to climate risk than less forward-thinking ones.

Studies have well-documented that extreme rainfall events have already increased in many regions, including the upper-Midwestern United States where the Minnehaha Creek Watershed District is located. This trend is expected to continue. The rate of increase in extreme events is exceeding climate model projections. Moreover, not only do all emissions scenarios understate already-observed atmospheric warming, but precipitation may be twice as sensitive to warming as is reflected by models.

The increase in extreme events causes more-frequent flooding than anticipated by the design specifications that stormwater management systems have been constructed to. These engineering specifications were chosen to limit how often a community must bear the damages and disruption from flooding. Design standards were based on assumptions about the amount of damages and disruption, i.e. the frequency and size of flooding, that over time a given community can be expected to absorb without inordinate or permanent degradation of the ability to thrive. The increase in extreme events stresses a community's limited financial and non-financial resources, and at the household-level limited insurance payments do not make-whole. Thus, communities are incurring unanticipated and excessive costs as a result of forestalling adapting systems. Climate scientists do not anticipate a significant reduction in the uncertainty of long-term climate projections. For these reasons, benefits are not apparent from a "wait and see" approach to adaptation of civil infrastructure.

Uncertainty and incomplete information are core conditions of government decision-making. Uncertainty in the hydrological modeling that supports drainage system design remains large even after a century of theory and practice development, and is comparable to uncertainty in long-term climate projections. Especially in Europe, communities have realized that uncertainty is not an obstacle to adaptation of civil infrastructure. The project described in this report introduced this realization to communities in the Minneapolis, Minnesota region.

Schedule of key findings:

Background

- The quantity of published adaptation studies lags a decade behind the quantity of published impacts assessments on which adaptation is predicated (Wilby et al., 2009);
- Detection of a climate change signal in extreme precipitation may not occur for 30-50 years. As a result, benefits from forestalling adaptation are not apparent (Fowler and Wilby, 2010);
- Infrastructure adaptation may be more urgent than generally assumed:
  - √ All SRES emissions scenarios understate already-observed warming (Rahmstorf et al., 2007);
  - √ Precipitation appears to be increasing at a rate of 7% per °C, rather than the 1-3% per °C modeled by coupled-climate models (Wentz et al., 2007);
  - √ Measured increases in daily extreme precipitation are exceeding coupled-climate model simulations (Allan and Soden, 2008; Lenderlink and van Meijgaard, 2008)
- Dessai et al. (2009), concluded that "society can, and indeed must, make adaptation decisions in the absence of accurate and precise climate predictions...[furthermore,] the limits to accurate and precise foreknowledge of future climate have been falsely constructed as an absolute limit to adaptation."
- There is a need, in hydrological impacts research, to move away from comparison studies into the provision of decision-making tools for planning and management that are robust to future uncertainties (Fowler et al., 2007a); Grove et al., 2008).

Purpose and aims

- The purpose of the project was to promote implementation of local-scale stormwater infrastructure adaptation;
- To achieve this purpose, projects aims were to:

√ Gain popular support (Lowe et al., 2009), and stakeholder confidence in the decision to implement infrastructure adaptation;
√ Promote visionary leadership and organizational learning (Wilby and Mengelt, 2010);
√ Provide science that is "actionable", i.e. that includes "...data, analysis and forecasts that are sufficiently predictive, accepted, and understandable to support decision making…" (Lowe et al., 2009);
√ Promote an adaptation plan that can be implemented through existing policies and regulations (Lowe et al., 2009); and provide guidance for practitioners (Wilby and Mengelt, 2010);
√ Clarify research issues pertaining to the budgeting, scheduling, and sizing of stormwater adaptation in the context of uncertainty in long-term climate information;
√ Add to the corpus of expertise in the implementation of adaptation, that is currently insufficient (Yohe and Mengelt 2010; Sanchez-Rodriguez, 2009), but indispensible for efficient, economical, and effective adaptation.

Overarching findings

- Foundational premises of this project were that: information and methods are available today to support adequately-reliable infrastructure adaptation; the resolution of certain key issues in infrastructure adaptation will be attained most efficiently through learning-by-doing; and these issues can be studied concurrently with providing actionable adaptation guidance to communities;
- Findings of this study have broad application nationally and internationally, as communities transition civil infrastructures to accommodate already-occurring and projected change, in order to maintain historically accepted risk-levels. Though focusing on stormwater management systems, the principles and methods developed provide a template for other local, regional, and national infrastructure systems. Findings significantly improve national and international capacities to respond to climate variability and change;
- This study extends previous work by the project team demonstrating that required stormwater management system capacity, and adaptation costs to achieve this capacity, can be determined for given combinations of climate model, emissions trajectory, and landuse, using established civil engineering design methods and standard construction cost compilations;
- As a result of factors that include an already changed precipitation climate, portions of stormwater systems are already undersized for current conditions (Table ST.1). Therefore, communities are already assuming a higher level of risk than intended under historical design standards. This contradicts the belief that a “wait and see” strategy is a valid response to changing climate conditions;
- A significant percentage of stormwater system components remain adequately sized even for pessimistic climate change impacts (Figures ST.2, ST.4). As a result, communities generally should expect that less-than 100% of their existing stormwater system will require adaptation in order to maintain historically tolerable risk levels;
- Recent extreme rainfall amounts in the region of the study site approximate, or exceed, pessimistic climate change projections (Figure ST.3). Previous studies in New Hampshire found similar results, and support a recommendation that communities adapt conservatively, providing a safety margin equivalent to adapting for pessimistic future conditions;
- Required capacity is insensitive to changes in precipitation intensity, and thus insensitive to uncertainty. For example, an approximately 150% increase in the design precipitation results in an approximately 30% increase in the number of undersized components (Figure ST.4);
- The vulnerability of stormwater systems to more extreme precipitation varies according to region, topography, engineering design standards, and type of drainage system (Figure St.4);
- *Low Impact Development* (LID) methods reduce required capacity and associated adaptation costs for less-intense storms. However, LID benefits are small at extreme precipitation intensities;
- A program of education and outreach can significantly increase a community’s motivation to protect itself from more extreme climate impacts. This motivation has persists past the completion of projects, and over the near- and mid-term can be expected to significantly reduce a community’s exposure to losses from flooding;

Uncertainty: significance and management

- As recognition widens that no significant decrease in the uncertainty of long-term climate projctions is likely in the foreseeable future, and as impacts from climate change increasingly manifest, communities need to understand the significance of uncertainty, and the size and affordability of safety factors that accommodate uncertainty;
- The study design used a large quantity of individually-modeled drainage system components, multiple landuse and climate-change scenarios, and established civil engineering and hydrological methods. This design promoted the reliability of capacity and cost estimates, and limited uncertainty to that which is inherent in hydrologic modeling and long-term climate forecasts;
- This study examined the effect of a high degree of uncertainty in long-term climate projections, by selecting precipitation scenarios that span a wide range of design storm intensities. For the design storm, modeled increases from the recent climate for the A1b and upper-95% confidence limit of the A1fi scenarios, for the GFDL 2.1 CCM, are 18% and 153%, respectively (Figure ST.4). This is a span of 135%, and can be compared with the range of uncertainty in hydrological modeling, to assess the validity of assumptions that long-term climate projections are too uncertain to support adaptation;
- Stormwater planners and engineers have routinely accepted, in the normal course of professional practice, a level of uncertainty in hydrological modeling that is comparable to that in long-term precipitation projections:
  √ A survey of hydrological calibration engineering reports obtained 205 peakflow and streamflow datapoints, from which the range

of variation between simulated and gauge-measured flows were determined. This range exceeded the range of mid-21st century design storms projected by the present study (Table ST.3, Figures ST.5, ST.6);

√ For this study, the calibrated hydrological models of the City of Victoria and City of Minneapolis Pipeshed 76-010 were found to vary up to 40% from gauge-measured flows at the watershed outlets, even though the Nash-Sutcliffe Efficiency coefficient was 0.83 (Table H.1). This range of uncertainty falls within the median variability between the current and projected mid-21st century 10-year design storms;

√ The National Weather Service recently updated the intensity-frequency isopluvial maps for the Midwestern United States, including the study site (Atlas 14, Volume 8). For the study site, Atlas 14 reports a 95% confidence interval of 28% for the recent 10-year 24-hour precipitation (Table ST.2);

√ The reference for design storm specifications for stormwater system design, since the early-1960s, has been Technical Paper 40 (TP-40; Hershfield, 1961). However, *TP-40* is neither accurate nor precise, and the decision to publish it was controversial (Wilson, 2013). Precipitation intensity-frequency was computed from historical datasets half the length, on-average, of that required for accurate results. *TP-40* provided only point estimates for precipitation levels, omitting confidence intervals and thus portraying a false degree of precision; Isopluvial contours for the 24-hour, 25-year precipitation, per *TP-40*, generally are 25% greater than contours published only twenty-five years earlier by Yarnell (Yarnell, 1935);

- In published literature, "soft" adaptations such as general resilience and capacity building remain the standard prescription for potential civil infrastructure vulnerability due to uncertainty in CCM output (e.g. Rosenberg, 2010). Yet "soft" adaptations are likely insufficient by themselves, requiring eventual supplement from "hard" adaptation methods (White House Climate Change Adaptation Task Force, 2010; Miller et al., 2010);
- The ability to quantify required capacity and related construction costs for specific climate change scenarios, the insensitivity of capacity and costs to uncertainty, and the percentage of pipes and culverts that never require upsizing, all serve to limit the impact of uncertainty inherent in climate change projections;
- In a rational decision framework, adaptation would proceed when the cost of damages from failure to adapt, exceeds the cost resulting from adaptation under uncertainty (Figure ST.7). We believe that the point of equilibrium has already been reached for many communities;
- By constructing systems for more extreme scenarios and to the upper limit of confidence intervals, a safety factor that buffers uncertainty is incorporated to adaptation programs. Moreover, the insensitivity of construction cost to increased precipitation intensity provides incentive to incorporate even a very large safety factor. Thus, the ability to manage uncertainty supports a conclusion that adaptation is viable under current levels of uncertainty in the severity of future climate impacts.
- The development of climate change-cognizant stormwater systems is possible under conditions of non-stationarity. European practice has applied design storm *change factors* to increase design standards for projected climate change, according to the useful life of the infrastructure being designed (Hennegriff et al., 2006).

Outreach program

- Overall, the project resulted in a significant increase in awareness, at watershed, municipal, and regional scales, of risks and possible responses associated with increases in extreme storms expected from long-term climate projections;
- The project earned significant visibility in local news media (Table O.1);
- To-date, at least eight conference presentations have transferred project results. At least three peer-reviewed publications are expected from the project;
- Stakeholders expected that the project would result in increased collaboration among governing organizations (Figure O.4);
- Stakeholders felt that, as a result of the project, as a group they developed a shared vision for stormwater management (Figure O.5);
- The outreach program utilized the Collaborative Planning Approach, and engaged a broad cross-section of stakeholders (Figures O.1, O.2);
- As a result of the first public forum, stakeholders felt more knowledgeable about issues and possible actions related to stormwater management in the Minneapolis-St. Paul metropolitan area (Figure O.3);

Precipitation downscaling model

- Current stormwater design practice in the Minneapolis-St. Paul metropolitan area specifies components sized for the peak flow from the historical once-in-ten-year (10-year) precipitation event (i.e. 10% annual probability), with a twenty-four (24) hour duration. The study projected a mid-21st century range of values for this intensity/duration;
- Data from an ensemble of fourteen combinations of model generation (CMIP3 and CMIP5), model group (NCAR and GFDL), *coupled climate models* (PCM, CCCM4, CM2.1, and CM3), and future climate trajectories (for CMIP3, greenhouse gas emissions from the SRES: A1b, A1fi; for CMIP5, greenhouse gas *Representative Concentration Pathways* RCP 4.5, 6.0, 8.5), and gridpoint size, provided a range of climate realizations to assess impacts and uncertainty;
- The fourteen (14) combinations were downscaled to the local scale for the Minneapolis-St. Paul International Airport. The *most likely* and *upper-95% confidence limit* estimators from these fourteen combinations were selected for hydrological modeling, resulting in a sample of twenty-eight precipitation projections. The mean precipitation for the sample was 5.7", with an *upper-95%*

confidence limit of 6.6" and a maximum of 10.1";

- From the sample of 28, a subset of five (5) values, representing a range of results, were selected to establish response curves for certain hydrologic and cost modeling. For other modeling, a subset of three values were used, labeled "Optimistic", "Moderate", and "Pessimistic" scenarios;
- National Climate Data Center (NCDC) historical records for climate stations proximate to the study sites, and sets of *CCM* gridpoints encompassing these NCDC stations, provided data for downscaling. Thirty-year records of precipitation were downloaded for each station, and for each gridpoint/model/scenario combination. Time periods obtained were 1926-1955 for validation baseline, 1971-2000 for validation predictand and climate change baseline, and 2046-75 for climate change predictand. This resulted in almost 1,000 historical or simulated precipitation datasets;
- A *point process, peaks-over-threshold* statistical method was used to derive the 10-year 24-hour rainfall event for each thirty-year dataset;
- A variation of the Change Factor, or Perturbation method, was used to statistically apply percentages of change, from the recent to projected future climates downscale long-term precipitation projections to the local scale.

Hydrologic/hydraulic, buildout, and low impact development (LID) models

- The EPA's Stormwater Management Model (SWMM; Rossman, 2010) was used to simulate rainfall-runoff processes and stormwater system hydraulics for both study sites. Existing SWMM models were available for Minneapolis Pipeshed 76-010 and the City of Victoria pipeshed, and were utilized as the basis in this study;
- The average impervious surface for Pipeshed 76-010 was 50%, and for Victoria was 14% for existing landuse and 29% with buildout (Table H-2);
- Mid-21st century landuse scenarios were developed for the study sites based on current zoning policies and projected population growth;
- Several adaptation tactics were examined for ability to accommodate increased runoff from climate change. These included upsizing existing infrastructure and implementing *low impact development* (LID) practices. In Pipeshed 76-010, three additional tactics were reviewed: over-curb surface storage in areas where structures would not be impacted, above-ground dry storage basins, and underground storage;
- For pipe upsizing scenarios, the diameter of surcharged pipes downstream of flooded model nodes was increased incrementally until flooding was reduced to zero for all mid-21st century 10-year design storm scenarios;
- The adaptive capacity of LID was simulated by defining an LID unit sized to capture the first 25 mm (1 in) of runoff from impervious surfaces within a given model subcatchment. In Pipeshed 76-010, we tested five rates of incorporation of LID: 100% of subcatchments; and, to simulate a more realistic adoption of retrofitted by residents, randomly selected 10%, 15%, 20%, and 25% of subcatchments in the pipeshed. In Victoria, LID scenarios included: LID units sized to capture the first 1" (25 mm) of runoff from existing and built-out impervious area; and LID units sized to capture the first 1" of runoff only from new construction;
- In both study sites, pipe upsizing was by far the most effective means of adapting the stormwater system. For Victoria, pipe-upsizing may not be the most economical means of adapting. In the case of Minneapolis Pipeshed 76-010, the effectiveness of pipe upsizing was limited to a design storm depth of about 6 inches. This depth is 50% greater than the current 10-year design storm and within the range of increase expected under a moderate climate change scenario;
- The inability to mitigate flooding through pipe upsizing beyond the 6 inch precipitation depth reflects a system in which backwater effects are dominant, and surface storage and other detention opportunities are limited. Such a condition is not uncommon in urban areas, particularly where surface storage and infiltration capacity have been lost to higher-density development;
- In both Victoria and Pipeshed 76-010, pipe upsizing led to an increase in predicted peak flows at the watershed outlet. This demonstrates that downstream impacts such as channel stability, water quality, and flooding of downstream communities should also be considered in assessing the effectiveness of adaptation approaches toward creating more climate-resilient communities;
- Projected increases in flooding were not mitigated through LID at either study site for even the most optimistic mid-century precipitation scenario. This is not surprising, however, as LID practices – as modeled here and in their typical application – are designed to capture runoff associated with relatively frequent, small storms (e.g. 1") rather than the 10-year storm modeled in this study;
- Victoria is relatively resilient to climate change impacts. This is not by accident. Through its development policies of buffer setbacks and restricting floodplain development, the City has retained much of the landscape's capacity to provide hydrologic ecosystem services. Victoria's existing network of stormwater ponds, wetlands, and lakes suggest that climate change resilience in Victoria (or in other communities with infiltration-limited native soils) can still be achieved by preserving (and/or creating systems that mimic) the hydrologic functions of naturally-occurring ecosystems, even apart from enhanced infiltration;
- A viable adaptation option for Victoria would be to allow flooding in streets and existing open spaces (e.g., a ball field and golf course), rather than upsizing pipes or adding additional capacity for infiltration;
- In an already built-out community such as Minneapolis, infiltration-based adaptation practices come with a different set of challenges, including retrofitting around existing foundations and utilities, and in brownfield applications the potential to mobilize contaminant plumes. Despite these challenges, LID practices have been applied more widely in the City of Minneapolis and neighboring urban communities. Coupling a moderate (e.g. 10%) rate of adoption of LID, with pipe upsizing, may be a viable tactic in an adaptation "tool-kit", even in a built-out community such as Minneapolis;

Pipeshed 76-010

- Curves were fit to establish the relationship between change in design storm depth and the number of undersized components in the existing storm sewer network (Figure H.3). A given conduit was only considered to be undersized if it was (1) surcharged *and* (2) upstream of a flooded node;
- Based on the practicalities of managing surface flooding in a built-out environment, the City of Minneapolis generally prioritizes flooding as either acceptable or unacceptable. Acceptable flooding pertains to flooding that is stored in streets or over curbs up to the elevation of structures. Unacceptable flooding includes any flooding that exceeds the elevation of structures, thereby posing a risk to property;
- Approximately 10% of existing pipes in Pipeshed 76-010 are too small to convey runoff associated with the recent 10-year storm (Figure H.3). This result likely stems from changes in design standards that have occurred over the life of the storm sewer system. The proportion of undersized pipes increases to approximately 18% and 42% for the moderate and pessimistic mid-century precipitation scenarios;
- The volume of flooding predicted for the range of mid-century precipitation scenarios also increases for the existing drainage system, up to a factor of 40 (Table H.4, Figure H.4);
- In order to identify points in the system most vulnerable to flooding, a series of "stoplight" maps were developed (Figure H.5). The elevation of flood waters relative to structures was determined outside of SWMM in ArcGIS using 1-meter resolution surface elevation data;
- Upsizing pipes to reduce flood volumes for the 4.15" to 5.65" precipitation scenarios required increasing the diameter of 3,439 to 12,272 linear feet of pipes in the system (Figure H.7);
- Pipe upsizing has limited ability to mitigate flooding. Upsizing pipes for storms of 6.56" and larger increased total flood volume compared with the drainage system (Figures H.6, H.7). This is due to backwater effects of the receiving water body which, under high flows, serves to restrict free discharge of runoff from the pipe network to the lake. Restricted discharge also contributes to negative (up-gradient) pipe flows as runoff unable to exit the system at backs up into the pipe network and is ejected as surface flooding at low-lying areas of the system. Figure H.8 provides an example of a location in the system in which upstream pipe upsizing resulted in a transfer of the flood volume downstream;
- Unacceptable flooding was not completely eliminated through any LID scenario, even for the most optimistic climate change projections (Table H.4, Figures H.6, H.7). Increasing the rate of utilization of LID did reduce the volume of unacceptable flooding, but with diminishing results;
- Although not completely eliminating unacceptable flooding, LID did reduce this for all precipitation scenarios, even when only applied to 10% of the total pipeshed impervious area;

Victoria

- The hydraulic response of Victoria's stormwater system contrasts sharply with that of Pipeshed 76-010 (Figure H.8), due to a lower percentage of land having been developed, and to the incorporation of runoff management methods. Fewer-than 1% of components in Victoria's stormwater system are undersized for the current design storm and up to a precipitation depth of about 5.6 inches. Thus, the system is adequately sized for up to a 40% increase beyond the current design storm;
- Beyond a 40% increase in the design storm, Victoria's system displays a similar rate of increase in the number of undersized components for a given increase in precipitation as observed for Pipeshed 76-010 (Figure H.8);
- In a developing community such as Victoria, changes in climate are expected to act in concert with land use change upon hydrological processes (Figure H.9);
- Constructed storage ponds, a prominent feature in the City's stormwater management system, have sufficient storage capacity up to the 6.56-in scenario, afterwhich eight (8) of the thirty-one (31) ponds (26%) overtopped (Figure H.10b). Thirteen (13) ponds, representing 40% of the total, overtopped in the most pessimistic scenario;
- Even for the most pessimistic climate scenario, 10.1", all surface flooding in Victoria was contained within streets and public open spaces. However, if the objective were to maintain the current level of service, i.e. no surface flooding, adaptation methods would be necessary;
- Three adaptation scenarios were considered for Victoria: allow flooding up to a level that would be confined to streets and public spaces, i.e. "do nothing"; upsize pipes to convey projected peak flows and eliminate flooding completely; and implement LID at various intensities to reduce flood volumes by increasing infiltration (Figure H.11);
- In contrast to Pipeshed 76-010, flooding associated with climate change projections could be completely mitigated through pipe upsizing. The total length of upsized pipes ranged from 577 ft. for the 4.15" and 4.77" precipitation scenarios, up to 14,132 ft. for the pessimistic 10.1" scenario (Figure H.12);
- Increasing pipe diameters increased the peak flow at the watershed outlet (Figure H.11a), however, the increase was nominal (1-5% across all mid-21st century precipitation scenarios). This is likely due to the buffering effect of the watershed's network of stormwater ponds and natural lakes and wetlands;
- As was the case in Pipeshed 76-010, projected flooding was not fully mitigated by LID practices (Figure H.11a). The reduction in flood volume was greatest for the 6.56" precipitation scenario (26% as applied to all impervious surfaces; 13% for new construction only). Flood volume reductions were generally less than 10% for all other climate scenarios;
- The addition of LID is not expected to have a substantial effect on the length of pipe that would need to be upsized to completely eliminate surface flooding for all projected precipitation scenarios. This likely reflects some limitation to infiltration by clay-like soils in the Victoria study area;

Cost model

- The cost analysis provided planning-scale cost estimates for several stormwater management alternatives, to adapt existing systems for conveying projected mid-21st century design runoff in Minneapolis and Victoria;
- Adaptation plans typically consist of a variety of tactics that can be combined in various ways (Hasnoot et al., 2013). A community selects a set of adaptation pathways that provide sufficient adaptive capacity and flexibility for accommodating uncertainty, and that are achievable within its tolerance for risk, its political environment, and its economic resources;
- Adaptation pathways consist of a combination of tactics that might include: creating barriers to the impact; changing infrastructure to assimilate the impact; changing expectations through policies, so to accommodate the impact; moving away from the impacted areas; and doing nothing, which implies accepting a higher-than historical risk. All have both quantifiable and intangible costs and benefits.
- For this study, cost analyses were performed for five adaptation actions:
  √ Replacing the existing system with larger pipes;
  √ Diversion of excess waters to detention basins;
  √ Diversion of excess waters to underground storage;
  √ Cost mitigation from instituting Low Impact Development;
  √ Damage costs for waters exceeding curb-height;
- Because of differences between the two cities in the conditions that determine the rate of undersized components (Figure C.1), costs are not comparable and the optimal mix of tactics will differ (Figures C.1, C.2);
- The analysis derived typical cost-per-linear-foot of pipe replacement, from actual costs of eight (8) recent stormwater pipe replacement projects provided by the City of Minneapolis (Table C.1). Data from these projects was fit to a power function (r^2 = 0.73) to derive cost-per-foot date, the *most likely* estimator was $890/LF, with the *95% confidence interval* $490-1,290/LF). (Figure C.3, Table C.2);
- Cost-per-linear-foot information was applied to the length of pipe that hydrologic/hydraulic modeling indicated was undersized for a scenario, to derive estimated total cost for a given scenario (Table C.3, Figure C.4);
- For Pipeshed 76-010, pipe upsizing can mitigate flooding caused by precipitation scenarios through 6.56". The *most likely* estimated costs range from $2.9m through $17.0m across this range of precipitation events (Table C.3);
- For Pipeshed 76-010, the estimated cost per million gallons (MG) of flood water that was mitigated by pipe upsizing, for the 4.15", 4.77", and 5.67" precipitation events, is $0.9m/MG, $1.9m/MG, and $2.5m/MG, respectively (Table C.4). For precipitation events of 6.56" and above, pipe upsizing is not viable due to increased flooding downstream;
- For Victoria, pipe upsizing can mitigate flooding caused by all precipitation scenarios. The *most likely* estimates range from $0.46m to $11.8m (Table C.5);
- Because of limits to the viability of pipe upsizing in Pipeshed 76-010 (Figure H.8), other options such dry storage basins or underground storage were evaluated for diverting excess water from rainfall events above 6.56";
- The high-estimates for dry detention basins costs for the 6.56", 8.07", and 10.1" precipitation events were: for Pipeshed 76-010, $2.6m, $4.1m, and $6.7m, respectively; for Victoria, $1.3m, $2.7m, and $5.4m, respectively (Tables C.9, C.10);
- The estimated cost of underground storage for the 6.56", 8.07", and 10.1" precipitation events were: for Pipeshed 76-010, $23m, $45m, and $84m, respectively; for Victoria, $2m, $7m, and $18m, respectively (Table C.13);
- The least expensive means of mitigating flooding from increased precipitation is estimated to be dry detention basins, followed by pipe upsizing, and underground storage (Table C.14). On a per-million-gallons (MG) of mitigation basis, dry detention basins cost $0.1m/MG, pipe upsizing $1.8m/MG, and underground storage $2.4m/MG. However, as noted above, pipe upsizing has limited benefit;
- The adoption of achievable levels of Low Impact Development (LID) methods reduces the cost of all three structural adaptation methods examined (Tables C.16, C.17, C.18; Figure C.10). However, the cost benefits of LID decline as precipitation increases beyond 6.56" Figure C.10).