

DRAFT for USWG Review
Vulnerability Analysis and Resilient Design
Considerations for Stormwater Best
Management Practices



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Summary

Climate change is expected to alter the volume and distribution of precipitation across the Chesapeake Bay watershed in the coming years. These changing hydrologic conditions, especially when coupled with ongoing development, pose a risk to stormwater infrastructure and public safety. Declining performance or outright failure of stormwater best management practices (BMPs) adds further challenges to meeting the water quality goals outlined by the Chesapeake Bay Total Maximum Daily Load (TMDL).

This memo identifies the types of risk facing stormwater infrastructure in the Chesapeake Bay watershed, as well as the most vulnerable features of these practices. Chesapeake Bay BMPs, including both traditional stormwater practices and more non-traditional restoration approaches, are covered. The memo also identifies resilient stormwater design principles and next steps that stormwater managers and Chesapeake Bay Program stakeholders may pursue to maintain and improve the long-term performance of their BMPs. The following is a summary of the key takeaways:

- Stormwater best management practices (BMPs) and conveyance infrastructure face risks that occur across a spectrum from catastrophic failure to diminishing pollutant removal performance. The risk type can be influenced by a variety of different factors, including:
 - The location of a practice in the urban landscape. Practices higher in the watershed tend to be more distributed, with smaller drainage areas than those lower in the watershed. In addition, practices that are “on-line”, or in the natural flow of runoff, face greater risks.
 - Older practices were more likely to be designed using outdated precipitation data and design guidelines, and therefore more likely to be undersized for future precipitation. Older practices are also more likely to be experiencing natural wear and tear, increasing their vulnerability to extreme events.
 - Design and maintenance condition. Many stormwater BMPs throughout the watershed are already at risk of failure due to a wide variety of design and construction flaws, as well as insufficient maintenance. Increasing storm intensity is likely to exacerbate design flaws, speeding up likely structural and performance failures, while demanding more routine maintenance to maintain water quality performance.
- Not all risks are driven solely by climate change – projected development across the watershed will continue to alter urban hydrology, while regular design and maintenance challenges continue to lead to practice failure even in the absence of direct climate change impacts.
- While the specific vulnerabilities differ between the BMP types, the most common vulnerabilities include:
 - More frequent overflow/bypass of runoff,
 - Loss of treatment capacity due to sedimentation or high groundwater tables,
 - Increased erosion where runoff enters and exits the practices.
- Overall, it is recommended that a Bay-wide effort be undertaken to closely evaluate and update stormwater design criteria and floodplain management regulations in the context of projected climate impacts and leading BMP vulnerabilities.

Table of Contents

1. Background	Page 3
2. Risk and the Urban BMP Landscape	Page 4
3. Upland Low Impact Development (LID) Practices	Page 7
4. The Conveyance Network	Page 12
5. Ponds and Wetlands	Page 15
6. Stream Corridors and Shorelines	Page 18
7. Other Chesapeake Bay Restoration Approaches	Page 21
8. Moving to Resilient Design	Page 23
9. Conclusions and Proposed Next Steps	Page 26
10. References	Page 28
Appendix A. CSN 90 th percentile rainfall event analysis	

Background

Maintaining and improving the resilience of stormwater infrastructure and best management practices (BMPs) is likely to be one of the most critical challenges faced by Chesapeake Bay watershed communities in the coming years. This is the fourth and final in a series of memos produced for the Chesapeake Bay Program partnership to clearly define the needs of local stormwater managers and identify the specific initiatives that will allow them to address their restoration and public safety functions under future climate conditions.

The first three memos outlined the greatest concerns of stormwater managers with regards to the resilience of their infrastructure and BMPs (Wood, 2020a), the current stormwater engineering design standards used across the watershed (Wood, 2020b), and the most recent climate change projections for the region, focusing on local precipitation intensity (Wood, 2020c). To best understand this memo, it is important to first review some of the key findings from the preceding work:

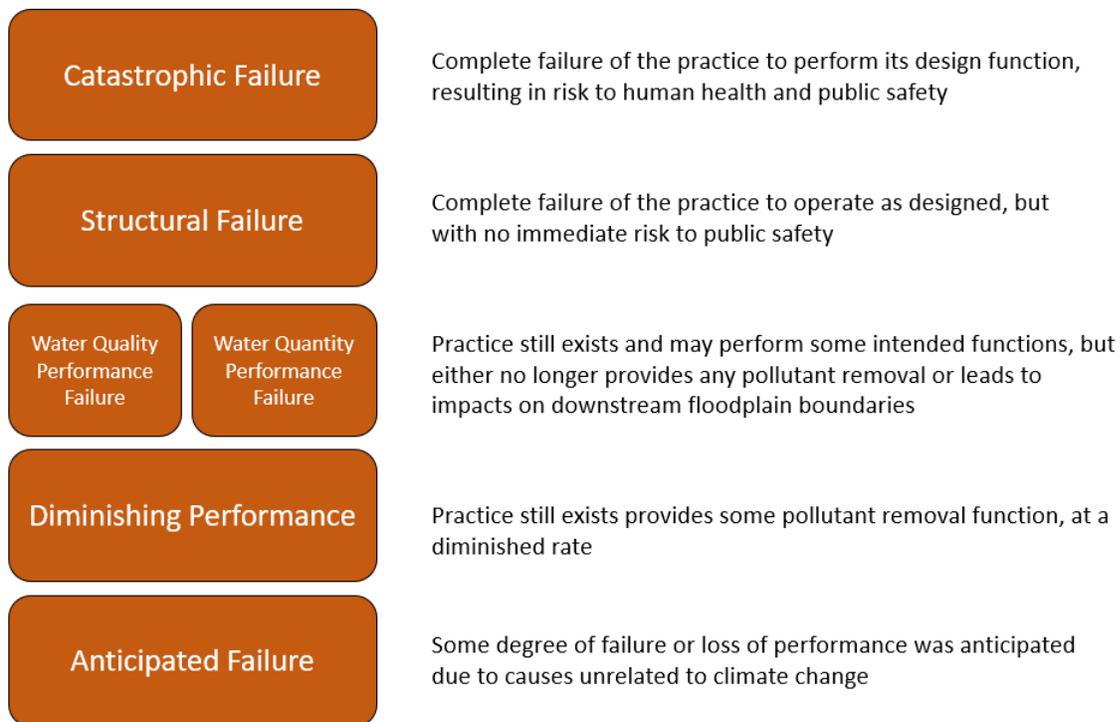
- **Stormwater professionals across the watershed are not comfortable with the current quality and utility of engineering design criteria on future rainfall intensity as currently provided by state and/or federal authorities.**
- **Each state and the District of Columbia uses different design criteria. Further, within states, there are often differences in how design storms and precipitation data sources are discussed by departments of transportation, environmental regulatory agencies and the departments overseeing dam safety. With one or two exceptions, the most recent wave of state stormwater manual updates occurred between 2006-2013.**
- **Engineering design criteria and stormwater runoff models generally rely on historic precipitation data. The most commonly used dataset, Atlas 14, has a period of record that is already twenty years old, while multiple studies suggest that stormwater design based on historic precipitation analysis are likely to underestimate future precipitation.**
- **Work to develop climate change projections with the temporal and geographic resolution needed for stormwater modeling show that precipitation intensity is generally expected to increase by 5-35% by the middle of the 21st century. Projections also predict approximately 2-3°F of warming and 1-2 feet of sea level rise in the same time period.**

Each of these factors contribute to increasing risks and vulnerabilities to both existing and future stormwater infrastructure and BMPs. This memo is based on the idea that climate change-induced risk occurs on a spectrum that ranges from catastrophic failure to diminished pollutant removal function. It also considers failure and loss of function that may have occurred even in the absence of climate change. Where practices occur within the urban landscape, the age of the practice, design flaws, and current maintenance conditions all impact the type of risk.

Risk and the Urban BMP Landscape

Stormwater BMP failure can take different forms. Failure occurs on a spectrum with varying levels of risk based upon the type of BMP, its position in the urban landscape and the ultimate management objectives the practice is intended to address. Therefore, the increasing volume and intensity of precipitation projected for the Chesapeake Bay watershed in the coming decades does not necessarily mean the same type of impacts for all types of infrastructure, and the decisions about how to build resiliency will be linked to the primary management objectives.

Figure 1. Climate Change-Induced Risk Spectrum for Stormwater Best Management Practices



Risk of Failure:

It should be unsurprising that catastrophic failure – damage to critical public safety infrastructure such as bridges, dams, roads, and culverts due to extreme storm events – is the greatest concern of stormwater managers across the watershed (Wood 2020a). But failure can look different depending on a practice’s location and management objectives. In the case of structural failures, the indicators may be

the same as those for catastrophic failure, but the BMP or infrastructure is located or designed in such a way that there is no risk to public safety.

Performance failure can be divided into two sub-categories: water quality failure and water quantity failure. Water quality performance failures are among the most challenging to detect. The pollutant reduction performance of stormwater BMPs is notoriously variable, both across sites as well as across storm events. Performance failure, or even just diminished performance, may be caused by an inlet obstruction preventing runoff from entering a BMP, or a large influx of sediment clogging the filter bed and preventing infiltration. Often, multiple factors combine to cause performance failure, making it difficult to pinpoint a single solution.

Water quantity failures can impact downstream properties, conveyance systems and, in some cases, floodplain boundaries. In other words, a practice that no longer captures the volume of runoff it was designed to capture can lead to an increase in runoff being delivered downstream, resulting in potential impacts to lower lying portions of the watershed.

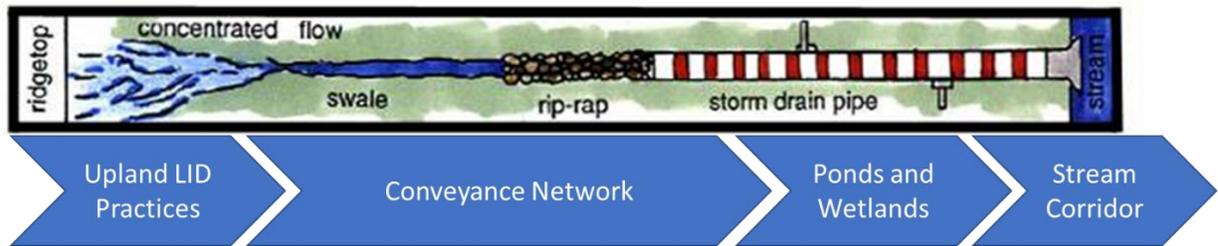
It is also important to realize that many vulnerabilities to stormwater BMPs are already present and are only further exacerbated by climate change. It is expected that a number of stormwater BMPs will suffer a previously described failure in the next few years, regardless of future climate change. Design flaws, ongoing development of the watershed, lack of routine maintenance, or improper BMP siting and construction may all play a role in the long-term performance of stormwater BMPs. Non-climate related changes to the urban landscape are ongoing and continue to exert significant impacts on runoff volume and pollutant loads. For example, Wang et al. (2016) found that peak runoff and total suspended sediment loads were more sensitive to the changes in impervious surface and progressive urban intensification than to climate changes.

These failures have already occurred across each of the Chesapeake Bay watershed jurisdictions and the challenge is only becoming more pronounced with the ever-increasing implementation needed to achieve the Chesapeake Bay TMDL goals. A detailed evaluation of over 200 stormwater BMPs in Virginia found that 46% of BMPs were in need of some form of maintenance, and that treatment was ineffective in over a third of the practices due to a variety of design flaws (Hirschman et al., 2009). In recent years, many states and MS4 communities have significantly improved their inspection and maintenance programs, developing better asset management systems and devoting more resources to staff training. However, the rate of BMP implementation across the watershed has led to a tremendous burden on verification and maintenance programs. As a result of this increasing maintenance burden, over 4,300 BMPs implemented for the Chesapeake Bay TMDL across the agriculture and urban sectors were reported to the Chesapeake Bay Program as having failed a verification inspection as of 2019, while another 58,300 expired due to a lack of reported inspection date (CBP, 2020). Between failure and expiration, that represents 19% of all reported BMPs.

The Urban BMP Landscape

The location of the BMP within the urban stormwater drainage network is also critical to consider when assessing its vulnerability to climate change. The urban stormwater drainage network can be thought of in four zones: upland practices, conveyance practices, ponds and wetlands, and stream corridor practices (see Figure 2).

Figure 2. The Urban Stormwater Drainage Network



As runoff moves “downstream” through the urban drainage network, it becomes more concentrated and the practices that capture, infiltrate, detain, or convey that runoff are designed to handle increasingly larger volumes of water. Small, highly dispersed upland BMPs typically aren’t designed to capture large volumes of runoff, but are so numerous that expected increases in routine maintenance needs will pose a risk to pollutant removal performance. Meanwhile, conveyance practices often run beneath or parallel to roads and other transportation corridors. Storm events that damage or overwhelm the conveyance network are likely to have a direct and immediate impact on public safety. Larger ponds and stream corridors are often at the low-points of the urban landscape and therefore the eventual collection point for stormwater runoff. Despite the best efforts of practices implemented in the previous zones, a significant amount of runoff eventually makes its way the stream corridor, subjecting practices and infrastructure in the corridor to the highest flows during intense storm events.

In addition to the different levels of risk carried by these four zones due to their location in the watershed, the BMPs or infrastructure in these zones also tend to be of varying age. The following is a “typical” timeline for the progression of stormwater infrastructure in most Bay communities, although the precise timeline for each era varies in each community due to the specific years in which new engineering criteria were adopted:

- 1960’s and before: Conveyance only (no detention storage)
- 1980’s and before: Detention pond era (quantity control, no quality control)
- 1990’s -2010: Quality and quantity control
- 2010 to present: LID era (and in recent years, the stream restoration era)

Communities can generally predict the era based on the average age of urban development in a local watershed. Thinking about it a different way, the age of a development can be used as an initial screening criterion when conducting flood risk assessments. Between a lack of detention in the community design, the increased maintenance needs of aging infrastructure, and outdated design criteria, these neighborhoods will likely be hotspots for inland flooding. Communities will need to target these areas by mapping the age of development and the condition and design era of their historic stormwater infrastructure, and implementing corresponding watershed strategies to reduce flooding risks.

The subsequent sections provide a review of the vulnerability of practices in each zone to the different categories of failure.

The Upland Low-Impact Development (LID) Practices

SUMMARY OF VULNERABILITIES

- **Upland LID practices are at high risk of climate change related impacts.**
- **Upland practices are most vulnerable to erosion at the inlet and outlet, clogging of the filter bed due to increased sediment loads, shifting vegetation communities, and increased bypass/overflow.**
- **There are limited data quantifying the loss in pollutant removal performance due to climate change. While studies show little change in the 90th percentile storm event, suggesting little impact on LID practice performance, both monitoring and modeling studies have found increasing volumes of untreated overflow under climate change scenarios.**
- **While overflow/bypass is one potential culprit, the mechanisms behind observed declines in pollutant removal performance are not well understood. Existing studies on changes to pollutant removal performance are almost entirely based on modeled data and show declining pollutant removal efficiencies on the order of 0-15%.**
- **While climate change is expected to exacerbate design and maintenance flaws, declining pollutant removal performance is already being observed due to the age and poor maintenance condition of many existing practices, as well as increasing impervious cover across the urban and ex-urban landscape.**

The BMPs:

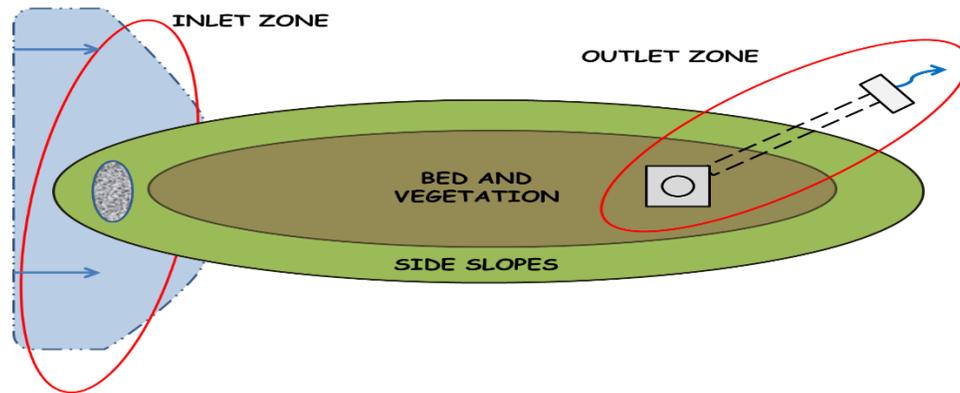
<ul style="list-style-type: none">• Bioretention• Rain Gardens• Permeable Pavement• Green Roofs• Conservation Landscaping	<ul style="list-style-type: none">• Rooftop Disconnection• Infiltration Basins• Sand Filters• Tree Pits• Manufactured Treatment Devices
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Upland LID practices are designed to treat small and moderate storm events. They are widely distributed across the landscape, with each practice typically treating a relatively small contributing drainage area. The practices are not usually designed to withstand runoff volumes or velocities above the 2-year storm event. Thus, extreme storms pose a high risk of damage or failure to individual practices, increasing the need for corrective maintenance.

Vulnerable Design Elements:

Most upland LID practices have several common design elements, each of which carry different vulnerabilities under changing climate conditions.

Figure 3. Schematic of a Typical Upland LID Practice



Inlet Erosion and Bypass:

Runoff enters the BMP through an inlet, which may be a curb cut or sheet flow. As the intensity of storm events increases and runoff volume is concentrated into fewer, large events, the risk of inlet erosion increases. Often, inlet erosion is the result of an existing design flaw, which may be exacerbated by climate change. Common causes of inlet erosion are:

- Improper design elevations
- Preferential flow paths through the facility
- An undersized curb cut
- Insufficient pre-treatment
- Insufficient bypass measures for storms larger than the design storm

Severe channelization and scour may undermine structural components of the facility, leading to failure. Inlet erosion can also contribute to performance failures by causing cascading impacts throughout the rest of the facility by depositing additional sediment in the bed, or short-circuiting treatment.

To help avoid erosion, some “offline” practices – practices outside the normal runoff flow path – may use bypass devices that prevent excess runoff from entering the facility at all. This can be controlled using flow splitters or setting an inlet at the maximum ponding height to moderate how much runoff can enter the facility. However, increasing storm intensity may result in larger runoff volumes bypassing treatment in order to protect the structural integrity of the BMP.

Clogged filter media:

As the runoff moves through the facility for treatment, any additional sediment from erosion in the contributing drainage area, or from the damaged inlet can be deposited in the filter bed. The filter bed media is a specialized sandy mixture designed to promote infiltration. Significant sediment deposition in the filter bed can clog up the media, reducing the permeability of the filter media, and subsequently, the total runoff reduction capacity of the practice.

Vegetation:

While not part of all upland LID practices, vegetation is a critical component of many BMPs, such as bioretention and green roofs. Vegetation is already one of the most challenging maintenance needs for

bioretention practices. As temperature increases and the precipitation events become more intense, but also more infrequent, studies have shown that vegetation in LID practices will suffer from drought stress in summer due to increasing evapotranspiration (Stovin et al., 2013; Vanuytrecht et al., 2014). That said, if an appropriate plant community is selected and properly maintained, increasing evapotranspiration can also help bioretention practices retain/reduce more stormwater, resulting in a larger volume of runoff reduction in summer. Thus, these same studies have accentuated the need for a deep substrate and a mixture of vegetation with diverse stress levels to balance a trade-off between runoff reduction and drought risks in the future (Sohn et al., 2019).

Outlet Erosion and Overflow:

Outlet structure design often depends on the design of the facility. “Online” practices – practices placed within the normal runoff flow path – typically have overflow structures. Some designs have a downgradient opening such as a gravel channel or curb cut that allow excess flow to exit the system and proceed along the normal stormwater runoff flow path. These designs can be prone to erosion if the overflow velocities are enough to mobilize undersized cobble in the overflow channel or create a “firehose” effect through the curb cut.

Other outlet designs use riser structures that accept water that exceeds the maximum ponding depth and conveys it to the underground storm drain pipes.

Either design means that more intense storm events are likely to result in more overflow. Risk of overflow is much higher for online practices than offline practices because they fall within the regular runoff flow path and therefore are more likely to be subjected to more flow during intense events.

Tidal Impacts:

While not a vulnerability for a particular zone of a typical LID practice, it is also important to note the potential structural and performance failures that can be caused by high groundwater tables and tidal flooding as sea levels rise. Infiltration-based LID practices can be rendered completely ineffective without significant design adaptations if implemented in low-lying regions of the Chesapeake Bay watershed. A rising groundwater table reduces the capacity of infiltration BMPs by filling otherwise available pore spaces. This, along with potentially submerged outlet structures during tidal flooding events, can cause back-up and permanent ponding that risks increasing peak flows with the installation of infiltration-based LIDs (Joyce et al., 2017).

Rising sea levels are also leading to saltwater intrusion in coastal communities. While usually more of a concern for drinking water protection and agricultural production, saltwater intrusion can also impact the performance of stormwater management practices. High chloride levels in BMPs can impact survival of vegetation, as evidenced in many roadside bioretentions, and there is some evidence that the presence of large amounts of salt in stormwater BMPs may reduce their effectiveness for total phosphorus removal (Soberg et al., 2020).

Figure 4. Examples of vulnerable design elements in upland LID practices.



Pollutant Removal Performance Impacts

Past experiments have consistently shown that LID systems perform better with low-intensity and short-duration storms under dry conditions (Alfredo et al., 2010; Gülbaz and Kazezyılmaz-Alhan, 2017). As climate change increases the intensity of storm events, it is important to understand the potential overall impacts to runoff reduction and pollutant removal performance.

The impact of climate change on upland LID practices is limited to a handful of field studies and a few additional modeling studies (Table 1). So far, there have been mixed results with regard to overall impact, though much of the difference may be related to the ability to calculate overflow vs. bypass in online and offline facilities.

Table 1. Summary of Select Climate Change Pollutant Removal Impact Studies

Citation	Type of Study	BMP	Performance Metric	Change in Performance
Hathaway et al., 2014	Modeled	Bioretention (online)	Overflow volume	70-136% increase in overflow volume by 2055
Catalano de Souza et al., 2016	Field (extreme weather as proxy for climate change)	Bioretention (offline)	Bypass volume	40% bypass during extreme events vs 23% bypass during non-extreme events
Butcher, 2020	Modeled	Bioretention	Overflow volume	11% increase in overflow volume by 2055
Alamdari et al., 2020	Modeled	Mixed	BMP removal efficiency	6-11% decline (TSS) 7-12% decline (TN) 11-17% decline (TP)
U.S. EPA, 2018	Modeled	Mixed	BMP removal efficiency	0-10% decline (TSS) 0-6% decline (TN) 0-5% decline (TP)

Overflow/Bypass

Hathaway et al (2014) found that the volume of overflow from a series of bioretention systems in North Carolina substantially increased by 70-136% under climate change scenarios. This is of particular concern because it represents uncontrolled, untreated runoff from the contributing watersheds.

In another study, a bioretention in New York was evaluated under both normal and extreme precipitation conditions. The site rarely ponded, and overflowed only once (during Hurricane Irene), generating an insignificant volume of overflow (Catalano de Souza et al., 2016). However, the researchers found that the site's performance was more often hindered by inlet bypass. Specifically, the facility captured only 60% of runoff generated in its drainage area during extreme events, compared to 77% of runoff generated during non-extreme events.

Both studies concluded that surface storage volume and infiltration rate appeared to be important in determining a system's ability to cope with increased yearly rainfall and higher rainfall magnitudes. They also found that the total amount of precipitation and peak-hourly intensity increase are significant predictors of, and negatively correlated with, the facility's stormwater capture performance (Catalano de Souza et al., 2016).

The 90th Percentile Storm

Another way to approach quantifying anticipated changes to BMP pollutant removal performance is by looking at projected changes in the 90th percentile storm event, commonly used as the basis for the water quality design storm across the Chesapeake Bay Watershed. A preliminary analysis by CSN of storm size distributions in the Washington D.C. metropolitan area shows there has been little movement in the 90th percentile storm event in the past 10-15 years (details in Appendix A). Comparing rainfall frequency tables compiled for Reagan National Airport for 1990-2020 vs 1977-2007, the 90th percentile storm increased by 6% from 1.14" to 1.21". In other words, designing a BMP to capture the 1" storm event now treats 85% of annual rainfall, rather than 88%.

Looking forward, a more detailed analysis by Butcher (2020) found that the predicted intensity of the 90th percentile, 24-hour event does not show a consistent increase at most Maryland stations under future conditions, suggesting that many water quality BMPs are likely to continue to provide expected services under future climate. However, additional modeling analysis found that while bioretention facilities can be expected to capture and treat the future 90th percentile storm without significant overflow, there is an increase in median overflow volume across the full range of storm events of 11% by 2055 and 21% by 2085 (Butcher, 2020).

Pollutant Removal Efficiencies:

Other studies have looked beyond overflow, attempting to model changes in pollutant removal efficiencies – change in pollutant loads from the inlet to the outlet of the practice – under different climate change scenarios. The findings generally revealed that the combination of larger storms, higher intensity, longer duration, and wetter initial conditions diminished the benefits of LID systems (Fassman and Blackburn, 2010; Hood et al., 2007; Jackisch and Weiler, 2017, Wang et al., 2016). However, it remains unclear as to which storm factors contribute more to LID performance than others, and the loss in pollutant removal performance has rarely been quantified.

One recent modeling analysis using projected climate change conditions found that median BMP removal efficiency for TSS, TN, and TP were projected to decline by 6%, 7%, and 11%, respectively, under a moderate future emissions scenario (RCP4.5); and 11%, 12%, and 17%, respectively, for a high emissions scenario (RCP 8.5) (Alamdari et al., 2020). Similar results were found in modeling analysis conducted by the U.S. EPA (2018) with TSS, TN and TP efficiencies declining between 0-10%, 0-6% and 0-5% respectively. Other studies have found that pollutant removal efficiencies by LID practices were largely unaffected by climate change in modeled scenarios because the amount of pollutants present in the urban area was constant even when the rainfall volume increased (Baeka et al., 2020).

Researchers have also investigated the potential effects of seasonality on pollutant removal performance of LID systems, but the results were mixed. Some empirical studies have found better LID performance in summer than winter (Emerson and Traver, 2008; Lewellyn et al., 2016) because increasing temperature reduces water viscosity and thus increases hydraulic conductivity of the soil medium. However, the dependency on temperature varied by the type of LID system and depth of soil medium. Further, a contradicting study found fewer seasonal variations in LID performance compared to conventional BMPs (Roseen et al., 2009).

The Conveyance Practices

SUMMARY OF VULNERABILITIES

- **Conveyance practices carry significant risk because of their importance and proximity to transportation corridors. Water quality is less of a focus for this range of practices, so declining pollutant removal performance is not well documented.**
- **Conveyance practices are found in older developments, built prior to current detention standards. The age of these systems and likelihood that pipes and channels were undersized, increases the risk of failure and flooding.**
- **The transition from upland areas to the conveyance network also represents a potential chokepoint within the urban drainage system. Backups above the storm drain pipe system can create unintended detention in the urban landscape that provides an additional, inadvertent amount of volume control to manage during large storm events.**
- **Key vulnerabilities exist at inlets, outlets and from loss of capacity. Inlets and outlets are at increased risk of erosion from high flow events. Loss of capacity can occur due to high levels of sedimentation within the conveyance practice, or due to tidal flooding.**

The BMPs:

<ul style="list-style-type: none"> • Vegetated Swales • Dry-Channel Regenerative Stormwater Conveyances (RSCs) 	<ul style="list-style-type: none"> • Open Channels • Storm drain pipes • Roadside Ditch Retrofits
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Conveyance practices serve a critical, and more traditional, function in stormwater management: moving water safely from urban areas to their receiving streams on both private property and public rights-of-way. These practices often run parallel to, or beneath, transportation corridors and close to houses and businesses. As a result, these practices inherently carry more risk of catastrophic failure and are often the highest priority for local governments. With the exception of step-pool systems, there has yet to be much implementation of water quality-focused retrofits in this zone of the urban drainage network, so there is less focus on pollutant removal failure or diminished performance. However, structural and catastrophic failure among these practices are among the greatest concerns for stormwater managers because of the impacts on public health and safety.

Further, the transition from upland areas to the conveyance network also represents a potential chokepoint within the urban drainage system. Backups above the storm drain pipe system can create unintended detention in the urban landscape that provides an additional, inadvertent amount of quantity control to deal with during large storm events. Deteriorating streets and parking lots, and clogged storm drains also increase the initial abstraction and event runoff storage found in aging urban subwatersheds. Paradoxically, most of the increased future flood damage will occur outside of and up-watershed from the defined floodways and floodplain insurance zones that have been the major focus of past floodplain management efforts. Floodwaters will back up above the 10-year storm drain “chokepoint” where the “softer” drainage path and LID practices can be overwhelmed by runoff volume and corresponding erosive velocities.

Vulnerable Design Elements to Catastrophic and Structural Failure

Vulnerability of practices in this zone is different than LID practices because their primary function is most often conveyance, not pollutant reduction. There are three primary vulnerabilities in conveyance practices:

- capacity loss due to debris/sedimentation or increasing magnitudes of precipitation;
- damage and erosion at the inlet;
- damage at the outfall into the headwater transition zone.

Ditch retrofits, bioswales, and dry-channel regenerative stormwater conveyances (RSCs) do perform pollutant reduction functions and therefore should be evaluated for vulnerabilities as both conveyance and LID practices.

Inlet and Outlet Erosion:

One similarity of conveyance practices to the upland LID practices is the vulnerability at the inlet and outlet. These conveyance systems are necessarily “on-line” and collect runoff from much larger contributing drainage areas than the highly dispersed LID practices, and therefore are subject to significant runoff volumes. Ditch and open channel designs with steep slopes or insufficient pre-treatment may experience similar scour and gully formation that can undermine the integrity of the channel. While engineered conveyance systems are designed to be non-erosive for the 2-year storm event, some of the “softer” BMPs, including grass channels and swales may not be non-erosive for larger storm flows. Further, non-engineered systems, like some rural roadside ditches or overflow from small LID practices may be more vulnerable.

These conveyance systems either convey flow to a larger detention practice, as will be discussed in the next section, or to the headwater transition zone. The headwater transition zone is the slope or channel that extends from an upland runoff source to the stream network. This zone has an exceptionally high potential for sediment erosion due in large part to a combination of uncontrolled stormwater runoff from upstream development, inadequate energy dissipation structures below the outfall and extreme storm events that exceed the design capacity of the channel (Group 2, 2019).

Loss of Capacity:

Within the conveyance channel, there are three primary ways of losing capacity within the system:

- significant sedimentation within the ditch, channel, or storm drain pipe.
- rising groundwater tables or submerged outfalls due to tidal flooding
- submerged outfalls due to backwater from undersized downstream pipes

More intense rainfall, and failure or bypass of LIDs can cause more erosion or sediment transport in upland areas of the watershed that will increase the likelihood that more sediment will be deposited within the conveyance network. Non-engineered roadside ditches may also experience erosional and depositional processes similar to ephemeral streams under frequent, high intensity events, leading to sediment build-up in sections of the ditch system. As sediment builds up, there is less capacity within the conveyance system to transport runoff within the channel or pipe, potentially leading to backups or overflow.

Figure 5. Examples of vulnerable design elements for conveyance practices.



Submersion of outfalls may mean that runoff has no place to go at the end of the channel or pipe, and water will back up into the upland areas. This could be due to undersized pipes downstream that are unable to handle high intensity storm events, or an outfall that is submerged by tidal flooding. Alternatively, rising water tables may mean that ditches or aging storm drain pipes may fill with groundwater. As runoff competes for space in these conveyance systems with groundwater, tidal floodwater, or backwater, failure is more likely. This type of capacity loss is becoming increasingly

common in coastal communities that are seeing the number of days with tidal (“blue sky”) flooding steadily rise.

Ponds and Wetlands

SUMMARY OF VULNERABILITIES

- **Stormwater ponds, particularly older, “legacy” ponds carry the greatest risk of any stormwater practice because of their age and their location within the watershed.**
- **Inlets, forebays, risers, emergency spillways, and outfall channels are all vulnerabilities of legacy ponds under climate change. There are also concerns about the capacity of stormwater ponds under future hydrologic conditions.**
- **Loss of capacity, leaching, and resuspension of pollutants are the primary mechanisms affecting future pollutant removal performance under climate change conditions, though the anticipated changes in pollutant removal performance have not been well-quantified.**

The BMPs:

<ul style="list-style-type: none"> • “Legacy” Ponds • Wet Ponds • Dry Ponds (Detention Basins) 	<ul style="list-style-type: none"> • Pond Retrofits (Extended Detention, “smart” BMPs, etc.) • Stormwater Wetlands
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Stormwater ponds represent the greatest potential risk for catastrophic failure within the urban drainage network because of their age, and their position within the landscape. Stormwater ponds collect runoff from large contributing drainage areas, often anywhere from 25 to 400 acres in size and are typically designed to safely pass the 100-year, 24-hour storm event. For the past several decades they have been the water quantity control practice of choice across the Chesapeake Bay watershed. But according to the 2017 infrastructure report card, more than 15,000 dams in the United States are listed as high risk due to the potential losses that may result if they failed, and yet by 2025, seven out of 10 dams in the United States will be over 50 years old (ASCE, 2017). While that report focuses primarily on larger, regulated dams, the small dams associated with stormwater ponds are also aging and likely to be in a similar maintenance condition.

Failure in this zone is not limited to catastrophic failure, as the impacts can range from loss of water quality performance, because of natural aging and resuspension, to structural damages. Further, due to climate change, in most future scenarios there is an increase in both the social and economic risks in comparison to the present risk level failure (ASCE, 2017; Fluixa-Sanmartin et al., 2016; Mallakpour et al., 2019). In many cases, a failure can begin without being catastrophic, but can escalate if not addressed.

Vulnerable Design Elements:

Just as stormwater ponds have higher risk levels than other zones, they also have more vulnerable design elements. Inlets, forebays, risers, emergency spillways, and outfall channels are all vulnerabilities

of legacy ponds under climate change. There are also concerns about the capacity of stormwater ponds under future hydrologic conditions (FEMA, 2018).

Figure 6. Examples of vulnerable design elements for stormwater ponds.



Age and Capacity Loss:

The majority of stormwater ponds were constructed in the previous century with limited observation data and with flood hazard assessments based on the natural water regime at the time (Ho et al., 2017). Therefore, their construction was based on outdated, historic precipitation data and likely did not incorporate the current and possible future changes in the hydrological condition. There is some natural “insurance” built into a number of pond designs as engineering criteria for overflow, bypass, freeboard and spillways tend to be conservative, and include factors of safety, which may offset some risk from future changes in hydrology.

In addition to outdated designs, capacity will be further limited as the conveyance network emptying into ponds deposits sediments, and the build-up over the productive years could decrease the water storage volume. This is largely an issue of deferred maintenance as a result of communities and homeowner associations lacking the financial and technical resources to dredge and restore pond

capacity. While not a direct impact of climate change, the current maintenance condition of these ponds will be exacerbated by future climate change, as greater precipitation intensity and subsequent surface runoff, increases the expected flooding and overtopping events (Lee and You, 2013; Shoghli et al., 2016). In addition, if the water carries more and bigger suspended material (including trees, branches, or debris) this could lead to blockages and further loss of capacity (Paxson et al., 2016).

Inlets, Outlets, and Spillways:

As more intense rainfall, coupled with changing land use conditions, leads to more soil erosion, there are a number of potential structural and performance failure mechanisms within the stormwater pond system due to increased sedimentation in the ponds (Salas and Shin, 1999; Yang et al., 2003).

Increased sedimentation can worsen the abrasion and erosion processes on any mechanical equipment, inlets, or the spillways (British Columbia et al., 1998), thus compromising their reliability. Similar to on-line conveyance practices, many ponds also have pilot channels with steep slopes or insufficient pre-treatment that may experience similar scour and gully formation that can undermine the integrity of the channel.

Diminishing Performance Impacts

Stormwater ponds, traditionally the water quantity practice of choice, have also recently become a target for retrofitting to achieve enhanced water quality gains. That means there is also a concern about impacts on pollutant removal performance under climate change. Most of those concerns are related to potential leaching or resuspension of pollutants due to high flow events and increasing temperatures.

Sedimentation is the primary removal mechanism in wet detention ponds for several stormwater pollutants, though other processes like adsorption, microbial degradation, and volatilization can also be important (Scholes et al. 2008). Removal of suspended solids (TSS) and other pollutants associated with solids via sedimentation depends mainly on long hydraulic residence times (HRT) leading to higher removal rates (U.S. EPA 1999; Vollertsen et al. 2007). High flows may disrupt the settling process and shorten the HRT of stormwater retention ponds during extreme conditions, which may lead to higher pollution concentrations and loads being released from the ponds (Sharma et al., 2016).

Other studies using model simulations have shown that the climate change increase of rainfall intensity led to an increase in the pollutant concentrations discharged from the catchment. The higher flows, combined with the increased inlet load caused a decrease in the pond removal performance (Morgan et al., 2007; Sharma et al., 2016). One study found that while the median pollutant removal efficiency remained relatively constant under the climate change scenario (32.5% vs 33.9% removal), the median yearly TSS load increased by 14% (Sharma et al., 2016). Another study found that simulations of more frequent storm events did not impact pollutant removal performance, but that increasing the magnitude of the storm increased the likelihood for loss of performance, with a decrease of 20% from the median removal efficiency when the storm size was increased from 1" to 5" (Morgan et al, 2007).

There is evidence that one potential cause for this loss in performance could be due to sediment-bound pollutants that can be resuspended back into the water column by high velocities during storms, particularly in shallower ponds and wetlands (Davies and Bavor, 2000).

Another issue expected to become more common is the release of pollutants, particularly P and TSS from ponds due to leaching and resuspension. Periodic and sometimes persistent thermal stratification has been observed during summer months in stormwater ponds, even in shallow ponds less than 6 feet in depth (Song et al., 2013). Thermal stratification can be especially problematic in warmer climates. This thermal stratification can create persistent anoxic conditions that lead to the release of phosphorus from pond sediments, reducing removal efficiency and even becoming a net source to receiving waters (Erickson et al., 2018).

Stream Corridors and Shorelines

SUMMARY OF VULNERABILITIES

- **While stream restoration and shoreline management practices are designed, in part, to protect against high flow events, their position within the landscape makes them particularly vulnerable to climate change.**
- **Without new upstream runoff controls, urban streams and their remaining corridors are likely to become more unstable, incised and disconnected in the coming years, leading to loss in habitat quality in the coming decades. While new stream and floodplain restoration techniques are promising, the need for designs that can withstand extreme flow conditions may detract from their habitat and ecosystem service functions.**
- **The impact on pollutant removal performance of these practices is more complicated than the previous practices. Increasing stream flow and erosion rates would theoretically increase the potential pollutant removal rates from well-designed practices. However, climate change may also impact assumptions about post-restoration erosion rates for these types of BMPs.**

The BMPs:

• Stream Restoration	• Shoreline Management
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Practices within the stream corridor are unique in the urban BMP landscape because until recently, stream restoration practices have not been considered a municipal asset that needs to be managed or maintained over the long run. This is changing as many of the larger Phase I MS4 communities are now creating methods to track and manage this new form of infrastructure within the context of an asset management system. While their location at the bottom of the watershed makes them vulnerable to impacts from increased precipitation, the understanding of the specific risks is still evolving.

Flooding of stream corridors beyond the limits of the 100-year floodplain certainly could be considered catastrophic failure due to the risk to property and public safety. Stream restoration can reduce these risks, though are still susceptible to excessive flood events that could destroy structural components of the restoration, reduce pollutant removal performance and potentially present public safety risks.

Shoreline management practices, while not technically part of the stream corridor, deal with similar, albeit tidal forces. Sea-level rise is a significant problem for shoreline management practices, and this

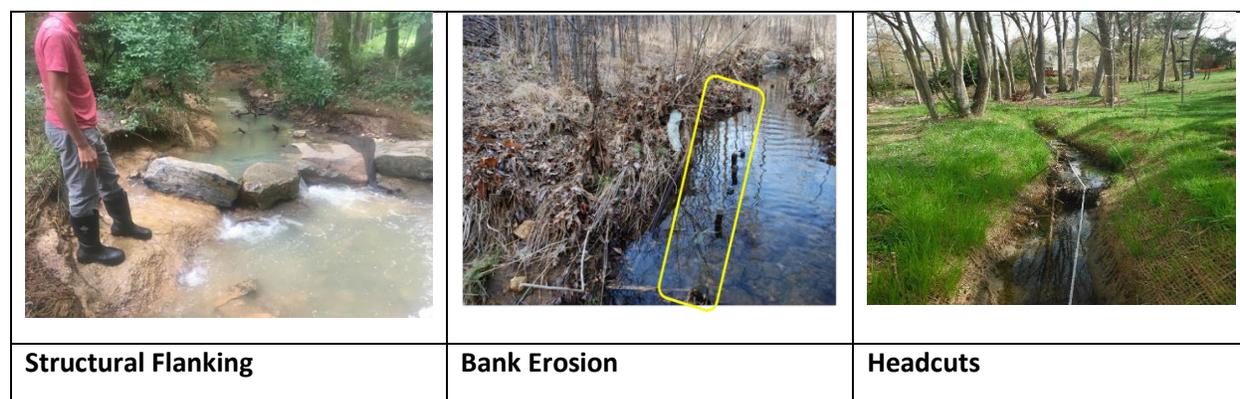
risk was not factored into the pollution reduction credit, though sea level rise considerations were offered in the expert panel report’s appendix (Shoreline EPR, 2015). In addition, there is no standard verification protocol for shoreline management practices that lose function or are destroyed by higher water levels.

Vulnerable Design Elements

Stream Restoration:

Stream restoration projects are designed based on a range of flood events in the channel and floodplain, and are intended to be sustainable, and allow for some natural adjustments over time. Still, some structural elements in the channel, especially the toe of the bank and stream bed, are particularly susceptible to damage. Certain fixed stream channel geometry, such as outside of meander beds, are also prone to damage.

Figure 7. Examples of vulnerable design elements for stream restoration practices.



Some studies have shown approximately 20-30% of structural stream restoration techniques experience some degree of damage or loss of functionality (Brown, 2000; Dave and Mittelstet, 2017; Miller and Kochel, 2010). In general, these failures are driven by inaccurate predictions regarding design parameters (width, depth, meander radii, etc.) or because reference sites are located in catchments with less impervious cover than the restoration target reach (Brown, 2000; Bernhardt and Palmer, 2007). These vulnerabilities are not specific to climate change, but are likely to be exacerbated by increasing flows and flashier storm events predicted due to climate change.

Many assessments of structural failure among stream restoration projects were conducted a decade ago, and there have been numerous advances in the design approaches since then. While constrained urban environments still may require some “hard” design elements, there has been a shift in the Chesapeake Bay watershed towards “softer” bank protection practices and more frequent reconnection with the floodplain. Floodplain restoration projects may actually provide more floodplain storage to help manage extreme flood event caused by future climate. However, if designers are given new precipitation intensity-duration-frequency (IDF) curves, there is a risk they will respond by making their projects harder to withstand future design velocities, which may reverse efforts to limit bank armoring and promote more channel habitat, as outlined in recent guidance from stream restoration experts (Group 3, 2020).

Another advancement in the practice of stream restoration is that there are now defined visual indicators to help identify and correct structural and performance loss (Group 1, 2019). Erosion of the banks, headcuts, or flanking of structures can all be signs of failure.

Shoreline Management:

Shoreline management practices are similarly difficult to assess. While “softer” approaches to shoreline management, such as living shorelines, are designed to adapt to rising sea levels to some extent by accreting sediments at roughly the same pace as sea level rise (Davis et al., 2015), a number of harder approaches are not as adaptable. Even living shoreline practices are often constrained by their upland environments, preventing them from migrating landwards to keep up with the changing sea levels. For living shoreline management projects, active marsh and/or wetland intervention – including practices like establishing landward buffers to allow inland migration over time – may be needed to combat the effects of sea level rise over time.

While only an eligible Chesapeake Bay BMP under very limited conditions, the vulnerability of harder shoreline practices is largely based on the age of the practice. Because shoreline management practices that include bulkheads or revetments are specifically designed to protect against intense wave action and sea level rise, recently designed projects should hold up well during their design life. However, older practices that may have used outdated climate projections or failed to account for sea level rise at all are likely to be undersized and prone to failure. Prolonged periods of heavy rain or the crashing of storm waves over a seawall or bulkhead can trap water behind them. If the seawall can’t withstand the pressure, it fails. Severe storm events can also erode the toe of the wall, reducing its stability and eventually leading to failure.

Pollutant Removal Performance Impacts

Stream Restoration:

Pollutant removal performance of stream restoration practices is inextricably linked to structural and performance failures. The stream restoration pollutant removal protocols are based on prevented sediment erosion, denitrification in the hyporheic zone, and floodplain reconnection.

Increasing precipitation intensity and the subsequent rapid discharge of stormwater accelerates channel erosion and pollutant transport downstream (Bledsoe and Watson, 2001). Higher flows during increasingly earlier snow melt could also result in earlier erosion and incision of banks, making areas more susceptible to spring precipitation events (Stryker et al., 2018). Both higher temperatures and longer storm durations would contribute to wetter conditions in the watershed, producing antecedent conditions where soils are more saturated and the watershed is more vulnerable to any precipitation event, even if not extreme in nature (Stryker et al., 2018).

The pollutant reductions calculated for prevented sediment are typically based on pre-restoration erosion rates. If those erosion rates are monitored, it could be expected that the calculated performance of stream restoration practices will increase in the future as pre-restoration erosion rates increase. Practitioners who rely on bank erosion rate curves, which are more static, may eventually end up with a more conservative estimate of pre-restoration bank erosion rates. Therefore, climate change further underscores the importance of pre- and post-restoration monitoring to determining an accurate estimate of the prevented sediment performance of stream restoration projects.

Pollutant removal calculations for hyporheic denitrification and floodplain restoration may also be influenced by changing hydrologic conditions. Although the annual minimum streamflows have increased during the last century, late-summer warming could lead to decreases in the minimum streamflows in the late summer and early fall by mid-century (Demaria et al 2016). This influences hyporheic denitrification because there will be potentially more hyporheic exchange during baseflow, but the seasonality may discount that benefit. Also, as more annual flow accesses the floodplain, it is likely that pollutant removal from floodplain reconnection will increase.

Despite the potential for initial gains in pollutant removal performance, the more important takeaway is the high level of structural vulnerability of stream restoration practices. There have been few, if any, formal studies of climate change impacts on stream restoration pollutant removal performance. While theoretically there is potential for increased load reductions from prevented sediment and floodplain restoration practices, it is also very possible that those gains can also be offset by a single extreme storm event.

Shoreline Management:

Many of the same principles applied to stream restoration can also be applied to shoreline management. Projected sea level rise and anticipated increases in large coastal storms are likely to increase coastal erosion rates in the Mid-Atlantic (CBP, 2005). That dynamic increases the prevented erosion potential from well-designed shoreline management projects, but it is unclear how long-lasting those effects will be. It is likely that further work will be needed to assess changes to practice lifespans, as well as the effectiveness of softer shoreline management techniques under extreme conditions and in constrained environments without a landward buffer component to the design.

Other Chesapeake Bay Restoration Approaches

SUMMARY

- **Non-traditional stormwater practices may also be vulnerable to climate change impacts, but not in the same ways as practices designed explicitly to capture, treat and convey stormwater.**
- **Tree BMPs, especially those within the riparian corridor, are at risk of changing temperature and moisture regimes that may shift their successful ranges and impact mortality rates.**
- **Impacts of climate change on programmatic BMPs, such as street sweeping or urban nutrient management are poorly understood, but likely to be minimal due to the current BMP crediting protocols.**

The BMPs:

<ul style="list-style-type: none"> • Riparian Buffers • Urban Tree Canopy Expansion • Urban Forest Planting • Urban Nutrient Management 	<ul style="list-style-type: none"> • Street Sweeping • Storm Drain Cleaning • Nutrient Discharges from Gray Infrastructure (NDGI)
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The remaining restoration practices don't fit as cleanly into the previous urban drainage network categories. Some, like the tree planting BMPs, can occur almost anywhere throughout the landscape. Others, like street sweeping, are programmatic approaches to pollutant reduction and therefore have a very different risk framework.

Tree BMPs

There are three categories of tree planting BMPs within the Chesapeake Bay TMDL framework: riparian buffers, tree canopy expansion, and forest planting. Because tree BMPs are relatively new to the urban stormwater treatment world, there is little research to directly assess climate change impacts on their pollutant reduction capabilities since there was little baseline performance data to compare to. However, they still have vulnerabilities that can impact planting success and mortality, which should be considered part of their performance as a BMP.

Riparian buffers may be the most vulnerable tree practice because of the expanding urban floodplain. As the runoff volume and intensity increases, floodplain water elevations rise, changing groundwater conditions to a level that may be unsuitable for existing riparian forest communities (Folzer et al., 2006; Garssen et al., 2015). While specific riparian plant communities may differ based on restoration design objectives, changing conditions due to climate change may render assumptions about groundwater tables inaccurate in the coming years.

All tree BMPs will also likely have to plan for shifting tree ranges due to increasing temperature and precipitation patterns. More sensitive species have already shown northward shifting ranges due to temperature changes (Woodall et al., 2009), while others are shifting westward to avoid the wetter conditions on the east coast (Fei et al, 2017).

Similar to stream restoration and shoreline management, trees traditionally do not perform quantity control functions on a site scale, but also should not be particularly vulnerable to increased storm intensity. While the benefits of canopy interception for runoff reduction are accepted and expressed as detention provided on a regional scale, tree canopy practices are not currently being used in the Chesapeake Bay watershed to meet site-scale detention requirements. More work is still being done to better quantify the water quantity benefits of tree BMPs so they can be further incorporated into future stormwater design. Best practices for preserving existing canopy and encouraging urban tree plantings remain highly encouraged, but the changing climate's impact on tree BMPs will be unlikely to significantly alter stormwater quantity objectives in the near future.

Street Sweeping, Storm Drain Cleaning and Nutrient Discharges from Gray Infrastructure (NDGI):

The Chesapeake Bay Program has also approved several "programmatic" BMPs that can be used toward achievement of the Chesapeake Bay TMDL. Vulnerabilities for these non-structural practices should be viewed differently because climate change may only threaten the pollutant removal dynamics of these practices.

Literature discussing the climate change impacts on these practices is almost non-existent. The most likely impacts to street sweeping and storm drain cleaning would be associated with changing build-up and wash-off dynamics. The anticipated shift towards more intense, but more infrequent rainfall events may improve the pollutant removal efficiency of street sweeping programs that sweep less often, though the impact is likely to be minimal. Likewise, higher intensity events may mobilize more

sediments that could collect in storm drains, but there is not good evidence to quantify the impact on storm drain clean-outs. More analysis would be needed to support any changes in presumed efficiencies.

Finally, credit for eliminating NDGI and for urban nutrient management are unlikely to be impacted by climate change. The credit for NDGI explicitly excludes wet weather overflows and discharges that are more likely to increase under climate change scenarios (NDGI EP, 2014), while urban nutrient management is driven by non-ag fertilizer application rates rather than climate variables.

Moving to Resilient Design

SUMMARY

- **Resilient design for stormwater best management practices can be grouped into two categories: sizing criteria, and resilient design and maintenance adaptations. The series of resilient stormwater design principles outlined in this section can help guide efforts to update the next generation of design specifications.**
- **In addition to protecting future projects from long term damage and risk of failure, it is also worth evaluating whether new design standards have the capability to not only protect against performance loss due to climate change, but to enhance runoff capture and pollutant removal rates over time.**
- **The Chesapeake Bay Program has an opportunity to advance design and resilient adaptation strategies for a wide range of restoration practices, but further investigation will be needed to develop recommendations that are actionable.**

Having established the potential risks and vulnerabilities that climate change exposes or exacerbates among stormwater BMPs and infrastructure, it is important to shift the focus to changes in design criteria, BMP sizing and/or runoff modeling procedures that can make the next generation of stormwater practices more resilient to future rainfall and runoff conditions. In addition to protecting future projects from long term damage and risk of failure, it is also worth evaluating whether any of these changes have the capability to enhance runoff capture and pollutant removal rates over time.

A series of foundational principles and more specific potential design adaptations are provided below to begin the movement toward more resilient stormwater design. The Chesapeake Bay Program partnership also has an opportunity to support further actions to address resilience needs among other restoration practices implemented across the watershed. A list of recommended actions is offered as a conclusion to this report.

Resilient Stormwater Design Principles

The following principles are proposed to guide the recommended development of next generation stormwater design standards and specifications:

1. *Comprehensive Watershed Management* – Design with consideration for watershed context to seek effective solutions for interrelated uplands, conveyance systems, regulatory and non-regulatory floodplains, and stream corridors. Working collaboratively across agencies, seek

projects and designs that are resilient to both changing climate and land use conditions in the community.

2. *Sizing* – Design using sizing criteria that provides an acceptable level of risk under future climate conditions. There are multiple approaches to resilient sizing criteria, that may include the use of projected IDF curves, adding a “factor of safety” to historic precipitation data, or establishing over-management criterion for quantity and rate control.
3. *“Flow-plains”* – Design the conveyance and treatment system to have capacity for safe overflow when there is failure. This “flow-plain”, similar to a floodplain for a stream or river, is an adaptation of the cloudburst approach to extreme storm event management. When overflow exceeds the capacity of the system, manage the plane/slope/distance to an area that is less vulnerable to flood damage. For example, directing excess flow to a buffer, forest or designated ballfield to avoid impacts on housing or transportation infrastructure.
4. *Full-Cycle Implementation* – Design with a “full-cycle” approach to implementation. Establish specific performance and maintenance targets for new implementation, including an anticipated design life, removal efficiencies for pollutants of concern, relevant maintenance indicators, and adaptive management for vegetation. Targets would ideally be tied to assessment timelines and triggers for management actions including repairs or “makeovers”.
5. *Redundancies* – Design with redundancies in the system – both within the practice and across the site and conveyance system. On a site scale, “treatment trains” route runoff through a series of BMPs in succession, increasing the opportunity for capture, infiltration, and pollutant removal along the way. Within practices, redundancies can provide protection against increased maintenance burdens, such as secondary design elements that safely pass excess flow if an overflow structure clogs.
6. *Performance Enhancers* – Design using “performance enhancers” for water quality to provide a buffer against future increases in loads or reduced efficiencies. Media amendments, “smart” BMPs, and stronger vegetation guidelines may all provide improved pollutant removal function under both current and future conditions. Adapting new standards for these BMP enhancements may advance water quality goals or, at a minimum, provide a buffer against any decline in performance due to climate change.

Stormwater BMP Design Adaptations

Sizing

One option for improving practice resiliency is to revisit stormwater design sizing criteria. There are several ways that sizing can be approached. One option is to keep the same design storm criteria, but update the underlying precipitation data used to arrive at the designated storm events. Due to the expected increase in precipitation intensity (5-35% by mid-century), using projected IDF curves would result in an increase in BMP and infrastructure sizing (Wood, 2020c).

Another approach is to use a “factor of safety” to increase sizing criteria. With the approach, rather than use projected IDF curves directly, future precipitation analysis was conducted and then a 20% factor of safety was added to existing design criteria. This approach has already been utilized by several communities (Wood, 2020c). Less likely would be a change to the actual design storm (ex. Increasing the conveyance storm from 10-year to 15-year).

Over-management criteria are another opportunity to provide more conservative sizing criteria. If a community is not comfortable with the precision of future rainfall projections, rather than try to predict that the future 100-year storm intensity, they will set a criterion that developers release the 150-year post-development storm at the 100-year pre-development level to provide a factor of safety.

The trade-offs for any of these options are cost and available space. Increased storage volume means larger, and therefore more expensive, practices. In constrained environments, land use and other major infrastructure restrict available space to simply increase the storage volume. In these instances, consideration must be given to other resilient design adaptations that may provide similar benefits but with a smaller physical and financial footprint.

Resilient Design Adaptations

“Smart” BMPs (Continuous Monitoring and Adaptive Control): Smart BMPs have already been deployed as a retrofit for legacy stormwater ponds in the Chesapeake Bay watershed. These techniques integrate information from field deployed sensors with real-time weather forecast data (i.e., NOAA forecasts) to directly monitor and make automated and predictive control decisions to manage stormwater storage and flows within the pond (Quigley and Lefkowitz, 2015). In other words, prior to a predicted rainfall event, the outlet of the pond can automatically draw down the water levels, creating additional capacity in anticipation of the storm. Monitoring of ponds with smart BMP technology has shown potential for improved water quality results and more downstream channel protection compared to traditional stormwater ponds (Braga et al., 2018; Marchese et al., 2018; Muschalla et al., 2014;), though the impact on larger design storms is less clear (Schmitt et al., 2020).

Media/vegetation amendments: There are opportunities to improve the resilience of LID practices by adjusting media to promote greater infiltration and soil storage capacity, or adapting vegetation guidelines to reflect changing growing conditions. Performance enhancing devices (PEDs), such as biochar, iron amendments, wastewater treatment residuals and internal water storage (ISW), all have demonstrated the initial ability to improve the runoff reduction capacity and/or pollutant removal efficiency of LID practices (Hirschman et al., 2017). Some of these may help add resilience to the design, or otherwise offset performance losses due to climate change.

Adapting vegetation guidelines has the potential to serve as both a performance enhancer, as well as a necessary maintenance adjustment to reflect changing growing conditions. In tidally influenced areas, rising groundwater levels may necessitate a shift to more salt-tolerant plant regimes or to more wet-tolerant species (Horseley Witten Group, 2015). A range of further actions can improve the overall performance of vegetation in LID practices, including:

- Use local natural plant communities as reference landscapes.
- Provide dense cover of the BMP surface with layers of vegetation.
- Intensely manage the plantings for the first 3 growing seasons.
- Use an adaptive management approach for long-term O&M.

Treatment Trains: Stormwater treatment trains are already relied upon in some new and redevelopment stormwater projects. The concept is to route runoff through a series of BMPs in succession, increasing the opportunity for capture, infiltration, and pollutant removal along the way. The combinations of practices are variable, depending on site conditions, and provide redundancies if one of the practices in

the chain were to fail or be bypassed (Horseley Witten Group, 2015). The treatment train approach can provide enhanced pollutant removal performance for the site, and reduce long-term maintenance costs by for the entire chain by provided layered treatment (Doan and Davis, 2016; Fassman and Liao, 2009; Pronchik, 2016).

Inlet/Outlet Protections: Enhancements to the traditional BMP “plumbing” is another route to ensuring the BMPs can safely accept and pass high intensity rainfall events. Proper sizing of inlet and outlet structures, avoiding steep slopes that can raise the risk of erosion, providing more effective pre-treatment, and re-thinking overflow and outfall design are all on the table. However, more work is needed in this area to develop specific design alternatives.

Better Maintenance: An often-overlooked element of the BMP lifespan is long-term maintenance. Many BMPs are designed without consideration of how to maintain them – either by designing practices that are likely to require frequent maintenance because of a lack of pre-treatment, or even failing to consider access to the BMP for routine maintenance activities. As climate change increases the need for both routine and non-routine maintenance of stormwater practices, there should be consideration of mechanisms for rapid inspection and maintenance delivery.

Coastal Design: As sea level rise and rising groundwater threatens to submerge outfalls or infiltrate drainage pipes, solutions will be needed to maintain capacity in the urban drainage network. There are several approaches being explored, including:

- Increased pipe/ditch sizing to compensate for lost capacity
- Elevating outfalls above projected high tide levels,
- Installing check valves to prevent backups,
- Implementing pump systems to move water through the conveyance network

Conclusions and Next Steps

Based on the anticipated risks and vulnerabilities to existing stormwater BMPs and conveyance practices, this memo presents the case that it is now time to begin development of the next generation of stormwater design standards. By looking at a comprehensive approach to resilient design – more than just increased practice sizing – communities will have the opportunity to not only mitigate the expected impacts of climate change, but potentially improve the pollutant removal performance of BMPs through enhanced design and maintenance practices. Between lower maintenance demands and increased cost-effectiveness, the hope is that these future modifications will provide cost-effective solutions over a longer planning horizon.

While there is enough evidence to support a call to action, there are a number of proposed steps that the Chesapeake Bay Program partners may consider to move towards implementation of new design guidance:

Table 2. Summary of Possible Chesapeake Bay Program Strategies to Promote Climate Resilience in Urban BMPs.

Urban BMP	Recommended Priority Level	Proposed CBP Strategy
Stormwater BMPs for New and Re-Development	Very High	<p>Given the number and complexity of stormwater BMP designs, the main strategy should be to develop effective new state stormwater design standards and specifications as updates to existing state stormwater engineering design manuals.</p> <p>The effort should look at new criteria to:</p> <ul style="list-style-type: none"> • Improve reliability in removing nutrients and other pollutants • Adjust BMP “plumbing” criteria to make sure they can convey runoff from extreme storms without damage or loss of function • Establish numeric triggers for BMP inspection and maintenance • Update BMP landscaping criteria to reflect species adapted to future growing conditions. • Promote smart BMPs that provide real time detention <p>An informal Bay-wide technical group could help facilitate sharing of cost-effective BMP criteria that are resilient to climate change and other factors that diminish pollutant removal performance over time.</p> <p>Pending proposed changes to standard BMP design criteria, revisit the Stormwater Performance Standards Expert Panel report to make adjustments to BMP pollutant removal credits and qualifying criteria.</p>
Stream Restoration	High	<p>STAC-sponsored (or other funding mechanism) design charette with stream restoration practitioners and researchers to establish recommended best practices for stream, floodplain, and riparian corridor design that is resilient to the range of extreme floods expected under future climate scenarios.</p> <p>The Modeling Workgroup and Watershed Technical Workgroup (WTWG) could coordinate efforts to assess how extreme flooding might influence the nutrient and sediment erosion, transport, and deposition from streambeds and streambanks.</p>

Shoreline Management	High	Convene small group of shoreline management practitioners and climate experts to recommend whether the existing BMP crediting protocols (or qualifying conditions) need to be adjusted to assure practice resiliency due to future sea level rise and blue-sky flooding.
Stormwater Retrofits	Moderate	Individual state stormwater/floodplain/dam safety agencies should work together to develop stream-lined design criteria for this class of projects.
Tree BMPs	Moderate	The Forestry Workgroup may wish to provide guidance on which tree planting species and techniques will work best in the warmer and wetter climate of the future. The FWG may also outline research on both the risk of riparian tree mortality during extreme floods, as well as impacts on canopy interception and pollutant removal capabilities of tree BMPs.
Urban Nutrient Management, NDGI, and Street Sweeping	Low	The effect of future rainfall patterns on air deposition, erosion, pollutant accumulation and wash off functions are not well known in urban watersheds (i.e., would these result in a meaningful change in simulated nutrient and sediment export rates from pervious and impervious land?) The Modeling Work Group or WTWG could supervise a contractor to integrate future precipitation and temperature scenarios into the hourly time step of pollutant export simulations to an appropriate watershed model.

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Appendix A.

CSN 90th percentile rainfall event analysis

Method:

The general method follows the approach established by the Stormwater Performance Standards Expert Panel (2012).

To analyze potential changes in the 90th percentile rainfall event, daily precipitation data was downloaded from the NOAA National Center for Environmental Information (<https://www.ncdc.noaa.gov/cdo-web/>).

Daily precipitation data from Reagan National Airport in Washington D.C. was downloaded for entire station record (1933 to 2020). The data were then filtered to a 30-year record, beginning in January 1990 and sorted from the smallest daily total to the largest. A 0.1 inch rainfall volume was established as the cut-off point, since it roughly corresponds to the depth of initial abstraction that occurs on impervious surface.

The percent of the annual rainfall that would be captured by a practice designed for the 90th percentile storm was estimated by summing the precipitation for all of the storms less than the control depth, plus the product of the number of storm events greater than the control depth multiplied by the control depth. This sum was then divided by the sum of the total precipitation:

$$\% \text{ Annual Rainfall} = \frac{(SUM P_{<CD} + CD(in) * (\# \text{ of Storms } P_{>CD}))}{Sum \text{ of Total Precipitation (inches)}}$$

Where:

$P_{<CD}$ = Precipitation of Storms less than Control Depth (inches)

$P_{>CD}$ = Precipitation of Storms greater than Control Depth (inches)

CD = Control Depth (inches): the depth of rainfall controlled by the practice

Table Excerpt:

	C	D	E	F	
1	DATE	PRCP	Rank	%	
1931	2/13/2008		1.17	1930	89.56%
1932	7/10/2010		1.17	1931	89.61%
1933	3/28/1996		1.18	1932	89.65%
1934	4/12/2004		1.18	1933	89.70%
1935	7/15/2005		1.18	1934	89.74%
1936	10/29/2011		1.18	1935	89.79%
1937	1/7/1996		1.19	1936	89.84%
1938	4/20/2009		1.19	1937	89.88%
1939	10/17/2009		1.2	1938	89.93%
1940	10/14/2003		1.21	1939	89.98%
1941	4/29/2014		1.21	1940	90.02%
1942	7/14/1990		1.22	1941	90.07%
1943	1/4/2000		1.22	1942	90.12%
1944	5/15/2012		1.22	1943	90.16%
1945	6/1/2012		1.22	1944	90.21%
1946	10/27/2009		1.23	1945	90.26%
1947	5/22/2018		1.23	1946	90.30%
1948	1/25/2020		1.23	1947	90.35%
1949	10/17/1991		1.24	1948	90.39%

Summary Table:

Rainfall Depth Controlled	% of annual rainfall (Retrofit Report 1977-2007)	% of annual rainfall (1990-2020)
0.05	9%	9%
0.1	18%	18%
0.25	41%	40%
0.5	65%	63%
0.75	80%	77%
1	88%	85%
1.25	93%	90%
1.5	95%	93%
2	98%	97%
2.5	99%	98%
90th percentile	1977-2007	1.14
90th percentile	1990-2020	1.21
	Percent Change:	6%

Citations:

Stormwater Performance Standards Expert Panel. 2012. Recommendations of the Expert Panel to Define Removal Rates for New State Stormwater Performance Standards. Approved by the Water Quality Goal Implementation Team. Chesapeake Bay Program. Annapolis, MD.