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A program of the Center for Watershed Protection, Inc.

Integrating Climate Change Science into Watershed and Stormwater Management

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This photo was taken along Young's Bay estuary in Astoria, OR. The Young's Bay estuary is a component of the Columbia River estuary, a nationally significant estuary in the northwest corner of Oregon that supports some of the largest anadromous fish runs in the world and provides unique habitat for sensitive and endangered species.

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Linking Stormwater and Climate Change: Retooling for Adaptation

Dave J. Hirschman[a*], Deb S. Caraco[b], and Sadie R. Drescher[c]

Abstract

Climate change will necessitate a reappraisal of existing approaches for stormwater management. Climate change is anticipated to impact every aspect of the water cycle, and many of the underlying assumptions that stormwater managers use for runoff and storm system design might become outdated if these predictions become a reality. While it is important to link stormwater and climate change, efforts to do so face several unique challenges. This paper addresses how climate change factors may influence such stormwater design hallmarks as the design storm, water quality volume, and stormwater conveyance. Climate change factors suggest that future design changes are needed at the site and community scales to manage stormwater effectively. Examples are presented to supplement this discussion using three case studies that incorporate climate change scenarios into infrastructure modeling, examine how low-impact development practices are predicted to dampen climate change impacts, and integrate climate change into a regional plan. This paper outlines a few key general issues for making the stormwater and climate change link in hopes of furthering this important discussion.

Introduction

Climate change will necessitate a reappraisal of existing approaches for stormwater management. Many of the underlying assumptions that stormwater managers use for runoff and storm system design might become outdated if the predicted impacts on every aspect of the water cycle become a reality (Funkhouser 2007; Oberts 2007). While climate models vary widely, they collectively paint a picture of what might be expected over the next century on an annual and seasonal basis.

The Intergovernmental Panel on Climate Change (IPCC) (Christensen et al. 2007) predicts a temperature increase ranging from 2.5°C to 5.0°C over the next 100 years in the continental United States, with the greatest increases in the northern states and during the winter months. The IPCC also predicts an overall increase in precipitation in the North, but decreased precipitation in the Southwest. The regional differences are expected to be most pronounced in the winter, with northern states experiencing a significant increase in winter precipitation and the already dry Southwest experiencing reduced winter rainfall. This would mean an increase of rain-on-snow events in northern climates and potential severe water shortages in southwestern states that rely on winter snowmelt for their water supplies.

Although these annual conditions present serious challenges in and of themselves, they may be just the tip of the disappearing iceberg. While the total annual rainfall is of course important from a water resources standpoint, stormwater engineers focus primarily on managing individual storm events, and most climate models suggest that most regions will experience a shift to less frequent storms of greater intensity. The potential effects of climate change on individual storm events are uncertain, and would affect stormwater mainstays, such as the *design storm.* This, and other stormwater design parameters, will need to be scrutinized to ensure that future stormwater designs are responsive to changing climate conditions. Further, rising sea levels will impact both flood management and the migration and expansion of existing wetlands on the coasts. Taken together, these impacts will necessarily cause a change in the way we think about stormwater management. Table 1 presents an outline of several climate change factors and the likely effects for stormwater design and management.

The remainder of this paper addresses several aspects of adapting stormwater management to climate change. We present several of the challenges associated with linking stormwater to climate change, followed by a discussion of "designing with uncertainty" at the site and community scales. Each section also includes a profile or case study of a community or institution that is analyzing, and planning for, some aspect of climate change.

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Table 1. Climate change effects on stormwater design and management.

Climate Change Factors	Possible Effects on Stormwater Design and Management
• Increased temperature of atmosphere • Increased temperature of runoff • Changes in rainfall depth, intensity, and frequency • Changes in drought frequency and severity • Decreased soil moisture (antecedent soil moisture between storms) • Increased variability in winds and drying conditions • Sea level rise • In northern climates, more winter precipitation and rain-on-snow events	• Exceedances of storm system capacity and safety • Increase in peak flows • Number of properties and structures subject to flooding • Decrease in annual infiltration volume due to higher evaporation and proportionally more runoff from more intense storms • Decrease in stream baseflow • Wider range of storm events to manage in order to achieve the same level of pollutant load reduction • Increased demand for water supply storage and reliability • Broader application and geographic coverage of drought-tolerant plants for vegetated stormwater practices • Impacts to sensitive waters, wetlands, and coldwater fisheries • Need for more land use planning, such as floodplain management and freeboard requirements for storm conveyance and treatment systems

Sources: Booth 2006; MWH 2009; Oberts 2007; and Shaw et al. 2005.

Challenges of Linking Stormwater Management to Climate Change

To adapt effectively, stormwater managers will need to overcome challenges related to the uncertainty of climate change, coupled with the inherent uncertainty of land use planning and stormwater management. Below, we articulate two brief examples of the challenges involved in linking stormwater and climate change.

Climate Change Impacts Are Offset by Overriding Land Cover Changes

While the expected hydrologic impacts of climate change are noteworthy, they can be dwarfed by the hydrologic changes created by land development. For example, a 0.4-ha (1-acre) site that is converted from a forested condition to a post-development land cover of 40% impervious cover, 40% managed turf (e.g., lawns), and 20% forest may see a ten-fold increase or more in the runoff coefficient and total phosphorus load (based on average values for the Mid-Atlantic), and an increase in peak runoff rates ranging from 50% to 170%, depending on the design storm and local hydrologic factors. By comparison, climate change scenarios could introduce changes in 24-hour rainfall of between 4% and around 25% (Rosenberg et al. 2009; Shaw et al. 2005). In other words, in the stormwater design world, land cover changes will continue to predominate, and changes in rainfall and runoff patterns associated with climate change will require an undetermined level of adjustment above and beyond the overriding land cover change factor (Booth 2006).

Potential Ranges of Change Are Too Large To Inform Engineering Design

Revising stormwater design parameters such as rainfall depth, intensity, and frequency; initial abstraction; and pollutant loading rates is a fairly straightforward exercise. However, whether these factors change by 3% or 40% creates a dramatically different outcome in terms of conveyance, storage, and treatment capacity. At present, the degree of uncertainty in climate change models, as well as region-specific considerations, make it necessary to consider various stormwater design scenarios, depending on the extent and severity of change anticipated (Shaw et al. 2005). This level of uncertainty is probably acceptable for conceptual or modeling exercises but is more difficult to accept for actual stormwater designs, where increases in the number and size of stormwater practices translates directly into increased costs and land area needed for stormwater management.

Understanding Impacts of Climate Change on Stormwater Design at the Site Scale

Even the most careful analysis of rainfall records and climate change model results does not lead to a simple fix for stormwater management design (see Case Study 1). Rather, it only highlights the range in uncertainty, pointing to a need to manage a wide range of project storm events (Rosenberg et al. 2010). However, stormwater engineers need to make design decisions at the site level, and these decisions have traditionally been shaped by selecting specific design storms and treatment volumes. Although the exact criteria vary depending on local and state stormwater requirements, stormwater management generally includes both the relatively large *water quantity* storms and the smaller *water quality* storms. It appears that climate change may affect each of these storms differently. Finally, climate change may impact *rainfall intensity*, which has perhaps the most profound impact on stormwater design.

Design Storm for Quantity Control

Many climate change models predict that the depths of relatively infrequent *quantity control* storms will increase as global temperature increases. Various modeling exercises and analyses of historic precipitation records generally support the notion that the rainfall depths of the less frequent storms (e.g., the 100-year flood event) could increase by the greatest percentage.

Design Storm for Quality Control

Nationally, a common design storm for water quality treatment is the "90th percentile" rainfall event. That is, the average annual rainfall depth associated with 90% of runoff-producing precipitation events is used to derive a volume that must be captured and treated by stormwater practices. In many parts of the country, this equates to about 25 mm (1 in) of rainfall. The effects of climate change on the water quality storm are largely unknown. Most analyses seem to indicate that, while large storms will increase significantly, small storm events will remain unchanged. At first glance, this prediction may suggest that the rainfall depth of the water quality storm would remain essentially unchanged, and this may indeed be the case in many regions of the country. However, truly understanding how climate change would affect this design storm event may be more complex and perhaps beyond our current understanding. Two potential factors that may affect water quality designs are the number of storm events in a given year and changes in the seasonality of rainfall under climate change scenarios. For those designers using continuous simulation tools, such as RECARGA (Atchison and Severson 2004) and WinSLAMM (Pitt and Vorhees 2002), a new series of rainfalls will have to be defined to achieve desired water quality benefits.

One somewhat counterintuitive aspect of determining how the water quality storm will be impacted by climate change relates to its calculation. While this storm is typically a small and frequent storm event, it is not generally tied to a return period. One result of this phenomenon is that the depth of this event may be just as influenced by the number of storm events in a particular year as it is by the depth of specific design frequency events. One possible outcome of climate change is that there will be fewer, more intense storms in a typical year. For example, if we assume that the number of storm events in a typical year is reduced to only ten, then the 90th percentile event would effectively be equal to the depth of the one-year storm. This would be a dramatic increase in most regions of the country. For instance, this could increase the water quality storm event from about 25 mm (1 in) to 76 mm (3 in) or more in certain parts of the country.

Other factors to consider are the seasonal and regional impacts of climate change. An increase in winter precipitation in northern regions will probably translate to greater rain-on-snow events. Such events typically produce a relatively high runoff volume and reduce the ability to store spring runoff for summer potable demand. If this trend is truly expected, models that create an annual runoff spectrum, accounting for elevated runoff coefficients during winter months, will prove valuable in developing new design volume curves.

Rainfall Intensity

Perhaps of greatest concern to stormwater designers is the change in rainfall *intensity*. Since rain will probably come in more intense bursts, we need to start thinking about how changes in the peak intensity of rainfall can impact the design and storage characteristics of stormwater practices. For water quantity events, we need to revisit our assumptions regarding the assumed shape of the rainfall hyetograph, which guides hydrologic modeling. As storms become more intense, designers may want to alter their assumptions about the shape of the design storm.

Rainfall intensity is also important for smaller *water quality* storms. Many designers use the "kerplunk" method to size stormwater practices. That is, they provide storage for the event (for instance, as free storage or within soil or gravel layers) and assume that flow enters and is treated in the facility. However, some practices can be easily bypassed by a short but very intense storm event. A good example is a bioretention facility, in which the filter media (with many small, albeit significant pore spaces) can act as a bottleneck and lead to system bypasses when rainfall intensity exceeds a certain threshold. In other words, runoff enters the practice too quickly to allow the soil media storage to effectively fill.

Stormwater Conveyance

For water quantity events, the primary focus is to convey flows safely through the site, without causing flooding. While it is uncertain how much each storm will vary from one event to another, site designs should, at a minimum, use conservative assumptions when designing a conveyance system and should build a certain amount of additional freeboard into drainage and overland flow path designs.

Related to this are assumptions about sheetflow. Stormwater designs may assume that some water will be conveyed (or even deliberately treated) by maintaining sheetflow conditions. However, if rainfall depths and intensities increase, sheetflow could easily be converted to concentrated flow, leading to system performance and maintenance concerns. In the future, sheetflow may require more careful design, such as use of level spreaders and tighter drainage area-to-sheetflow ratios.

Case Study 1: Understanding Future Precipitation and Resulting Watershed Discharge in the Puget Sound Region

A study in the Puget Sound region used hourly historic rainfall data to examine changes in extreme events and climate models to predict changes in future rainfall patterns (Rosenberg et al. 2009, 2010). Such analyses are critical for understanding the implications of climate change in managing stormwater systems. Researchers analyzed extreme precipitation data from weather stations in three major Washington and Oregon metropolitan areas (Seattle–Tacoma, Spokane, and Vancouver–Portland) for changes from 1949 to 2007. The results were generally nonsignificant, except in Seattle–Tacoma, where Rosenberg et al. (2009, 2010) found an increase of about 25% for the 24-hour design storm. The researchers then used two weather research and forecast (WRF) regional climate models (RCMs) to simulate rainfall from 1970 to 2000 and from 2020 to 2050, and again analyzed changes in extreme precipitation between the two periods. Results indicated increases in extreme rainfall intensities, with statistically significant increases of 15% to 22% projected for the 24-hour design storm.

Changes in streamflow projections are more directly related to design storms and, therefore, to changes in stormwater infrastructure needs. Rosenberg et al. (2009, 2010) modeled streamflow in two watersheds representing urban and suburban areas. Hydrologic streamflow simulations were generated using Hydrologic Simulation Program–Fortran with precipitation data from 1970 to 2000 and simulated data from 2020 to 2050. Based on these results, both stream systems exhibited higher flows at the watershed mouth, although the range of predicted changes varied widely, depending on the recurrence interval, watershed, and underlying WRF RCM precipitation data.

The authors determined that "concern over present design standards is warranted" (Rosenberg et al. 2010, 341) and suggested that "drainage infrastructure designed using mid-20th century rainfall records may be subject to a future rainfall regime that differs from current design standards" (Rosenberg et al. 2010, 340). However, the range of projections was too large to modify current stormwater design assumptions.

Designing for Uncertainty at the Site Scale

Since the level of uncertainty in predicting climate change is high, and specific design standard modifications have not been ascertained, the design community needs to focus on broader design principles that build system resiliency for climate change. Designers should rely on approaches that (1) enhance storage and treatment in natural areas, (2) use small-scale storage and treatment, and (3) provide conveyances that allow for a margin of safety for flood conveyance and water quality treatment. These design principles reflect current thinking in stormwater design and the low-impact development (LID) design framework (see Case Study 2). In the face of climate change, the use of distributed storage and open-channel flow practices provide some insurance against flood control and water quality storm events that may be changing now and in the future.

Design modifications of individual stormwater practices may also be necessary in response to the climate change factors noted above. Since our understanding of design storms may change, the design community may want to focus on what may be fairly modest modifications of existing designs to better accommodate more intense rainfall events. The examples below provide two illustrations of how individual practices could be modified at relatively low cost. These examples are intended to be illustrative and not necessarily authoritative with regard to the best possible solution for a particular issue. The intention is to spur thought and discussion on what types of adaptations will be necessary.

Example 1: Reallocating Storage in Bioretention

The Issue: Increasing rainfall depths and intensities may force a rethinking about how storage is allocated to the various layers within a bioretention facility. More frequent high-intensity rainfall will lead to increased bypassing of the treatment mechanism and lower overall performance. The most vulnerable flow path element may be the rate at which water stored on the surface of the filter can effectively percolate down and fill the void spaces within the soil media.

Possible Adaptation: Increasing the surface area allocated for storage above the soil media can create a "holding zone" for water to move down through the soil voids. Importantly, this does not necessarily mean that the surface area (or volume) of engineered soil media needs to increase, as that could have profound cost implications. One possible solution is to have a surface ponding area that is not underlain by soil media, as shown in Figure 1. In fact, this method has already been adopted in existing specifications, such as those on the Virginia Stormwater Best Management Practice (BMP) Clearinghouse, albeit not as a climate change adaptation (Virginia Department of Conservation and Recreation [VADCR] 2010a).

Example 2: Pretreatment for Rainwater Harvesting

The Issue: Rainwater harvesting systems are designed to capture a target amount of water. However, both ends of the spectrum feature designed bypasses—first-flush diverters, vortex filters, and additional pretreatment devices to keep leaves and gross solids out of the storage tank (Figure 2) and bypasses for higher flows once the storage device fills to capacity. With changing rainfall depths and intensities, more water than desired may bypass at the front end, resulting in a loss of precious water that could be stored for future use, and overflow at the back end, creating downstream problems.

Possible Adaptation: The efficiencies for vortex filters and other pretreatment devices can be increased so that higher-intensity rainfall events will not lead to excessive bypassing of the storage tank. For instance, some current specifications call for a filter efficiency of 95% for a storm intensity of 25 mm (1 in) per hour (VADCR 2010b). The assumed intensity could be increased to 38 or 51 mm (1.5 or 2 in) per hour. To address more frequent overflows from the tank itself, on-site or off-site downstream infiltration or filtering practices can be coupled with the rainwater harvesting system, as is already called for in some state specifications (Figure 3).

Case Study 2: Understanding How LID Stormwater Practices Can Help Communities Attain Climate Change Resiliency

The University of New Hampshire's Stormwater Center (UNH SC) investigated LID stormwater management practices to reduce runoff and manage the more intense storm events expected as a result of climate change impacts. UNH SC used published estimates of the 2-, 10-, and 100-year design storm events. The UNH SC models demonstrated dramatic runoff increases in the future due to climate change. For New Hampshire, Stack et al. (2009) predicted increased mid-twenty-first century precipitation compared to mid-twentieth century (Figure 4).

Figure 1. Adaptation of bioretention facility. Additional surface ponding area can be incorporated (light blue line) while the surface area and volume of soil media remain the same (yellow line). The photo shows a conceptual approach of how the design adaptation may be accomplished. Photo courtesy of: Williamsburg Environmental Group, Inc.

Figure 2. This vortex filter is an example of a pretreatment device for rainwater harvesting. The vortex filter diverts the first amount of rainfall, which tends to have a lot of solids and vegetative debris. Vortex filters come in different sizes based on efficiency curves for rooftop area treated and rainfall intensity. Photo courtesy of: Rainwater Management Solutions, Inc.

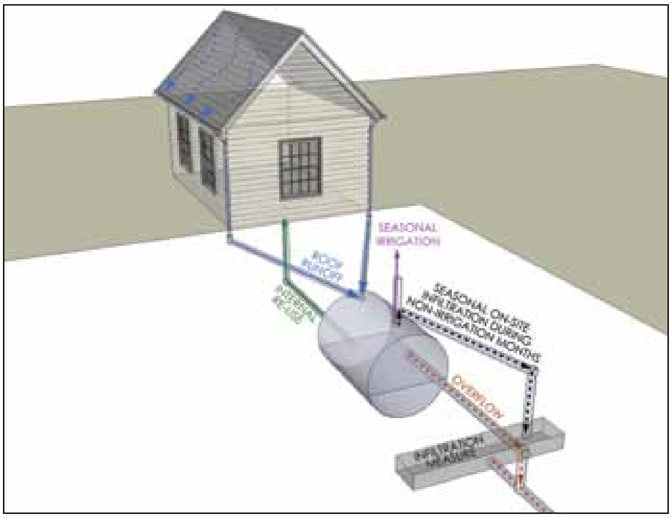

Figure 3. Schematic of a rainwater harvesting system designed for internal use, seasonal irrigation, and treatment in a downstream filtration or infiltration practice during nonirrigation or rainy season months when the tank overflows routinely. Source: VADCR 2010b, figure 6.3.

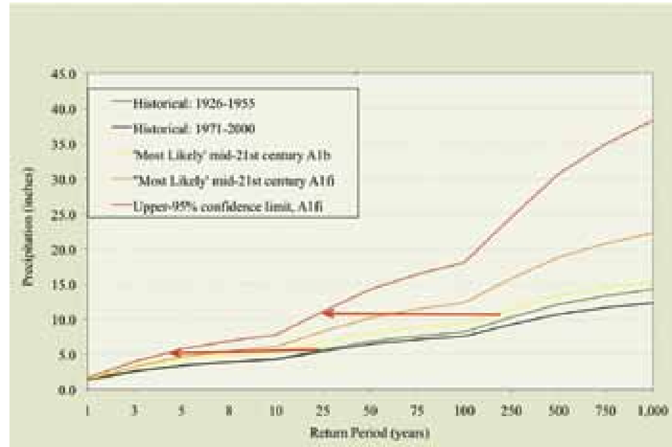

Figure 4. Estimated change in the intensity–return period relationship due to climate change. Source: Stack et al. (2010); reprinted with permission from L.J. Stack, Syntectic International LLC.

UNH SC researchers Robert Roseen, Iulia Barbu, and Tom Ballestero studied a typical site undergoing development. They estimated the total runoff volume for these climate change scenarios for LID practices, predevelopment conditions, and conventional practices, and found that LID practices can reduce the runoff volume for these design storms. In fact, in the typical site scenarios, the LID practices will retain about 15% to 22% of the design storm volume on-site and provide greater groundwater recharge (Ballestero et al. 2009). LID practices demonstrated improved resiliency for the consequences of climate change by reducing storm runoff on-site through infiltration; this also increases groundwater recharge and/or collection and storage for on-site use (Ballestero et al. 2009).

Designing for Uncertainty at the Community Scale

Given the degree of uncertainty, many efforts are underway to frame stormwater management approaches for climate change at the broader community scale. Admittedly, most of these deal more with the infrastructure side of the equation, such as storm system capacity, and less with water quality or stormwater BMP design. However, it is critical to start to frame stormwater management implications and adaptations.

Integrated stormwater and land use solutions have an important role to play in this task. It is safe to assume that we cannot rely solely on "hard," or technological, solutions to deal with such climate change scenarios as more frequent flooding and more prolonged droughts. Solutions that are rooted in the integrated management of stormwater and land use planning will need to play a role. These solutions will include improved floodplain management, urban watershed forestry, and strategies to promote more efficient development patterns at the community and neighborhood scales.

These strategies are necessary to promote multiple and overlapping objectives, such as enhanced stormwater treatment, storage, and use; water conservation; and energy efficiency (see Case Study 3). For instance, land use planning and site and stormwater design can lead to reduced runoff volume; less demand for municipal and potable water supplies (e.g., through rainwater harvesting); and more compact, energy efficient development (e.g., requiring fewer and shorter trips by automobile).

Table 2 provides several conceptual ideas for how integrated stormwater and land use tools can help adapt to both the hydrologic and policy implications of climate change.

Table 2. Climate change and conceptual land use and stormwater management adaptations.

Hydrologic Impacts of Climate Change	Land Use and Stormwater Management Adaptations
More frequent flooding	• Remap floodplains based on "new" frequent and infrequent events. • Adopt stringent regulations to restrict development within floodplains. • Develop mitigation programs to remove susceptible structures from floodplains. • Conduct more frequent cleaning of storm sewer infrastructure in urban areas to maintain hydraulic capacity. • Ensure that all new development has overland relief in case of system failure. • Model storm sewer infrastructure using new climate scenarios and coordinate with emergency response plans.
More prolonged droughts	• Extend rainwater harvesting beyond the individual rooftop scale to the neighborhood or community scale. Use stormwater as a local supplemental water resource—potable and nonpotable. • Adopt small-scale (household) and larger-scale (community) water budgets for indoor and outdoor uses as a tool to prioritize uses and to promote the most efficient use of water. • Implement drought-resistant planting plans for stormwater practices and municipal landscaping. • Promote urban forestry and forest protection to promote shade and the retention of moisture. • Incorporate groundwater recharge into all stormwater practices where safe and feasible.
Increased runoff temperature	• Include trees and other plantings in BMP designs. • Develop methods to reduce straight-piping of runoff to streams; use disconnection methods to direct runoff to buffers, planted areas, pervious parking, forested stormwater practices, etc. • Develop impervious limits and minimum tree canopy requirements for special temperature-sensitive receiving waters (e.g., high-value trout streams).
More combined sewer overflows	• Incorporate runoff volume–reduction measures across the landscape (e.g., for individual homes, streets, and businesses), including rain gardens, rainwater harvesting, and dry wells. • Strategically locate and use open-space areas for runoff capture to reduce flows into the system.
Policy Goals in Response to Climate Change	
Reduce carbon emissions	• Promote compact development to reduce vehicle trips and vehicle miles. • Provide stormwater incentives for redevelopment close to urban centers and more stringent requirements for new (greenfields) development that requires more driving. • Provide stormwater credits for transit and bicycle facilities at development sites. • Consider the energy embodied in BMP materials and installation (e.g., plastic or wood components or land cleared for stormwater practices) as a BMP selection criterion.
Increase carbon sequestration	• Use urban forestry as a stormwater BMP. • Incorporate trees into all or most new stormwater practices. • Design integrated stormwater or carbon sequestration facilities; incorporate planting maintenance plans that maximize carbon uptake.
Increase clean, renewable energy sources	• Incorporate small-scale power generation into some BMP and storm sewer designs that have adequate head. • Co-locate neighborhood-scale stormwater practices with solar, wind, and other renewable-energy facilities.

Source: Adapted from Center for Watershed Protection (2008), table 3.9.

Case Study 3: Adaptive Management To Combat Climate Change in Punta Gorda, Florida

Adaptive stormwater management is called for in the Southwest Florida Regional Planning Council (SWFRPC) Resolution 08-11 (2008) to address water quality, infrastructure, and flooding in the face of climate instability. The City of Punta Gorda, Florida is taking steps (City of Punta Gorda n.d.) to mitigate and adapt to climate change impacts using an adaptation plan that builds on the *Comprehensive Southwest Florida/Charlotte Harbor Climate Change Vulnerability Assessment* (Beever et al. 2009a). The adaptation plan (Beever et al. 2009b) includes detailed mapping, aerial photography, a vulnerability analysis, and involved community stakeholders and decision makers tasked with developing specific implementation actions. Flooding, water quality, infrastructure, water supply, and/or drought were identified as major concerns.

The adaptation plan targets climate stressors by calling for specific stormwater adaptations, such as the following:

- Build roads and sidewalks from porous materials to adapt to more frequent flooding.
- Increase stormwater management capacity to address inadequate water supply and more frequent flooding and to modify the stormwater design criteria.
- Modify stormwater conveyance systems to be relative to sea level instead of at set elevations.
- Construct stormwater infrastructure improvements.
- Require Florida residents and developers to use native landscaping and xeriscaping (the use of plants with less need for watering) to reduce pollutants and to promote water conservation (SWFRPC Resolution 07-01, 2007).

Conclusion

Linking stormwater and climate change will involve adapting several existing concepts. These improvements in stormwater design and implementation are needed to address our current challenges with land use change, pollutant loads, degraded stream health, aging infrastructure, and wise use of water resources. The climate change driver adds some incentive to adopt these practices and to accommodate the uncertainties associated with changing hydrologic conditions. This paper outlines a few key general issues for making the stormwater and climate change link in hopes of furthering this important discussion.

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