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North Carolina Policy Collaboratory on Coastal Flood Resilience:

Nature-Based Solutions

An Update to the Coastal Minimum Design Criteria to Enhance Stormwater Control Measure Resiliency

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Executive Summary

Stormwater control measures (SCMs) are a community's first line of defense against flooding associated with large storm events; yet, often that line of defense fails. Interviews were conducted with a wide range of professionals in the stormwater management field with practical experience in SCM design, construction, and/or maintenance. The purpose of these interviews was to gather insight into how SCMs can be made more resilient, so that their integrity was less likely to fail during large storm events. NC State personnel synthesized that information and produced these recommendations.

The interviews yielded the following conclusion: SCMs that are (1) appropriately situated, (2) well designed, (3) constructed per design, and (4) reliably maintained are more resilient than SCMs that are not. Hereafter, these four elements are referred to as "SCM Resiliency Fundamentals." Per the interviewees, many SCMs fail at least one of the above fundamentals.

Of the four resiliency fundamentals, reliable maintenance stands out as most problematic. It appears that upkeep needs that help ensure long term performance of SCMs are not being reliably conveyed to the property owner. Perhaps the most important action we can take to improve SCM resiliency is to improve maintenance reliability of SCMs, so that they can operate with minimal damage during large events. In short: the maintenance and operation of the SCM must be first understood by the property owner/ manager and then enforced by the governing jurisdiction.

While the report provides many recommendations regarding the four SCM Resiliency Fundamentals, notable highlights among them are: (1) designing and constructing emergency spillways that work, (2) avoiding internal erosion within forebays, and (3) ensuring healthy vegetation stands as appropriate in SCMs. Lastly, designers and maintenance personnel strongly requested more latitude in maintaining SCMs in advance of imminent large events. In particular, they would like the flexibility to pump water from SCMs into waterways before large storms hit. In some jurisdictions, this might require a change in code enforcement.

Lastly, there was general consensus among the interviewees that (1) well-vegetated SCMs are likely more resilient and (2) that visible SCMs are more likely to be maintained. Remembering that well-maintained SCMs are more resilient SCMs, perhaps stormwater practices should be incorporated into the landscape as amenities?

The summary guidelines presented in this report address each of the four SCM resiliency fundamentals. NC DEQ's response to earlier NC legislative action (the development of Minimum Design Criteria for SCMs) provides a strong foundation for SCM resilience. In other words, we are not "starting from scratch."

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Introduction

Coastal stormwater control measures (SCMs) can substantially reduce peak flows, increase basin lag time, and improve water quality via runoff storage and pollutant removal. However, changing boundary conditions (e.g., seasonal high water table (SHWT) and pluvial event characteristics) can impair SCM storage and conveyance capacity, consequently reducing treatment efficiencies. Storm event variability with respect to intensity, duration and frequency can change the hydroperiod and storage volume needed to treat the water quality event. Currently, SCMs within the coastal plain of North Carolina are designed to capture and treat the entire volume of runoff generated from the contributing watershed during the 1.5-inch storm event or, if discharging to shellfish areas, the volume difference between post- and pre-development conditions during the 1-year, 24-hour storm. This requires a volume of runoff to be captured, known as the water quality volume; the depth of which is selected so that at 80-90% of all rain that falls is treated during normal antecedent moisture conditions. Along the Outer Banks, some localities require volumes associated with the 4.3-inch storm event from a commercial development to be captured and treated. Currently, stored water is required to be released from detention-based practices in two to five days. With more frequent precipitation events, water may not vacate an SCM in time to make room for the next event. In many coastal communities, groundwater is rising, especially in watersheds with shallow unconfined aquifers. Because of shallower-than-normal water tables, not only will SCM treatment efficiencies decline, but storage and conveyance capacity can become greatly impaired. Extended periods of inundation, especially that by brackish and saltwater from storm surge, can devastate freshwater flora further reducing treatment efficiency, while concomitantly increasing the risk of erosion and resuspension of sediment-borne pollutants. Therefore, updated SCM design and maintenance guidance is needed to address the issues of the changing boundary conditions. The purpose of this report is to suggest such guidance. Presented is a synthesis of the opinions from a diverse field of stormwater engineers, designers, managers, and maintenance specialists working with green stormwater infrastructure in coastal and near-coast communities.

Methods

Professionals representing a variety of backgrounds and geographic locations were interviewed. The research team met with the individuals in person listed in Table 1. The interview process consisted of organized questioning and discussion regarding flood resilient designs and types of stormwater control measures.

Table 1. Professionals interviewed for the synthesis of SCM resilience guidance

Interviewee Name	Position Title	Place of Employment
Edward Coleman	Chief of Maintenance	Retention Pond Services (Wilmington)
David Deel, PE	Design Engineer and SCM Inspector	Deel Engineering (Kill Devil Hills)
Pat Donovan-Brandenburg	Stormwater Director	City of Jacksonville
Tim Early	Owner Coastal Retention Ponds	SCM Inspector and Maintainer (Jacksonville)
Hunter Freeman, PE	Design Engineer	WithersRavenel (Raleigh)
Timothy Grady, RLA	Landscape Architect & SCM Inspector	G2 Design (Apex)
Nash Hardy	Landscape Contractor & SCM Inspector	Hardy Landscapes (Fuquay-Varina)
Dave Klebitz	PE Design Engineer	Bissel Professional Group (Nags Head)
Drew McCain	Stormwater BMP Selection Supervisor	City of Wilmington
Fred Royal, PE	Director of Stormwater Services	City of Wilmington
Abby Stanley	Maintenance Estimator	Retention Pond Services (Wilmington)

Findings

The Fundamentals

While it might be considered elementary, the interviews yielded the following conclusion: SCMs that are (1) appropriately situated, (2) well designed, (3) constructed per design, and (4) reliably maintained are more resilient than SCMs that are not. Hereafter, these 4 elements are referred to as “SCM Resiliency Fundamentals.” Per the interviewees, many SCMs fail at least one of the above fundamentals.

The summary guidelines presented in the next section address each of the 4 SCM resiliency fundamentals. NC DEQ’s response to earlier NC Legislative action (the development of Minimum Design Criteria for SCMs) provides a strong foundation for SCM resilience. In other words, we are not “starting from scratch.”

Of the four resiliency fundamentals, reliable maintenance stands out as most problematic. That is probably because professionals who understand SCM purpose (designers) are responsible for the first three resiliency fundamentals. They then hand off the practice to an entity (a developer, a homeowner association, etc.) that may not understand SCM purpose. Hence, upkeep needs that help ensure long term performance of SCMs are not reliably conveyed to the property owner. Perhaps the most important action we can take to improve SCM resiliency is to improve maintenance reliability of SCMs, so that they can operate with minimal damage during large events. In short: the maintenance and operation of the SCM must be first understood by the property owner/ manager and then enforced by the governing jurisdiction.

What Designers Can Do to Enhance Resiliency

Siting SCMs for Resiliency

Along with current design guidance (NCDEQ 2017), designers should ensure that the SCM design and operation account for the four resiliency fundamentals. Appropriately situating an SCM can extend the design life, reduce restorative maintenance, and avoid costly retrofits. Picking the best location for an SCM requires a knowledge of the proposed site's (1) soil types, (2) seasonal high-water table (SHWT), (3) land use and condition within the watershed, and (4) proximity to nearby surface waters.

Soil texture and drainage class determines the applicability of an SCM. Infiltration-based practices (infiltration basins, permeable pavement, and infiltration swales) should be situated on well to moderately-well drained sand for desired exfiltration and aerobic filtration. Retention-based SCMs (constructed stormwater wetlands, wet retention ponds, and wet swales) should be situated on somewhat poorly to very poorly drained sands, clays, or marine organics since these practices continue to function properly when saturated. A group of practices can be located in a wide range of soil types, with a modification of design elements needed per *in-situ* soil. These SCMs include sand filters, bioretention cells, dry detention basins, underground detention basins, and detention-based permeable pavement.

Existing soil surveys should first be reviewed to determine soil texture and drainage class and then be confirmed on site. Soil core sampling is highly recommended. While on site, the SHWT needs to be determined by a licensed professional. The location of the SHWT has a dramatic impact on the functionality of most SCMs. High water tables, for example, tend to prohibit the use of bioretention.

Along with the soils and hydrologic analysis of the contributing drainage area, the designer requires an understanding of (1) the upstream land use and (2) how adjacent surface waters impact the SCM. When the watershed draining to the SCM is unstable and therefore is likely to contribute a high sediment load (e.g., from a large row crop operation or active construction site), an SCM's storage and conveyance capacity will likely be severely affected. SCMs located downstream of unstable watersheds are not likely to be resilient.

Nearby surface waters (e.g., sounds, estuaries, and large rivers) can cause two problems for SCMs: inundation and reverse flow-caused erosion. Designers are often not accounting for reverse flow from downstream, and because they do not plan for excess shear stress from the downstream direction, berm blowouts are likely. Long-term SCM damage could result from extended periods of inundation by brackish or saltwater killing many of the non-salt tolerant plants. Once protection provided by vegetation (i.e., stabilization of internal features by vegetation) is lost, subsequent (usually smaller) storms then erode exposed soils. This may lead to the resuspension and release of many years' worth of captured sediments and their associated pollutants. Siting an SCM with sufficient gravitational drainage (whenever possible) will limit the period of inundation, thus helping vegetation rebound. Healthy vegetation directly relates to SCM resiliency.

Designing SCMs for Resiliency

Along with Minimum Design Criteria (MDC), additional attention should be given to other design features that are critical to SCM resilience. Properly designing a SCM requires consideration of (1) side slopes, (2) inlet structures, (3) forebays, (4) outlet structures and trash racks, and (5) emergency spillways.

Parts of the coastal plain are predominantly sand, and thus the side slopes of an SCM constructed in mainly sandy soils should not exceed 3:1 (H:V) to prevent soil slippage, or sloughing. Some sands, even at slighter slopes, may be unstable unless amended with compactable fill. During floods, side slopes become saturated. This increases soil pore pressure which reduces the effective stress of the soil such that when the surface water drains away the side slopes slough.

Design of the inlet structures should consider both energy dissipation of the rising limb and peak discharge conveyance (even when inundated). Erosive failure can be mitigated by directing or angling inflows away from the back berm of the forebay (Figure 1). Another option is to add distance between the inlet and the berms.

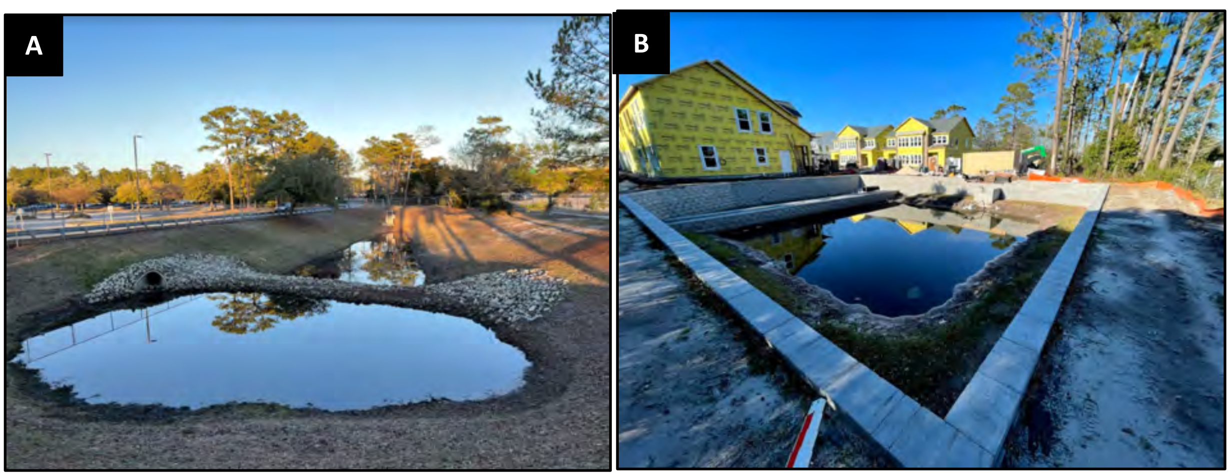

Figure 1. Design Fundamental: Inlet structure angled away from forebay berm, and well armored berms. A. Flared end section with energy dissipators to reduce scour. Forebay with protected internal flow path – berm side slope – armor. B. Well armored forebay with concrete walls protecting the internal flow path.

The forebay's first role is to dissipate energy of the incoming flow. As water slows, coarse sediments and gross solids fall out, leading to the forebay's second function (storage of pollutants). Current MDC standards generally require a forebay to be approximately 10 to 15% of the SCM's surface area. Anecdotal evidence suggests that proportionally larger forebays improve SCM resilience. To prevent erosion of internal features (e.g., earthen berms, concrete or wooden weirs) the designer must protect internal flow paths (Figure 1). Forebays are protected by a lining (or armament), which typically consists of riprap (Figure 1A), gabion baskets, concrete walls (Figure 1B), or reinforced turf matting. Proper installation of forebay armament is essential. For example, when using riprap, the rock must be underlain by non-woven geotextile, to prevent the cobbles from sinking into the *in-situ* soil. If a geotextile is used, it must be keyed-in (i.e., tucked into and buried under the soil on the edges) so that it does not ravel or wash away.

Figure 2. Design Fundamental: Well-armored forebay berm. A. Well-armored primary flow path – side slope of berm – with nonwoven geotextile. B. Coir geotextile keyed-in under rip rap and soil along secondary flow path – top of berm. Well armored internal flow path – upper berm.

Wet pond MDC's require the outlet to be sufficiently far from the inlet to avoid short-circuiting. Similarly, the outlet of any SCM should be sufficiently far away from the berm or basin side slope to avoid erosive back eddies unless well armored (Figure 3). Designers must also provide access to the outlet to facilitate maintenance (Figure 3). This can be done via an earth and rock peninsula or elevated walkway.

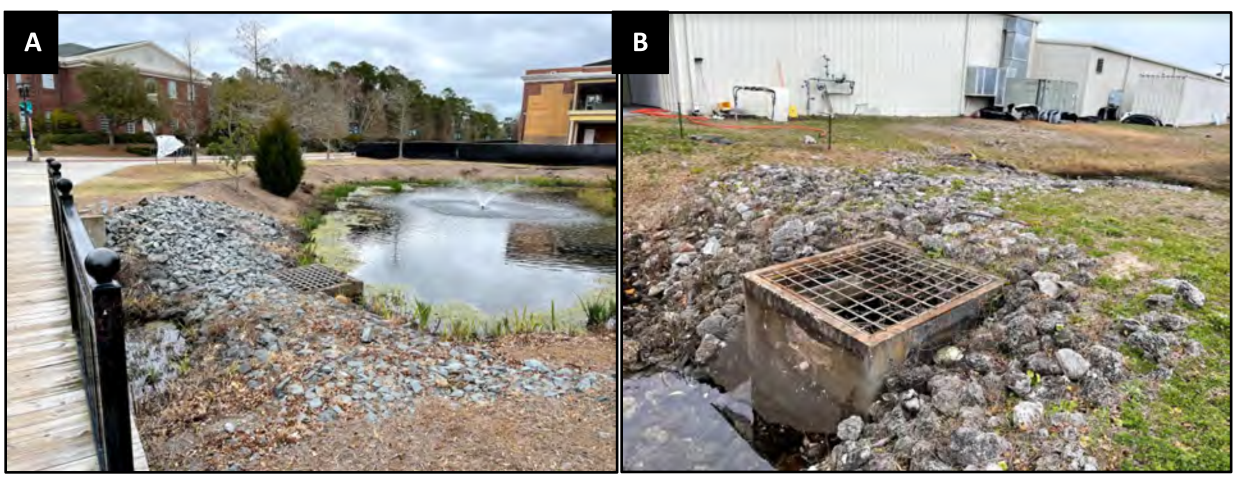

Figure 3. Design Fundamental: Accessible outlet structure on well armored berm. A. Well armored access berm for outlet structure. B. Well armored access berm for outlet structure.

Trash racks can become clogged, accumulating substantial debris jams that reduce the conveyance capacity of piping infrastructure (Figure 4B). Flow blockage will prematurely flood the basin and activate the emergency spillway. Trash racks and outlet structures should be designed with a redundancy of flow paths (Figure 4A) to reduce the likelihood of complete blockage by accumulated debris (Figure 4B). For example, the wet pond in Figure 4B is holding an extra foot of water due to excess straining of accumulated debris on the trash rack. This can be prevented by designing the trash rack to be sufficiently above, below, and offset from the orifice. Anti-seep collars must be used along with proper pipe bedding. This prevents piping (i.e., erosion of soil through cracks in pipes) inside a berm or dam that cause sinkholes.

Figure 4. **Design *Fundamental: Redundancy of flow paths for trash racks and outlet structures. A. Four flow paths are present*: *a draw down skimmer orifice, an intermediate flow weir, an overflow weir, and an emergency spillway. B. Clogged low and intermediate flow orifice lacking redundancy and offset trash rack.***

Overflow (or emergency) spillways are the designated location for overflow from an SCM, and, as such, their design is critical for SCM resiliency. To avoid dam/berm overtopping, the overflow spillway must be located sufficiently below the lowest point of the dam/ berm (Figure 5). This ensures that only the well-armored portion of berm (the overflow spillway) experiences erosive flow. Emergency spillway armament is typically concrete (Figure 4A), riprap (Figure 5) or reinforced turf matting. The armor should vertically extend well into the normal pool (for retention SCMs) or the basin bottom (of detention or infiltration SCMs) to prevent erosion during high flow discharge (Figure 5). Moreover, the “back” (or downstream side) of the SCM needs to be protected from storm surge inundation. This necessitates the emergency spillway design, notably the lining/armament, to extend to at least the outside toe of the berm/ dam (Figure 5B). Hydraulic modeling of the spillway should inform the extent, sizing, and placement of this protection. Finally, the spillway overflow must be directed away from at risk properties to further reduce flooding.

Figure 5. Design Fundamental: Overflow (emergency) spillway well armored and below top of berm. A. Spillway is sufficiently below the top of berm **and rip rap** ***extends below the normal pool. B. Spillway armament extends to toe of berm slope*.**

For some SCMs, adaptive designs should be employed. For example, dry detention basins may need to be designed with flexible planting schemes if the practice remains unintentionally wet post-construction. This is also a maintenance concern and will be further addressed in that section. Due to low gradients found within coastal watersheds, conveyance SCMs like swales will experience extended durations of inundation. Wetland vegetation that can tolerate these conditions should be considered within an adaptive planting plan. If flow conveyance SCMs are apt to grow wetland vegetation, then their cross-section will likely need to be enlarged to account for increased resistance to flow caused by larger wetland vegetation.

Engineers design with factors of safety to account for uncertainty. For stormwater engineers, that factor of safety should account for the observed – and sometimes shocking – depths of precipitation and severity of clogging. A factor of safety for precipitation would require (1) SCMs to capture larger water quality volumes and (2) swales and channels to safely convey flows resulting from higher precipitation intensities. It is noted that enlarging the footprint of SCMs likely makes them less attractive to developers. Factors of safety for clogging severity of outlet structures could include redundancy of flow paths. For example, utilizing two three-inch drawdown orifices in lieu of one four-inch orifice would discharge similar flow rates, but likely be redundant in the event of clogging. MDC’s require most basin SCMs to retain runoff for two to five days. The designed drawdown should be on the short end of this range (i.e., two to three days), because this allows for some amount of clogging to occur and provides time for captured runoff to still vacate within five days.

Constructing SCMs for Resiliency

Constructing vegetation-based SCMs per design requires contractors who have experience with landscaping, soil excavation, utilities, and often aquatic habitat restoration. Resiliency of an SCM is dependent upon a contractor: (1) verifying vegetation stabilization, (2) preventing internal erosion, and (3) protecting against berm failure. Thus, contractors should focus on meeting both soil compaction and soil fertility requirements for the various areas within an SCM.

If the practice is an infiltrating SCM, then care should be taken to prevent unwanted compaction of the subsoil. Compaction can be remediated with scarification of the subsoil, using methods detailed in multiple chapters of NCDEQ's MDC guidance. If the practice is intended to retain water, then compaction of the subsoil is warranted. Moreover, Internal topography (such as inner berms) should be sufficiently compacted to prevent erosion, but care must be taken not to over-compact soil for plant growth and survival. Well-established vegetation protects soil. If topsoil is placed within the basin for plant establishment, then it should be well mixed with the first few inches of the subsoil (e.g., to the depth of the excavator bucket teeth).

Planting plans must be followed by the contractor. To help ensure that contractors follow the planting guidance within the MDCs, designers should explicitly include planting zones, applicable plant species for each zone, and instructions for planting each species. To facilitate the vegetated shelf establishment to the extent necessary to prevent erosion, a denser planting scheme (i.e., less than on 2-foot centers) can be employed. Anchoring of the newly planted plugs will occur if the planted depth is equivalent to the height of the soil-root matrix of the plug (i.e., typically five inches), followed by boot compaction of the soil around the planting hole.

For low-lying or near-to-surface water SCMs, extended periods of inundation should be considered when selecting vegetation type. Natively adapted shrubs, grasses, and trees survive while inundated, and potentially increase SCM resiliency even when overgrown (i.e., non-manicured, potentially neglected, vegetation growth). Dense vegetation improves internal soil stability during inundation (Figure 6). Undesirable species include black willows (*Salix nigra*), common reed (*Phragmites*), and cat tail (*Typha*) due to the rapid colonization of these species which leads to undesirable monocultures. Resiliency is lost with a monoculture due to the potential for mass die off caused by one source, like extended periods of brackish inundation. Some monoculture-forming species are still recommended in specific locations, however; *Spartina sp.*, is suggested for adaptive planting plans. While this species does develop monocultures within salt marshes, it does so based upon distinct boundaries separated by tidal inundation and salt concentration.

Along with properly siting an SCM to take advantage of the natural topography and drainage, contractors should minimize disturbance of existing soils and vegetation. This can be explicitly stated by the designer within the construction notes. Requiring heavy equipment to stay on a construction access road also prevents excessive soil disturbance. Existing native seed banks in the soils coupled with newly planted vegetation will help the SCM establish vegetated cover quickly both upon construction completion and after damage caused by large storms. Again, vegetation promotes resiliency because it prevents erosion.

Berm failure can occur because of internal erosion caused by a lack of vegetation stabilization, soil slope stability, and compaction errors. A contractor must ensure that required compaction levels are achieved. Standard Proctor is a measure of soil compaction that should be specified to be at least 85% for low head berms, and up to 95% for taller berms. To obtain these levels of compaction, soil with more fines may need to be brought on site. Never utilize organics for berm fill as it can cause berm sloughing once it degrades. Always remove any surface vegetation and topsoil before placing structural fill. The existing organics will provide a slip surface if not removed. After structural fill has been placed, amend the surface with topsoil, seed, and erosion control matting. The topsoil should be mixed into the top layer of structural fill to a depth of the excavator bucket teeth (several inches, Figure 6).

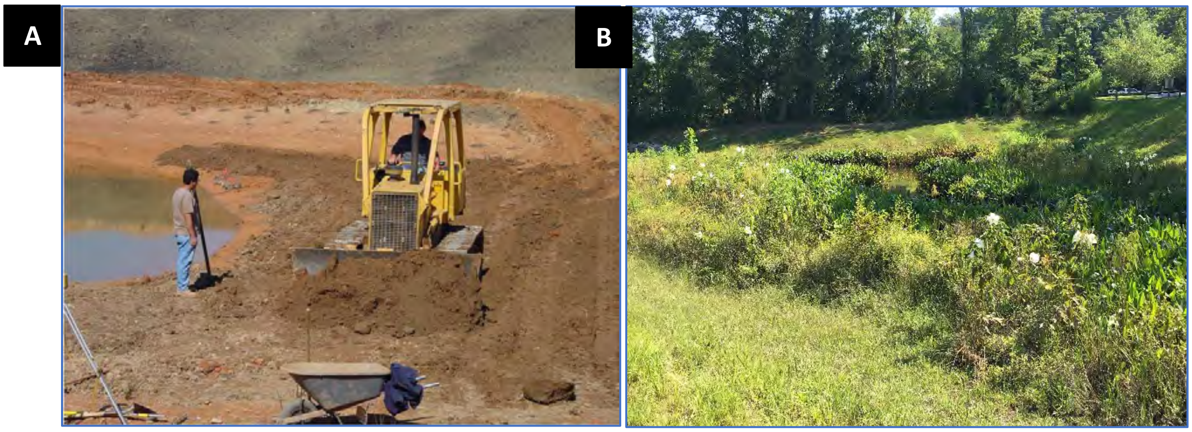

Figure 6. Construction Fundamental: Establishing stable vegetation cover is key to resiliency. A. placing a plant-friendly soil over a compacted berm helps create B. conditions supporting a thriving vegetative community.

Maintaining SCMs for Resiliency

As stated at the beginning of this report, the most likely reason for lack of SCM resiliency is unreliable (or no) maintenance. To be serious about SCM resiliency is to be serious about SCM maintenance. Reliable maintenance will require an <u>enforceable</u> agreement between the designer, owner, municipality, and/or (potentially) a nutrient trading entity. The agreement should particularly enforce compliance on (1) the functionality of pumps, valves, and hydraulic structures, (2) emergency (or preparatory) flood management, and (3) vegetation establishment and mowing.

Pumps, valves, sluice gates, and flashboard risers will become more widely implemented within SCMs due to the likelihood of extended periods of inundation from storm surge (or riverine flooding). These “devices” enable active management of internal water levels. Maintenance and operations staff should understand how these components work; thus, the design engineer needs to supply sufficiently detailed operational instructions. The instructions should explain both the process and frequency of cleaning/debris removal for each component. Additional maintenance guidance should account for various weather scenarios (i.e., *status quo* versus emergency flood management) and then detail how to operate each of the valves, gates, and risers.

Many large storms (such as hurricanes, tropical storms and nor’easters) are predicted to arrive days in advance. As such, maintenance professionals need to be aware of and then implement the emergency management protocols in advance of, and often immediately thereafter, a storm. This could include drawing down wet ponds and wetlands to elevations below normal pool elevation in advance of a storm’s arrival. This provides additional storage capacity. A potential option for infiltration basins is to pump down the underlying shallow water table to create added pore storage during the event. Ensuring that all hydraulic structures including inlets and overflow spillways are free of debris before the storm arrives helps to (1) limit flooding and (2) prevent breaching of berms/ dams. Forebays should be excavated on a regular interval based on accumulation of sediments; however, during emergency management, quick (pre-storm) assessments of the armament and berm integrity will ensure the forebay is less vulnerable to excessive erosion or blowout.

Designers should provide vegetation maintenance plans for multiple stages of the SCM's life. During the establishment period, irrigation of side slopes immediately after planting and sodding help secure vegetative establishment. Maintenance staff should consider irrigating throughout the entire first growing season. Upon the establishment of some SCMs, maintenance personnel should maintain line-of-sight requirements via mowing or pruning. However, "no-mow" zones should be defined for the vegetated shelves of wet ponds and along the perimeter of many stormwater wetlands. If a dry detention basin remains saturated and/or inundated for longer periods than designed, the maintenance plan should provide a list of wetland plants to replace vegetation intolerant of soggy conditions; moreover, replacement wetland plants must also be adaptable to the dedicated no-mow zone. Further, eradication of monoculture-forming species should employ best practices for removal. That is, widespread herbicide application is typically not recommended.

Recommendations & Management Implications

Designers, property owners, regulatory authorities, and maintenance professionals are recommended to remember the four fundamentals of SCM resiliency. SCMs that are: (1) appropriately situated, (2) well designed, (3) constructed per design, and (4) reliably maintained are likely to be resilient. Table 2 summarizes key aspects of each of those fundamentals.

Table 2. Summary of guidance for coastal resiliency fundamentals of SCMs

Aspect of Fundamental	Guidance for Coastal Resiliency	Applicable Stormwater Control Measure
	Fundamental of Resiliency	
	Siting	
Soil Type	Determine soil textural classification and drainage class. Utilize infiltration practices on well drained sand. Utilize detention practices on poorly drained sand, fines, or organics.	All except above-ground rainwater harvesters and green roofs.
Seasonal High-Water Table (SHWT)	SHWT should be determined by a professional soil scientist or geotechnical engineer.	All except above-ground rainwater harvesters and green roofs.
Watershed Land Use and Condition	The upstream drainage area should be assessed remotely and with a site visit. If unstable, additional sediment load calculations need to be performed for forebay sizing.	All except aboveground

		rainwater harvesters and green roofs.
Adjacency to Surface Waters	Determine storm surge inundation elevations from previous storms. Position the SCM to promote positive drainage of the surge water.	All except green roofs.
	Design	
Side Slopes	No steeper than 3:1 unless amended with compactable fill.	Wetlands, wet ponds, dry detention basins, infiltration, bioretention
Inlet Structures	Angle away from the berms and provide small catch basin for sediments to prevent blinding of infiltration practices.	All except rainwater harvesters and green roofs.
Outlet Structures and Trash Racks	Design redundancy into the hydraulic pathways. Oversize structures for clogged conveyance.	All
Emergency Spillways	Design using a factor of safety freeboard. Hydraulically model overflow and reverse flow to determine armament design.	All
Forebays	Oversize and increase erosion control armament.	All except rainwater harvesters, permeable pavement and green roofs.
	Construction	
Vegetation Establishment	Require irrigation of newly planted vegetation. Require less than two-foot centers. Establish vegetation zones within the practice.	All except rainwater harvesters and permeable pavement
Internal Erosion	Ensure boot compaction of internal vegetated topsoil.	All except rainwater harvesters, permeable pavement and green roofs.
Berm Failure	Achieve required compaction.	All except rainwater harvesters and green roofs.
	Maintenance	
Pumps, Valves, and Hydraulic Structures	Create an enforceable operations manual based upon maturation of the system.	All except rainwater harvesters, permeable pavement and green roofs.
Emergency Management	Require debris removal and active water level control before storms.	All except green roofs.
Vegetation Establishment and Control	Create an adaptable planting plan.	All except rainwater harvesters and permeable pavement.

There was general consensus among interviewees that SCMs with vegetation were generally more resilient than those without. This aligned with research studies (Lucas and Greenway, 2008; Komlos and Traver, 2012). Thus, where appropriate, SCMs such as constructed stormwater wetlands should be given extra consideration. There was further consensus that SCMs that are more visible are more likely to be maintained (Moin et al., in review; Gobster et al. 2017). Maintained practices are more resilient practices. Perhaps treating SCMs as project amenities and incorporating them into the landscape design will yield resiliency?

Implementation Actions

While it is nominally required, care must be taken to ensure that all stormwater control measures are reliably maintained. It appears that an important obstacle is the "hand off" of an SCM to the property owner, who typically has little understanding of why SCM's are implemented and what they are responsible for regarding its upkeep. To foster resilience, it is recommended that (1) every jurisdiction employs an active inspection and maintenance program and (2) a process is established by jurisdictions to educate owners of SCMs every time the property (& therefore SCM) is sold or conveyed.

Not all SCMs are created equally resilient (e.g., Johnson and Hunt, 2019, versus Winston et al., 2015). While resilience alone is not the only factor important for SCM type selection (others such as land value, pollutant removal need, flood mitigation requirements are all notable), designers should consider this general rule regarding resilience: the more prominent vegetation is in the SCM, the more likely the practice is to be resilient. As such, constructed stormwater wetlands are going to be more resilient than permeable pavement. Regulating authorities could ask designers during the permitting process if and how they considered SCM resilience in the design process.

A few notable design features have been shown to enhance resilience, yet these functional versions of these features are not reliably included in SCMs. Key design features include:

- Emergency spillways. This is water's path of last resort and it needs to be stable and sufficiently broad and deep to convey emergency flows. Well-designed and maintained emergency spillways prevent berm or dam breaching.
- Forebay features. As water enters the forebay it should not be directed directly at the back berm. Having water flow directly into the back berm has caused the forebay to blow out. Forebays receive the full force of inflowing runoff and should be appropriately armored.
- Consider back flow of brackish water into the SCM for practices along the coast. Can this occur in a non-erosive manner? Will the emergency spillway allow for this?

Before impending events (hurricanes, nor'easters) the design and maintenance community has requested emergency authorization to pump down SCMs that hold water. Lowering the water level well below normal pool creates (often a lot) of additional storage capacity in the stormwater practice, allowing the SCM to better manage large floods. Jurisdictions can be encouraged to allow this specific emergency maintenance.

As mentioned initially, the foundation from which we start is solid. The NC General Assembly required of NCDEQ the production of Minimum Design Criteria (MDCs) for SCMs.

These MDC’s were introduced in 2017. The consensus of all interviewed was that adhering to the MDC’s enhance the resilience of stormwater control measures.

List of Research Team Members

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