TASK 4
DEVELOP CATEGORICAL IMPROVEMENTS
PHILLIPPI CREEK WATERSHED

Prepared for

Sarasota County

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1.0 BACKGROUND AND OBJECTIVES

The Phillippi Creek watershed is an extensively modified drainage network, largely consisting of canals constructed along former wetland strands and sloughs that occurred prior to development. The canal system improved drainage in support of residential and commercial land use but has had some unintended environmental consequences concerning downstream water quality impacts, excessive sedimentation, and extensive natural aquatic and wetland habitat losses. Most of the canals are trapezoidal in cross-section and many lack woody vegetation on their banks. These unnatural conditions lack an energy-dissipating floodplain, which when coupled with banks held together by low-strength grasses instead of woody plants with stronger roots masses, makes the channels more susceptible to erosion than a natural stream. This erosion is a significant impact to Sarasota County's open channel maintenance budget.

The primary purpose of the overall project (**Tasks 1-10**) is to provide procedures most likely to reduce the long-term operation and maintenance costs of the canals. In other words, to enable the channel systems to become more self-sustaining. Investments are recommended to reduce the perennial maintenance and operation costs and concurrently improve downstream water quality, reduce sediment transport, improve fish habitat, and create recreational/aesthetic conditions for public benefit and that improve property values. In essence, the design philosophy is to migrate canal corridor conditions closer to those of natural riparian corridors without compromising the primary flood protection mission of the drainage network. Florida riparian corridors often naturally include patterns of in-line wetlands, strands and sloughs as well as open stream channels.

Categorical improvements were developed to meet the overall project goal of providing cost-effective channel improvement recommendations. The specific objective of this **Task 4** technical memo is to identify and describe ways to improve the open channel systems to operate within hydraulic performance constraints and achieve channel stability, water quality, aesthetics, and fish habitat improvements. This can be achieved in a variety of ways, falling into two broad categories – green and gray. River engineers can stabilize banks by providing surrogates for natural bank features in a variety of ways along a gray to green infrastructure gradient. Green infrastructure uses natural materials like native vegetation, soils, and field stone. Gray infrastructure uses inert materials and relies on concrete, steel, plastic or rock rubble solutions like riprap, articulated concrete blocks, or gabions, among others. Some approaches integrate gray and green components. Various green and gray infrastructure options are described below. The approaches vary in the overall benefits they can provide and vary in their applicability to particular site conditions.

2.0 GREEN INFRASTRUCTURE

Green infrastructure includes treatments designed to be largely self-sustaining incorporating natural forms and processes. For this reason, mowed grass channel banks do not typically apply. Green treatments tend to strengthen over time, in contrast to gray materials that deteriorate as they age. In general, green infrastructure provides a natural aesthetic, financially sustainable option, with multiple environmental benefits. The recommended alternatives analysis starts with identifying the highest and best green treatment options. Gray infrastructure is reserved for situations where it is the only physically-suitable option, is clearly more cost-effective, or perhaps where a community prefers an urban architectural aesthetic over a more natural one.

The more a water conveyance system can be patterned and dimensioned to mimic natural meandering stream and floodplain morphology, the more self-maintaining it becomes, its resiliency increases, and the environmental benefits are maximized. This approach is called natural channel design (NCD). However, this ideal state is not ubiquitously possible given physical constraints in the urban landscape. Also, NCD requires considerable inter-disciplinary expertise to apply correctly. It is a holistic and carefully integrated design approach. Getting any single variable incorrect will cause adjustments in other design variables. These adjustments can be catastrophic to project outcomes in some cases. Most NCD designs are based on observable data and are further validated by numerical modeling. Experience with stream restoration outside of Florida is unlikely to apply very well, mainly because of the peninsula's unique combination of huge wet season flood pulses, low relief, highly erodible soils stabilized by particular native plant assemblages, and other factors.

Further, even in canals where sufficient right-of-way (ROW) exists to implement NCD, the segment may lack the valley slope and flow volumes necessary to provide stream power sufficient to maintain a naturally meandering channel. In such cases the canal is better suited to be configured as a different kind of in-line waterbody (ILWB), like a wetland if shallow or a pond if deep (or a little of both). Florida is full of valleys that naturally alternate between stream channels and in-line waterbodies, thus forming chains-of-wetlands or chains-of-lakes. An obvious example is the Myakka River and its tributaries. Deer Prairie Slough and Alligator Creek historically also had this morphology prior to ditching. Phillippi Creek's watershed was full of chains-of-wetlands prior to development. The existing array of canals replaced that natural drainage morphology. This conversion greatly homogenized the drainage network, thus inadvertently reducing the environmental services of the streams. Natural channel design with in-line waterbody construction can restore much of the pre-development complexity and its environmental benefits.

In cases where NCD or ILWB cannot be accomplished because of a lack of area to work with, then the channel must be stabilized-in-place (SIP). A variety of green and gray approaches can be used for in-place stabilization depending on site-specific factors related to cost, bank height, bank slope, grade, stream width, power and velocity, among other variables. Green bank stabilization approaches are typically referred to as soil bioengineering (SBE) treatments.

In some cases, gray components are integrated into a predominantly green approach. Also, some SBE bank and aquatic enhancement treatments applicable to SIP are common components of NCD. This is discussed further under the applicable treatments.

Design concepts using green infrastructure encompass a hierarchy of scale starting with decisions regarding the applicability of changing the waterbody type from a trapezoidal canal to something patterned after nature. If this is not physically feasible or affordable, then a variety of canal stabilization techniques and aquatic habitat amendments are considered depending on what surfaces of the channel need to be addressed (bed or banks), the available slopes and right-of-way, what kinds of treatments are compatible and sustainable within a given position along the drainage network, and the desired benefits. For these reasons, green treatments are categorized as those that create new waterbody types followed by smaller scope treatments that apply to bank stabilization, grade control (bed stabilization), or are purely to provide instream habitat amendments.

2.1 Waterbody Types

2.1.1 Natural Channel Design (NCD)

River restoration based on natural channel design principles is most commonly accomplished by restoring the dimension, pattern, and profile of a disturbed creek system by emulating natural, stable stream corridors. Restoring streams involves securing their physical stability and biological function, rather than the unlikely ability to return them to a pristine state. Natural channel design, or geomorphic channel design, incorporates a combination of analog and analytical methods for assessment and design.[1] Because all stream corridors do not exhibit similar morphological, sedimentological, hydraulic, or biological characteristics, it is necessary to group those of similar characteristics into discreet stream types. Such characteristics are obtained from stable reference reach locations by discreet valley types, and then are converted to dimensionless ratios for extrapolation to disturbed stream reaches of various sizes.

The Rosgen Geomorphic Channel Design methodology is described in Chapter 11 of the NRCS Handbook: Part 654 — Stream Restoration Design (2007). Rosgen's pioneering approach is expanded and adapted to Florida stream types, with greater emphasis on watershed and floodplain conditions in Kiefer et al's. (2015) hydrobiogeomorphic (HBG) approach to stream classification and restoration. Both are variations on NCD. As such, streams are viewed as multi-stage channels with an open bankfull channel meandering through a floodplain channel. The bankfull channel is what most people typically view as the stream. It is where the water flows most of the time, defined by well-formed banks and a sandy bottom. The flood channel is the wetland bottomland adjacent to the bankfull channel. It carries flow about 25% of the time in perennial Florida streams. The Florida-specific HBG approach applies well for conceiving opportunities and limits for rather fully naturalizing Phillippi canals.

[1] Analog methods include mimicry of natural stream forms and typically rely on statistical associations among variables characterizing channel shapes and sizes. Analytical methods use numerical modeling or physics-based equations to calculate sediment transport and hydraulic outcomes resulting from design patterns and dimensions.

Stream restoration requires sufficient undeveloped land or available right-of-way for construction. If the minimum stable floodplain width cannot be accommodated, then stream restoration is removed from further consideration. The necessary floodplain width increases with drainage area and varies by stream type. **Figure 1** was developed to illustrate different screening criteria to evaluate if enough lateral room exists to build the floodplain. It shows minimum floodplain width requirements of Rosgen and HBG natural channel designs for four broad categories of stream type (Rosgen B and C, HBG Flatwoods and Highlands).[2] The scatterplot shows measurements from 20 canal segments in the Phillippi watershed to illustrate use of the chart. For example, all of those sites provide sufficient right-of-way for constructing Rosgen C stream types, and all but three sites meet the HBG Highlands stream type's required flood channel dimension. The three sites not meeting the Highlands requirement were all in Group 1 which is the largest of 3 canal types derived from hierarchical cluster analyses (HCA) presented in the **Task 3** memorandum. Several sites in the smallest canal cluster (Group 3) meet the requirements for Flatwoods stream types.

The watershed drainage characteristics must be determined before deciding on whether to apply Rosgen or HBG floodplain width design criteria. This is because streams draining areas with at least 40% well-drained soils have smaller geomorphic floodplain requirements than systems with a higher relative amount of poorly drained soils (Kiefer et al., 2015). **Figure 1** illustrates that the floodplain widths for HBG flatwoods stream types governs requirements for all poorly drained watersheds greater than 0.25 square miles. Below that, the Rosgen floodplain criterion for C channels is more robust. For well-drained watersheds, HBG highlands stream type requirements govern at or above 6 square miles, while Rosgen C channels apply in smaller drainage areas. Rosgen B channels represent the hypothetical minimum flood channel widths for NCD, but this is not recommended as a primary design objective except along short distances scattered within an otherwise wider floodplain segment.

Although the Phillippi watershed was poorly-drained prior to development, calibrated soil drainage variables used in County flood studies imply the system currently functions more like a well-drained system overall. This makes sense because most of the canals have lowered the water table at a regional scale, and the overlying soils are sandy. Thus, the larger of either Rosgen C or HBG Highlands floodplains depicted on Figure 1 should be viewed as a starting point of design in the Phillippi watershed. Nevertheless, site-specific designs need to be confirmed on a case-by-case basis as part of a complete hydrologic and hydraulic evaluation of flood protection performance.

[2] For stream classification purposes, 'well drained' soils are defined as NRCS hydrologic soil groups A, B, and C, and 'poorly drained' soils are in group D. In the parlance of Kiefer et al. (2015), the drainage landscapes are categorized based on their historic ecosystem associations as 'Flatwoods' if poorly drained, and 'Highlands' (scrub, sandhill) if well-drained. Rosgen C streams have well-developed floodplains at least 2.2x as wide as their bankfull width at twice the maximum channel depth, and B streams have flood channel widths between 1.4 and 2.2x bankfull width. Rosgen (1996) refers to flood channel 'width as the width of the floodprone area' (WFPA).

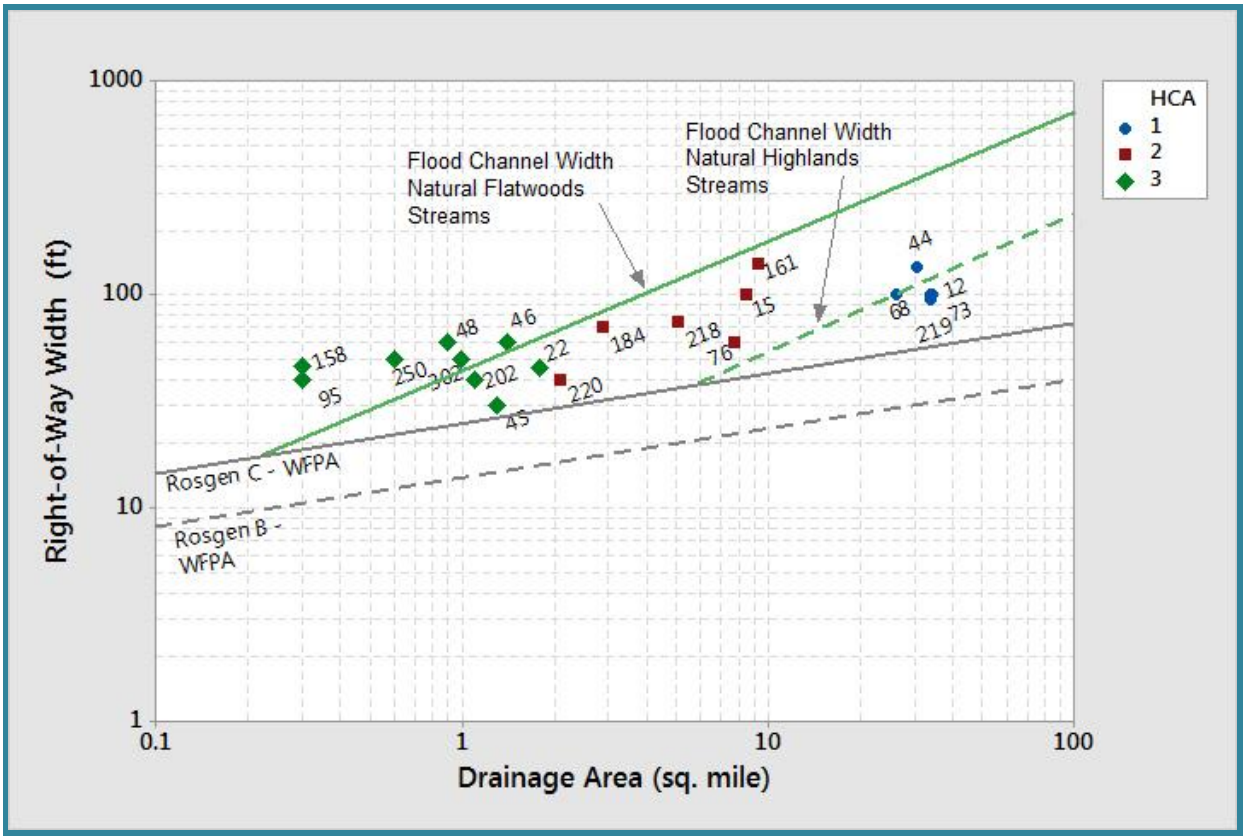


Figure 1 - Minimum Right of Way Required for Natural Channel Design versus Drainage area in Peninsular Florida

While NCD is primarily a major geomorphologic adjustment to the conveyance, it characteristically also requires some of the soil bioengineering bank treatments and aquatic habitat enhancement improvements which are described in more detail below. The overall NCD result is a shallow open channel meandering across a vegetated floodplain (**Figure 2**). The open channel is referred to as the bankfull channel. The flood channel flanking the bankfull channel consists of the relatively flat bankfull bench and the canal's outer slopes to the top of the canal. The flood channel can be terraced to promote recreation and biodiversity, assuming hydraulic objectives are met.

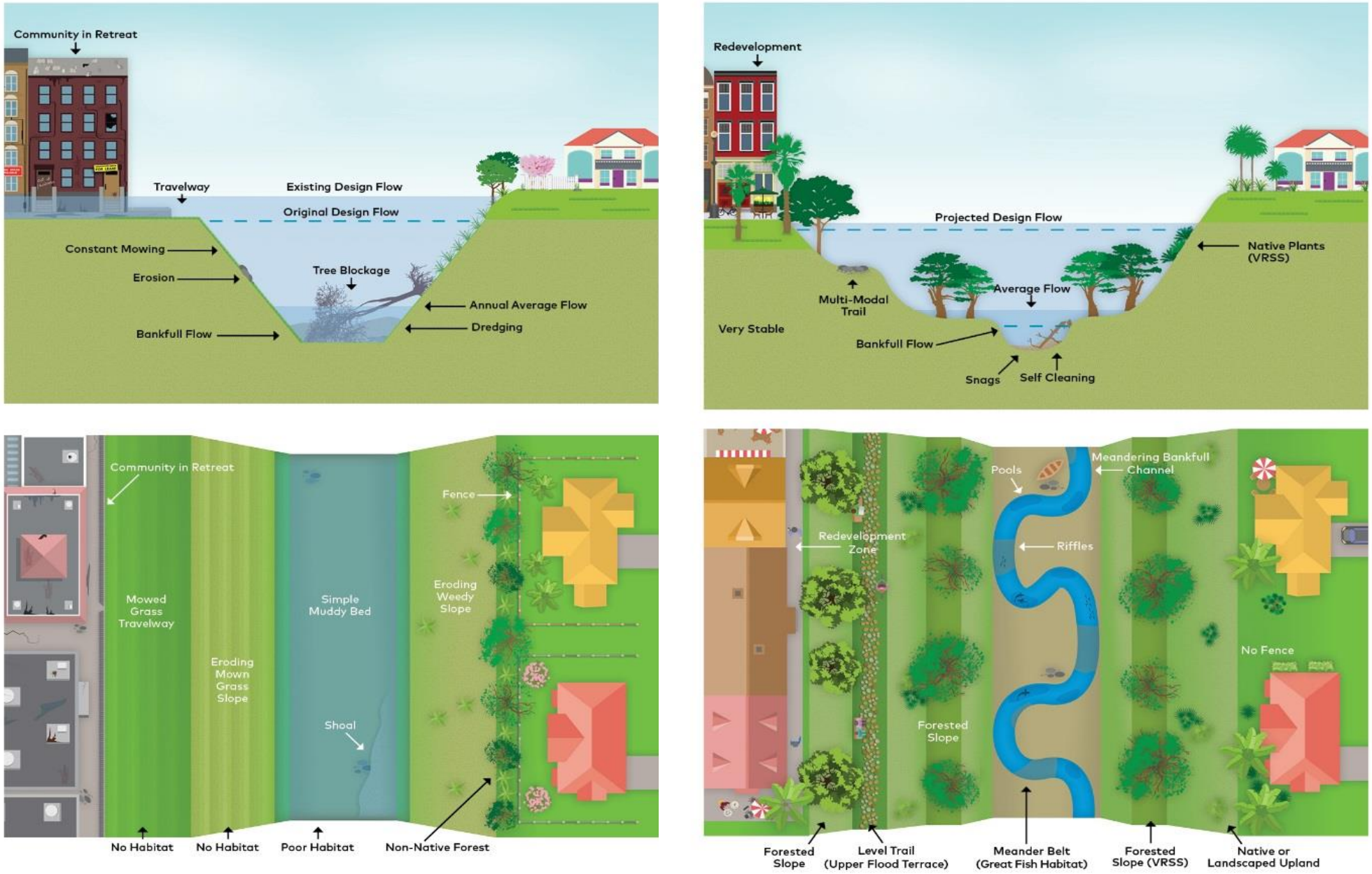


Figure 2 - Comparison of Characteristic Southwest Florida Canals (left) and Natural Channel Design Conveyances (right)

The flood channel is typically forested. The whole system is designed to accommodate some fallen trees and dead logs in the bankfull channel and is in fact more stable with such woody debris. Based on critical flow and specific energy relationships, snags in natural channels function like low head weirs that do not raise the water levels of flood flows. Snag removal can cause significant erosion and sediment transport, which in turn clogs culvert openings and can worsen flooding. It is thus usually counterproductive to de-snag an NCD conveyance.

Although friction factors are higher for flow through a forest than across a mowed lawn, the overall conveyance and in-line detention capacity is characteristically greater for NCD than those of the trapezoidal canal being replaced. Thus, NCD can improve the level of service for flood protection and is usually at least neutral. The degree of improvement depends on whether the existing drainage system is rate- or volume-limited and whether bottleneck conditions at crossings or other areas not affected by the changes in cross-section or sedimentation control the hydraulics. This rule of thumb regarding flood flow profiles should be tested using an appropriate hydraulic model. Two-dimensional models are increasingly being applied for this purpose because most codes with that capability also provide velocity and shear stress vectors that can be used to assess potentially erosive areas and enable design countermeasures against undesirable sediment movement. Those same vectors can factor into fisheries enhancement design analysis as well.

Sediment transport and deposition are critical design considerations affecting habitat value, hydraulic performance during flood events, and sustainability of stream morphology. Enlarging the bankfull channel versus dimensions that are regionally correct for a given watershed size results in failure and is not recommended as a means to accommodate high sediment loads.[3] If greater flood conveyance or sediment capacity is desired, enlarge the floodplain, not the bankfull channel. Sediment transport capacity and continuity through the project area need to be addressed by the design. This includes providing the sediment management requirements in the associated operations and maintenance plan for the project.

The bankfull channel carries almost all of the transportable parts of the sediment load in a small part of the overall flood conveyance. This creates sorting between sediment-laden bankfull flow and relatively unburdened floodplain flow which is one of the great efficiency factors of the multi-stage natural channel form. In contrast, trapezoidal canals are designed to carry water alone, at maximum efficiency for whatever the particular single design flow of the channel was determined to be. Yet, they are also carrying sediment and a host of variable water discharges over time. This is one of the reasons a 'stable' canal design erodes and requires routine maintenance. In contrast, natural channels evolve to sustain something closer to an optimal overall efficiency for variable flows of water *and* sediment. Canals are seldom operating at their optimal effectiveness for water flow, and rarely, if ever, for sediment transport. There are reasons straight, simple cross sections do not often form in nature.

[3] For example, all 16 of the initial urban NCD projects in North Carolina failed because designers thought they needed to enlarge the bankfull channel (Dave Rosgen, personal communication).

It is beneficial, and in many cases necessary, to retrofit road crossings with culvert arrays that maintain parallel rather than convergent flowlines under the road such that the bankfull channel's sediment laden flows and relatively clear flows of the flood channel remain segregated. This crossing design approach is referred to as 'fish passage culvert design' because it leads to a stable morphology through the crossing that fish and most debris can pass through during and after the storm event. Not only is that good for aquatic fauna, it also sustains the greatest available hydraulic capacity of the crossing during the flood.

2.1.2 In-line Waterbodies (ILWB)

For combinations of valley slope and drainage area insufficient to support NCD (**Figure 3**), different kinds of in-line waterbodies (ILWB) can be configured in lieu of a meandering channel and floodplain. These can include forested wetland strands (in-line swamp – ILS), non-forested wetland sloughs or swales (in-line marsh – ILM), and deep open waters such as ponds or lakes (in-line pond – ILP). These areas do not maintain as much continuity of sediment transport as streams and thus can serve as intrinsically good locations for sediment management features. Sediment management features are built to capture eroded or disturbed soils that are washed off during rain storms in order to protect hydraulic performance downstream. Most of Sarasota County's pre-development drainage systems were comprised of ILWBs connected by short reaches of meandering stream channel. So, perhaps not surprisingly, most canal segments are conducive to ILWB rather than NCD repatterning (**Figure 4**). Restoring repetitive sequences of NCD and ILWB zones along the drainage network restores an analogue to the pre-disturbance chain-of-wetland form, and thus restores key aspects of the region's lost biophysical functions.

Further, recent research by Mote Marine (Locascio et al. 2018) on Phillippi canals shows that sediment traps can be excellent habitat for juvenile snook and largemouth bass. The occurrence of these species was associated with combinations of slackwater water habitat bordered by emergent wetland and overhanging vegetation, consistent with findings in other studies of Gulf coast tidal streams. Creation of a variety of in-line waterbody types can promote habitat development not only for fish, but also wading birds and other wildlife of value to an urban community. Varying the overflow depths between stream channels and their ILWBs, and the depths within the waterbody itself, not only enables greater recovery of the natural hydro-ecological variability of the freshwater drainage network, but Florida Fish and Wildlife Conservation Commission (FWC) biologist Dave Blewett describes such variability in the 'limited connections' of the system as major drivers for segregating fish nurseries from areas more suitable for large adults and predators in coastal streams. For these reasons, it is recommended to consult with regional biologists and the nearby community stakeholders to develop priority objectives for the ILWBs.

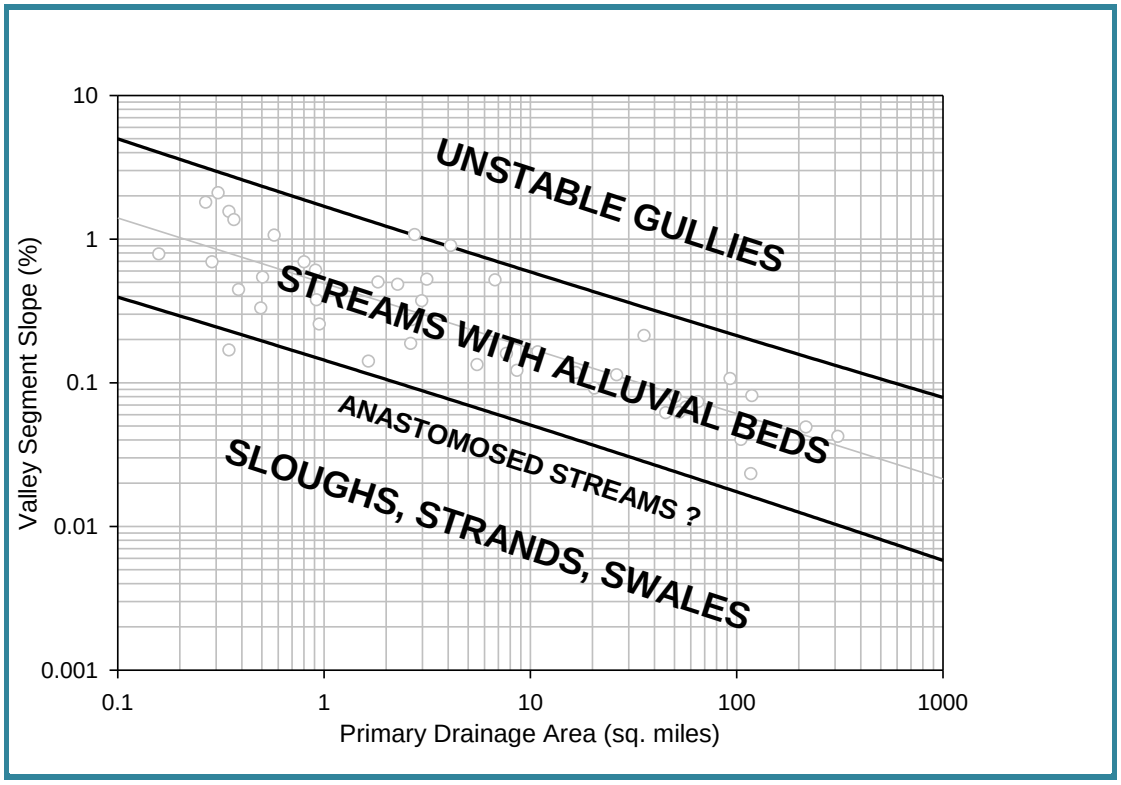
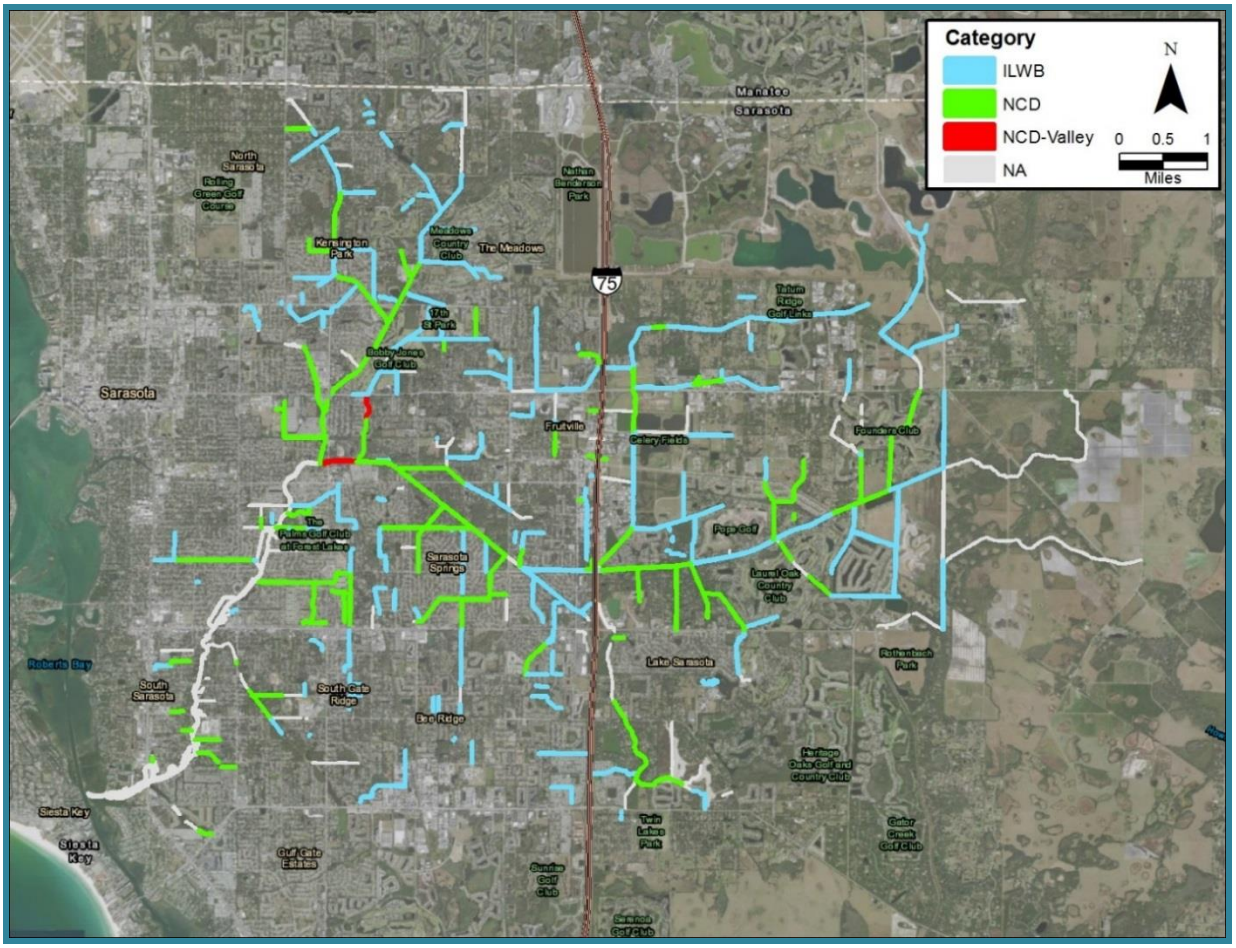


Figure 3 - Valley and Drainage Area Zone of Confidence for Alluvial Channel Formation[4]

[4] Alluvial channels have predominantly inorganic bottom substrates (beds) that are transported by flowing water. The dominant bed alluvium is usually sand in Florida streams. The question mark next to anastomosed streams denotes a highly variable transition between valleys with multiple crossings of shallow meandering channels versus those without observable channels at all.



ILWB – pond, slough, strand, marsh swale. NCD – natural alluvial channel and wetland floodplain.
NCD-valley – NCD would otherwise be possible, but ROW is insufficient to construct a floodplain. NA – not assessed.

Figure 4 - Waterbody Type Potential by Canal Segment

2.1.3 Trapezoidal Canals – Stabilization in Place (SIP)

If NCD or ILWB conditions do not apply, then the canal is stabilized with limited to no changes in its morphology, referred to as stabilization in place (SIP). Critical decisions regarding which green treatments to apply relate to where the erosion is occurring, the kinds of appurtenant benefits desired, channel dimension, and whether the stabilization will adversely affect level of flood service.

2.2 Bank and In-Stream Treatments

Once the kind of waterbody is decided, certain types of bank and bed treatments are selectively applied. The applicability of these selections primarily depends on waterbody type and channel dimension and are further refined based on project goals including those specific habitat, water quality, and aesthetic objectives. Bank treatments are discussed first, followed by a section on the instream or bed amendments.

2.2.1 Bank Stabilization Treatments

Vegetation Bank Stabilization – Soil Bioengineering via Afforestation (SBE)

If a mowed bank is eroding but is at a slope less than the internal friction angle of the bank soils[5], then it can be stabilized by changing the vegetation from a lawn to a forest. This afforestation can be accomplished in a variety of ways. If soil moisture is sufficient, one of the most effective means is to use lives stakes and branches. Live branches are stem cuttings from living plant materials that are maintained in a viable condition for root and leaf sprouting when installed in a properly hydrated soil medium. Otherwise a wide variety of nursery stock ranging in size from bare root to over 10-gallon plants can be installed using standard techniques developed for wetland mitigation and landscaping projects. Nursery stock is more common in Florida usage because live branching species are more limited than those occurring in temperate and boreal climates. Potential live branch species in peninsular Florida include buttonbush (*Cephalanthus occidentalis*), Carolina willow (*Salix caroliniana*), sweetspire (*Itea virginica*), and elderberry (*Sambucus canadensis*). Contract growing is essential, typically providing vendors at least 6 to 8 months advance notice. These species form a rapidly developing shrub layer that can be an early phase of an overall reforestation program installed contemporaneously with a wide variety of more slowly growing climax canopy species that are fit to different hydrologic zones along the bank. Use of container stock is more expensive but proven for Florida application. Live branching is more experimental.

Afforesting a bank should be viewed as part of a successional process, starting with an abundance of native sun-loving groundcover and woody species and phasing in shade tolerant species on an as-needed basis as the forest canopy develops. Some non-native grasses such as cogon grass (*Imperata cylindrica*) can interfere with forest establishment, while others like bahia grass do not. Generally, native bunch grasses such as Fakahatchee grass (*Tripsicum floridana* and *dactyloides*), sand cordgrass (*Spartina bakeri*), various broomsedges (*Andropogon* sp), Gulf coast muhly grass (*Muhlenbergia capillaris*), and purple lovegrass (*Eragrostis spectabilis*) are beautiful choices compatible with bank reforestation.

Most natural stream banks and riparian corridors support forests, even where these corridors occur in non-forested landscapes. Riparian meadows generally occur only in areas with combinations of high fire frequencies and long-duration shallow flooding that lasts many weeks to several months at a time. In other words, forested corridors are more characteristic and self-organizing for the urban landscape, while non-forested corridors will require maintenance to create a surrogate for

[5] This is about 2.5:1 horizontal to vertical for sand.

fire (pruning, herbiciding, or mechanical removal of any colonizing woody vegetation while it is young). Further, woody vegetation provides greater shear strength in the embankment. It is nature's rebar. This enables Florida channels to have very stable banks and fixed bend patterns that are unstable absent the forest. In fact, much of our team's streambank erosion control work occurs at sites where land owners had cleared the forest. It should also be pointed out that a row or two of trees does not constitute a forest. In fact, such thin arrays are so susceptible to wind throws they are counter-productive to long-term bank stability and it would better to not plant any trees than to establish a single row of them along the bank. The root systems need to be laterally extensive to hold up under wind storms.

Live cuttings and sun-loving grass and forb plantings are nurse crops that hold banks in place while the slower growing and ultimately dominant shade species, called climax species, mature over a period of several years to decades (see photo sequence, **Figure 5**). An example of climax tree species occurring along a gradient from seldom to frequent inundation includes live oak (*Quercus virginiana*), south Florida slash pine (*Pinus elliottii v. densa*), cabbage palm (*Sabal palmetto*), laurel oak (*Quercus laurifolia*), red maple (*Acer rubrum*), water hickory (*Carya aquatica*), and bald cypress (*Taxodium distichum*). Slow-growing climax sub-canopy species can be added for increased stability, plant and avian biodiversity, and an even greater natural aesthetic. Examples common along riparian corridors include saw palmetto (*Serenoa repens*), wax myrtle (*Myrica cerifera*), bluestem palmetto (*Sabal minor*), dahoon (*Ilex cassine*) and ironwood (*Carpinus caroliniana*), among others.

Figure 5 - Florida Freshwater Stream Restoration of Various Ages and Watershed Sizes

Kiefer et al (2015, pages 175-242 and 390-392) provide further guidance regarding the kinds of native vegetation most characteristically found along a variety of Florida stream types. A wide variety of native Sarasota trees, shrubs, grasses, and forbs are available from regional nurseries. These suppliers can provision afforestation efforts that range from parklands with a landscaped urban aesthetic to structurally and biologically diverse forests more akin to wilderness areas. The latter is more self-sustaining with lower maintenance costs and greater ecological benefits and is the focus of cost-benefit assessments.

Bank Slope Reduction (BSR)

Overly steep banks will continue to erode as the planted vegetation root systems develop. This can destroy the planting effort. Countermeasures to this can involve changing the bank slope, covering the slope with a rolled erosion control product (RECP), or placing reinforcement materials within the bank. If the bank angle is steeper than 2.5:1 H:V, then bank slope reduction can make the slope less likely to fail by gravity. This involves some earthwork and requires sufficient right-of-way to accommodate. BSR is followed by soil bioengineering with tree and shrub plantings (SBE).

Vegetation Reinforced Soil Slope (VRSS)

A Vegetation Reinforced Soil Slope (VRSS) is a soil bioengineering technique employed for stabilizing banks steeper than the soil's angle of repose. It can accommodate banks as steep as 0.5:1 H:V and up to 60 feet high. VRSSs are more complex and expensive to construct than the previously described bank treatments and are only recommended in situations where bank slopes are too steep and high to support other soil bioengineering measures. VRSSs consist of a series of 12- to 18-inch thick soil layers typically wrapped in several feet of a reinforcement material that allows root and water penetration. Living, rootable, livecut, woody plant material branches, bare root, tubling or container plant stock are installed between the layers, and their root systems bind the layers together over time. If toe scour is occurring or likely to occur, VRSSs are typically built above a foundation of inert bank material designed to eliminate adverse amounts of scour that could undermine the rebuilt streambank (Sotir and Fischenich 2009). The inert foundation can be riprap, native field stone, articulated concrete block, or Rosgen toe wood (described later). VRSSs provide a living shoreline that offers ecological benefits and a naturalistic aesthetic. They can be implemented and managed to provide a landscaped look (**Figure 6**) or as a genuinely natural and wild embankment (**Figure 7**). They also are highly adaptable and can be configured around a variety of penetrations and obstructions, thus enabling the preservation of old trees or historic structures.

Photo credit: Tensar Corp.

Figure 6 - VRSS with Landscaped Aesthetic

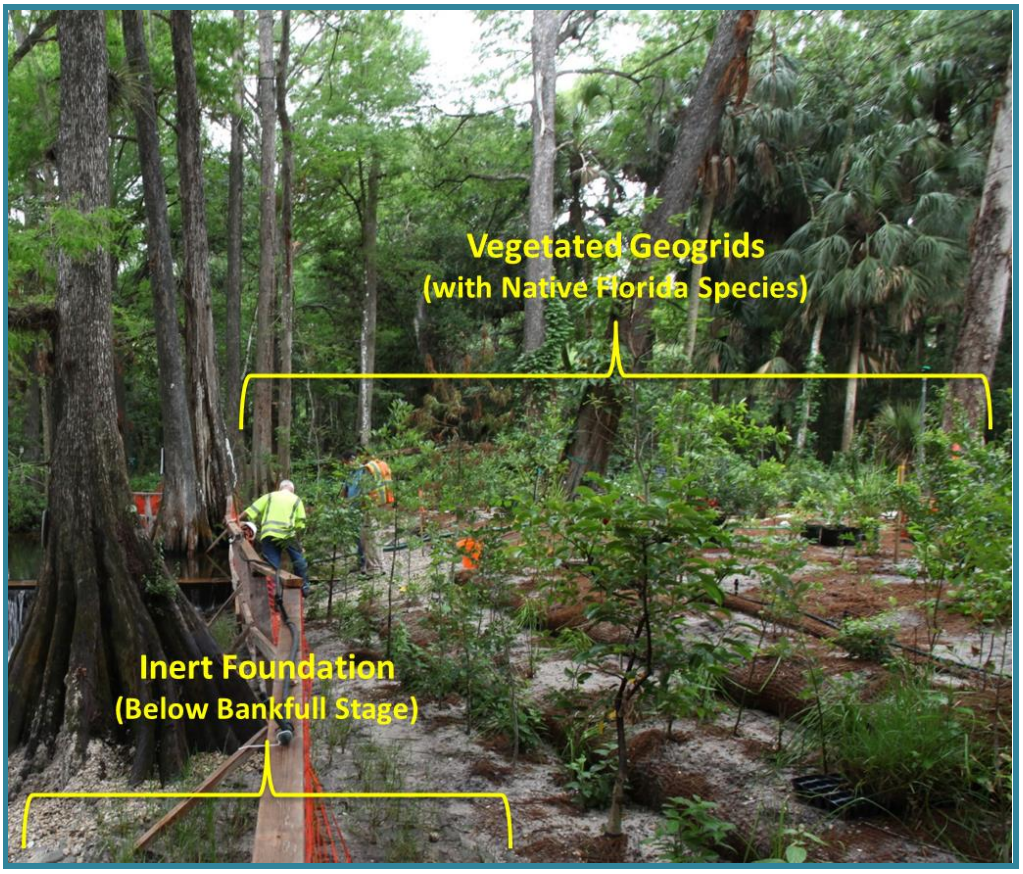


Figure 7 - VRSS Designed with a Natural Florida Aesthetic. Photo Taken After Initial Planting of Large Container Stock (on the National Scenic Loxahatchee River)

2.2.2 Instream Treatments

Instream treatments are added to provide a variety of objectives that vary by treatment type and can include grade control[6], raising water surface profiles to a desired elevation, reducing sediment and nutrient pollutant loads, and creating fish and macroinvertebrate habitat. Instream treatments patterned after natural stream features that are compatible with natural forces, even when constructed from inert materials, are deemed to be green infrastructure if they also provide stream ecosystem processes. Inert instream structures that are designed primarily to resist natural forces, are not patterned or dimensioned in accordance with natural analogues, and do not provide stream ecosystem processes are labeled as gray infrastructure.

[6] Grade control is a countermeasure against bed erosion and channel incision. This is generally not an issue for Phillippi canals, but there are exceptions. Loss of grade control is a very serious form of erosion that progresses in an upstream direction (headcuts) and can trigger subsequent bank failures. Also called channel degradation, this form of erosion wipes out important aquatic habitats. Loss of grade control is characteristically diagnosed by the presence of knickpoints which are abrupt changes in streambed elevation resembling shallow waterfalls. Some countermeasures aim to arrest the headcutting knickpoints in-place, while other approaches distribute treatments along the affected reach.

While some instream treatments are physical, others are strictly biological. Of course, some physical and biological treatments are combined for greater effect. Certain instream treatments are stand-alone practices while others are common or even necessary components of natural channel design.

Regenerative Stormwater Conveyance (RSC)

Regenerative stormwater conveyance (RSC) systems are open-channel filtration systems utilizing a series of pools and riffles to treat and safely convey stormwater (**Figure 8**). Step-pool and small riffle-pool streams are their natural analogues. The riffles can be designed to provide grade control or water surface profile adjustments. The riffles are designed with a rocky surface over an underlying carbon-enriched sand or gravel bed to allow baseflow infiltration and reduce nutrient pollutants such as nitrogen. Carbon sources can include wood chips. The pools trap debris and sediment. Redox coupling between the pools, riffles, and through the riffle media and associated microbial action provide the treatment mechanisms. RSCs enhance the natural phenomenon referred to as hyporheic exchange, which allows portions of the streamflow to alternate through porous channel bed materials and open waters.

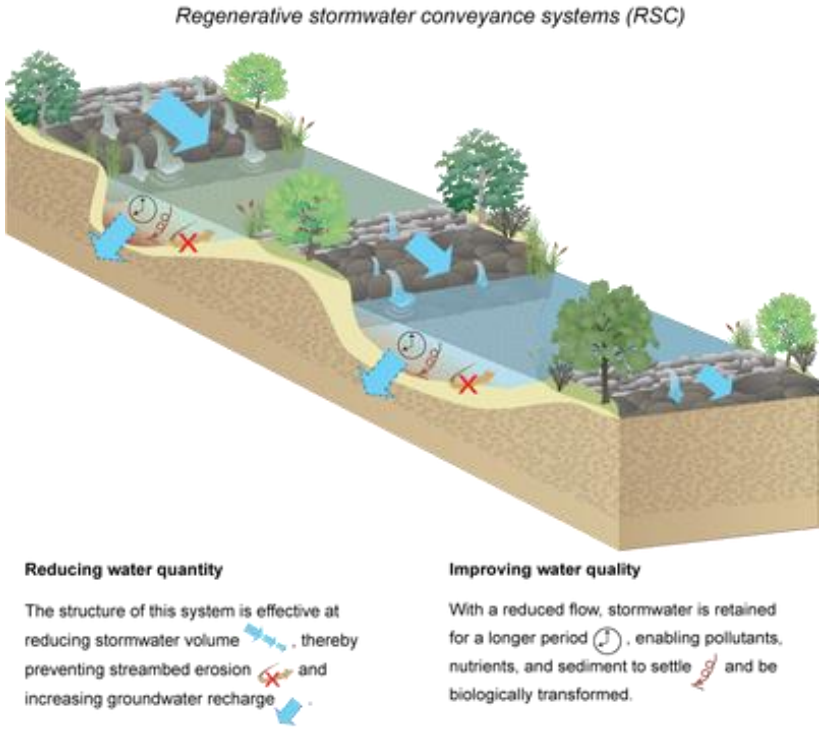


Photo credit: http://rrstormwater.com/addressing-headwater-drainage-regenerative-stormwater-conveyance-rsc

Figure 8 - Regenerative Stormwater Conveyance Oblique Section (RSC)

The approach aims to improve local hydrology by tempering the influence of stormwater runoff at the headwater drainage positions, dissipating energy before it is released to downstream larger stream systems. RSC is applicable in new development, retrofit, and restoration scenarios, and it is consistent with the principles of low-impact development. The benefits of RSC include water quality improvements, reduced stream erosion, aquatic habitat enhancement, increased riparian vegetation, restoration of shallow groundwater, increased baseflow, and aesthetic improvements.

RSC can be used as a stream restoration technique and has been applied to incised channels. This involves using an RSC to raise the channel bed and reconnect the stream with its floodplain and riparian wetlands and optimizing the conversion of stormwater to groundwater. It can be a stand-alone treatment in steep, narrow valleys where building a floodplain is not feasible, or as an appurtenant component to some natural channel designs incorporating a floodplain. It is one of the best ways to foster nutrient reduction in fully-shaded (heterotrophic) channels. The pools form excellent habitat for a variety of small fishes.

Newbury Riffles

These are rock weirs dimensioned, patterned, and positioned along a meandering channel to dissipate energy, create riffle-pool sequences, provide grade control, and raise flow profile elevations in larger streams than those where RSC applies. They are large stone riffles characterized by long, gently sloped tails (**Figure 9**). Their design is based primarily on river hydraulics calculations that are formulated to be compatible with natural stream morphology. In effect, Newbury weirs could be viewed as a hybrid between green and gray approaches in settings where NCD alone would not suffice. They apply best as appurtenant structures to natural channel design, specifically in situations where they are the most cost-effective means to provide grade control or raise a flow profile to enhance floodplain exchange. They also can provide an excellent means to assure fish passage across a weir and can be designed to provide virtually any degree of limited connectivity between in-line waterbodies and open channels. Further, they could be designed with internal media akin to that used in RSC to provide enhanced hyporheic water quality treatment.

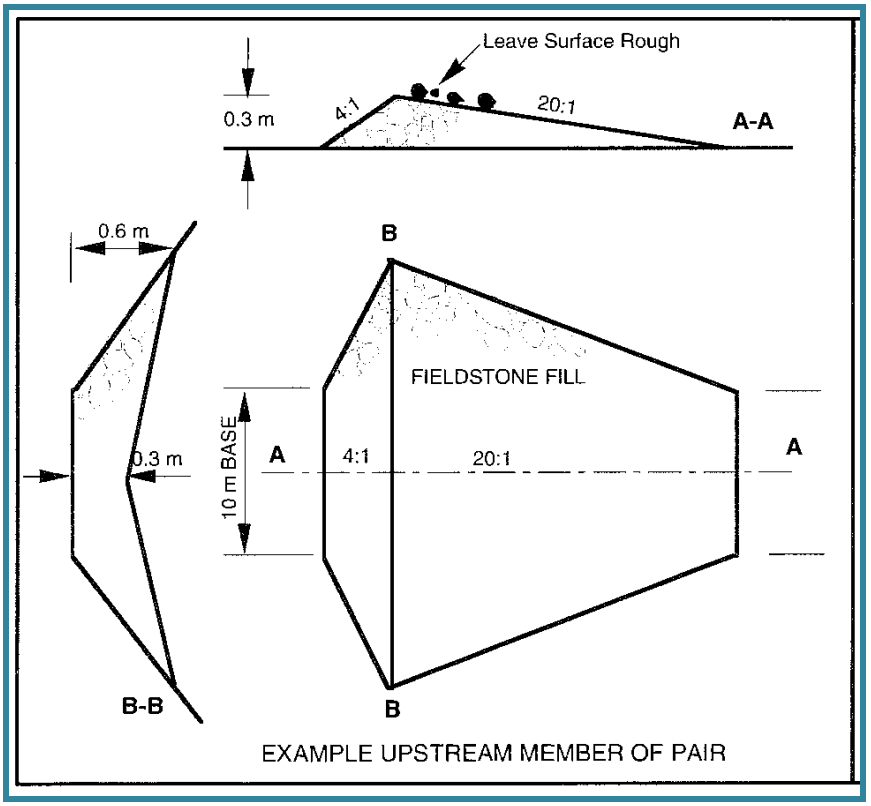


Figure 9 - Typical Newbury Riffle (from Newbury and Gaboury, 1994)

Submerged Aquatic Vegetation (SAV)

Submerged aquatic vegetation can be established on stable streambeds wide enough and shallow enough to allow sufficient light penetration. It is not recommended in areas designated as sediment traps which are subject to burial. SAV can improve stream metabolism and reduce downstream nutrient loads. It also provides highly productive nursery habitat for small fishes and macroinvertebrates. Some SAV occurs sporadically in Phillippi canals and, once stabilized, these sites should offer opportunities to expand this habitat. Native taxa used in ecological restoration plantings include *Vallisneria* sp. and some S*agittaria* sp., among others.

Emergent Littoral Vegetation (ELV)

This treatment consists of emergent herbaceous wetland plants and floating leaved emergents rooted on channel bars and margins, and on the littoral shelves of in-line waterbodies. They are not normally contributors to bank stability and require stabilized conveyances to thrive. They provide significant habitat for fish and other wildlife. For example, FWC biologist Blewett (personal communication) reports that juvenile snook prefer open water ponds flanked by ELV on littoral shelves. They can also contribute to effectiveness of water quality treatment and sediment trapping in shallow waters. A wide variety of native species are available from the regional nursery trade covering a gamut of hydroperiods and water depths from moist soils seldom inundated to

areas perennially flooded at depths up to 4 feet. These species add a natural aesthetic to channel and pond margins.

Certain species are characteristic of gently flowing swales or sloughs and channel margins such as sawgrass (*Cladium jamaicense*), versus others more commonly occupying littoral shelves of ponds such as pickerelweed (*Pontedaria cordata*). A wide variety of marsh plants can be used.

Rosgen Log Vanes and Toe Wood (LWD)

These treatments use large woody debris (LWD), sometime with stone, to create aquatic habitat and dissipate energy. They mimic the natural woody debris loads in native streams and are essential components of NCD. Each type of vane has a specific purpose, design protocol, and position along the meandering channel.

Cross vanes are placed on straight reaches to induce pools and direct flow to the channel center, thus relieving near bank stresses. J-hooks are placed at the outer bank where a bend commences to perform identical functions to cross vanes but are specific to bends. Randomized arrays of woody debris are not a Rosgen structure but can be used to establish additional substrates for macroinvertebrates and to provide a debris load in the channel that falls within the range of nature. Kiefer et al (2015) provides such ranges for Florida streams.

Rosgen toe wood is a cantilevered array of cross-stacked logs and root wads used to provide foundation and toe armoring functions at river bends (**Figure 10**). It replaces riprap where it might otherwise be used as part of soil bioengineering bank stabilization treatments such as the VRSS, or in NCD projects where bank migration is unacceptable. It is most applicable to perennial streams and rivers to preserve the wood from decay and because the structures are fairly massive. It is especially deployed along the outer banks at bends and is usually integrated with a j-hook at the upstream edge of each treated bend. Toe wood provides superior fish habitat and energy dissipation versus riprap at similar to lower cost and potentially at greater resiliency because it is not subject to particle erosion.

Figure 10 - Newly Constructed Toe Wood (Edwards Bottomlands, Starke FL)

2.3 In-Line Waterbody and Stream Channel Transitions

These transitions occur frequently in nature along chains of wetlands and ponds. Kiefer et al. (2015, chapter 6) describes their patterns and dimensions for a series of case studies and provides guidance for implementing 'natural transition designs' in chains of wetlands. Although intended for stream and wetland restoration in rural settings, this approach may be adaptable to portions of the Phillippi drainage network.

2.4 Some Common Treatment Materials Used in Green Infrastructure

Soil bioengineering stabilization requires plant growth, which takes time. Therefore, surrogates for bank strength and erosion protection are needed while the roots develop. These are usually made of biodegradable materials, except in settings requiring more strength than vegetation alone can ultimately provide, and then permanent materials are integrated with the vegetation to add strength to the array. Three common materials are coir logs, biodegradable rolled erosion control products (RECP), and permanent high-performance turf reinforcement mats (HPTRM).

2.4.1 Coir Logs

Coir logs are a biodegradable erosion control option for banks, shorelines, and other erosion prone areas (**Figure 11**). Standard design of the coir log features a strong, coir twine outer netting that surrounds a mixture of mattress coconut coir. They come in varying lengths and diameters and are relatively easy to place, use, and install. The logs create a natural control area that helps establish growth, by allowing for deep rooting of plants and effectively holding seeds and saplings in place, and control erosion. Logs have high air and water permeability, are safe to surrounding wildlife, and are designed with a typical lifespan of anywhere from 2 to 5 years.

Photo credit: http://www.erosionpollution.com/coconut-coir-logs.html

Figure 11 - Coir logs

2.4.2 Rolled Erosion Control Blanket (RECB)

These are biodegradable mats that promote vegetation establishment and are frequently used to protect newly contoured banks on SBE and BSR areas from erosion. They are also used to build VRSS geogrid layers. They can be made from a variety of organic materials, most commonly coir, straw, and wood fibers. Some include photodegradable plastic meshes requiring more time to degrade. Such meshes can become a hazard to small fish and reptiles when the organic materials are completely decayed. Depending on the application, it may be preferable to use 100% organic RECBs. RECBs are rated for their useful performance period, typically for 12, 24, and 36 months. Actual performance periods may vary, with longevity about half the rated value under Florida's intense moisture, heat, and long growing season. Two and three-year blankets are suitable for most soil bioengineering applications.

2.4.3 High Performance Turf Reinforcement Mat (HPTRM)

High performance turf reinforcement mats (HPTRM) are non-biodegradable ('permanent') mats that allow and promote vegetation establishment, especially grasses but also including other forms of vegetation. For that reason, they are included here as a green infrastructure item, but they can also be used in ways that require routine maintenance and do not provide the full range of ecosystem services of most soil bioengineering treatments. The mats have longevity ratings of 25 to 50 years and can provide the necessary protection should the vegetation be insufficient alone. Some HPTRMs can be used in settings where a mowed lawn is desired, thus eliminating the erosion that frequently occurs on mowed banks but otherwise retaining the aesthetic and performance of a mowed surface.

Photo credit: http://www.conteches.com

Figure 12 - High Performance Turf Reinforcement Mat

2.5 Green Infrastructure Summary

Green treatments are selected for their ability to perform channel stabilization functions in settings where multiple additional benefits are desired and site conditions are suitable. Capital investment requirements cover a wide range of values, commensurate with the suite of ecosystem and social benefits provided. In some cases, the level of investment is similar or less than that of gray infrastructure while providing more benefits and less maintenance. The economics are discussed under **Tasks 5** and **6**.

Table 1 provides a broad summary matrix of site condition applicability, water quality benefits, habitat benefits, and maintenance regimes required for natural channel design and a variety of soil bioengineering and habitat enhancement techniques useful for channel stabilization.

Table 1 - Green Infrastructure Categorical Improvements Summary

Treatment	Applicability			Water Quality Benefits		Habitat Benefits			Maintenance
	Canal Type	Morphology	Aesthetic	Sediment	Nutrient	Aquatic	Wetlands	Terrestrial	
Natural channel design (NCD)	All	ROW ≥ FPL W	Natural meandering stream & native vegetated floodplain	Bank stabilization, Grade control, Sediment detention	Treats baseflow & stormflow, Buffer treatment	Large & small fish, Autochthonous & allochthonus food web	Large	Neotropical migrants, wading birds, biodiversity	Contigent - Decreasing
In-line waterbodies (ILWB)	All	ROW ≥ FPL W	Native - shrubby forest, Native - parklike forest, Native - open & grassy, Landscaped vegetation	Bank stabilization, Sediment retention	Treats baseflow & stormflow, Buffer treatment	Large & small fish, Autochthonous & allochthonus food web	Fringing to large	Neotropical migrants, wading birds, biodiversity	Contingent - Decreasing if native, Annual or more frequent if a sediment trap or landscaped
Soil bioengineering afforestation (SBE)	All	All ROW, SS ≥ 2:1, BH unlimited	Landscaped - shrubby, Native - shrubby forest, Native - parklike forest, Integrated Hardscapes	Bank stabilization	Buffer treatment	Allochthonous food web	Fringing	Neotropical migrants, biodiversity	Contigent - Decreasing, Sporadic snag removal may be required absent NCD
Vegetation reinforced soil slope (VRSS)	All	All ROW, SS ≥ 0.5:1, BH < 60 feet	Landscaped - shrubby, Native - shrubby forest, Integrated Hardscapes	Bank stabilization	Buffer treatment	Allochthonous food web	None to Fringing	Neotropical migrants, biodiversity	Contigent - Decreasing, Sporadic snag removal may be required absent NCD
Live stakes & branches	All	All ROW All traversable SS, BH unlimited	Landscaped - shrubby, Native - dense shrubby forest	Bank stabilization	Buffer treatment	Allochthonous food web	Fringing	Neotropical migrants, biodiversity	Contigent - Decreasing, Sporadic snag removal may be required absent NCD
Regenerative stormwater conveyance (RSC)	Low- & Mid-Order	All ROW, Channel W < 20 feet	Discrete/submerged at high flow. Creates short rapids and small cascades at low flow)	Grade control, Sediment detention	Treats baseflow	Small Fish	None	None	Contigent - may be required after large floods
Aquatic vegetation - submerged aquatic vegetation (SAV), emergent littoral vegetation (ELV)	High-Order (mid-order in patches)	All ROW, Channel W > 20 feet	Native - open & grassy	Sediment detention	Treats baseflow	Large & small fish, Autochthonous food web	Fringing to large	Wading birds, biodiversity	Contigent - Decreasing, Requires upstream stabilization
Coir logs	All	All ROW	Discrete/hidden	Bank stabilization	None	NA	NA	NA	Temporary measure
Rolled erosion control blanket (RECB)	All	All ROW SS < 2:1, BH unlimited in areas of low NBS	Discrete/hidden	Bank stabilization	None	NA	NA	NA	Temporary measure
High performance turf reinforcement mat (HPTRM)	All	All ROW SS < 2:1, BH unlimited in areas of low NBS	Landscaped - neat & trim, Native - shrubby forest	Bank stabilization	None	None	None	None	Annual or more frequent, Routine mowing if turf used

Notes: ROW = Right-of-Way, W = Width, SS = Side Slope, BH = Bank Height, FPL = Floodplain

3.0 GRAY INFRASTRUCTURE

Inert structures are widely implemented treatments for channel stabilization largely because they are proven commodities familiar to civil engineers. They also provide an urban aesthetic. They require comparatively high capital costs for construction. Maintenance tends to be low between the retrofits that are required after partial or complete failure of the structure. They address the same suite of erosion countermeasures needed in the Phillippi canals that can be addressed using green infrastructure, but do not require establishment of vegetation and can often be fit to areas with minimal earthwork. However, they provide limited environmental value and generally deteriorate over time. For those reasons, gray treatments are recommended only after consideration and rejection of green solutions. A table summarizing various gray infrastructure treatments' applicability, water quality benefits, habitat benefits, and maintenance needs is provided at the end of this Section (**Table 2**).

3.1 Riprap

Riprap is rock or other material used to armor shorelines against scour and erosion. It is made from a variety of rock types (i.e. granite, limestone) and occasionally concrete rubble. Riprap is perhaps the most commonly used countermeasure against toe erosion with good reasons; especially because it is proven, adaptable in construction, readily maintained, and consists of a deformable matrix than is not so overly rigid as to be subject to all-or-nothing failures (Julien 2002). However, riprap is dimensioned to provide a certain level of service, and larger more powerful flows can destroy it. When riprap does fail, the materials are often recoverable and reusable. Riprap is sometimes used to form a foundation beneath various kinds of soil bioengineering bank stabilization treatments, or to create rock-riffles in certain kinds of natural channel design approaches to streambed stabilization (**Figure 13**). VRSS can be used in lieu of riprap in many cases.

Riprap design includes decisions concerning the following:

- Rock type and shape.
- The median diameter of the stones (D50) and the gradation of sizes around the median. (Can also be expressed as weights).
- Revetment thickness (T).
- Flank treatments at the upstream and downstream ends of the revetment.
- Filter type (synthetic or gravel), thickness, placement, and gradation (if a gravel filter is used).
- Depth of revetment to counter scour below the streambed.

Figure 13 - Riprap Channel Protection and Riffle Around Aerial Pipeline (Edwards Bottomlands)

3.2 Articulated Concrete Blocks (ACB)

Articulated concrete block (ACB) systems are used to provide protection to underlying soil materials from erosion. ACB systems are composed of preformed concrete blocks that are interconnected through a combination of form and/or cables. The blocks are able to "articulate" to some degree along their adjoining faces, allowing the system to conform to changes in the subgrade while maintaining the protective cover. The interlocking property also allows for expansion and contraction. ACBs provide a flexible option to other erosion countermeasures such as riprap, soil cement, grout-filled mattresses, etc. As they are not intended for slope stabilization, slope stability must be ascertained prior to considering an ACB system. Typical applications include channels, shoreline restoration and boat ramps. Open-cell forms of ACB that allow vegetation to be established, improving stability and aesthetic appeal, are also available (**Figure 14**).

Figure 14 - Open Cell Articulated Concrete Block Integrated into a VRSS Foundation (Loxahatchee River at Masten Dam Renovation)

3.3 Gabions

A gabion is a cage, cylinder, or box filled with rocks or concrete that can be used to stabilize shorelines, stream banks, or slopes against erosion (**Figure 15**). Gabion baskets have some advantages over loose riprap because of their modularity and ability to be stacked in various shapes and their resistance to being washed away by moving water. They effectively allow a mass of small, less expensive stones to be used in lieu of pricey boulders. Gabions are superior to completely rigid structures because they have the ability to conform to a greater amount subsidence and can drain freely. Contrary to some claims, they do not dissipate energy very well. Over time, silt and vegetation may fill the interstitial voids. The life expectancy of gabions depends on the occurrence of a catastrophic flood exceeding the design level of service, and on the lifespan of the wire (the structure will fail when the wire fails). Galvanized steel wire is the most commonly used, but PVC-coated and stainless steel wire are also used. The propensity for failure of non-stainless steel baskets in Florida is high due to water acidity and intense sunlight. Well-known stream restoration expert Dave Rosgen refers to gabions as 'time-released bedload capsules.' They are a greatly over-utilized treatment. VRSS's perform similar erosion control and slope stability functions without deterioration over time. They add a genuine energy dissipation function and provide a suite of ecosystem values gabions do not.

Photo credit: http://gabion1.co.uk/river-bank-protection/

Figure 15 - Gabion Revetment

3.4 Reno Mattress

Reno mattresses are a mattress-shaped version of the gabion used for river bank and scour protection, channel linings for erosion control, and embankment stability when the retaining properties of box gabions are not required and placement on the streambed is required (**Figure 16**). The base section of the reno mattress is divided into compartments and filled with stones at the project site to form flexible, permeable, monolithic structures. The compartments help restrict the movement of stone and strengthen the structure. They can allow growth of natural vegetation in some circumstances. The strength of the reno mattress lies in the mesh of their steel or plastic wire, with various manufacturers providing different types and amounts of internal reinforcement and flexibility for installation. Reno mattresses are also referred to as marine mattresses.

Photo credit: http://www.gabionbasket.info/gabionmattress.html

Figure 16 - Reno (marine) Mattress

3.5 A-Jacks

A-Jacks are a commercially-made concrete product, owned and patented worldwide by Poseidon Alliance Ltd., consisting of two T-shaped pieces joined perpendicularly at the middle and forming six legs. They are used in both open channel and coastal applications. Open channel applications include bank stabilization, flow and grade control, scour protection for bridge piers, and biostabilization. A-Jacks offer protection by increasing the relative roughness of the channel bank (as characterized by the Manning's Roughness Coefficient), with a relatively high Manning's n of 0.1. A potential advantage of A-Jacks over other hard armoring solutions is the comparatively large area available in the interstitial spaces for native vegetation to take root, which enables them to be integrated into green treatments (**Figure 17**). In coastal applications, A-Jacks are used as breakwaters, revetments, artificial reefs, and habitat development. A-Jacks have the advantage of being interlocking and self-stabilizing. For artificial reefs and habitat development, typical reef-building biota find areas of low turbulence within the open spaces to establish colonies. Certain fauna are dependent on substrates with a different biochemical surface, however, and cannot colonize concrete.

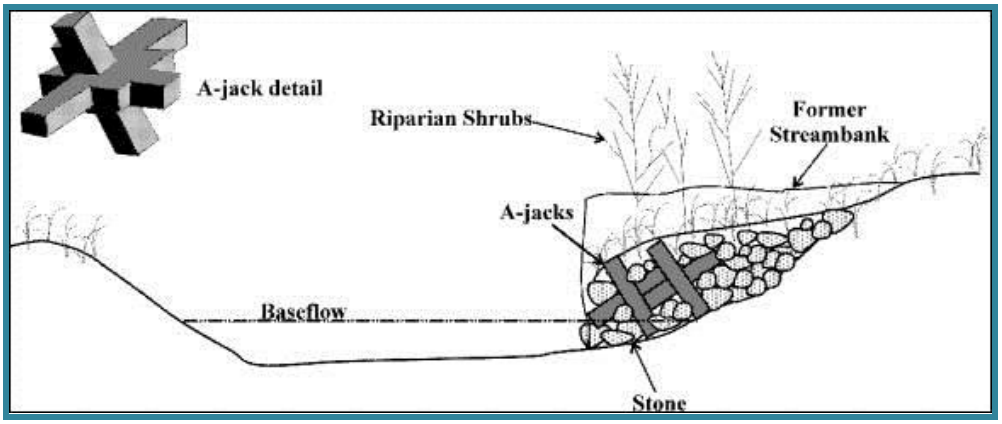


Photo credit: http://www.stormwatercenter.net/Assorted%20Fact%20Sheets/Restoration/bank_protection.htm#5

Photo credit: http://www.a-jacks.com/Coastal/DesignInfo/DesignInfo.aspx

Figure 17 - A-jacks

3.6 Poured Concrete Seawalls

Concrete seawalls can be prefabricated or poured on site. Their distinct advantage is that they are vertical structures that can be established in laterally confined areas where a sloped bank is impractical or impossible. Seawalls can also be constructed of a variety of other materials, steel sheetpile being a common alternative. Seawalls require geotechnical engineering assessments to determine wall materials, footer type and dimension, internal reinforcements, abutment treatments, and groundwater management design components. Seawalls fronting important terrestrial infrastructure should be routinely inspected, akin to bridge safety principles.

3.7 In-Line Waterbody and Stream Channel Control Structures

A wide variety of prefabricated and custom-designed concrete and steel weirs, drop structures, operable structures, fish ladders, and pipes are available to manage changes in water elevation and control such elevations across transitions from one waterbody type to another. Describing the full array of these is beyond the scope of this report. Implementation of these kinds of structures is a matter of civil engineering, sometimes a substantial amount given the forces involved. These are only recommended in situations where green alternatives cannot provide a sufficient level of risk management or gradients are so large that they would not be stable.

3.8 Gray Infrastructure Summary

Gray treatments are selected for their ability to perform channel stabilization functions in settings where green treatments are unsuitable or require additional reinforcement to succeed. This occurs in physically constrained areas requiring vertical shorelines, and in areas subject to extremely powerful flow exceeding the velocity and shear stress thresholds of stand-alone bioengineering treatments. With the exception of A-jacks, gray treatments do not dissipate much energy and are thus favored where low friction is an absolute necessity. In fact, the majority of gray treatments displace energy, often leading to unintended and counterproductive erosion downstream.

Some gray treatments are routinely integrated with soil bioengineering. For example, they are commonly deployed along the high shear stress areas at the bottom of the channel slope, thus forming a rigid foundation under an otherwise more natural streambank constructed above. The inert foundation occurs below the plant growth line and simply protects the work above it from being undermined, analogous to a bedrock outcrop. This is a normal pattern for VRSS construction. It creates a layered solution that allows for a fully native streambank to be established, resulting in a high level of biodiversity and close to a natural amount of energy dissipation and sediment trapping capacity.

Instead of layered configurations, some integrations consist of tightly spaced reticulations of green and gray materials, where soils and plants are established in open interstices of a concrete or plastic matrix. Manufacturers of gray materials recognize this as a marketable 'compromise' solution and have gone to increasing lengths to offer products with interstices that can be vegetated. In concept, this can provide the armoring benefits offered by the inert materials and the energy dissipation and habitat structure offered by soil bioengineering. However, such structures are really only sensibly recommended in intrinsically harsh environments because stand-alone soil bioengineering approaches would otherwise work at lower cost, and the plantable interstices are necessarily small to achieve the armoring benefit, thus further limiting the kinds of plantings that can succeed. Generally, self-sustaining forests are precluded from development and the overall biodiversity potential of reticulated integration is severely limited. In some cases, the vegetation fails to establish even after repetitive attempts. In worst case scenarios, woody vegetation can act as a lever to move the inert materials during major floods or wind storms. This can happen with riprap joint plantings (putting live stakes in poorly sorted rock linings). Woody joint plantings are not recommended for Florida waters.

Capital investment requirements cover a wide range of values. In some cases, the level of investment is similar or less than that of green infrastructure while providing fewer benefits and greater replacement costs once the infrastructure deteriorates. The economics are discussed under **Tasks 5** and **6**.

Table 2 provides a broad summary matrix of site condition applicability, water quality benefits, habitat benefits, and maintenance regimes required for a variety of inert treatments used in channel stabilization.

Table 2 - Gray Infrastructure Categorical Improvements Summary

Treatment	Applicability			Water Quality Benefits		Habitat Benefits			Maintenance
	Canal Type	Morphology	Aesthetic	Sediment	Nutrient	Aquatic	Wetlands	Terrestrial	
Riprap	All	All ROW, SS > 2:1, BH unlimited	Industrial hardscape - irregular, Toe of VRSS, Rock riffles	Bank stabilization, Grade control	None	None	None	None	Contigent - Increasing, Required after large floods, Herbiciding may be required
Articulated Concrete Block (ACB)	All	All ROW, SS < 2:1, BH unlimited	Industrial hardscape - linear, Landscaped - rough/weedy, Toe of VRSS	Bank stabilization, Grade control	None	None	None	None	Contigent - Increasing, Generally low until corrosion/weathering takes effect, Herbiciding may be required
Gabions	Mid- & High-Order	All ROW, SS vertical to 3:1, BH unlimited	Industrial hardscape - linear, Landscaped - rough/weedy	Bank stabilization	None	None	None	None	Contigent - Increasing, Generally low until corrosion/weathering takes effect
Reno (marine) mattress	All	All ROW, SS < 2:1, BH unlimited	Industrial hardscape - linear, Landscaped - rough/weedy	Bank stabilization, Grade control	None	None	None	None	Contigent - Increasing, Generally low until corrosion/weathering takes effect, Herbiciding may be required
A-jacks	Mid- & High-Order	All ROW, SS < 2:1, BH unlimited	Industrial hardscape - irregular	Bank stabilization, Sediment detention	None	Small Fish	None	None	Contigent - replacement upon concrete breakdown
Reinforced concrete wall	All	All ROW, SS = vertical, BH < 20 feet (typical)	Industrial hardscape - linear	Bank stabilization	None	None	None	None	Contigent - replacement upon concrete breakdown or corrosion

Notes: ROW = Right-of-Way, W = Width, SS = Side Slope, BH = Bank Height, FPL = Floodplain

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