City of Winston-Salem

Stream Management and Restoration Manual

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Stream Management and Restoration Manual

Prepared for
City of Winston-Salem

and

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Disclaimer

Groups or entities that plan to utilize the approaches and techniques presented in this document should consider the following:

The erosion and sediment control and storm water management best management practices, as well as the stream restoration and channel stabilization techniques presented in this document have very specific design, installation, and maintenance criteria. As a consequence, successful application of these practices and techniques requires that the criteria be followed. Failure to follow the criteria could cause a given practice or technique to function improperly, thereby reducing its long-term effectiveness, increasing the potential for structural failure, and increasing the cost of maintenance and repairs.

The research literature reviewed in the preparation of this document indicates that the best management practices and restoration techniques included are effective at meeting their intended use. However, some of the newer practices and techniques have not had a sufficient period of application to thoroughly evaluate their long-term effectiveness or the cost of maintaining and repairing them.
WATERSHEDS AND STREAMS

2.0 – Introduction

From the time the last glaciers receded from the North American continent, up until the early colonial period, most of the country’s landscape was in a relatively stable condition. Although the native people worked the land, clearing forests for villages and cultivating fields, their numbers were relatively few and their settlements were widely dispersed over millions of square miles. Consequently, extensive forests and prairie grasslands characterized the country. With the exception of brief catastrophic natural events, this was an environment in which changes occurred very gradually. Natural stream ecosystems evolved under these relatively stable conditions.

When European settlers came to America, large tracts of forest were cleared for farms and pastures. European forests had made the transition to fields over a thousand years, but the North American forests fell in a much shorter time. Although sediments and nutrients had always entered aquatic systems from adjacent land, the rate at which they entered was now greatly accelerated, as thousands of acres of land poorly suited for cultivation were laid bare. Soil erosion, which formerly progressed at relatively low rates, suddenly increased dramatically. As sediment yields in watersheds rose sharply, stream channels began to fill with fine sediments, channels became wider and shallower, and in-stream habitat was reduced.

In a short time, the poor farmlands of the eastern seaboard were abandoned and farmers moved west to New York, then Ohio, Indiana and Illinois. Vacating farms with poor or depleted soils became a common pattern in the settlement of North America, especially in the South.

As former farmland reverted to old-field and then to forest, watersheds entered a new phase of adjustment. Sediment yields decreased and stream channels scour, stabilizing over time at a lower base elevation, abandoning former floodplains. The westward expansion carried these same changes to watersheds dominated by prairie grasslands as they were plowed for the production of crops, or heavily grazed by livestock. Many of these activities occurred in the fertile floodplains of streams and rivers. Throughout this country, thousands of acres of bottomland forest were cleared, drained, and converted to crops or pasture. Severe flooding prompted measures to protect towns and farms that were situated in low-lying areas. Dams were built to control flooding and levees were constructed to separate the river from its developing floodplain.

The building boom which began shortly after World War II and which has continued virtually unabated to the present has resulted in a radically altered landscape. This construction activity has promoted the clear-cutting of millions of acres of forests. It has resulted in the draining and filling of thousands more acres of wetlands and the damming and diversion of miles of rivers to provide drinking water and hydroelectric power to cities that continue to grow in population. Lawns, concrete, and asphalt have replaced forest, cropland, and pasture.
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In this section, you will learn the basic characteristics of watersheds and streams, the
dynamic processes that form and maintain them, as well as how changes in land use affect
them.

2.1 – The Watershed Perspective

Because streams are landscape features that interact with the surrounding land areas it is
appropriate to start with a discussion of streams at the watershed level. Watersheds are the
landscape units that provide the most relevant basis for understanding natural stream
systems, their components, and the physical processes that form and maintain them. They
are also the most appropriate landscape unit for managing and restoring streams.

2.1.1 - What is a Watershed?

*Watershed* can be most simply defined as an area of land that drains water, sediment, and
dissolved materials into a particular stream. A watershed or drainage basin boundary can
be determined at any point along any stream or river by delineating the points of highest
elevation in the surrounding land area that drains to the selected point on that stream.
Watersheds can range in size from less than an acre to thousands of square miles. Each
stream and its contributing watershed are part of an increasingly bigger drainage area.

![North Carolina’s major watersheds](image)

Figure 2-1. North Carolina’s major watersheds (NCDENR, 1998).

For example, the Salem Creek watershed is part of or a subwatershed of the Muddy Creek
watershed, which is a subwatershed of the Yadkin River watershed, which is a
subwatershed of the Pee Dee River watershed. The Pee Dee River eventually flows into the
Atlantic Ocean.

The major portion of Forsyth County’s 424 square mile land area lies within three sub-
basins of the Yadkin River watershed. The largest percentage is situated in the High Rock
Lake - Muddy Creek sub-basin, a 4,000-square mile watershed that includes Winston-
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Salem, numerous smaller municipalities, and significant rural land area. A relatively small area on the eastern side of the county drains to the Abbotts Creek sub-basin, and a portion of the western side of the county contains tributaries that drain directly to the Yadkin River. About one-fifth of the County’s land area drains to the Dan River watershed, which is a sub-basin of the Roanoke River.

Examining streams from a watershed perspective allows us to see the “big picture” and to appreciate the fact that almost everyone lives downstream of someone else.

Figure 2-2. Abbotts Creek Watershed and Upper Yadkin River Watershed.

2.1.2 - Watershed Hydrology

Understanding how water flows into and through streams is critical to making management and restoration decisions. Decision-makers must know how much, how fast, how deep, how often, and when water flows in order to implement appropriate management and restoration measures.
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2.1.2.1 - Hydrologic Cycle

The *hydrologic cycle* describes the continuous cycling of water from atmosphere to earth and oceans and back again. The cycle is powered by solar energy, which drives evaporation and transpiration, transfers water from the surface of the land, from plants, and from oceans, lakes and rivers into the atmosphere. Precipitation, primarily as rain and snow, transfers water from the atmosphere to the land surface. A portion of the precipitation evaporates directly to the atmosphere. A portion of the precipitation infiltrates the land surface, is absorbed by plants and transpired to the atmosphere. A portion flows downslope rather quickly as shallow subsurface flow or *throughflow*. The rest percolates deeper to become part of the groundwater reservoir, which moves downslope very slowly. That portion of the precipitation that does not infiltrate is stored in surface depressions or runs off quickly downslope as *overland flow*.

![Figure 2-3. Hydrologic cycle.](image)

2.1.2.2 - Streamflow and Flow Regimes

*Streamflow* is that portion of precipitation which reaches the stream channel from shallow subsurface flow, groundwater, or overland flow. Streamflow is subdivided into two components: baseflow and direct runoff or storm flow. It is conventionally referred to as *discharge* (i.e., volume of water passing through a channel cross-section per unit time). In the United States, discharge is measured in cubic feet per second (cfs).
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Baseflow is that streamflow that originates from groundwater. This component is influenced by climate and watershed characteristics that affect infiltration and storage capacity. Because groundwater moves very slowly, its discharge lags well behind precipitation and tends to vary slightly for streams with good groundwater reserves. Where groundwater reserves are naturally low, or they have been reduced by drought or land use changes, baseflow can be extremely variable. The variability associated with baseflow can best be characterized by describing three distinct flow regimes: perennial (i.e., carry water year-round, fairly stable groundwater flow), intermittent (i.e., carry water part of the year, receiving groundwater discharge when the water table is high), or ephemeral (i.e., carry water only during or immediately after a storm, no baseflow component).

Direct runoff consists of overland flow and a substantial portion of subsurface flow. This component is influenced by climate, watershed characteristics that affect the storage capacity, timing, and volume of runoff, and the intensity of individual storm events. The variability associated with direct runoff can best be characterized by describing two distinct stormflow regimes: bankfull flow and flood flow.

Bankfull flow is that streamflow when the channel is flowing at or near capacity and the water surface is just at floodplain level but has not overtopped the stream banks. Nearly all stream channels, whether large or small, will contain without overflowing that discharge that occurs about once a year. Higher flows, occurring on average once in 2 years or once in 5 years or more, will be too large to be contained in the natural channel and will overflow the banks.

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Figure 2-4. Streamflow diagram showing pathways precipitation follows to become stream discharge as baseflow or direct runoff.
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Flood flow exceeds the capacity of the stream channel, overtops the stream banks and moves out onto the adjacent land surface. In confined streams, this land surface may be an adjacent hillslope or terrace. In unconfined streams, this land surface is most often a floodplain. Although a stream is considered at flood stage once its banks have been overtopped, the extremely high discharge events only occur on average once in 50 years or once in 100 years or more.

Figure 2-5. Regimes that characterize streamflow.

2.1.2.3 - Describing Flow Variability

- Hydrographs

Hydrologists routinely measure and record streamflow. They use hydrographs to show how streamflow varies with time. The portion of the hydrograph that lies to the left of the peak is the rising limb and shows the time that elapses as streamflow increases from baseflow discharge to its peak or maximum discharge in response to a precipitation event. The portion of the hydrograph to the right of the peak is the recession limb and shows the time that elapses as streamflow decreases from the peak discharge returning to baseflow conditions after the precipitation event has passed.
Although hydrographs can illustrate how a stream’s discharge varies for an individual storm, shown above, they can also be utilized to show how streamflow varies daily, monthly, yearly or over a longer time period.

- Flood Frequency and Probability of Exceedance

Flood frequency and recurrence interval are terms hydrologists use to refer to extremes of streamflow. *Flood frequency* indicates how often a discharge of a given magnitude or volume will be exceeded during a given time period. *Recurrence interval* indicates the average interval of time within which a given discharge event, such as a flood, will be equaled or exceeded one time. For example, when Winston-Salem experienced flooding associated with Hurricane Fran in 1996, news reports characterized the event as a 50-year flood. Although such a flood might have occurred again the following year, or the year after, on average the frequency with which a 50-year flood would be expected to occur is once in 50 years.

Discharge extremes can also be referred to in terms of their *probability* or likelihood of being exceeded. For example, a 50-year flood of 1000 cfs means that discharge has a 1 in 50 chance, or 2 percent probability of being exceeded in any given year. At the opposite extreme, a 10 year low flow of 5 cfs means that a discharge of less than 5 cfs has a 1 in 10 chance or 10 percent probability of being exceeded in any given year. More simply stated,
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a discharge of less than 5 cfs will occur as an annual minimum flow on the average once in 10 years.

The two flow variability descriptors most commonly used by hydrologists in dealing with high flows include peak flows and flood volume averages. Peak flows describe the maximum instantaneous flow rates that will be equaled or exceeded with specified frequencies (i.e., 2-yr, 10-yr, etc.). For example, if the 100-year peak discharge is determined to be 10,400 cfs for Salem Creek at Main Street in Winston-Salem, this means that a peak of 10,400 cfs will be exceeded at that site once every 100 years (on average). This peak flow data can be used in the planning and design of bridges, culverts, and channel modifications.

Flood flows are also described by maximum average flow rates over designated time periods. The average discharges are anticipated to increase above these flow rates with specified frequencies (i.e., 2-yr, 10-yr, etc.). For example, at the same location on Salem Creek, a 7-day 10-year flood volume discharge of 6500 cfs (average over the highest 7 consecutive days in the year) means a discharge of 6500 cfs will be exceeded at that site once every 10 years (on average). This flood volume data can be used in developing estimates of flood-storage capacity for a flood mitigation project.

Similarly, low flows can be described by minimum average flow rates over designated time periods. The average discharges are anticipated to decrease below these flow rates with specified frequencies. For example, a 7-day 10-year low flow discharge of 10 cfs (average over the lowest 7 consecutive days in the year) at a site means a discharge of less than 10 cfs should be expected at that site once every 10 years (on average). Low flow data is used in the design of wastewater treatment plants, determining time of travel and dilution for toxic spills, evaluating streamflow-temperature degradation, and evaluating water withdrawal and diversion proposals. For example, the City of Winston-Salem is proposing a new water intake on the Yadkin River to meet water demands. In order to protect aquatic habitat in the river, the North Carolina Division of Water Resources recommended that the City be required to maintain the 7Q10 (i.e., 7-day 10-year low flow discharge) streamflow target for the gage site at Enon, North Carolina.

2.1.3 - Watershed Processes and Channel Formation

2.1.3.1 - Surface Runoff and Erosion

Most streams originate on newly formed land surfaces and carve their own channels and valleys. This process is initiated by surface runoff and erosion. Surface runoff begins when the rainfall or snowmelt rate exceeds the infiltration rate and all depression storage is filled. The erosive potential of this flowing water depends on its velocity, depth, turbulence, and the type and amount of material it transports. Soil erosion by water involves the detachment of soil particles and their transport. This is a mechanical process that requires energy. Energy is supplied directly by falling raindrops and by the runoff moving downslope creating a shear stress. Runoff moving downslope concentrates into rivulets and depressions where it gains depth and velocity. The concentrated runoff...
removes enough soil to form small, well-defined channels called *rills*. Continuous erosion of these rills results in the development of *gullies*. These gullies, in turn, increase in width, depth, and length, forming larger channels.

2.1.3.2 - Drainage Networks

At the watershed level, stream systems are described in terms of *drainage networks*. These networks formed as channels were eroded in the landscape. When observed from an airplane or shown on a topographic map, these networks have different drainage patterns. The patterns reflect the surface topography and underlying geology. *Dendritic* or branched patterns indicate land surface of uniform resistance to erosion. Channels tend to form along joints in weaker bedrock layers where erosion resistance is not uniform. Under these conditions *rectangular* or *trellised* patterns develop.

![Figure 2-7. Drainage Patterns typical of natural drainage networks.](image)

Stream size and location in the drainage network can be characterized by use of a ranking method called *stream ordering*. A smaller order number indicates a smaller stream and a location closer to the watershed boundary. The most common method of stream ordering is shown in the watershed diagram below. You can see that first order streams have no tributaries. A second order stream has only first order streams draining to it, and so on.
2.1.4 - Effects of Watershed Characteristics

Flowing water and the materials carried by that water form stream channels. Regional climatic conditions and watershed geology, soils, topography and land cover have a significant effect on the volume, timing and routing of water and sediments from adjacent uplands into a stream, and along the stream to the outlet of the watershed. These factors interact to profoundly affect the nature of stream systems and how resistant they are to disturbance.

2.1.4.1 – Climate

*Climate* refers to the prevailing weather conditions in an area, which affects the flow, pattern, and shape of streams by influencing:

- Amount and type of precipitation
- Timing of runoff
- Evaporation rate
- Vegetation type
- Erosion rate
- Groundwater recharge rate
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Because climate influences the amount and seasonal distribution of precipitation, it determines which processes (rain, snowmelt, rain-on-snow) are most important in controlling the current hydrologic regime of a stream and its watershed. For example, floods associated with hurricanes or violent thunderstorms periodically affect the Southeastern region of the United States. These storms tend to occur during summer months in this region. On the other hand, mountainous areas of the Northeast and Pacific Northwest sometimes experience flooding that results from rain events that occur during late winter or early spring when there are large accumulations of snow at higher elevations.

Climate also affects stream flow and sediment by influencing the type and density of watershed vegetation. In the humid southeastern United States, more vegetation grows than in the arid Southwest. The increased vegetative cover in the southeast reduces runoff by increasing transpiration losses and developing soil conditions that favor infiltration and help bind the soil. This increased vegetative cover also reduces erosion by intercepting rainfall and slowing the downslope movement of water where runoff is generated. Although the volume of rainfall that occurs in those southeastern watersheds during intense summer thunderstorms can be substantial, the presence of dense vegetative cover and low antecedent soil moisture conditions typical for this time of year serve to reduce runoff potential to some degree.

In addition, climate has a significant effect on the chemical characteristics of streams. The chemical composition of streams derives from atmospheric, soil and rock sources. Chemical and physical weathering of rock and soil contribute the greatest proportion of dissolved and suspended material to natural stream systems.

North Carolina has four distinct seasons, each with its characteristic climatic patterns. Summers are generally warm to hot, and humid. Winters are cool, mild, with little snow, except in the western mountains. Spring and fall usually provide pleasant weather. More specifically, the climate of Winston-Salem and Forsyth County is warm and humid. Winter lows average right around freezing (32° F), and summer highs average in the upper 80s. Temperatures above 90° F can occur from late April through September. There are an average of 35 days above 90° F each summer.

The weather of North Carolina is dominated for most of the year by that portion of the global air circulation known as the Westerlies (i.e., a broad band of eastward-moving air that encircles the globe throughout the latitudes 30 to 60 degrees north). This general flow is characterized by waves of air currents, the best known of which is the Jet Stream. These waves are responsible for the movement of rain-bearing atmospheric depressions. The moisture from such depressions is commonly widespread, prolonged, and fairly gentle, giving the good soaking rains that farmers prefer. Several depressions pass over North Carolina in any winter, and the precipitation in them is relied on to fill reservoirs and recharge groundwater supplies.

In summer, when the Jet Stream tends to be further to the north, North Carolina’s weather is dominated by air masses that originate over the tropical Atlantic Ocean, drifting in from a southerly direction. These warm, moist air masses bring the hot, humid, hazy conditions
with afternoon thunderstorms, typical of summer. These thunderstorms produce intense, short duration rain events that are highly localized and often widely scattered. As a consequence they do not provide a reliable source of precipitation for agriculture or water supply purposes. However, there is a strong correlation between the outbreak of these storms and the number of flash floods experienced in the region. The majority of these thunderstorms develop between May and August.

Winston-Salem and Forsyth County are situated in a region of North Carolina where the average annual precipitation is less than 46 inches. With the exception of an area that includes parts of Madison, Haywood and Buncombe Counties, this region has the lowest average annual precipitation in the state. Average monthly rainfall ranges from 2.8 inches in the winter, to 4.6 inches in the summer. In spite of this rainfall deficit, the U. S. Geological Survey rates the streams in this area has having at least a moderate potential for maintaining year-round baseflow.

The increased precipitation during the summer months is due primarily to the thunderstorms noted above. Historic stream flow records indicate that Winston-Salem and other areas of Forsyth County have experienced periodic flash flooding associated with intense thunderstorms. However, the tropical storms from the Atlantic Ocean and Gulf of Mexico that cause significant damage along the North Carolina coast are usually weakened by the time they move as far inland as Forsyth County. The notable exceptions were Hurricane Hugo in September 1989 and Hurricane Fran in September 1996.

Average total winter snowfall is about nine inches. Generally, only one to two inches of snow accumulate at any given time, and melt within a few days. As a consequence, snowmelt is not a significant contributor to baseflow maintenance or peak flood flows.
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2.1.4.2 - Physiographic Regions

Traveling from east to west, the North Carolina landscape transitions from the flat terrain at or near sea level along the Atlantic Coast, to the rolling hills of central Carolina, to a mountainous region that includes Mt. Mitchell, which is the highest peak in the eastern United States. North Carolina’s landscape has been divided into three major physiographic regions based on geologic and topographic characteristics.

The Coastal Plain forms the eastern edge of North Carolina, comprising about 45 percent of the state’s total land area. To the east is the Atlantic Ocean and to the west is the Fall Line, a broad zone where the soft sedimentary rocks of the Coastal Plain meet the hard crystalline rocks of the Piedmont region. The Coastal Plain is further subdivided into two subareas. The Tidewater, closest to the ocean, is an extremely flat, poorly drained, low-lying area characterized by swamps and lakes. The Inner Coastal Plain is higher in elevation and better drained. Locally there are distinctive wetlands or upland bogs known as pocosins or Carolina Bays (elliptical lakes of unknown origin). Steep river gradients and rapids characterize the boundary between the Coastal Plain and Piedmont (i.e., Fall Line). Downstream of the Fall Line, low gradient streams meander across broad, low valleys carved in the soft, easily eroded sediments.

The Piedmont is a geologically ancient region situated west of the Fall Line that is underlain by a complex of metamorphic and igneous rocks. The rolling plateau of the Piedmont formed as ancient mountains were worn down by erosion. As the mountains were worn down, areas of more resistant rock formed hills known as monadnocks. Pilot Mountain, in Surry County, is a sandstone-capped monadnock. The Piedmont covers about the same amount of land area as the Coastal Plain, but is higher in elevation, ranging from 300 feet at the Fall Line to 1500 feet at the foothills of the Blue Ridge Mountains. Seven major rivers and their tributaries (Dan, Tar, Neuse, Cape Fear, Yadkin, Catawba, and Broad) drain the eastern slopes of the Blue Ridge, carving narrow, deep valleys in the hard rocks of the Piedmont.
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The Appalachian Mountains begin abruptly at a major fault line, west of which rises a steep escarpment, the edge of the Blue Ridge Mountains. The escarpment is visible at places such as where Interstate 77 crosses into Virginia and where Interstate 40 crosses the Blue Ridge Mountains and enters the Asheville Basin. These mountains are underlain by a variety of rock types, the predominant being metamorphic rocks, which are relatively resistant to erosion. The Blue Ridge Mountains form the eastern continental divide, with streams draining the eastern slopes flowing to the Atlantic Ocean and streams draining the western slopes flowing to the Mississippi River system.

Winston-Salem and Forsyth County are located in the northwestern part of the Piedmont physiographic region. The topography is gently rolling to steep, with sharp breaks in topography occurring along the edge of floodplains. Generally, the floodplains are broad along the mainstem of streams such as Muddy Creek, Salem Creek, Silas Creek, Monarca Creek, and Mill Creek. Tributary streams are numerous and have steep gradients and relatively narrow floodplains.

2.1.4.3 – Geology and Soils

Geology refers to the bedrock underlying an area, while soil is the material that develops as a result of weathering or wearing away of the bedrock or parent material. These characteristics affect streams by influencing:

- Permeability and porosity
- Infiltration rate
- Groundwater recharge rate
- Volume of water stored
- Rate of water movement through the watershed
- Erosion rate
- Sedimentation
- Stream bank material
- Water chemistry

When we discuss the geology of a watershed, we are referring to the type of rock or mineral formations (i.e., igneous, sedimentary or metamorphic) that underlie the area. These bedrock formations developed as a result of geologic processes (e.g., volcanic eruptions, mountain uplift and erosion, tectonic forces, and deposition of sediments in alluvial, coastal and shallow marine environments) that have operated over a span of more than a billion years. Soil consists, at least in part, of material weathered in place from the underlying parent material (i.e., bedrock) and mixed with organic material near the surface. As such, a soil’s character is related to the interaction of the parent bedrock material from which it derived, climate, and biotic and climatic factors.

Geology and soils help to define the nature of watersheds and streams by affecting the quantity and quality of both groundwater and stream water, as well as the stability of landscape features such as hillslopes, terraces, floodplains and stream channels.
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During rainfall and snowmelt, water may flow rapidly to a stream over the ground surface (i.e., overland runoff), through the soil laterally as throughflow, or downward as recharge for groundwater. To a large extent the pathway taken is determined by characteristics of the geology and soil.

Bedrock formations vary in physical characteristics such as permeability, porosity, and resistance to erosion, as well as in their mineral and chemical composition. In addition, watershed runoff characteristics are greatly influenced by the predominant type of soil because of differences in infiltration and water storage capacity and transmissivity.

For example, streams draining watersheds of the Coastal Plain region of North Carolina are all underlain by sedimentary formations and the soils that weather from these formations (i.e., clay, silt, sand and gravel). Those watersheds with clay soils have high runoff potential and very low potential for sustaining year-round baseflows. In these watersheds rain and snowmelt do not readily infiltrate and percolate through the low permeability soils. These watersheds tend to generate more overland runoff and contribute less water to baseflow. Therefore, stream flow is highly sensitive to rainfall inputs. Conversely, watersheds in the Sand Hills area of the Coastal Plain with sandy soils have low runoff potential and the highest potential for sustaining year-round baseflows in the State. The precipitation that falls on these watersheds will readily percolate through the highly permeable soil and into the underlying rock formation generating less overland runoff. They have significant groundwater storage capacity and the volume and rate of water movement through the rock sustains reliable baseflows.

A soil’s characteristics also determine how susceptible it is to erosion by rainfall and overland runoff. A soil’s structure, texture, and the percentage of organic matter influence its erodibility. The most erodible soils generally contain high proportions of silt and very fine sand. The presence of most clay minerals or organic matter tends to decrease soil erodibility. Clay tends to bind particles together, while organic matter helps maintain stable aggregate structure.

While a soil may be fairly resistant to erosion by surface runoff, this does not guarantee that it will be stable and resistant to some type of mass wasting or slippage. Soil moisture can have a significant influence on the stability of some soils. For example, the addition of water to clayey soils can transform them from solid to plastic and liquid states, thereby reducing their resistance to displacement. In addition, groundwater seepage can result in undermining of hillslopes by sapping and piping, and pore water pressure near seepage zones may weaken the skeletal strength of soil materials within a slope.

The structural stability of soils also relates to the steepness of the hillslope on which they formed. For any earth material there is a maximum angle, called the angle of repose, at which it can be safely inclined and beyond which it will fail. The angle of repose varies widely for different materials, from 90° in strong bedrock to less than 10° in some unconsolidated materials. In unconsolidated materials, it can vary substantially with changes in water content, vegetative cover, and the internal structure of the particle mass. This is especially so with clayey material: a poorly compacted mass of saturated clay may
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give way at angles as low as 5º, whereas the same mass of clay with high compaction and lower water content may be able to sustain angles greater than 100º.

The nature of the geologic formations and soils in a watershed also influence stream channel stability. For example, granitic, metamorphic rock and consolidated sedimentary bedrock are relatively resistant to the hydraulic forces of flowing water. Channel shaping and migration are very slow processes in these formations. On the other hand, unconsolidated alluvium (i.e., silt, sand and gravel material deposited by streams) is particularly susceptible to scour and lateral erosion. Where unstable conditions exist due to man-made channel modifications, rapid channel adjustment and lateral migration can occur in response to high discharge, high sediment transport flow events.

Basin geology also has a significant effect on surface water quality. Chemical and physical weathering account for a significant proportion of dissolved and suspended material in natural systems.

As pointed out previously, Winston-Salem and Forsyth County are in the northwestern Piedmont region. Primarily gneiss and schist underlie the watersheds in this area, with granite occurring in localized areas. These materials are generally low in permeability and porosity. Consequently, water doesn’t flow easily through them and they have relatively low capacity to store water. The U. S. Geological Survey characterizes most of the watersheds in this area as having an intermediate potential for sustaining year-round baseflows. The dominant soils, weathered from these formations in upland areas are well-drained, moderately permeable loamy soils with clayey subsoil. These soils have moderate to slow infiltration rates and surface runoff is medium to very rapid depending on slope. The erosion hazard for these upland soils is moderate to severe. The dominant floodplain soils of the area formed from alluvium. They are poorly drained loamy soils with loamy subsoils. These soils generally have a low permeability, moderate infiltration rates, slow surface runoff, and moderate to high erosion hazard. They also have a high seasonal water table and are subject to frequent flooding.

2.1.4.4 – Landscape Topography

Landscape topography is comprised of the natural and man-made features that characterize the surface of the land. Topography affects streams by influencing:

- Surface storage of precipitation
- Infiltration rate
- Runoff rate
- Erosion rate
- Sedimentation
- Vegetation type
- Flood storage and conveyance
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Topography is a product of the underlying geologic formations and the geologic history of an area, as well as human activities that alter the natural landscape. The topography or terrain of an area has a significant influence on runoff and erosion processes, valley and stream morphology, stream energy, and conveyance of floodwaters.

Natural storage of water in depressions on the ground surface during rainfall reduces surface runoff volume and velocity. On relatively flat terrain, precipitation stored in surface depressions has the opportunity to infiltrate the soil. Depending on soil characteristics and vegetative cover, the rainwater may be taken up by plants and transpired back to the atmosphere, flow subsurface down the slope, and/or percolate to the groundwater. Unfortunately, natural surface depressions, while highly effective on flat areas, diminish rapidly in volume and effectiveness as the surface slope increases. In small watersheds on steep hillslopes, most surface depressions are filled to capacity very quickly, reducing opportunities for infiltration and increasing overland runoff.

Increasing surface slope not only decreases surface storage and infiltration, but also increases the velocity of overland runoff generated. Increased runoff velocity means that erosion rates increase as soil particles are more easily detached and transported down the slope. The terrain adjacent to the stream also influences sedimentation rates by providing opportunities for water-borne soil particles to settle out prior to reaching the stream channel.

The topography of the watershed determines the character of the stream valleys as well as the streams themselves. For example, the steeper, headwater areas of a watershed tend to have steeper stream channels confined by adjacent hillslopes, while lowland areas downstream tend to be flatter, with broader valleys. As a result, headwater streams generally have more energy available to erode and transport stream bank and streambed materials. They also have relatively few areas to store flows that overtop the stream banks. As a consequence, floodwaters are conveyed quickly to downstream reaches. On the other hand, unaltered streams flowing across broad, flat valleys tend to have less energy available for erosion and transport of materials, while they usually have significant areas available for storing and slowing the downstream conveyance of floodwaters.

In Winston-Salem and Forsyth County the topography is gently rolling to steep, with broad, gently sloping ridges, and smooth side slopes. Sharp breaks in topography occur along the edge of floodplains. Generally, the unaltered floodplains are broad along the mainstem of streams such as Muddy Creek, Salem Creek, Silas Creek, Monarcas Creek, and Mill Creek. Tributary streams are numerous and have steep gradients and relatively narrow floodplains.

The Upper Salem Creek watershed is a typical example. It is characterized by moderately steep terrain, with slopes in some areas in the 5-10% range. Many of the headwater tributaries of Salem Creek are moderately steep with relatively narrow valleys confined by adjacent hillslopes. Kerners Mill Creek, a tributary upstream of Salem Lake, is an exception with a relatively broad floodplain. Long stretches of the mainstem through Winston-Salem are relatively flat. The overall slope of the upper mainstem of Salem Creek is approximately 0.5%. Areas along the mainstem Salem Creek, upstream and downstream
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of the Gorge, as well as the reaches through Civitan, Central and Washington Parks have broad floodplains. Some of these areas currently support or historically supported wetlands.

2.1.4.5 – Land Cover and Land Use

*Land cover* refers to the types of vegetation found in an area. A related factor is *land use*, which refers to the types of activities which people conduct on a given land area. Together, land cover and land use influence:

- Streambank stability
- Stream temperature
- Nutrient and sediment inputs to the stream
- Stormwater runoff quantity, quality, and rate
- In-stream and riparian habitat

Land cover and land use are major factors controlling the volume and rate of runoff from a watershed, soil erosion and sediment loadings, the stability of valley hillslopes, stream channel morphology, and overall water quality. The location and intensity of a particular land use activity will determine its effect on the watershed.

The vegetation that covers the land surface of a watershed is a major factor influencing the amount of surface runoff generated and the amount of sediment eroded and transported from upland areas. Interception on leaves, stems, and surface litter allows water to be retained during smaller storms, evaporating back into the atmosphere without ever reaching the ground. It also lessens the impact of raindrops by preventing the dislodgement of soil particles.

Where there is appreciable vegetative cover, and especially where there is a humus or litter layer, overland flow generally occurs only during larger storms due to increased infiltration rates. Vegetation aids infiltration by preserving loose soil structure and diffusing the flow of water where runoff is initiated, thereby increasing infiltration opportunity. Vegetation also depletes soil moisture to greater depths, increasing available water storage and allowing more water to infiltrate. These effects are more pronounced under forest cover where roots penetrate deeper and transpiration rates are greater. Forest cover, litter, and lower vegetation also moderate soil microclimate, in particular the depth and frequency of soil frost. Thus infiltration may occur even during colder months when the ground may be frozen elsewhere.

All of these mechanisms tend to increase infiltration rates and capacity and thereby reduce the volume of runoff generated. Once runoff has commenced, vegetation interrupts overland flow, slowing the velocity, physically binding the soil and inhibiting erosion.

Land use and land cover in Winston-Salem and Forsyth County spans the spectrum from forested open space, to agricultural croplands, to manicured and landscaped residential properties, to asphalt-dominated commercial centers and industrial complexes. The Legacy Comprehensive Plan describes the pattern of development in Forsyth County as a central
downtown in Winston-Salem, older close-in neighborhoods, new suburban residential and commercial development, small towns, and rural areas. Winston-Salem forms the geographic core of the county, with development radiating out along key transportation corridors. Rural areas are situated primarily in the northeast, southeast, northwest, and southwest corners of the county.

The headwaters of Muddy Creek and its upper tributaries flow from the rural parts of the Forsyth County in the Tobaccoville and Rural Hall areas. As it flows south across the county, Muddy Creek is joined by Mill Creek, which drains the suburban areas in northwest Winston-Salem; Silas Creek, which drains the suburban/urban areas of west-central Winston-Salem; Salem Creek, which drains the Kernersville town center and surrounding rural area, the suburban areas in northeast Winston-Salem, and the urban areas of central Winston-Salem; and the South Fork Muddy Creek, which drains the suburban and rural areas of southeast Forsyth County.
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2.2 – The Stream Reach Level

Now that we have looked at streams from the watershed level, we can shift our focus to the stream itself and its immediate surroundings. Our goal is to become familiar with the characteristics used to describe streams and evaluate their condition or overall health, and to develop some understanding of how channels change over time.

2.2.1 - Stream Channel Morphology

The stream channel presents a three dimensional form defined by its cross-sectional geometry, meander pattern, and longitudinal profile.

![Figure 2-11. Stream channel morphologic characteristics.](image)

2.2.1.1 - Cross-sectional Geometry

One of the characteristics of streams is that each cross-section, on any stream, has been shaped and dimensioned over time to convey a range of flows. The size and shape of a stream’s cross-section is a function of its flow regime, the quantity and type of sediment transported through the section, and the character or composition of the materials that make up the streambed and banks. The size and shape of the channel cross-section determine how energy is distributed within the channel and how sediment and other material are
transported. Streams in cross-section tend to be trapezoidal in straight reaches and asymmetrical at curves or bends.

Figure 2-12. Stream channel cross-sectional geometry.

Channel cross-section shape and size is described by a number of terms:

- **width** \((W)\) - the horizontal distance across the channel at a given discharge

- **depth** \((D)\) - the vertical distance between the water surface, at a given discharge, and some point on the streambed

- **width:depth** \((W/D)\) - describes the dimension and shape of the channel as the ratio of channel width to mean depth

- **cross-sectional area** \((A)\) - the area of water across a given section of stream, at a given discharge; \(W \times D\)

- **wetted perimeter** \((P)\) - the distance along the streambed and banks at a cross-section where they contact the water; a close approximation is \(W + 2D\)

- **hydraulic radius** \((R)\) - the ratio of the cross-sectional area to the wetted perimeter; \(A/P\)

- **thalweg** - the path of the deepest thread of the stream
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2.2.1.2 - Meander Pattern

A stream’s pattern or plan form describes the form of the channel one might observe from an airplane. Natural streams are seldom straight for more than a relatively short reach of stream; most have curves, bends, or meanders. Sinuosity is a way of describing how much meandering a stream exhibits. The straighter the channel, the greater the energy available to erode the stream’s bed and banks.

Figure 2-13. Stream channel meander geometry – sinuosity.

Streams in mountainous areas where the channel is confined by the adjacent hillslopes have naturally low sinuosity, while streams flowing through broad, flat valleys are highly sinuous.

Channel pattern is also described by a number of other terms:

*meander wavelength* - twice the linear distance between successive inflection points

*radius of curvature* - the radius of the central portion of a channel bend

*meander amplitude* - distance between tangents drawn on the convex sides of successive bends
Although most streams have a single channel, two or more channels, divided by bars or islands characterize braided streams. Braiding generally indicates that the stream has lost its ability to transport its sediment load. Braided channels are very unstable. Significant bank erosion and rapid lateral migration is common. The exceptions are the heavily vegetated, very stable anastomosed braided channels, which are usually associated with riverine wetland systems.
2.2.1.3 - Longitudinal Profile and Streambed Forms

The *profile* of a stream describes the way in which a stream’s elevation changes as it flows in a downstream direction. A stream’s overall slope or gradient is a measure of that change in elevation and refers to the steepness of the channel. The steeper the channel, the greater the energy available to erode the stream’s bed and banks.

For many streams, slope decreases continuously from headwaters to mouth, forming a characteristic concave shape. Local topography, bedrock features, and bed materials
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modify the profile. Harder rock (e.g., granite) produces steeper profiles, while streambeds that are more easily eroded produce flatter profiles.

A related characteristic is streambed forms. Natural streams rarely have flat beds. The energy of flowing water molds streambeds into various forms. The most commonly recognized streambed forms include riffles, which are relatively steep areas of fast moving, shallow water formed by the accumulation of coarse materials (e.g., gravels, cobbles, and boulders) and pools, which are relatively flat areas of slow moving, deep water formed by scouring of the streambed material. Riffles are usually formed in the crossover or straight reach between successive meander bends, while pools are usually formed in the bends.

In steeper streams, riffles may be replaced by steps, which are areas of steep drops or jumps formed by the accumulation of large material such as boulders and fallen trees or logs. The steepest bedforms include cascades, dominated by jet-and-wake flow and hydraulic jumps, longitudinally and laterally disorganized bed material of cobble and boulders; and pool spacing less than one channel width.

Regime streambed forms are typical of low gradient sand or silt channels. These types of streams exhibit a succession of bed forms with increasing velocity - planar bed, ripples, dunes, and anti-dunes.
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2.2.1.4 - Streambed and Stream Bank Materials

Although streambed and stream bank material is generally a mixture of various size materials, it is common to characterize a stream by describing the most common or average size material present. For example, we may describe a stream as a gravel-bed or sand-bed stream. Stream channel material will usually fall into one of these categories: bedrock, boulder, cobble, gravel, sand, silt, or clay.

The character of these materials determines: erosion potential; ability to support vegetation that stabilizes the stream channel; the amount of roughness to slow the water velocity and reduce its energy; and the physical habitat available to aquatic organisms for feeding, resting, reproducing, and hiding.

Although the size distribution of streambed material may be determined using a variety of streambed sampling techniques, the most commonly used method is called a “Wolman Pebble Count”. This technique provides information that allows characterization of the streambed relative to its dominant particle size ($D_{50}$), degree of fine material ($D_{16}$), and the largest material sizes ($D_{84} - D_{100}$).
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Streambed Materials

Figure 2-20. Bedrock

Figure 2-21. Boulder

Figure 2-22. Cobble

Figure 2-23. Gravel
2.2.2 - Floodplain

The basic geomorphologic unit of the stream corridor is the *floodplain*. The floodplain is the area adjacent to the stream channel that is periodically inundated or flooded with water, when the stream overflows its banks.

Figure 2-26. Floodplains as geomorphologic units of the stream corridor (FISRWG, 1998).
The hydrologic floodplain is that land adjacent to the channel that is situated above the elevation of baseflow but below the elevation of the bankfull stage. It is inundated by storm flows that occur on average every two years out of three (i.e., 1.5 year recurrence interval). Some streams do not have a hydrologic floodplain. This is often the case with urban streams that have incised into the landscape and become isolated from their former floodplain. The topographic floodplain is that land adjacent to the channel that is situated above the elevation of baseflow but below the elevation of a given peak flood stage. For example, the 100-year recurrence interval flood is generally used in flood studies, and cited in planning and regulatory standards.

The presence or absence of a functioning floodplain has a significant effect on how and where floodwaters are conveyed along the stream corridor. The ability of a stream to overflow onto a floodplain decreases the concentration of energy in the channel, thus decreasing the potential for channel down-cutting and bank erosion.

A flood wave moving through a watershed is usually decreased through storage in the floodplain. Storage of floodwaters in natural floodplain areas slows the downstream movement and reduces the risk of flooding in developed areas.

Trees, shrubs, and debris on the floodplain surface create resistance to the movement of floodwaters. As such, they slow water velocity, depositing sediments that build fertile floodplain soils, allow detention and infiltration of floodwaters, thereby slowing the rate at which the flood wave progresses, and reducing the total volume of water that moves to downstream areas. Receding floodwaters carry organic material from the floodplain into the channel that is a critical source of energy for the stream ecosystem.

2.2.3 - Riparian Vegetation

Riparian or streamside vegetation plays many roles in maintaining the health of a stream. Streambank vegetation, especially trees and shrubs, physically hold the stream banks intact. Trees and shrubs also provide shade for the stream, keeping water temperatures cool and increasing the dissolved oxygen in the stream water. Roots and branches that overhang or extend into the stream channel provide habitat for fish and other aquatic organisms. Leaves and twigs are an important food source for aquatic insect larvae, which are an important food source for fish.

Vegetation in the floodplain and on adjacent slopes mitigates the effects of runoff by slowing the velocity of water as it flows over the land, decreasing the potential for erosion to occur. Materials suspended in water and attached to soil particles (e.g., nutrients and toxic chemicals) tend to settle out and may be broken down by soil microorganisms and absorbed by plants, when runoff water is detained by vegetation.
2.2.4 - Groundwater Reserves

Water that is absorbed into the soil through the process of infiltration moves downward through the force of gravity, and in all directions due to capillary action (similar to wicking). Water continues to move downward until it reaches a completely saturated area known as the *groundwater table*. As water continues to collect in the soil, the water table rises until it is exposed in the bottom of the deepest notch or depression in the area, which is usually a stream channel. Thus water flowing in a stream channel long after a rainstorm generally indicates that the groundwater is high enough to enter the channel. For most streams, groundwater enters the channel by seeping through the banks or upwelling through the bed.

Figure 2-28. Groundwater system showing related features (FISRGW, 1998).
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Locations where groundwater and surface water are exchanged are important. An area that freely allows the movement of water into the saturated zone underground is called a recharge area, while localized areas where groundwater emerges are called springs or seeps.

Interactions between groundwater and the channel can vary spatially (i.e., along the stream system throughout the watershed) depending on geology and soils, as well as temporally (e.g., seasonally) as groundwater elevations fluctuate. For example, gravel bed streams with well-developed alluvial floodplains generally have the greatest interaction with groundwater. During wet periods when groundwater elevations are high most, if not all, stream reaches may be functioning as effluent reaches. That is, they are gaining or receiving water from the groundwater aquifer through their banks and bed. During dry periods when groundwater elevations are low, many of those same reaches may be functioning as influent reaches. That is, they are losing water to the groundwater aquifer through their banks and bed.

Figure 2-29. Stream cross-sections of influent and effluent reaches (FISRWG, 1998).

2.2.5 - Physical Habitat

The physical habitat available in a given stream reach can be characterized by a variety of interdependent components that include macrohabitat features such as temperature and water quality, as well as channel structure, dimension, pattern, slope and discharge, which influence microhabitat features such as depth, current, surface area, substrate, cover, and pool/riffle ratios. Utilization of the various living spaces created by these features varies diurnally and seasonally by species and life stage, and depends on the activity in which the organism is engaged.

A variety of water quality parameters determine the suitability of water for its intended use, whether by aquatic organisms or by people. These parameters include but are not limited to
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temperature and chemical constituents such as pH, dissolved oxygen, nutrients, hardness, alkalinity, turbidity, suspended sediment, heavy metals, etc. The amount, concentration, or magnitude of each parameter helps determine overall water quality.

Historically, water quality has been defined strictly by physical and chemical characteristics. Although these are important descriptors, they are insufficient to fully describe and understand the ability of water resources to support living systems. For many purposes, especially biological ones, high quality water resources are characterized by stable and natural temperature, high oxygen but low nutrient concentrations, pH within a natural range determined by bedrock and soil weathering, and levels of other constituents that support diverse biological communities including abundant organisms with narrow environmental tolerances.

Channel characteristics such as slope, dimension, pattern, channel structure and bed material size are interdependent and relate to discharge and sediment load. They affect sediment transport processes and how water velocity varies within a channel section. They affect temperature by controlling the amount of surface area and substrate that is directly exposed to sunlight. They also affect the capacity of the channel to detain and cycle organic material (e.g., leaves, twigs, etc.) and nutrients that collect behind boulders and debris jams and settle in pools or in the voids between coarse substrate material.

Discharge directly influences channel characteristics and available habitat. Baseflow is the most critical flow relative to aquatic habitat. The volume of water carried by a stream under baseflow conditions directly influences its habitat features, including surface area, depth, velocity, cover, temperature, and concentrations of dissolved oxygen and carbon dioxide. The overall surface area available as habitat fluctuates with discharge. During periods of seasonal low flow and droughts, very little surface area may be available to stream organisms. As discharge increases during periods of higher baseflow, or during storms, side channels and isolated pools become available even in headwater areas. The timing of discharge has a very strong influence on biological activities, including feeding, spawning and migration of fish, the downstream drift of aquatic insects, and the growth and development of most aquatic organisms. Consequently, two streams with similar channel dimensions but different baseflow regimes will have different habitat characteristics.

Water depth to a large extent determines the amount of space available for organisms to utilize. It limits upstream and downstream movement, determining access to critical areas such as spawning grounds. For example, shallow flow through road culverts can create impassible barriers to migrating fish. Deep water provides overhead cover, protecting large fish from predation by wading birds and mammals. Shallow water protects small fish from predation by piscivorous fish. Depth also influences other parameters such as velocity (relative to the effect of streambed roughness) and temperature (relative to the degree of insolation and vertical variability).

Current influences the character of the streambed or substrate by controlling sediment transport and deposition. It determines the distribution of photosynthetic organisms. For example, periphyton are generally tolerant of swift currents, phytoplankton tolerant
moderate currents, and vascular macrophytes are generally found only in very slow moving reaches. Current influences oxygen concentration through physical aeration. It maintains high oxygen levels in spawning gravels and transports metabolic waste products away from developing fish embryos. Current influences the capacity of the channel to retain and cycle organic material and nutrients. Torrential or cascading reaches generally transport material downstream before bacteria, fungi, and aquatic insects process it. Current can function as a barrier to fish movement. This is particularly a problem where road culverts steepen the gradient of the stream reach.

Substrate is one of the most critical habitat features for the benthic community. Macroinvertebrate diversity and abundance are strongly influenced by the substrate size and embeddedness (i.e., the percentage of finer sediments filling the voids around larger streambed material). Studies have shown that the most diverse communities are found in gravel-cobble substrates with a low percentage of fine sediment. Many fish spawn in or on the substrate. Again studies have shown that fish such as trout have a strong preference for gravel-cobble sized material. As embeddedness increases, the suitability of the substrate for fish and macroinvertebrates decreases significantly. For many streams, particularly those with natural sand or silt bottoms, beds of aquatic vegetation and large woody debris (e.g., logs, branches, etc.) provide additional critical substrate to which organisms cling.

For macroinvertebrates living in or on the bottom substrate or in beds of aquatic vegetation, cover from predation is provided. They also avoid swift currents by staying within the boundary layer or beneath the substrate. Fish utilize cover to avoid predation or unfavorable current conditions as well. Fish abundance in streams has been correlated with the abundance and quality of cover available. Large woody debris, undercut banks, overhanging vegetation, water depth, water turbulence, and even turbidity are all forms of cover for fish. The preferred cover varies diurnally and seasonally, and by species and life stage.

Figure 2-30. Typical habitat in a gravel bed stream.
Pools are important resting areas, which provide cover from disturbance and predation and areas for avoiding current. Riffles are generally the major source of aquatic insects for insectivorous fish, and provide critical spawning areas. The ratio of pools to riffles is key to the number of fish a stream can support and how much pressure from predation and competition they will experience.

2.2.6 - Aquatic Organisms

In any ecological community, at the base of the food chain are the plants that utilize the energy of the sun to produce organic compounds for their own growth and reproduction. Headwater streams depend upon terrestrial plants as their primary energy source. Leaves and twigs fall or are blown into the stream and supply food for macroinvertebrates, which are small aquatic organisms such as insect larvae, worms, crustaceans, clams and snails, that live in stream bottoms and along banks. Macroinvertebrates are a critical component in the processing of organic material and nutrients, and they in turn are an important food source for fish.
In a healthy headwater stream, there is a great diversity of macroinvertebrates with no single species dominating the community. Organisms found in such streams include stoneflies, caddisflies, mayflies, gilled snails, water pennies, riffle beetles, and hellgrammites. These animals, and the fish that feed on them, such as trout and smallmouth bass, sculpin, and darters require fast flowing, cool water with high dissolved oxygen concentrations. In addition, some of the fish inhabiting these areas need sediment-free gravel streambeds for spawning. The animal community found in healthy headwater streams is usually considered pollution-intolerant because of its very specific habitat requirements.

As we travel downstream in a watershed, stream size increases and a greater surface area is exposed to sunlight. Algae and rooted aquatic plants become the primary source of energy production. The macroinvertebrates inhabiting larger, warmer streams include crayfish, sowbugs, scuds, dragonflies, damselflies, aquatic worms, and snails. The fish found in these streams are those such as largemouth bass, sunfish, catfish, dace, and minnows which are able to tolerate the relatively warmer temperatures and lower concentrations of dissolved oxygen which occur in slower flowing reaches. The animal community found in healthy lowland streams is adapted to the habitat conditions typical of these areas.
Figure 2-33. Changes in habitat, energy sources and biota along a river continuum (FISRWG, 1998).

2.2.7 - Fluvial Processes

Although all stream reaches are unique, early studies on streams demonstrated that relationships exist between discharge and stream channel characteristics, and between the channel characteristics themselves. These relationships have provided a basis for explaining the apparent similarities from one stream to another and between one reach and another on the same stream. Understanding the processes that shape and maintain stream reaches is more challenging.
2.2.7.1 - Flow in Channels and Flow Resistance

Water flowing in a stream on a mountain or hill possesses potential energy. The amount of energy is in proportion to the difference in elevation from the top of the mountain or hill to the lowest point to which the water can flow. The water flows downhill under the influence of gravity, converting the potential energy of position into kinetic energy of motion. The flowing water performs work in the form of eroding stream banks and beds, and transporting sediment and debris. Resistance created by bends in the stream channel, changes in channel width, turbulence, friction along the channel boundary (i.e., banks and bottom), and obstructions (e.g., boulders, woody debris, overhanging vegetation, etc.) retard the flow.

This resistance causes the velocity (rate of flow) to vary vertically from water surface to stream bottom, laterally across the channel from bank to bank, and along the channel in an upstream-downstream direction.

![Figure 2-34. Flow velocity varies vertically, laterally and longitudinally (Redrawn from Gordon, McMahon, & Finlayson, 1992).](image)

The extent to which obstructions retard the flow depends on the relative roughness of the channel (i.e., depth of the water relative to the size of the obstructions). For example, boulders protruding from a streambed create considerable resistance under shallow, baseflow conditions, while those same boulders offer much less resistance under flood flow conditions.

The relationship between the forces of gravity and the resistance determines the energy available to erode and transport materials, and is therefore the key to the processes that shape and maintain stream channels.
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2.2.7.2 - Sediment Supply and Sediment Transport Processes

- Sediment Supply

The amount of sediment carried through the outlet of a watershed depends on two factors: the amount of sediment eroded and transported to the stream from upland sources; and the ability of the stream to carry the washed in sediments and to rework and transport bed and bank materials.

The first factor is dependent on climate, land use, and the geology and topography of the watershed. The second factor is dependent on the hydraulic and hydrologic properties of the channel and the erodibility of its bed and banks. Streams may be either supply limited or capacity limited, depending on whether their ability to carry sediment exceeds the amount available or vice versa.

- Sediment Transport

Sediment movement consists of three stages - initiation of motion, downstream transport, and sedimentation. Flowing water exerts a force on the streambed and banks. Tractive force and shear stress are the most common expressions for the force exerted. Critical shear stress is that force initiating motion for a particle of a given size. Once in motion, particles continue to be transported until velocity drops below the threshold of motion.

![Diagram showing velocity required to erode and transport various sizes of material.](image)

Figure 2-35. Velocity required to erode and transport various sizes of material.
Sediment is transported downstream as *dissolved load* (consisting of material transported in solution), *wash load* (comprising small particles, primarily clays, silts, or fine sand, readily carried in suspension), and *bed material load* (including material in motion which has approximately the same size range as streambed particles). Bed material load may be transported as *bed load*, when particles move by rolling, sliding, or saltation (hopping) or *suspended load*, when particles are transported and maintained in suspension by turbulent eddies, but settle out quickly when velocities drop.

Figure 2-36. Modes of sediment transport (Adapted from Abbott and Francis, 1977).

2.2.7.3 - Channel Erosion Processes

Stream channel erosion occurs because water flowing in the channel exerts a force that exceeds the critical shear stress for erosion. Stream channels erode in different ways depending on their location in the channel, the direction of flow, and the characteristics of the bed and bank material. For example, tractive forces undercutting or eroding the toe of a bank initiate the adjustment process. This causes the upper part of the bank to overhang. The weight of the overhanging bank can exceed the shear strength of the bank material causing the bank to fail, falling into the channel under the influence of gravity.
2.2.7.4 - Depositional Processes

A stream carries its load until it lacks the energy to do so. Bed load materials deposit when they stop rolling, sliding, or saltating. Suspended materials settle out of suspension. Three major processes lead to deposition: a particle’s orientation in the flow changes, thereby increasing resistance; the competence of the stream decreases, meaning the energy available for transport decreases; and the quantity or size of the sediment load suddenly increases.
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A variety of depositional features can form as a result of sedimentation. For example, in stable meandering streams, point bars generally form on the inside of meander bends. Alternating or side bars form along the channel margin in straight stream reaches. They generally alternate from left to right bank creating a sinuous thalweg within the straighter active channel. These features often form in streams that have been artificially straightened and may indicate the early stages of meander redevelopment. Delta bars form along channel margins immediately downstream of tributary confluences. Mid-channel bars form toward the center of the channel or just off of the channel margin. These features cause the flow to split and may deflect flow towards adjacent banks. Mid-channel bars are usually indicative of a significant loss of sediment transport capacity and channel stability.

Figure 2-39. Typical depositional features (Rosgen and Silvey, 1996).
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2.2.7.5 - Channel Changes

Stream channels change in response to changes in streamflow and sediment supply. The adjustments can include changes in cross-section, planform, and longitudinal profile. Changes in channel form may occur gradually, over geologic time periods. Stream slopes become less steep as uplifted terrain is worn down. Some changes occur abruptly as a critical *threshold* value is exceeded. A stream with a meander radius that has decreased over a long time period will suddenly cut off that meander bend by forming a chute across the inside of the meander bend or floodplain. Some changes are short term. The streambed may scour as stream power increases with the increasing channel flow in response to a storm, and fill as material transported from upstream deposits due to the loss of stream power when the flow recedes after the storm has passed.

- Lateral Adjustments

Under natural conditions, the erosion of the stream bank on the outside of a meander bend is compensated by *accretion* (i.e., deposition of material) or the formation of point bars on the inside of the meander bend. A result of this process of erosion and accretion can be the migration of the channel across the floor of the valley. If the rate of erosion and accretion are similar, a channel can completely change its location in the landscape, while maintaining its cross-section dimensions. These adjustments generally occur very gradually.

Over time, meanders tend to become more tortuous. As their radius of curvature decreases some bends become very sharp. The angle at which flow strikes the bank becomes more severe, stress on the bank increases, and the erosion rate accelerates. If the bend becomes tight enough, a cutoff channel may form across the point bar or floodplain on the inside of the bend, abandoning the meander, and creating a relatively straight reach with an adjacent oxbow lake or wetland. The meandering of the stream leaves topographic features that can be observed on the floodplain.

![Figure 2-40. Topographic features on the floodplain created by a meandering stream (FISRWG, 1998).](image-url)
Unstable conditions may result in bed forms that are significantly steeper or flatter than normal. For example, if a stream loses its ability to transport its sediment load it may start filling with sediment. This process is known as aggradation. The slope of the channel section upstream of the filling area will flatten as the upstream/downstream elevational difference decreases. The slope of the channel section downstream of the filling area will steepen as the upstream/downstream elevational difference increases.

Figure 2-41. Aggradation in riffle.

Figure 2-42. Aggradation in pool.

Figure 2-43. Longitudinal profiles of a natural stable channel and an aggrading channel.
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Figure 2-44. Stages of aggradation from stable channel to braided channel.

If the energy of the water flowing through a stream exceeds that necessary to erode and transport the sediment carried from upstream the channel may **incise** or erode downward through the bed material. This process is known as **incision**. This results in a steeper local channel slope increasing the available energy even more. A **knickpoint** or abrupt change in elevation can be observed at the point at which the bed erosion was halted. Incision of the streambed may progress further upstream or **headward** with each successive storm.

Figure 2-45. Channel incision and lateral adjustment.
2.2.7.6 - Morphological Equilibrium

Morphological equilibrium refers to a mean or average channel form about which short/long term and abrupt/gradual fluctuations occur. Consequently, stream channel stability is not a static state. It is a dynamic process in which a stream adjusts its form to maintain a balance between sediment supply and sediment transport. We may refer to a stream as a self-regulating system. In response to changes in streamflow and sediment supply it adjusts local riffle and pool slopes, rearranges bed material, transports more or less sediment, and adjusts its pattern and cross-section. Therefore, a stable stream is:

- able to maintain over time, its pattern, profile, and cross-sectional dimensions (shape and size);
- laterally stable, that is, slow rates of bank erosion on the outside of meander bends are matched by slow rates of deposition on point bars and lateral migration (movement back and forth) across its floodplain is gradual;
- vertically stable, that is, it is neither aggrading (filling) or incising (down-cutting);
- able to effectively convey the various flows and sediment delivered to it by its watershed.
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2.2.7.7 - Channel Maintenance and Channel Forming Flows

Channels are formed and maintained over time by flowing water eroding and depositing sediment. The effectiveness of these processes increases with discharge. Low discharges are very common, but not very effective at eroding and transporting sediment. On the other hand, high discharges erode and transport the most sediment during a given event, but are not very common. However, there is an intermediate range of discharge events that occurs frequently enough and has enough energy to erode and transport sediment such that, over time, they actually accomplish more work than the higher, less frequent discharge events. Studies have demonstrated that for most stable streams, the effective discharge, that is, the discharge that carries the largest amount of sediment over a long period of time, is equivalent to the bankfull discharge.

You will recall that the bankfull flow is that streamflow when the channel is flowing at or near capacity and the water surface is just at floodplain level but has not overtopped the stream banks. The size channel that is formed and maintained by the bankfull flow is not large enough to convey unusually high discharges. Nearly all stream channels, whether large or small, will contain without overflow approximately that discharge that occurs about once or twice a year, approximately the 1.5-year discharge. Higher flows, occurring on average once in 2 years or once in 5 years or more, will be too large to be contained in the natural channel and will overflow the banks.

Bankfull flow is a key parameter in determining the relationship between the volume of sediment transported and stream flow and is critical in evaluating stream channel stability. Field identification of channel features associated with this flow (e.g., top of point bars, scour marks along the outside bank, etc.) and accurate estimates of this discharge are essential in stream assessment and restoration work, since the cross-sectional geometry and meander pattern of the stable channel form are closely linked to it. Because this range of flows directly influences channel characteristics (e.g., shape, size, streambed material size and distribution, etc.) it directly influences habitat features as well.

Flood flows exceed the capacity of the stream channel, overtop the stream banks and move out onto the adjacent land surface. These large volume flows also have geomorphologic significance in that they actually build adjacent landforms by carrying sediment from upland and upstream areas and depositing it along the stream corridor. Although most sediment leaving a watershed is transported by the more frequent bankfull flow, higher volume storm events can carry very large amounts of suspended and bedload material that significantly alter the stream channel and floodplain characteristics.
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2.3 – Components of a Healthy Stream System

Stable stream channels have:
- constant width and depth over time
- vegetated, stable banks
- sufficient slope to transport materials delivered to it, neither aggrading (filling in) nor incising (downcutting)

Groundwater is the water contained below the land surface, in the pores between soil particles. Groundwater is the primary source for streamflow between periods of precipitation and is critical for sustaining abundant year-round baseflows.

Floodplains are areas of land adjacent to streams where water overflows during floods, allowing settling of materials and the return of water to the ground and the stream.

The major components of a healthy stream system are:
- a stable stream channel
- an active floodplain
- healthy streamside vegetation
- adequate groundwater reserves
- high quality physical habitat
- abundant and diverse living organisms

High quality physical habitat means cool temperature, good water quality (i.e., high dissolved oxygen, proper amounts of nutrients and minerals, little to no pollution), adequate surface area, clean substrate free from fine sediment, highly varied and abundant cover, and appropriate pool/riffle ratios.

Streamside vegetation is important for:
- physically holding streambanks in place
- providing food and habitat for aquatic and terrestrial animals
- moderating water temperature

An abundance and diversity of living organisms indicates that the other pieces of the puzzle are in place.
2.4 – Healthy Stream Types in North Carolina

Mountain Streams

- steep slopes
- V-shaped valleys
- narrow floodplain and riparian area
- narrow, deep channels
- straight to slightly sinuous
- cascading riffles, step-pools, and falls
Foothill Streams

- moderate to steep slopes
- U-shaped valleys
- moderate floodplain and riparian area
- moderate width and depth channels
- slightly sinuous
- riffle-pools, and step-pools
Piedmont Streams

- moderate to relatively flat slopes
- U-shaped to broad valleys
- moderate to broad floodplain and riparian areas
- narrow to wide, deep to shallow channels
- slightly sinuous to meandering
- riffles and pools
Coastal Plain Streams

- very flat slopes
- very broad, flat valleys
- very broad floodplain and riparian areas
- narrow, deep channels
- highly sinuous
- runs, glides, and pools
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2.5 – Effects of Land Use on Watersheds and Streams

Like many other urbanizing areas of this country, the Winston-Salem and Forsyth County area has undergone dramatic change and growth since the German Moravians first settled it in 1753. In fact, the Piedmont Triad (Greensboro, Winston-Salem and High Point) along with Charlotte/Mecklenburg County is part of the Piedmont Crescent, one of the most rapidly developing regions in the country. It is anticipated that this growth will eventually result in a solid band of urbanized counties from Raleigh to Charlotte. The population of Forsyth County alone is expected to increase as much as 20 percent by 2020. Unmanaged, this growth has the potential to significantly impact the region’s natural resources.

Stable watersheds are generally characterized by forest vegetation, a thick humus layer that protects the soil from the impact of precipitation, high infiltration rates, low runoff rates, and low soil erosion and sediment transport rates in upland areas, a stable stream channel, high quality water, and a healthy aquatic community.

Disturbance of a forested watershed leads to a chain of interrelated events that can destabilize the stream ecosystem. Most stream water quality, channel stability, and habitat problems can be traced to a change in the supply of water or sediment in the stream, or to alterations of the stream channel and banks. Every activity undertaken by people to render the landscape more suitable to a specific purpose begins with the removal of native vegetation and the disturbance of the soil.

2.5.1 - Changes in Watershed Hydrologic and Sediment Regimes

By altering the structure of plant communities and soils, human activities often conflict with the hydrologic and geomorphic functions of stream corridors. Land clearing activities, which precede all other land use activities (e.g., agriculture, mining, urban land development, etc.), influence the hydrologic and sediment regimes of watersheds in the following ways:

- Vegetation removal decreases the volume of rainfall intercepted and transpired back into the atmosphere.
- Soil disturbance and compaction reduce the volume of water infiltrated into the soil and stored in surface depressions.
- The volume of water conveyed as overland runoff directly to the channel increases significantly.
- Soil erosion and sediment transport increase significantly.
- Stream channels, adjusting to the increased runoff and sediment inputs, become unstable and contribute additional sediment from streambed and stream bank erosion.

Although these processes occur to varying degrees in all disturbed watersheds, streams in urban watersheds undergo the most dramatic changes. For urban streams, the degree of stream degradation is directly related to the amount of impervious cover (hard surfacing) and storm drainage.
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Impervious cover and storm drainage:

- Decrease the volume of water infiltrated into the soil;
- Decrease groundwater recharge;
- Decrease stream baseflow;
- Increase the volume of direct runoff;
- Decrease the time it takes to convey runoff from streets, sidewalks and parking lots to the nearest stream channel; and
- Increase the energy available to erode the stream channel.

Figure 2-47. Relationship between percent impervious surface and runoff (FISRWG, 1998).
As a consequence, urban streams tend to have flashy hydrologic regimes. Many urban streams experience a significant reduction in baseflow. Streams that were perennial prior to development of the watershed may become intermittent or ephemeral. Conversely, even moderate rainfall events can generate a noticeable increase in stream flow volume and velocity.

Smooth, hard pavement and storm drain systems route urban runoff rapidly to nearby streams. As a result the rising limb of the storm hydrograph shifts to the left reflecting the decrease in lag time. In addition, the peak is higher reflecting the greater volume of water entering the stream as direct runoff.

2.5.2 - Impacts on Stream Channels and Floodplains

2.5.2.1 - Channel Stability

We can expect that stream channels will react to alterations in the watershed’s flow and sediment regimes, especially changes in the frequency and magnitude of the bankfull and higher discharges. These alterations in flow and sediment load do not necessarily produce an immediate change in the stream channel but initiate a response that may extend over a period of time. The situation is further complicated by the fact that the changes in flow and sediment yield may not occur simultaneously. As a consequence, it has not been
determined with certainty how much alteration in the rainfall-runoff-erosion relation is necessary to cause a given type and amount of channel change. However, studies suggest that as little as 10% impervious cover within a watershed can cause significant channel stability problems.

We do know that urban channels adjust over time, eroding and enlarging in response to increased storm flow volume and velocity. A typical channel evolution sequence following the development of a watershed includes:

*Initial bed degradation* - particularly in channels with fine-grained bed material, the bed provides little resistance to the increased stream energy that develops as a greater volume of runoff is conveyed rapidly to the channel. This situation usually causes the channel to incise with a subsequent lowering of the bed elevation. As the degree of incision increases, the stream becomes entrenched and disconnected from its floodplain. Flood flows, which normally overtopped the banks, become increasingly confined to the channel. Stream energy and stress on the banks increase as depth of flow increases in a confined channel.

![Figure 2-49. Bed degradation resulting from changes in watershed hydrology associated with urbanization exposed this sanitary sewer line.](image)

*Lateral adjustment* - lowering of the streambed due to incision increases bank height confining the channel even further and places additional stress on the banks. Hydraulic forces eroding the toe of the banks result in steeper bank angles with increased susceptibility to gravitational failures. As these failures become common the channel adjusts laterally, becoming wider.
Figure 2-50. Bank erosion and lateral adjustment following initial streambed degradation.

2.5.2.2 - Riparian and Streamside Vegetation

Riparian and streamside vegetation is routinely impacted by mechanical removal and spraying with herbicides for: preparation of riparian land for cultivation or grazing; maintenance of power line, utility, and road rights-of-way; maintenance of public parks, recreation and open space areas; maintenance or expansion of residential recreation facilities and yard areas. Overgrazing by livestock can either eliminate streamside vegetation altogether or significantly reduce the vigor and density of more palatable plants. Under all of these circumstances the effects are similar:

- Increased bank erosion and lateral migration
- Increased channel width, decreased depth
- Increased water temperature
- Lowered water table
- Increased velocity of flows in overbank areas
- Reduced trapping of sediments
- Increased damage to property and adjacent utilities
- Increased maintenance costs
- Increased loss of land
- Decreased fish and wildlife habitat
2.5.2.3 - Floodplain and Channel Alterations

As noted previously, a flood wave moving through a watershed is usually attenuated (decreased) through storage in the floodplain. Filling of floodplains to accommodate new development, channelization and/or construction of flood dikes to protect existing properties in the floodplain, channel straightening to eliminate channel migration and overbank flows can result in a loss of flood storage capacity and channel instability. These channel and floodplain “improvements”:

- Eliminate access to the floodplain
- Convey passing floodwaters more rapidly to downstream areas
- Increase peak flood stage
- Increase the energy of the flood downstream
- Decrease sediment transport capacity under bankfull flow conditions
- Decrease channel stability
- Increase channel migration
- Increase bank and bed erosion on neighboring properties
- Lower water tables
- Increase loss of riparian wetlands
- Decrease recharge of groundwater aquifers
- Degrade in-stream habitat
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Figure 2-52. Channelized reach with concrete revetment.

Figure 2-53. Channelized reach with gravel berms.
Figure 2-54. Channelized reach with timber walls on left bank and sheet piling on right bank.

Figure 2-55. Channelized reach with riprap on banks.
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2.5.3 - Impacts on Physical Habitat and the Biotic Communities

The most significant influences on water quality, in-stream habitat, and biotic communities are the land use activities conducted in the adjacent floodplain and throughout the watershed.

Since the Clean Water Act was passed, significant progress has been made in reducing point-source pollutants (i.e., discharges that come from a fixed location, usually through a pipe) from industries, sewage treatment plants, large livestock feedlots, mine sites, and other sources. Although point-source discharges can still have dramatic and deleterious effects on stream systems they are generally few in number and localized within a given watershed. On the other hand, non-point source pollutants come from diffuse sources, such as runoff from cropland and grazing land, forestry operations, construction sites, urban land, highways and landfills. Progress has been made on controlling non-point pollutants as well. However, these types of land disturbing activities are generally widespread and can affect significant land area within a given watershed. As a consequence, they have the greatest potential to negatively affect our streams.

Figure 2-56. Impacts due to vegetation removal and livestock grazing.

Removal of streamside and stream bank vegetation can result in increased erosion, lateral migration, channel widening, loss of stream bottom habitat due to sedimentation, and increased water temperature due to increased insolation.
Stream channel alterations (e.g., channelization and/or channel straightening) associated with flood mitigation and stabilization projects create channels that are virtually devoid of habitat and ultimately unstable. These situations are commonly associated with engineered channels, which are relatively straight, wide, trapezoidal channels, with uniform profiles. They are generally designed to convey all flows (baseflow, bankfull flow, and flood flow). As a consequence, baseflow is usually very shallow or may actually flow beneath the substrate because it is spread out over such a large surface area. The uniform profile replaces the typical riffle-pool sequence with a continuous riffle that provides no cover from predation or strong flushing currents. Vegetation on the banks is replaced with riprap or gabions (concrete revetment in more urbanized areas) in an effort to maintain the engineered form, and grade control structures may be installed to maintain bed stability.

Because the channel is oversized for bankfull flows as well, its sediment transport capacity is significantly reduced. This results in increased substrate embeddedness and ultimately aggradation, which reduces flow conveyance capacity. Because these channels are generally designed to convey the 50-year or 100-year flood, the larger flows are confined, creating significant stress on the bed and banks that leads to channel instability.

Development and its effects on hydrologic and sediment regimes can have an effect on the physical habitat by causing streambed and bank erosion and sedimentation that alter channel characteristics (e.g., dimension, pattern, slope) and microhabitat features (e.g., depth, substrate, cover, and pool/riffle ratios).
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Channel instability and sediment is a significant problem for urban streams. During the development phase most sediment enters streams from construction sites in upland areas. Post development sources of sediment are primarily from within the channel as streambeds and stream banks are eroded by increased runoff from compacted soils and paved areas. Sedimentation causes substrate embeddedness and aggradation, which reduces the flow conveyance capacity of the channel. Stream bank erosion and flooding can significantly affect water quality by exposing or inundating private sewage disposal systems, public sanitary sewer lines, underground and above ground fuel storage tanks, and landfills.

Figure 2-58. Urban runoff and sewage spills impact water quality.

Sewage spills that occur when septic systems or sanitary sewer lines are exposed and damaged by channel erosion contribute oxygen consuming organic wastes, nutrients, and pathogens associated with human waste that have serious health consequences for aquatic life and humans.

Runoff from urban land contains a variety of pollutants from trash to toxic compounds. The ubiquitous shopping carts, bicycles, soda cans, and plastic containers some how manage to find their way into most urban streams. Rain falling on streets, sidewalks and parking lots washes particulate material worn from automobile tires and brake linings, as well as waste oil, antifreeze, and road salts into storm drain inlets for conveyance to the nearest stream. Pesticides, fertilizers, and pet wastes washed from lawns, golf courses, and parkland are also common contributors to the degraded water quality typical of urban streams. During the hot days of summer, runoff from heated paved surfaces can significantly increase stream temperature. The biological availability of many toxic pollutants is enhanced as water temperature rises.
Refuse and other waste products such as old batteries, paints and solvents, and pesticides discarded by homeowners usually end up in a sanitary landfill. When precipitation falls on a landfill it percolates through the layers of refuse and waste, where it picks up pollutants. Many newer landfills have drainage systems and clay and/or plastic liners designed to collect and contain this contaminated rainwater or leachate. Unfortunately, older landfills or dumps usually did not have leachate collection or containment systems. Plus, landfill liners degrade and can eventually develop leaks. As a consequence, leachate from sanitary landfills and dumps may percolate into groundwater and eventually reach nearby streams, where it can be toxic to aquatic organisms.

As noted previously, healthy fish and macroinvertebrate populations in headwater streams depend on relatively cool water temperatures and high levels of dissolved oxygen. Some species of fish, such as trout, are especially intolerant to increases in water temperature above natural background levels. Because dissolved oxygen levels are a function of water temperature, a stream warmed due to the loss of streamside vegetation and channel widening will have lower dissolved oxygen levels than a stream with tree cover. Increased insolation due to loss of vegetation plus an influx of nutrients from fertilizers and manure washed into a stream can stimulate massive blooms of algae. As the algae die, they are broken down by bacterial decomposition, which consumes what little oxygen may be available. The further depletion of oxygen levels can severely stress resident aquatic organisms. This stress can affect the ability of less tolerant aquatic organisms to survive.

Sediment in runoff from cropland and construction sites, and eroded from banks damaged by livestock grazing and urban runoff deposits on the streambed, smothering bottom
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dwelling insects and fish eggs buried in the gravel substrate. Sediments carried in suspension can irritate or clog the gills of adult fish.

Figure 2-60. A sediment-laden tributary entering a less turbid mainstem.

The effects of land use activities have been documented for the streams of Forsyth County. The North Carolina Department of Environment and Natural Resources indicated in the Yadkin-Pee Dee River Basinwide Water Quality Management Plan that Muddy Creek and Salem Creek have been impacted by urban runoff, permitted wastewater discharges, and agricultural land uses. As pointed out at the beginning of this manual, NCDENR has identified the majority of the streams in the High Rock Lake – Muddy Creek sub-basin as being support threatened.

The Forsyth County Environmental Affairs Department has been conducting physical and chemical monitoring of Muddy Creek and its tributaries since 1988. Results of their efforts indicate elevated levels of total phosphorus throughout the Muddy Creek watershed. In addition, they found elevated levels of heavy metals (e.g., lead and cadmium), especially at the more urban sites such as Peters Creek and Salem Creek in Winston-Salem. Although most streams sampled were very turbid, low dissolved oxygen did not appear to be a problem. Most streams in agricultural areas, including the South Fork of Muddy Creek and Salem Creek above Salem Lake, were assigned a good-fair rating, although severely degraded habitat is typical. Their report indicates that the cobble/gravel substrate typical of Piedmont streams has been significantly embedded by massive inputs of coarse sand, thereby reducing available habitat for benthic macroinvertebrates and fish.
Macroinvertebrate and fish community studies conducted by the North Carolina Division of Water Quality in 1996 demonstrated that water quality problems still exist in parts of Muddy Creek and Salem Creek. Their results suggest that improvements in wastewater treatment and/or control of urban runoff have reduced the severity of the problems.

2.5.4 - Impacts to Property, Infrastructure and Water Supplies

Channel instability caused by changes in watershed hydrology, vegetation removal, and/or channel alterations impact property, infrastructure and water supplies with significant economic and public safety consequences.

Channel erosion and sedimentation damage public and private property resulting in a loss of land, lower property values, and increased maintenance costs. Erosion of streambeds and banks exposes and damages underground utilities (e.g., septic systems, sanitary sewer, water, gas lines, communication cables) and undermines and damages above ground utilities and infrastructure (e.g., telephone and power poles, transmission and distribution towers, bridge piers and abutments). Sediment eroded from upland and in-channel sources deposits at culvert and bridge openings and clogs storm drains. The cost of protecting and maintaining utilities and infrastructure can be considerable for homeowners, and private utility companies, as well as state and local highway and public works departments.

Figure 2-61. Bridge footers exposed by streambed degradation.
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Figure 2-62. Sanitary sewer line exposed by streambed degradation.

Figure 2-63. This incised stream is experiencing significant lateral erosion. Note remains of undermined and broken concrete channel.
Figure 2-64. Lateral adjustment and property damage resulting from historic channelization work.

Figure 2-65. Bed degradation, failure of gabions, subsequent lateral adjustment and property damage resulting from historic channelization work.
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Maintenance dredging of navigation channels is another costly item. A study conducted in the mid-1970’s estimated that the cost of dredging sediment eroded from in-channel sources alone, ranged from $55,000 per square mile to $229,000 per square mile (1976 dollars) of watershed. Add to this sediment eroded from upland sources and the frequency and cost of maintenance dredging increases dramatically.

Throughout this country public water supplies have been significantly impaired and reservoir capacities reduced by sedimentation. For example, studies on siltation rates for three water supply reservoirs in the Baltimore, Maryland region showed that all three reservoirs had lost considerable capacity due to sediment deposition. In fact, the newest reservoir had lost nearly 20 percent of its capacity over a thirty-year period. A study conducted in the early 1980’s indicated that the cost of removing sediment from the nation’s reservoirs to maintain their storage capacity would be approximately $1 billion (1983 dollars).

Many municipalities that historically relied on high quality lakes and reservoirs have been forced by population growth and the loss of reservoir capacity to draw water from regional sources, such as streams and rivers. Because many streams and rivers have impaired water quality, water treatment costs can be substantial. The higher treatment costs are passed on to domestic and industrial users of the water supply system. High quality water supply reservoirs are an exhaustible natural resource and many are threatened by poor land use practices. Preservation of existing water supply capacity and quality is critical.

The main sources of drinking water for Forsyth County residents are the Yadkin River and Salem Lake, which provide 65-70% and 30-35% of the water needs respectively. As indicated previously the Yadkin-Pee Dee River Basinwide Water Quality Management Plan prepared by NCDENR has documented the effects of land use activities on the water quality of the Yadkin River and its tributaries. Although that same study found Salem Lake is fully supporting its uses, sedimentation and runoff from urban development and agriculture has raised concerns about the future water quality of the lake.
STREAM MANAGEMENT

3.0 – Introduction

Local watershed management programs can preserve, protect, and restore our natural resources. At the core of the process are cooperative efforts among those who are affected by and those who will benefit the most from the resources within our watersheds. This group includes all of us (i.e., public officials, private citizens, public interest groups, economic interests, and any other groups or individuals) who are interested in or might be affected by these programs. There are numerous tools available for managing and protecting streams from the adverse effects of human activities. In general terms, these tools can be classified as planning tools, regulatory tools, best management practices, and educational tools. In this section of the guidance manual we will be discussing each of these tools.

3.1 – Planning Tools

The Legacy Comprehensive Plan adopted by Forsyth County and the City of Winston-Salem is a document that assesses the current social, economic, and environmental conditions in the region, and proposes changes to the management of growth and development in order to meet specific goals. A major theme of the Plan is the control of suburban sprawl and a move toward sustainable development. From an environmental perspective, the Plan states the desire to promote economic opportunity while protecting and restoring the natural environment upon which community well-being and quality of life depends. In relation to the protection of streams, the Plan identifies two objectives:

- Protected watersheds, wetlands, and streams resulting in reduced pollution runoff, soil erosion and flooding, and clean, high quality water to meet the domestic, economic and recreational needs of the community.
- Environmentally sensitive development, which respects natural areas and enhances the quality of our built environment.

In order to meet these objectives, the Plan outlines policies and action agendas for the future, which include:

3.1.1 - Policies

- Continue to monitor water quality and conditions in water supply watersheds to determine the effectiveness of regulations and recommend changes as needed.
- Promote the utilization of building methods that emphasize reducing the amount of impervious surface.
- Promote more environmentally sensitive and aesthetically pleasing stormwater management systems.
- Educate landowners and businesses about the benefits of best management practices for stormwater protection.
- Enforce floodplain regulations more effectively.
- Consider the adoption of guidelines and/or regulations to manage development in environmentally sensitive areas.
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- Integrate natural areas such as streams and wetlands into the site design of development projects and ensure that these areas are protected during development.

3.1.2 - Action Agenda

- Identify and consider restoration of degraded urban streams.
- Promote a system of vegetative buffers along streams to filter pollutants.
- Implement a countywide stormwater management program that addresses the quality and quantity of stormwater runoff.
- Review and amend, as necessary, the erosion control ordinance.
- Develop an environmental checklist for ensuring compliance with existing regulations.
- Consider an environmental review procedure, which includes assessing the environmental effects of development proposals.
- Study existing environmental protection practices for effectiveness.

3.2 – Regulatory Tools

3.2.1 - Federal Regulations

The largest federal regulatory programs for stream protection evolved out of the Clean Water Act passed by Congress in 1972. The stated objective of this Act is to restore and maintain the chemical, physical, and biological integrity of the nation’s waters. The Clean Water Act guarantees citizens the right to know about the quality of their water and participate in programs and systems designed to keep those waters healthy. Citizens can get involved and provide comments about proposed permits for a variety of activities that could potentially adversely impact resources in their watershed.

The Section 404 Program controls the placement of fill and dredge materials in waters of the United States. Waters of the U.S. include lakes, rivers, streams, natural ponds, and wetlands. Permits are required from the U.S. Army Corps of Engineers (USACOE) before any fill or dredge activities can occur within these areas. The USACOE and other federal review agencies consider adverse impacts to waters of the U.S. during the permit application review process.

The National Pollutant Discharge Elimination System (NPDES) Program requires industrial and municipal point-source dischargers to obtain a permit before releasing wastewater to surface waters. NPDES permits require identification of pollutants in wastewater and set limits on these pollutants.

In 1990, Phase I of the U. S. Environmental Protection Agency storm water program was initiated by amending the Clean Water Act to target non-point pollution sources. Through the use of NPDES permits, municipalities populated by 100,000 people or more are required to develop storm water management plans for controlling and treating urban runoff. Under Phase I, the City of Winston-Salem, as well as the City of Charlotte were
subject to these storm water permit requirements. The Phase I storm water permit requirements also applied to large construction activities (i.e., disturbing 5 acres of land or more), and various categories of industrial activities.

The Phase II storm water program expanded the NPDES permit requirements to smaller urban municipalities and towns outside of urban areas that have populations of 10,000 or more and a population density of 1,000 people per square mile. Under Phase II, Forsyth County, Bethania, Clemmons, Kernersville, Lewisville, Rural Hall, and Walkertown were subject to these storm water permit requirements.

3.2.2 - State Regulations

Section 401 of the federal Clean Water Act mandated that states establish water quality standards for their surface waters. As part of this mandate, the states are also required to certify that certain activities do not cause a violation of the water quality standards. For example, damming a stream to construct a pond may violate the state’s water quality standard for temperature. In North Carolina, the Department of Environment and Natural Resources (NCDENR) administers the Water Quality Certification program, as required by the federal Clean Water Act.

In addition, North Carolina has adopted its own regulations for the protection of its streams. These regulations are codified in Title 15A of the North Carolina Administrative Code, Environment and Natural Resources. Chapter 2, Environmental Management contains sections that outline the state’s water quality certification requirements and storm water management regulations. Chapter 4, Sedimentation Control, adopts minimal mandatory standards to permit development activities to proceed with the least detrimental effects from pollution by sedimentation.

The U.S. Environmental Protection Agency (USEPA) grants states the authority to administer NPDES programs that comply with national standards and guidelines set by the Clean Water Act. In North Carolina the State Division of Water Quality (NCDWQ) is the permitting authority.

In the early 1990’s, North Carolina adopted regulations that set forth watershed protection requirements for drinking water supplies and required local municipalities to adopt and enforce these regulations within their local ordinances.

3.2.3 – Current Local Stream Protection Regulations

While administration, permitting and enforcement authority for many of the federal and state programs have remained with the respective state and federal regulatory agencies, implementation of some programs has been delegated to local municipalities. For example, the USEPA granted the State of North Carolina authority to administer the NPDES storm water permit program. In addition, local municipalities, such as Winston-Salem and Forsyth County, are responsible for obtaining permits and developing their
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own storm water management plans for controlling and treating urban runoff within their jurisdictions.

Response at the local level to these state and federally mandated programs has been highly variable nationwide. Some municipalities have moved forward rapidly to develop and implement the required programs. Some smaller cities and towns have not had the resources to dedicate to these programs and therefore have not yet met their objectives.

The City of Winston-Salem, Forsyth County, and a number of the surrounding towns have been working diligently to meet many of the state and federally mandated requirements. State and federal requirements notwithstanding, we recognize the critical importance that protecting our natural resources plays in maintaining the quality of life and economic viability of our communities.

The City of Winston-Salem is developing an approach to the environmental assessment of development projects that includes policies and standards that ensure protection of natural resources and promote environmentally sensitive development. The City’s current efforts focus on several key resource-protection issues including: drinking water supply watersheds, wetlands, storm water runoff, streams and floodplains.

3.2.3.1 - Water Supply Watersheds

The Legacy Comprehensive Plan notes that Winston-Salem, Forsyth County, Kernersville, Lewisville, and Clemmons have adopted local watershed protection regulations for seven watershed areas that drain to the Yadkin River and Salem Lake. The goal of these watershed regulations is to minimize the impacts of storm water runoff on the drinking water supply by limiting development and retaining as much of the existing natural vegetation in these drainage basins as possible.

The Unified Development Ordinances (UDO) adopted by Winston-Salem and Forsyth County includes, among other measures, the Yadkin River Conservation District, which was created to “protect the community’s main water supply, preserve the historic features of the area, and preserve the natural beauty of a continuous conservation corridor along the Yadkin River.” This zoning district is the most restrictive, allowing primarily low-density residential development and establishing other protective requirements.

The Environmental Ordinance section of the UDO also provides guidelines for new development in the Salem Lake Watershed Protection Area that include: density restrictions, limits on impervious area, requirements for storm water quality management plans and permits, design and maintenance standards for storm water control structures, and maintenance of vegetated buffers along tributary streams and around the lake.

3.2.3.2 - Wetlands

The USACOE and the State of North Carolina regulate activities that impact wetlands in Forsyth County. Developers are required to demonstrate that their proposed project has
avoided and minimized impacts on wetlands. Modifications to the City and County review process will include coordination with federal and state regulatory agencies to confirm that the necessary approvals and permits have been obtained prior to issuance of local permits.

3.2.3.3 - Stormwater Runoff

The Unified Development Ordinances (UDO) adopted by Winston-Salem and Forsyth County contain regulations that establish guidelines for erosion control during construction, storm water management for development post-construction, and storm water management utility fees.

The UDO requires erosion control measures for land disturbances equal to or greater than one acre. The City/County Inspections Division currently enforces these regulations.

In 1996 the City of Winston-Salem initiated its storm water management program, in response to the USEPA’s Phase I storm water permit requirements. The City’s storm water policy was initially focused on controlling the runoff rate from individual development parcels. The City’s Public Works Department reviewed storm water plans submitted by developers on an individual site-by-site basis. This type of approach made it difficult to evaluate the potential effects of runoff from an individual land development parcel on the existing stormwater collection system and available floodplain storage and conveyance capacity within a given watershed. In addition, there was no evaluation of potential water quality impacts associated with the stormwater runoff. The program is evolving toward a more comprehensive approach with watershed master plans being developed to address water quantity and quality control for the City’s fifteen drainage basins.

The stormwater management utility fee provided for in the UDO will allow the City to fund those facilities and activities necessary to meet the water quality requirements of the NPDES stormwater permit issued by the NCDENR.

3.2.3.4 - Streams and Floodplains

The USACOE and the State of North Carolina regulate activities in streams and floodplains in Forsyth County. In addition, the Environmental Ordinance Section of the UDO provides the City with the authority to regulate activities in floodplains by limiting the nature and extent of development in flood prone areas. The requirements set forth under this local ordinance are more restrictive than the minimum requirements of the federal government.

Protection of those components of a healthy stream we identified in the Watershed and Streams Section, including a stable stream channel, healthy streamside vegetation, an active floodplain, adequate groundwater reserves, high quality physical habitat, and abundant and diverse living organisms requires a proactive approach to stream protection.
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Monitoring of the area’s streams and lakes is an important component of an overall protection effort. The City of Winston-Salem and Forsyth County Environmental Affairs Department have been conducting physical and chemical monitoring of Muddy Creek and its tributaries since 1988. The North Carolina Division of Water Quality periodically conducts macroinvertebrate and fish community studies in Muddy Creek and Salem Creek. In 1998, the NCDWQ completed the water quality management plan for the Yadkin-Pee Dee River Basin. The study area includes the Yadkin River and tributaries to it in Forsyth County. The purpose of the plan is to share information on the current status of the streams in this watershed and to recommend actions needed to restore and maintain the health of these waterways. NCDWQ reviews the water quality of the Yadkin River Basin every five years.

All of the regulations in the Unified Development Ordinances cited above were promulgated with the intention of protecting our streams from the impacts of various land use activities.

The City has initiated an urban stream restoration program that thus far as completed restoration/stabilization projects on Church Creek in Bethabara, and Tanners Run and Town Creek in Old Salem. Current and future projects include Salem Creek in Civitan and Central Parks and Peters Creek along Peters Creek Parkway.

3.2.4 - A Comprehensive Approach to Stream Protection

Current stream protection requirements and restoration efforts are already having a positive effect on historically degraded streams in the area. In addition, the City is adopting a more comprehensive approach to stream protection that includes stream naturalization (i.e., maintaining stream systems in a natural state), long-range water supply planning, growth management and urban storm water planning to prevent future stream degradation.

Any stream protection program that is adopted by the City will be unique to the geographic, political, and environmental conditions of the Winston-Salem and Forsyth County area. However, as the City formulates its comprehensive stream protection program, it helps to understand the rationale that has guided the development and implementation of successful programs in other regions of the U.S. Schueler (1994) identified four elements that are essential for any successful local stream protection effort.

3.2.4.1 - Stream Protection Ordinance

A comprehensive stream protection ordinance is the foundation of every effective local stream protection program, and it will generally incorporate seven key principles.

- Establish a clear basis for a stream protection approach.
- Set rational thresholds for development.
- Provide funding mechanisms to support the program.
STREAM MANAGEMENT

- Reduce the potential for future conflict in plan review.
- Ensure compliance.
- Avoid legal landmines.
- Set practical performance criteria.

3.2.4.2 – Local Development Review Process

The primary vehicle for effective local stream protection is the development review process. The following 12-step process ensures that stream protection is considered at each stage of development, with the goal being to design, implement, and maintain the best system of practices and land uses for stream protection.

- Watershed-based zoning
- Predevelopment consultation at the site
- Delineation of resource protection areas
- Submission of preliminary concept plan for the site
- Obtaining non-local environmental permits
- Submission of final site plan for review
- Preconstruction meeting
- Inspection during construction
- Final inspection and submission of as-built drawings
- Issuance of occupancy permit and release of performance bond
- Maintenance inspections
- Recapture of the site during redevelopment

3.2.4.3 – Performance Criteria Governing Development

Performance criteria set forth general goals that must be met at the site. To the extent possible, they provide flexibility for both the consultant and the plan reviewer to devise the best method for protecting the stream. General performance criteria are usually accompanied by more detailed development guidelines, which are typically contained in a technical manual that is specifically referenced in the stream protection ordinance. Four broad categories of performance criteria include:

- Protection of resource areas
- Site design to minimize impervious area
- Clearing, grading, and sediment control during construction
- Control of stormwater runoff quantity and quality

3.2.4.4 – Local Stream Protection Program

Fifteen key ingredients of a successful local stream protection program have been identified through the examination of different local programs around the country.

- Take a comprehensive and unified approach to stream protection.
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- Designate a single agency to implement and administer the program.
- Employ a single and unified development review process.
- Consider stream protection at all stages of the development cycle.
- Use interdisciplinary teams to review individual development plans.
- Implement the stream protection program in an incremental manner.
- Find diverse and stable financing mechanisms to support the program.
- Invest in continuous training of plan review and inspection staff.
- Support the development review process with watershed-based zoning.
- Have a strong local commitment to inspection, enforcement, and maintenance.
- Use clear and simple performance criteria to guide development review.
- Include all stakeholders in the development of the stream protection approach.
- Work in partnership with state and federal agencies.
- Invest in public awareness, education, and stewardship.
- Be responsive to the need of the development community for a fair and timely review.

Further, more detailed information about these four elements is available in The Stream Protection Approach (see References).

3.3 – Best Management Practices: Planning

Best Management Practices (BMPs) are a combination of structural and nonstructural measures designed to mitigate or compensate for impacts to a particular stream and its watershed that result from various land use activities.

Structural BMPs focus on safely conveying storm water runoff, reducing the hydrological impacts due to increased quantity of storm water runoff, and reducing the pollutant loadings delivered by storm water runoff. Major structural BMPs are usually implemented by organizations such as public works departments, developers and businesses. Structural BMPs include: silt fences, sediment traps and basins, grassed swales, infiltration trenches and basins, sand filters, water quality inlets, constructed wetlands, and retention or extended detention ponds.

Nonstructural BMPs focus on reducing storm water runoff and preventing contamination of runoff through planning, design, maintenance, and education. Major nonstructural BMPs are usually implemented by organizations such as public works departments, businesses, neighborhood associations or private citizens. Nonstructural BMPs include: land use planning and zoning; site design performance criteria (e.g., reduced impervious area); protection of sensitive areas (e.g., riparian buffer zones, easements, etc.); street sweeping; alternatives to road salting; publicly operated facilities for waste oils and homeowner chemicals; waste handling and spill prevention programs at municipal facilities and private businesses; and public education programs.

Although urbanization is a gradual process that spans decades and occurs over a wide region, it involves many individual developments that take place over a much shorter span and alter only a few acres. As such, the degradation of streams in urbanizing
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watersheds is a classic example of the difficulty of addressing long-term cumulative environmental change (Schueler, et. al., 1991). Planners and engineers in urban watersheds have the difficult task of evaluating the impact of each individual development proposal over the long term and at the watershed scale. They must identify and design the appropriate measures that mitigate those impacts.

In this section we provide general guidance on developing effective best management systems to mitigate some of the adverse impacts associated with development activity. We also provide a brief outline of some currently used best management practices that can be combined to develop an effective best management system. It is not our intention to provide detailed design criteria, as those criteria have been thoroughly developed in other available publications (see Appendix).

3.3.1 - Developing Realistic Targets for Urban Watersheds

Schueler, et. al. (1991) suggest that the first step in identifying and designing an urban BMP system is the selection of appropriate and achievable watershed management targets. Watershed management targets refer to the level of stream quality within a watershed that will exist when all development is completed. A developer’s engineering consultant should coordinate with the City’s stormwater engineers and County’s planners for guidance on the management targets for the specific watershed in which their development is proposed.

Schueler, et. al. (1991) identified six general categories of watershed management targets. Their six watershed management target categories are ranked from the lowest level of stream quality provided to the greatest. Clearly, it is more difficult to design a BMP system that meets a high stream quality target than a lower stream quality target. Each of the watershed management targets is described below:

3.3.1.1 - Flood Control

This target is focused on preventing downstream flood damage within the watershed and reducing the extent of channel destruction. As such, the target can be achieved with only modest difficulty, through a combination of stormwater detention, floodplain delineation and improvements in channel conveyance. However, the flood control target provides a low degree of stream quality.

3.3.1.2 - Generic Urban Non-Point Source Control

The objective of this target is to reduce the magnitude of the increase in urban pollutant loads in a watershed. The basic strategy is to treat the first flush of pollutant washoff with urban BMPs, as well as to trap sediments during the construction stage of development. However, achievement of this watershed target will still result in some degradation to the stream and its receiving waters.
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3.3.1.3 - Generic Urban Stream Protection

In this watershed target, the primary goal is to reduce the magnitude of the severity of urban stream degradation that is likely to occur. A number of additional BMP system components are needed to accomplish this task, such as stream buffers, extended detention to control frequent floods, and some watershed and site environmental planning measures. These planning measures are intended to partially protect the major functional components of the stream – its channel, floodplain, wetlands, and riparian forests. However, in all but the most lightly developed watersheds, this target is not capable of maintaining the integrity of a stream ecosystem as it may have existed prior to development.

3.3.1.4 - Control of Non-Point Source Specific Pollutants

The goal for this watershed target is to reduce the delivery of urban pollutant loads such that a specific water quality standard or pollutant load allocation can be met. Examples of this target include control of nutrient inputs to alleviate eutrophication in lakes and estuaries, control of bacteria to shellfish harvesting areas, and reduction of sediment toxics. In many cases, this target implies non-degradation (that is, no net increase in the delivery of a particular set of pollutants). Given the upper limits of BMP performance, this target cannot consistently be met unless the BMP system includes moderate limits on watershed and site imperviousness, more stringent urban BMP requirements, and stream buffers.

3.3.1.5 - Protection of Sensitive Streams

For this high quality target, the goal is to maintain the integrity of the predevelopment stream ecosystem. Its achievement is typified by the persistence of sensitive aquatic indicator species and/or habitat areas. These sensitive stream indicators include salmonid and anadromous fish, certain assemblages of aquatic insects, and tidal or nontidal wetland complexes. Sensitive streams have little tolerance for even moderate levels of watershed development. In the mid-Atlantic region, for example, sensitive trout streams cannot persist when watershed imperviousness exceeds 15%, and are difficult to maintain even at lower levels of development. Therefore, BMP systems in most sensitive streams require severe restrictions on both watershed and site imperviousness, enhanced stream buffers, extraordinary sediment and erosion control during construction, and extremely sophisticated BMP design.

3.3.1.6 - Restoration of Degraded Urban Streams

Urban stream restoration is arguably the most difficult of all watershed targets to attain. The broad objective is to restore the functional integrity of a stream ecosystem, as demonstrated by the reestablishment and persistence of important aquatic species or ecosystem functions that had been diminished over time by urbanization. It is a complex and costly process of repair that involves stormwater retrofits, riparian reforestation, stream and wetland restoration, fish reintroduction, and removal of fish barriers. The
ability to meet this target in an urbanized watershed is governed by two factors. First, enough opportunities must be available to retrofit BMP systems into urban watersheds to provide meaningful hydrologic control and pollutant removal. Second, any new watershed development that occurs must be accompanied by stringent BMP systems so that the improvements brought about by retrofits are not cancelled out.

3.3.2 - Considerations in Choosing the Appropriate Best Management Practices for Your Site

After the management targets for the watershed in which the development is proposed have been identified the appropriate practices or combination of practices must be identified.

Each BMP option has both unique capabilities and persistent limitations. These, in turn, must be balanced with both the physical constraints imposed by the development site and the overall management objectives for the watershed. In practice, this balance is achieved through a negotiating process between the engineering consultant and the local storm water engineer or planner. Typically, the engineering consultant is responsible for developing the initial BMP plan, and represents the interests of the developer. The stormwater engineer or planner reviews the plan to ensure that it conforms to local policies and design standards, and represents the interests of the community.

During the BMP review process, it is important to identify the ultimate objectives for managing runoff from the site. The objectives in non-point source pollution and stormwater management have gradually evolved over the years, and may vary considerably among jurisdictions. However, the local stormwater engineer/planner and engineering consultant often do recognize several common and general goals which should be incorporated into a BMP plan. Schueler, et. al. (1991) suggest that at a minimum, the BMP plan jointly developed for a site should accomplish the following goals:

- Reproduce Predevelopment Hydrologic Conditions

The historical concern in stormwater management has been to reduce the frequency and severity of downstream floods. In most areas, this goal is achieved by controlling the peak discharge computed for a specific design storm to predevelopment levels. However, you may recall from our discussion in the Watersheds and Streams Section that floods are but one of a series of hydrologic changes brought about by watershed development. Other hydrologic changes can have equally negative impacts on the quality of downstream aquatic habitat and/or the severity of stream bank erosion. Some BMP options are capable of mitigating these impacts through artificial groundwater recharge or the control of small to intermediate storm events. Both the planner and the engineering consultant should check the condition of stream channels downstream of a proposed development to determine if such options should be required.
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- Provide Moderate Pollutant Removal Capability

In recent years, BMP designs have been developed to enhance pollutant removal during storms, and thereby improve the quality of stormwater runoff delivered to the receiving waters. BMPs differ markedly in the pollutant removal mechanisms they employ, and consequently, their performance in removing different pollutants can vary significantly. However, the engineering consultant has some ability to enhance removal rates by increasing the volume of runoff effectively treated by the BMP, or by adding extra design features. The storm water engineer/planner’s responsibility is to provide specific guidance to the engineering consultant on which urban pollutants are to be targeted for removal in the watershed.

- Feasibility for the Site

Many BMPs are constructed on sites for which they are not suitable. As a consequence, some BMPs experience chronic maintenance problems or nuisance conditions, and in extreme cases, may no longer function as designed. To prevent these sorts of problems from occurring, both the storm water engineer/planner and the engineering consultant should clearly understand the physical restrictions associated with each BMP. In addition, the engineering consultant should perform field tests to verify the physical conditions of the site. Depending on the results, the engineering consultant may have to modify the BMP plan or incorporate preventive design features.

- Cost-effectiveness

The construction costs for different BMP options can vary substantially, even on similar sites. This is due to inherent differences in the methods and materials used for BMPs, as well as certain economies-of-scale. Since BMP costs are eventually passed on to the consumer, cost-minimization should be a priority for both the engineering consultant and the stormwater engineer/planner. Generally, the engineering consultant, who has an interest in developing the lowest cost plan for his client, will perform the cost analyses.

- Acceptable Future Maintenance Burden

BMPs can only continue to be effective if they are regularly inspected and maintained. Maintenance tasks for most BMPs include both low cost routine tasks and more expensive non-routine tasks, such as rehabilitation or sediment removal. Maintenance costs for BMPs can be significant. Over a twenty-year period they will often equal or exceed the initial construction cost. The cost and responsibility for maintenance is normally passed on to future residents or the public sector, and not the original developer.

Consequently, the storm water engineer/planner must clearly vest responsibility for maintenance: how and when tasks will be performed, how it is to be financed, and who will inspect the BMP. In most cases, the maintenance burden of a BMP is determined by the initial design and construction of the facility. The engineering consultant and storm water engineer/planners should work together in this phase to anticipate future
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maintenance problems at the site and develop designs that can alleviate them. If maintenance requirements are addressed during the design and construction phases, both the scope and cost of future maintenance activities can be sharply reduced.

- Neutral Impact on the Environment

Urban BMPs nearly always represent a significant modification to both the natural environment and the adjacent community. As such, BMPs can either enhance or degrade the amenity values that both provide. Comparatively small investments in design, landscaping, and maintenance can make a BMP an attractive feature of a community, or at least an unobtrusive one. Without such efforts, many BMPs become “dead space” in a development; that is, they appear unsightly or discordant, provide no habitat or recreational opportunities, and are plagued by nuisance problems. The importance of enhancing the amenity values of a BMP cannot be overemphasized, as resident perceptions about a BMP are generally formed by the amenities they do or do not provide. These perceptions, in turn, strongly influence their acceptance of and support for these BMPs, which is critical if these same residents are expected to pay for maintenance.

3.3.3 – Best Management Practices Screening Tools

Schueler (1987) provides very effective tools to assist the engineer/planner in choosing the best BMP for a given site. These screening tools can be used to identify which BMP options: 1) are feasible given a site’s physical constraints; 2) are appropriate for achieving the desired storm water management objectives; 3) are appropriate for achieving the desired water quality management objectives; and 4) provide specific natural or human amenities. We have not attempted to replicate Schueler’s work here. However, to illustrate the utility of these screening tools his discussions of storm water and pollutant removal screening is presented below. Further, more detailed information about these screening tools is available in Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs (see Appendix).

3.3.3.1 - Screening BMPs Based on Stormwater Benefits Provided

The objective of stormwater management is to attempt to reproduce the predevelopment hydrology of the site. This can be accomplished through a combination of peak discharge control, volume control, groundwater recharge, and stream bank erosion control. Very few BMP options can achieve the full spectrum of desirable stormwater benefits. This is because a different flow condition and/or frequency must be controlled to provide each benefit. As an example, the designer needs to control very large, infrequent storms to attain peak discharge control, yet must concentrate on much smaller and more frequent storms to provide groundwater recharge.

The design variations for infiltration BMPs deserve some additional explanation. The term “exfiltration” refers to the amount of runoff that is effectively infiltrated through the soil profile. Full exfiltration occurs when all of the runoff delivered to an infiltration BMP is completely exfiltrated back into the soil. As one might imagine, full exfiltration
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BMPs need to be very large in volume. Partial exfiltration BMPs only divert a fixed volume of runoff into the soil (the remaining runoff is conveyed through the BMP, but may be detained long enough to provide some peak discharge control). In water quality exfiltration BMPs, a small, fixed runoff volume is diverted into the soil. The remaining runoff is conveyed away, and is not detained long enough to provide any peak discharge control.

- Peak Discharge Control

Peak discharge control is often required for one or more design storms under local regulations. Schueler (1987) correctly notes that, historically the most commonly used design storm was the 2-year storm. This storm was considered a reasonable approximation of the bankfull flood (i.e., a flood that fills a stream to the top of its banks). However, more recent research suggests that the 1-year or 1.5-year storms may be more appropriate design targets for stormwater management facilities designed to control the bankfull flood in urban watersheds. Some jurisdictions also require control of the 10- or 100-year design storms, particularly if there is unprotected development further downstream on the floodplain. Even if a BMP does not control these larger design storms, they must still be designed to safely pass them through (e.g., using an emergency spillway or an overflow pipe).

Peak discharge control is accomplished in pond BMPs by temporarily detaining a large portion of the runoff volume for the design storm, and then releasing it at the lower predevelopment rate. Using a vertical riser with a control orifice or weir provides detention. A single pond can control a series of design storms by using a series of orifices and weirs at progressively higher elevations. In general, pond BMPs are an excellent means of providing peak discharge control.

Infiltration BMPs have a more limited capacity to control peak discharges. Full exfiltration systems are normally only capable of controlling peak discharges for the 2-year storm (in rare cases, the 10-year storm). Most partial exfiltration systems can control the 2- and 10-year storms, and pass the 100-year storm. Water quality exfiltration systems, water quality inlets, swales and filter strips normally have little or no capacity to control peak discharges.

- Volume Control

Infiltration BMPs can help to reduce the increased runoff volumes generated from small and intermediate storms, since they divert a significant fraction of storm runoff volume back into the soil. Pond BMPs, on the other hand, are ineffective in reducing runoff volume. Ponds only detain or retain runoff for a short period of time before releasing it downstream.
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- **Groundwater Recharge**

Infiltration BMPs are an excellent means of providing for groundwater recharge, which is often lost as a consequence of watershed development. “Natural” levels of groundwater recharge can be duplicated by diverting a significant fraction of the runoff from frequent small and moderate storms back into the soils. Most exfiltration designs recharge the groundwater sufficiently to sustain normal low flows in headwater streams during the critical summer months. Vegetative BMPs, such as grassed swales and filter strips, have a more limited capability, and pond BMPs generally have little or none.

- **Stream Bank Erosion Control**

All BMPs that control peak discharges for the 2-year storm provide some degree of stream bank erosion control. However, the 2-year storm creates an erosive condition in natural channels. To adequately protect downstream channels, it is necessary to control both the post-development increase in the 2-year flood and the increased frequency with which it occurs. This normally entails the control of storm events less than the 2-year storm and greater than the mean storm (i.e., the 1 to 1.5-year storms). It appears that extended detention ponds and some infiltration BMPs can effectively reduce the frequency with which bankfull flooding occurs, if sized properly. Wet ponds (without extended detention), vegetative BMPs, and water quality inlets show little capability in this regard.

3.3.3.2 - Screening BMPs Based on Pollutant Removal Benefits

The pollutant removal capability of a BMP is primarily governed by three interrelated factors: 1) the removal mechanisms used; 2) the fraction of the annual runoff volume that is effectively treated; and 3) the nature of the urban pollutant being removed. The designer has a limited ability to control the first two factors, but has no influence on the third.

The nature of the pollutant being removed often sets an upper limit on the potential removal rate that can be achieved. From an operational standpoint, pollutants can be said to exist in either particulate or soluble forms, or more commonly, as a mix of both forms. Particulate pollutants, such as sediment and lead, are relatively easy to remove by common BMP removal mechanisms, including settling and filtering. Soluble pollutants, such as nitrate, phosphate, and some trace metals, are much more difficult to remove. Settling and filtering removal mechanisms have little or no effect. Therefore, biological mechanisms, such as uptake by bacteria, algae, rooted aquatic plants or terrestrial vegetation, must be used.

Most BMPs can achieve an extremely high removal rate for suspended sediment and trace metals that exist largely in particulate forms. Much lower removal rates are generally obtained for total phosphorous, oxygen-demanding materials, and total nitrogen, since they typically exist as a mix of particulate and soluble forms.
3.4 – Best Management Practices: Fact Sheets

The following subsections include fact sheets that describe the most common BMPs used for sediment and erosion control during the construction phase of a development and storm water management during the post development phase. More detailed information and the standards and specifications for these, as well as other BMPs, are available in the North Carolina Erosion and Sediment Control Planning and Design Manual and on the USEPA, Office of Water Website (http://www.epa.gov/npdes/menuofbmeps/pub_ed.htm).

3.4.1 – Construction Site Storm Water Runoff Control

During construction, vegetation is removed from a site, exposing the soil. Rainfall erodes bare soil and transports it to nearby streams, where it is deposited. Both temporary and permanent sediment and erosion control BMPs can be used during construction to prevent this erosion. Temporary BMPs are designed to control erosion for days to months and are removed when they are no longer needed. Permanent BMPs are designed to remain in place over the long term. Sediment and erosion control BMPs fall into the following categories:

- **Diversions** are temporary or permanent channels with a dike built across the downslope side to divert runoff around a construction site to a receiving area, such as a sediment basin.

- **Management of overland flow** is achieved through the use of filter fabric fences (silt fence), straw bale dikes, straw mulching, hydroseeding, and sodding. The purpose of these BMPs is to filter sediment from the overland flow and to stabilize the bare soil on the site.

- **Sediment traps and sediment basins** are depressions that are constructed to collect sediment-laden runoff. The size of the drainage area determines whether a sediment trap (for smaller sites) or a sediment basin (for larger sites) will be used. These devices are often converted to permanent stormwater management facilities post-construction.

- Areas of concentrated flow can be stabilized with seeding and mulching, sodding, construction of grassed waterways, and construction of riprap channels. These BMPs are called **permanent drainageway stabilization**.

- Straw bales or filter fabric barriers used to protect existing storm drain inlets from sediment inputs are called **inlet protection**.

- **Dewatering settling basins** are used in situations where water must be pumped from the construction site. These basins provide a place for suspended sediments to settle before the water enters the stream.
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Earth Dikes

*Earth dikes* are temporary berms or ridges of soil, compacted, stabilized and located as to direct water to a desired location. Earth dikes are utilized to:

- direct runoff from the construction area (i.e., sediment-laden water) to a sediment trapping device;
- divert runoff from upslope (i.e., clean water) away from disturbed areas.

It is important that diversions are properly designed, constructed and maintained since they concentrate water flow and increase erosion potential. Frequent inspection and timely maintenance are essential to the proper functioning of diversions. The least costly method for building diversions is to excavate a channel and form a dike on the downhill side with the spoil.

Diversions that are to function longer than one month should be seeded and mulched immediately after they are constructed. If design velocities will exceed 2 ft/sec, a channel liner should be utilized to prevent erosion. The North Carolina Erosion and Sediment Control Planning and Design Manual includes details for the design, construction and maintenance of diversions.

Source: North Carolina Erosion and Sediment Control Planning and Design Manual
An earth dike diversion is shown here directing construction site runoff to a sediment trap (foreground).
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Silt Fence

*Silt fence* is a temporary permeable barrier of woven geotextile fabric used to intercept, reduce velocity and filter surface runoff from disturbed areas on construction sites. Silt fences filter sediment from runoff so that deposition of transported sediment can occur. Silt fences are effective for intercepting sheet flow only.

The potential for undercutting, overtopping, or collapsing can be minimized by restricting the drainage area and locating the fence so that water depth does not exceed 1.5 feet at any point. They should not be used as velocity checks in ditches or swales, or placed where they will intercept concentrated flow.

Check silt fences after each significant rainfall, remove accumulated sediment, and make repairs promptly. The design life of silt fence is 6 months or less. The North Carolina Erosion and Sediment Control Planning and Design Manual includes details for the design, construction and maintenance of silt fences.

Source: North Carolina Erosion and Sediment Control Planning and Design Manual
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Source: North Carolina Erosion and Sediment Control Planning and Design Manual
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Super Silt Fence

Super silt fence is a temporary barrier of Geotextile Class F over chain link fence used to intercept sediment-laden runoff from small drainage areas. Super silt fence reduces runoff velocity and allows deposition of transported sediment to occur. Super silt fence provides an effective barrier that can collect and holds debris and soil, preventing that material from entering sensitive areas, such as woods, wetlands and streams. It is particularly useful for areas where installation of an earth dike would damage sensitive areas.

Super silt fence should be placed as close to the contour as possible. No section should exceed a grade of 5% for a distance more than 50 feet.

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DETAIL 33 - SUPER SILT FENCE

NOTE: FENCE POST SPACING SHALL NOT EXCEED 10' CENTER TO CENTER

GROUND SURFACE

FLOW

2½" DIAMETER GALVANIZED OR ALUMINUM POSTS

CHAIN LINK FENCE WITH 1 LAYER OF FILTER CLOTH OVER

10' MAXIMUM

16" MINIMUM

33" MINIMUM

36" MINIMUM

8" MINIMUM

FLOW

CHAIN LINK FENCING

FILTER CLOTH

EMBED FILTER CLOTH 8" MINIMUM INTO GROUND

STANDARD SYMBOL

SSF

Construction Specifications

Fencing shall be 42 inches in height and constructed in accordance with the latest Maryland State Highway Details for Chain Link Fencing. The specification for a 6 foot fence shall be used, substituting 42 inch fabric and 6 foot length posts.

1. The poles do not need to set in concrete.

2. Chain link fence shall be fastened securely to the fence posts with wire ties or staples.

3. Filter cloth shall be fastened securely to the chain link fence with ties spaced every 24" at the top and mid section.

4. Filter cloth shall be embedded a minimum of 6" into the ground.

5. When two sections of filter cloth adjoin each other, they shall be overlapped by 6" and folded.

6. Maintenance shall be performed as needed and silt buildups removed when "bulges" develop in the silt fence.
Slope Drains

A *slope drain* is a temporary pipe that is installed to convey surface runoff down the face of an unstabilized slope. It is used to minimize erosion on the face of the slope. Flexible pipe is preferred. Slope drains are usually installed in conjunction with earth dikes. The dikes direct surface runoff to the slope drain, which conveys concentrated flow down the face of the slope. The North Carolina Erosion and Sediment Control Planning and Design Manual includes details for the design, construction and maintenance of slope drains.

Source: North Carolina Erosion and Sediment Control Planning and Design Manual
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Source: North Carolina Erosion and Sediment Control Planning and Design Manual
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Sediment Traps

A *sediment trap* is a temporary sediment control device formed by excavation and/or construction of an embankment across a drainage swale to form a small sedimentation pool during rainfall events. Sediment traps are installed at points of discharge from disturbed construction areas, such as diversions, channels, slope drains and other points where sediment-laden water is concentrated. The contributory drainage area should be restricted to 5 acres or less.

The outlet spillway is constructed of stone and provides drainage for the sedimentation pool. The inside face of the outlet section is lined with gravel to slow the release of drainage water and improve sediment trap efficiency. The North Carolina Erosion and Sediment Control Planning and Design Manual includes details for the design, construction and maintenance of sediment traps.
Source: North Carolina Erosion and Sediment Control Planning and Design Manual
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Sediment Basins

A *sediment basin* is a temporary sediment control device formed by excavation and/or construction of an embankment and installation of an approved outlet structure used to intercept sediment-laden runoff and retain the sediment. Sediment basins are installed at points of discharge from disturbed construction areas.

Storage capacity is based on the contributory drainage area. To improve trap efficiency the basin should have the maximum surface area possible, and sediment-laden runoff should enter the basin as far from the outlet as possible. The North Carolina Erosion and Sediment Control Planning and Design Manual includes details for the design, construction and maintenance of sediment basins.

Source: North Carolina Erosion and Sediment Control Planning and Design Manual
Source: North Carolina Erosion and Sediment Control Planning and Design Manual
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Temporary Stream Crossings

A temporary stream crossing is a structure placed across a waterway to provide access for construction purposes for a period of less than one year. Temporary crossings should not be used to maintain traffic for the general public.

Temporary stream crossings provide a safe pollution free access across a waterway for construction equipment by establishing minimum standards and specifications for the design, construction, maintenance, and removal of the structures. These structures are utilized to prevent construction equipment from damaging the waterway, blocking fish migration, and tracking sediment and other pollutants into the waterway. Stream crossings are of three general types: bridges, culverts, and fords.

A temporary access bridge is a structure made of wood, metal, or other materials, which provide access across a stream. Bridges are the preferred method for crossing the waterway. Generally bridges cause the least disturbance to the streambed and banks when compared with other waterway crossing methods. Bridges should be constructed to span the entire channel. Channel widths exceeding 8 feet will require construction of a footing, pier, or bridge support.

A temporary access culvert is a structure consisting of a section or sections of circular pipe, pipe arches, or oval pipes of reinforced concrete, corrugated metal, or structural plate, which is used to convey flowing water through the crossing. Temporary culverts are used where:

- the channel is too wide for normal bridge construction,
- anticipated loading may prove unsafe for single span bridges, or
- access is not needed from bank to bank.

A temporary access ford is made of stabilizing material, such as rock. Fords should only be used where crossings are infrequent. They are especially adapted for crossing wide, shallow waterways.

The North Carolina Erosion and Sediment Control Planning and Design Manual includes details for the design, construction and maintenance of temporary bridges, culverts and fords.
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Detail Temporary Ford Crossing

Source: North Carolina Erosion and Sediment Control Planning and Design Manual

3.4.2 – Post Construction Storm Water Management Practices
Historically controlling storm water runoff from developed areas focused on reducing the potential for downstream flooding. This was generally achieved by controlling (i.e., detaining) the peak discharge calculated for a given design storm (e.g., 50-yr or 100-yr storms) to predevelopment levels. Over time the focus has broadened to include control of smaller more frequent storms (e.g., 1.5-yr or 2-yr) that cause streambank and streambed erosion and degrade aquatic habitat. Methods for controlling these storms have included infiltration practices designed to get the excess water back into the ground and structures (e.g., ponds) that detain the peak discharge calculated for these small-intermediate storms and release the excess water into the stream over an extended period of time.

Increasing emphasis has been placed on the removal of pollutants and improving the water quality of storm water runoff conveyed to streams. In fact, the USEPA’s Phase II Storm Water Management Regulations require the implementation of best management practices that provide water quality treatment for urban runoff. A variety of new storm water management practices have been developed and some existing practices have been modified to provide moderate-very good pollutant removal capability. Best management practices vary considerably in the pollutant removal mechanisms they employ as well as their pollutant removal efficiency. Engineers can enhance pollutant removal rates by increasing the volume of runoff treated, by adding extra design features, or by using a variety of practices in tandem.
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Infiltration Trenches

An infiltration trench is a shallow, excavated trench that has been backfilled with stone to allow for the temporary storage of runoff. Stormwater runoff diverted into the trench gradually exfiltrates from the bottom of the trench into the subsoil and eventually into the water table.

Source: Schueler, 1987

Advantages:

- Infiltration practices best replicate the pre-development hydrology, increasing baseflow and reducing the frequency of bankfull flows.
- Infiltration trenches have a high capability for removing fine particulate pollutants, and a moderate capability for removing soluble pollutants.
- They are easy to fit into the margins, perimeters, and unutilized areas of development sites.
- They are cost effective and practical for smaller sites.

Disadvantages:

- Infiltration trenches are infeasible in many locations due to incompatible soils, high water table, steep slopes, high bedrock.
- Pretreatment of stormwater is required to remove coarse particulate pollutants.
- These facilities require significant maintenance and may have short life spans.
- They are not practical or economical on sites larger than 10 acres.
- There is a small but possible risk of groundwater contamination.
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Infiltration trench managing runoff from commercial properties at an business park
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Infiltration Basins

An infiltration basin is a stormwater impoundment that detains stormwater runoff and returns it to the ground by allowing runoff to infiltrate gradually through the soils of the bed and sides of the basin.

Source: Schueler, 1987

Advantages:
- Infiltration practices best replicate the pre-development hydrology, increasing baseflow and reducing the frequency of bankfull flows.
- Infiltration basins remove both soluble and fine particulate pollutants.
- Infiltration basins can be designed to control peak discharges from relatively large design storms.
- Infiltration basins can serve as sediment basins during construction.
- The thermal impacts associated with retention ponds are not a factor with infiltration basins.
- They are relatively cost-effective as compared to detention ponds.

Disadvantages:
- Infiltration basins are infeasible in many locations due to incompatible soils, high water table, steep slopes, high bedrock.
- Pretreatment of stormwater is required to remove coarse particulate pollutants.
- These facilities require significant maintenance and have short life spans.
- Infiltration basins have the highest failure rate of any stormwater BMP.
STREAM MANAGEMENT

Sand Filters and Peat-Sand Filters

A sand filter is a technique for treating stormwater whereby the runoff is diverted into a self-contained bed of sand. The runoff is then strained through the sand, collected in underground pipes and returned back to the stream channel. Sand filters can be enhanced with the use of peat, limestone, gravel, and/or topsoil and may have a grass cover.

**Advantages:**

- Sand filter removal rates are high for sediment and trace metals, and moderate for nutrients and pathogens.
- Sand filters that are enhanced with the mentioned additional are significantly more effective at pollutant removal.
- Groundwater recharge and protection are significant benefits.
- Sand filters are adaptable to most development sites.
- They have excellent longevity and relatively simple maintenance requirements.

**Disadvantages:**

- Sand filters provide water quality management only, no quantity management benefits.
- Require frequent, although simple maintenance.
- More costly than other practices of similar scope.

Source: Claytor and Schueler, 1996

Peat-Sand Filter
SECTION THREE

Sand Filter

Source: Claytor and Schueler, 1996
**STREAM MANAGEMENT**

**Grassed Swales**

A *grassed swale* is a channel lined with grass or erosion-resistant plants that is constructed for the stable conveyance of stormwater. Grassed swales use the ability of vegetation to reduce the flow velocities associated with urban runoff, allowing pollutants to be removed by filtration through the vegetation and infiltration through soil.

Grassed swales have a low capability of removing urban pollutants, except when site conditions include extremely gentle slopes, permeable and uncompacted soils, installation of check dams and maintenance of dense grass turf. If constructed under these conditions, pollutants can be removed through the filtering action of the grass, by deposition in low velocity areas, and by exfiltration through the soil layer. Moderate removal of particulate pollutants, and low removal of soluble pollutants can be expected under these optimal conditions.

*Source: Schueler, 1987*

**Advantages:**
- Grassed swales can be used as a stormwater conveyance system in place of conventional curb and gutter, thereby decreasing impervious surface area.
- They are applicable wherever the local conditions favor the growth of dense vegetation.
- Grassed swales are less expensive than curb and gutter.
- They have significant longevity and require minimal maintenance.

**Disadvantages:**
- Grassed swales are not intended to provide stormwater quantity runoff and have only limited ability to provide pollutant removal.
- Applicability of grassed swales is limited to residential areas and highway medians. They are not suitable for highly urbanized situations.
- They must be used in conjunction with other BMPs for the greatest benefit to be realized.
SECTION THREE

Filter Strips

A filter strip is a vegetated section of land designed to accept runoff as overland flow from adjacent developed sites. They may adopt any natural vegetated form, from grassy meadow to small forest. Level spreaders can be incorporated into the design of the vegetated filter strips to increase their effectiveness by distributing runoff over the full length of the strip.

Filter strips have a low to moderate capability of removing pollutants in urban runoff, and exhibit higher removal rates for particulate rather than soluble pollutants. Removal mechanisms include filtering (through vegetation and/or soil), settling/deposition and uptake by vegetation. Forested buffer strips appear to have a higher removal capability than grass buffer strips. However, length, slope, and soil permeability are critical factors that influence the effectiveness of any strip. Another practical design problem is how to prevent runoff from concentrating and thereby “short-circuiting” the strip. Special design modifications and regular maintenance are needed to provide optimal removal rates in the field.

Source: Schueler, 1987

Advantages:

- Filter strips can effectively reduce particulate pollutants where runoff volume is low to moderate.
- Filter strips can prevent streambank erosion.
- If properly maintained, filter strips have good longevity.
- Filter strips are low cost and low maintenance.

Disadvantages:

- Filter strips are not effective on slopes.
- Runoff must arrive at the filter strip as sheet flow in order for the filter strip to be effective.
- Filter strips have limited feasibility in urbanized areas where runoff velocities are high and flow is concentrated.
A constructed wetland is a shallow pool excavated on non-wetland sites as part of the stormwater collection and treatment system. The conditions in these pools are suitable for the growth of marsh plants. Stormwater wetlands are designed to maximize pollutant removal through wetland uptake, retention and settling. They are essentially a type of wet pond with greater emphasis placed on vegetation and depth/area considerations. This type of constructed wetland differs from wetlands constructed for mitigation purposes in that the former do not replicate all the ecological functions of natural wetlands.

**Advantages:**
- Constructed wetlands have high pollutant removal and sediment removal capability.
- Wetlands can be designed to provide wildlife habitat.
- Wetlands can be used at most development sites.

**Disadvantages:**
- Wetlands must be constructed to ensure adequate hydrology to support the wetland plants.
- Cost is higher than for wet ponds of similar size.
- Maintenance is initially greater than for other types of ponds.
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Constructed wetlands in a residential subdivision of condominiums and apartments

Source: R. Powell, 1994

Constructed wetlands in a commercial-office park

Source: R. Powell, 1999
STREAM MANAGEMENT

Retention (Wet) Pond

A wet pond is a depression constructed by excavation and embankment to temporarily store stormwater runoff at a site. After a runoff event, pond overflow is released at a controlled rate by an outlet device designed to release flows at various peak rates and elevations until the design elevation of the pool is reached. Wet ponds maintain a permanent pool of water. Wet ponds have a moderate to high capability of removing most urban pollutants, depending on how large the volume of the permanent pool is in relation to the runoff produced from the surrounding watershed. Wet ponds utilize both settling and biological uptake, and are capable of removing both particulate and soluble pollutants. In addition to increasing the volume of the permanent pool, wet pond removal rates can be enhanced by establishing marshes around the perimeter, and by adjusting the geometry of the pond.

Source: Schueler, 1987

Advantages:

- Wet ponds provide moderate to high removal of particulate and soluble pollutants.
- These facilities have long life spans, especially when properly maintained.
- Wet ponds can be designed to be esthetically pleasing amenities.
- Wet ponds can provide wildlife habitat.
- Maintenance requirements are moderate.

Disadvantages:

- If improperly sited, wet ponds can cause thermal pollution and trophic shifts to the downstream watercourses.
- Wet ponds cause the loss of in-stream habitat or wetlands if they are built in these resources.
- Wet ponds cost significantly more than dry ponds.
SECTION THREE

Schematic Design of an Enhanced Wet Pond System


Wet pond in a residential subdivision of apartments

Source: R. Powell, 1989
STREAM MANAGEMENT

Extended Detention Pond

A conventional extended detention pond stores stormwater runoff up to 24 hours after a storm and releases it at a controlled rate by use of a fixed outlet. Standard extended detention ponds rely primarily on settling to remove pollutants. They are designed not to have permanent standing water and are usually dry between storm events. Depending on how much and how long runoff is detained, it is possible to achieve moderate or high removal rates for particulate pollutants that are relatively easy to settle. Removal rates for most soluble pollutants are low for dry extended detention ponds.

Enhanced extended detention are designed to prevent clogging and resuspension of settled material. These facilities provide greater flexibility for detention times by incorporating a plunge pool at the inlet, a micro-pool at the outlet, and an adjustable reverse-sloped pipe as the control device. Biological removal mechanisms (e.g., establishing a shallow marsh in the bottom stage of an extended detention pond) or using an extended detention pond in combination with a wet pond provides greatly enhanced pollutant removal rates.

Source: Schueler, 1987

Advantages:

- ED ponds are an adaptable BMP with widespread application.
- ED ponds provide excellent protection from downstream channel erosion.
- Enhanced ED ponds provide good pollutant removal rates.
- If properly landscaped, ED ponds can provide wildlife habitat.

Disadvantages:

- ED ponds are variably effective in providing stormwater quality management, especially removal of soluble pollutants.
- If improperly maintained, ED ponds can become nuisances by becoming clogged with sediments.
- Many ED ponds do not operate as intended.
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Cross-section View of a Standard ED Pond System Design


Schematic Design of a Dry In-filter System

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Schematic Design of an Enhanced Wet ED Pond


Schematic Design of a Shallow ED Marsh System

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Source: R. Powell, 1992

Shallow marsh extended detention pond in a residential subdivision with townhouses
STREAM MANAGEMENT

Source: R. Powell, 1997

Shallow marsh extended detention pond managing runoff from a highway.
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Water Quality Inlet

A water quality inlet or oil and grit separator is an underground concrete vault with one to three chambers. These structures are designed to remove sediments and hydrocarbons from stormwater runoff. Current designs of water quality inlets appear to have low to moderate removal rates for particulate pollutants, and low to zero rates for soluble pollutants. Water quality inlets rely primarily on settling for removal, and given their small storage capacity and brief residence times, it is likely that only coarse grit, sand, and some silts will be trapped. Inlets do show some promise in removing hydrocarbons, such as oil, gas, and grease, from runoff. Due to resuspension problems, however, pollutant removal can only be attained in water quality inlets if they are cleaned regularly.

Source: Schueler, 1987

Advantages:

- Water quality inlets can trap oil, grease, trash and debris, preventing them from entering downstream waters.
- Structural failure of these devices is practically nonexistent.

Disadvantages:

- Water quality inlets have limited pollutant removal capability.
- The application of these facilities is limited to small, highly impervious drainage areas such as parking lots.
- Water quality inlets are very expensive.
- Maintenance is burdensome.
Bioretention

*Bioretention* areas are landscaping features adapted to provide on-site treatment of storm water runoff. They are commonly located in parking lot islands, within small pockets of residential land uses, and adjacent to tees, greens, and fairways on golf courses. Surface runoff is directed into shallow, landscaped depressions. During storms, runoff ponds above the mulch and prepared soil mix in the system, filters through these layers where it is collected by a perforated underdrain, and routed to the storm drain system. Runoff from larger storms is generally diverted past the facility to larger storm water facilities (e.g., ponds) or directly to the storm drain system.

**Advantages:**
- Pollutant removal rates are fairly high for nutrients and heavy metals.
- Bioretention areas can be utilized for retrofitting highly developed areas where space is limited.
- Structural failure of these devices is practically nonexistent.

**Disadvantages:**
- Bioretention cannot be used to treat large drainage areas.
- Construction cost is relatively high.
- Maintenance is intense initially, but less over time.
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Riparian Buffer

A riparian buffer is an area of land adjacent to a stream, river, or wetland that is intentionally kept in open space, preferably in undisturbed native vegetation. Riparian buffers may be established by allowing existing native vegetation to remain undisturbed, by allowing the process of natural succession to re-establish the native vegetation, or by planting the desired vegetation. The width of riparian buffers and their allowed uses vary according to specific local regulatory requirements, where applicable. If riparian buffers are voluntarily established, their characteristics will vary to suit the purpose of the landowner.

Riparian buffers should be a standard component of site design criteria for any new development, regardless of the type of development (i.e., residential, commercial, etc.) proposed or the watershed in which it will be located. To be effective performance criteria for such resource protection areas should be reviewed and enforced at all stages of the development process.

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**Advantages:**

- Streamside trees physically anchor streambanks, reducing the potential for in-stream erosion.
- Riparian buffers filter sediments, nutrients, and other pollutants from overland runoff.
- Infiltration of runoff and groundwater recharge are maximized in these areas.
- Flood waters are slowed and detained, reducing flood damage.
- Forested buffers provide terrestrial wildlife habitat.
- Streamside trees improve aquatic habitat, providing shade and in-stream cover, increasing dissolved oxygen, and providing food for aquatic invertebrates.
- Riparian buffers provide recreational opportunities.
- Riparian buffers are low cost and easy to implement.

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**Disadvantages:**

- Riparian buffers are less effective in areas where shallow sheet flow cannot be maintained into and across the buffer.
- Storage capacity for nutrients and sediments may be limited in some situations.
- Where pollutant loads are high, slopes are steep, or erosion is severe, other BMPs may be required upslope from the buffer for it to be effective.
- The buffer’s effectiveness may be compromised by human encroachments that cause soil compaction.
- If natural succession is employed as a reforestation method, it may be difficult to control exotic and invasive vegetation.
- Mandatory riparian buffers may be difficult to enforce.
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Riparian Buffer Width influences pollutant filtering, shading and habitat functions (FISRWG, 1998).

Schematic of a Three Zone Riparian Forest Buffer System (USEPA, 1995)
**STREAM MANAGEMENT**

<table>
<thead>
<tr>
<th>Best Management Practice</th>
<th>Cost</th>
<th>Maintenance</th>
<th>TSS</th>
<th>Phosphorus</th>
<th>Nitrogen</th>
<th>Metals</th>
<th>Bacteria</th>
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<tr>
<td>Bioretention</td>
<td>Expensive</td>
<td>Intense Initially, Less over time</td>
<td>NA</td>
<td>65 – 85</td>
<td>49 – 92 *</td>
<td>43 – 97</td>
<td>NA</td>
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<tr>
<td>Grassed Swale</td>
<td>Moderate – Low</td>
<td>Low</td>
<td>81</td>
<td>29</td>
<td>38</td>
<td>14 – 55</td>
<td>-50</td>
</tr>
<tr>
<td>Infiltration Basin</td>
<td>Cost Effective</td>
<td>High to maintain effectiveness</td>
<td>75</td>
<td>60 – 70</td>
<td>55 – 60</td>
<td>85 – 90</td>
<td>90</td>
</tr>
<tr>
<td>Infiltration Trench</td>
<td>Somewhat Expensive</td>
<td>Very High, Moderate with pretreatment</td>
<td>75</td>
<td>60 - 70</td>
<td>55 – 60</td>
<td>85 – 90</td>
<td>90</td>
</tr>
<tr>
<td>Riparian Buffers</td>
<td>Low, increase property values</td>
<td>Low</td>
<td>63 – 89**</td>
<td>8 – 74**</td>
<td>17 – 99**</td>
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<td>NA</td>
</tr>
<tr>
<td>Sand and Organic Filters</td>
<td>Moderate – High</td>
<td>Very High, Moderate with pretreatment</td>
<td>66 – 98***</td>
<td>4 – 84***</td>
<td>44 – 47***</td>
<td>26 – 100***</td>
<td>55</td>
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<tr>
<td>Storm Water Wetland</td>
<td>Cost Effective</td>
<td>Moderate</td>
<td>71 – 83***</td>
<td>39 – 64***</td>
<td>19 – 56***</td>
<td>21 – 85**</td>
<td>78</td>
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<tr>
<td>Water Quality Inlets</td>
<td>Moderate – High</td>
<td>Very High</td>
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<td>17</td>
<td>5</td>
<td>17 – 24</td>
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<tr>
<td>Wet Pond</td>
<td>Cost Effective</td>
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<td>67</td>
<td>48</td>
<td>31</td>
<td>24 – 73</td>
<td>65</td>
</tr>
</tbody>
</table>

Table 3.4.1   Comparison of Post-Construction Best Management Practices

Notes: NA – Not Available; * varies with chemical form; ** varies with filter/buffer width; *** varies with design components
3.5 – Design and Construction Guidelines for Infrastructure Projects

The purpose of these guidelines is to provide engineering consultants and public works engineers a standardized approach for evaluating the design and construction of private or public infrastructure projects for avoidance and minimization of impacts on streams, wetlands, floodplains, terrestrial and aquatic wildlife and their habitats, and maintenance of hydrologic processes and water quality.

3.5.1 - Roads, Bridges, and Culverts

3.5.1.1 - General

- Road crossings, including all attendant features, both temporary and permanent, that are part of a complete project for crossing a stream, wetland, or floodplain, should be located to avoid or minimize clearing of riparian forest, grading on steep slopes and/or erodible soils adjacent to streams and wetlands, filling streams and wetlands, and altering stream channels.
- Alternative means of access and alternative road alignments should be explored to determine whether another option would cause less adverse impact.

3.5.1.2 - Design

- Road widths should be the minimum required by the Department of Public Works.
- Open section roads with grassed side swales are preferred over closed section roads with curbs, gutters, and storm drains, and should be used wherever permitted by the Department of Public Works.
- Bridges and culverts should be designed to minimize changes in the bankfull channel geometry (width, depth), as well as channel gradient, meander pattern, substrate, and channel hydraulics.
- Bridges and culverts should be designed to accommodate the bankfull channel. Splitting the bankfull flow with bridge piers or multiple culverts should be avoided.
- If the bankfull channel is too large to avoid splitting the flow through multiple structures, a multi-level or tiered design approach should be used. This approach includes a primary structure set at the invert of the existing channel that conveys the low flow (i.e., baseflow) and a portion of the bankfull flow. A second structure set at a higher elevation conveys the remaining bankfull flow. In addition, auxiliary structures should supplement the main structures in order to drain the floodplain (i.e., convey flood flows through the roadway).
- Bridges and culverts should be designed to allow fish passage.
- Upstream and downstream streambank protection may be required. The length of erosion protection required will depend upon the velocity of stream flow and the requirements of the Department of Public Works.
STREAM MANAGEMENT

3.5.1.3 - Construction

- Sediment and erosion control practices must be installed in accordance with the requirements of the Unified Development Ordinances.
- Stream diversions must be designed and constructed to minimize alterations to the stream channel and to limit clearing of streambank vegetation.
- Staging and stockpile areas should be located outside of wetlands, floodplains, and riparian forests.
- Clean upland fill materials should be used for the roadway, shoulder bedding, and side slopes. Side slopes should extend on a 2:1 or flatter slope, and should be stabilized within 15 days post-construction.
- Temporary access roads should be constructed such that clearing of vegetation is the minimum needed for construction equipment and that normal downstream water flow are not impeded. Wetland and stream bottom surfaces should be restored and the disturbed areas replanted with native vegetation.

3.5.2 - Storm Drainage

3.5.2.1 - General

- The objective of storm drainage projects should be to reproduce to the extent practical the predevelopment hydrologic conditions through:
  - limiting the amount of forest clearing on a site;
  - minimizing the amount of impervious area on a site; and
  - utilizing open section roads, vegetated swales, and infiltration practices.

- Where required, closed stormwater conveyance systems should be designed to serve smaller drainage areas and have multiple outfalls directed to suitable locations.
- Storm drain outfalls should be designed to minimize erosion of slopes, sedimentation of watercourses and wetlands, and destabilization of stream banks.

3.5.2.2 - Design

- Closed storm drainage systems should be designed to avoid collecting and concentrating large volumes of runoff. They should reproduce to the extent practical the natural drainage patterns and hydrologic processes.
- The preferred location for a standard storm drain outfall is relatively flat terrain (<5% slope) and outside of wetlands and riparian forests.
- Sites with extensive areas of steep slopes and erodible soils may not have a suitable outfall location proximate to the development area. Under these conditions, it may be preferable to modify the standard outfall design to make it suitable for the available location rather than to clear and grade on slopes to reach flatter terrain. The use of level spreaders is encouraged.
- All outfalls should be designed to reduce discharge velocities to those suitable for the slope, soils, and vegetation below the outfall.
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• Water quality management requirements may necessitate that the standard outfall structure be modified to provide additional detention and increased infiltration.
• Public systems constructed to reduce property flooding may impact watercourses and wetlands. These projects should incorporate and maintain the natural system to the extent possible, avoiding channelization, filling wetlands and floodplains, and disturbance of riparian areas.

3.5.3 - Stormwater Management

3.5.3.1 - General

• Stormwater management facilities should not be located in watercourses, wetlands, floodplains, or riparian forests, except where the appropriate reviewing agency has determined that the physical constraints of the development site preclude adherence to this restriction, and/or that the proposed facility is consistent with the following objectives for watershed protection:

  • Reproduction of pre-development hydrologic conditions as nearly as possible through peak discharge control, volume control, groundwater recharge, and stream bank erosion control.
  • Maximum pollutant removal capability, concentrating on the pollutant(s) targeted for removal in a particular watershed.
  • Selection of the most feasible stormwater management practice(s) given the physical constraints of the site, such as soil permeability, slope, depth to the water table or to bedrock, land consumption, and proximity to site improvements.
  • Cost benefit.
  • Future maintenance requirements for the facility.
  • Neutral or minimal impact on the various components of the watershed ecosystem (e.g., material and energy flow, habitat and niche functions, and trophic structure and dynamics). These factors should be considered:
    • maintenance of stream base flow
    • reduction of the potential for increased sediment loads to the stream by maintaining relatively stable streambanks
    • maintenance of particulate organic material inputs, processing efficiency and downstream export
    • maintenance of nutrient recycling in the watershed rather than downstream export
    • maintenance of state water quality standards in the stream
    • maintenance of relatively stable communities of aquatic micro- and macroorganisms
    • avoidance of barriers to upstream and downstream movement of fish and downstream drift of macroinvertebrates
STREAM MANAGEMENT

3.5.3.2 - Design

- When stormwater management facilities are permitted to be located in watercourses, wetlands, floodplains, and/or riparian forests, disturbance to these areas for construction of the facility should be limited to that necessary for placement of the embankment, emergency spillway, and inlet and outlet structures.
- Ponds with a permanent pool of water should not be constructed in watercourses or wetlands where there exists a population of temperature-sensitive fish (such as trout).
- Mitigation of adverse impacts resulting from the construction of stormwater management facilities in watercourses, wetlands, floodplains, or riparian forests should be required.

3.5.4 - Utilities

3.5.4.1 - General

- The installation of utilities (e.g., sanitary sewers, water mains, gas pipelines, electrical and telecommunication lines) is generally considered a temporary disturbance. This type of activity involves the clearing of the right-of-way, cutting or plowing of a trench, laying of the specific utility line, backfilling the trench with the previously excavated material, and stabilizing the area with vegetation or riprap. However, poorly located lines can become long-term maintenance problems that are costly to repair and that require additional alteration of natural systems to protect. Sanitary sewer lines and gas pipelines are routinely exposed as streams downcut and erode laterally. Traditional repair techniques include gabion protection or concrete encasement.
- Vegetation in a right-of-way is routinely maintained in early successional stages, preventing re-establishment of forest canopy along streams.
- Pumping stations, gas transfer stations, and electrical substations may be located in wetlands and floodplains with permanent impacts to these areas.
- Trenching through wetlands can result in permanent changes to surface and subsurface hydrology.
- These impacts can be avoided and/or minimized through environmentally sensitive design and strict construction requirements.

3.5.4.2 - Design

- Disturbance of wetlands and streams should be avoided or minimized through the use of practical alternatives such as designing the utility line in a proposed or existing roadway, or using an existing right-of-way. Where this is not feasible, locating the utility line parallel to the outer edge of the wetland, along the toe of an adjacent slope, or along the outer edge of riparian forest is preferred. A minimum 50-foot undisturbed buffer should be maintained between watercourses and the edge of the utility right-of-way.
- Where stream crossings are required, they should be perpendicular to the channel to minimize clearing of the stream bank vegetation and to reduce the linear feet of
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stream bank that must be cut. The elevation of the top of the utility line should be a minimum of 4 feet below the streambed. Crossings should be located in segments with low, well-armored banks and avoided in areas with steep, erodible banks that are easily destabilized and difficult to repair.

- Temporary construction access roads should be located in accordance with the above guidelines for roads, bridges, and culverts. The clearing of vegetation should be limited to the minimum width needed for the construction equipment. Normal downstream water flows should not be impeded.
- Maintenance access roads should be located along the right-of-way. A 20-foot-wide maximum access pathway may be maintained in herbaceous vegetation. Any permanent roads located in wetlands should be constructed at-grade.

3.5.4.3 - Construction

- Sediment and erosion control practices must be installed in accordance with the requirements of the Unified Development Ordinances.
- The top two feet of excavated soil should be stockpiled and replaced after the trench is backfilled.
- All fill and construction material not used in the project should be removed to an upland disposal area.
- The post-construction bottom contours of waters and elevations of wetlands should be the same as the original contours and elevations.
- No material should be placed in any location or in any manner so as to impair surface or subsurface water flow into or out of any wetland area.
- Permanent work should not:
  - restrict or impede the movement of aquatic species;
  - restrict or impede the passage of normal or expected high flows;
  - cause the relocation of the water; or
  - cause the impoundment of water.

- Heavy equipment working in wetlands should be placed on mats or be suitably designed to prevent damage to the wetland.
4.0 – Introduction

As we discussed in the *Watersheds and Streams Section*, many streams have been severely impacted by urbanization as a result of changes in their hydrologic and sediment regimes, loss of stream bank vegetation, and channel alterations (e.g., piping, straightening, channelization, and/or revetment with concrete or gabions). Often, water quality has been significantly impaired and natural hydrologic and ecologic functions completely lost. In some urban areas, streams are not much more than drainage ditches that convey storm water, sediment, sewage, and other urban pollutants. Ann Riley (1998) points out that stream restoration projects combined with watershed management and protection can turn a stream from a public nuisance to a public amenity.

She also points out that, although restoration is widely thought of as a means of attempting to bring back the environmental values of an ecosystem after damage has occurred, it should be regarded as a way of avoiding impacts to begin with. In a sense, this approach views stream management and restoration as two sides of the same coin.

In the *Stream Management Section* we discussed stream protection regulations and policies, as well as watershed and stream management measures that are designed to maintain and restore water quality and the natural hydrologic and ecologic functions of streams in developing and urban watersheds. In this section we will focus on alternatives to traditional stream stabilization/restoration approaches. In particular, we will discuss the geomorphic or natural channel design approach to stream restoration. We will also discuss how to plan and implement a restoration project and provide information on recommended techniques for restoring the natural physical attributes of stream channels that are unstable or have been altered.

4.1 – Traditional Approach versus Geomorphic Approach

Traditional programs designed to evaluate stream condition and restore natural functions have been based on two widely different approaches. Biologists, watershed managers, and environmental planners have focused their efforts on water quality monitoring, biological surveys, in-stream habitat improvement projects, and channel stabilization. Many of their restoration projects have involved stream bank stabilization utilizing bioengineering and riparian plantings, and/or installation of structures designed to provide overhead cover or shelter for fish from high velocity flow, capture spawning gravels, or create more varied habitat conditions. Generally little or no thought was given to the effects these improvements might have on flood conveyance, sediment transport processes, or overall channel stability.

Engineers have relied on engineering principles and solutions. For many jurisdictions stream improvement projects are often initiated as a result of complaints about erosion and/or sedimentation or as part of on-going maintenance programs related to public infrastructure. In addition, the development in floodplains, typical of urban areas, can result in localized flooding problems and damage to property, structures or roads. As a consequence, traditional channel improvement efforts have generally been project-
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oriented. Projects are generally focused on repairing eroding stream banks or removing sediment deposits to protect public infrastructure, and channelization and berming of stream reaches to protect properties in the floodplain by preventing floodwaters from overtopping stream banks. The traditional engineering approach has commonly been associated with channels that are relatively straight, wide, trapezoidal channels, with uniform profiles designed to convey all flows (baseflow, bankfull flow, and flood flow). The channel banks are often hardened or armored with riprap, gabions or concrete revetment in an effort to maintain the engineered form, and grade control structures may be installed to maintain bed stability.

The end result of both approaches has seldom meshed and the results often have been unsatisfactory to either group. Unfortunately many of the projects implemented utilizing both approaches have been exercises in treating symptoms rather than effective efforts at finding a cure for what caused and/or was maintaining an unstable situation, poor habitat, or contributing to flooding. These traditional approaches have not been successful over the long-term principally due to their failure to recognize the natural processes that shape and maintain stream channels, interactions between the channel and adjacent riparian areas, and how these processes and interactions are affected by channel and floodplain maintenance practices and land use in the watershed.

Source: R. Powell, 1997

Figure 4-1. Traditional engineered straight, wide, trapezoidal channel, with uniform profile.
Figure 4-2. Traditional engineered channel with rip-rap along banks.

Source: R. Powell, 1997

Figure 4-3. Traditional engineered channels with uniform gabion baskets along banks.

Source: R. Powell, 1988
Over the last two decades there has been an increasing awareness of the importance of considering the effects of fluvial processes on stream channel stability, water quality, and in-stream habitat. *Fluvial Geomorphology* (i.e., the study of landscape features formed by the action of flowing water) was a field of science known chiefly by those who worked for academic institutions or research divisions of federal agencies, until it was introduced to a broader audience of practitioners.

This increased awareness is due in large part to the work of a few hydrologists and geomorphologists, who in the early 1980s began taking the field of geomorphology into an applied phase that other practitioners would come to view as extremely relevant to their work with streams and watersheds. As a result of their work, the *geomorphic* or *natural channel design* approach has evolved as a viable alternative to the traditional approaches to working with streams. Today many watershed and stream assessment programs routinely include geomorphic assessments. Channel stabilization and habitat improvement projects are increasingly based on a geomorphic approach to restoration.

The geomorphic approach is system-oriented and works with, rather than against, the natural processes that shape and maintain stream channels. Channel improvement efforts are focused on: restoring a stable, self-maintaining channel form; reestablishing the critical interactions between the stream and adjacent riparian areas; and restoring the natural functions of floodplains. This approach also recognizes that natural streams are composed of three distinct channels, that include: a baseflow or low flow channel, which provides habitat for aquatic organisms; a bankfull channel, which is critical for maintaining sediment transport; and a floodplain, which effectively conveys flows greater than bankfull.
This approach promotes stream channel stabilization techniques that utilize natural materials (e.g., rootwads, logs, boulders, etc.) and live plantings. In addition, this approach promotes modifying channel and floodplain maintenance practices that are inconsistent with these objectives; minimizing the effects of land use by relocating structures from high hazard areas, and adopting land use controls throughout the watershed that are based on landscape capabilities.

4.2 – Watershed Level Restoration

The geomorphic or natural channel design approach can be applied effectively at the watershed or reach level. When restoration projects are part of comprehensive watershed restoration efforts they are generally implemented by local or state government agencies or watershed associations funded by government grants. On the other hand, public or private landowners that simply want to protect their property from damage caused by
unstable channel conditions may implement restoration projects along individual stream reaches.

At the watershed level, restoration efforts may involve planning, design and implementation of restoration projects or management measures focused on protecting natural resources from the impacts of land use activities. At both the watershed and reach level restoration involves to greater or lesser degree all of the following steps: organization, assessment, planning, implementation, monitoring and evaluation.

4.2.1 – Organization

At the watershed level, restoration requires cooperative efforts among those who are affected by and those who will benefit the most from the restoration/management projects. This group may include public officials, private citizens, public interest groups, economic interests, and any other groups or individuals who are interested in or might be affected by the project. The group with the greatest investment in the outcome of the project is called the stakeholders. Often the stakeholders in a watershed restoration effort will form a business-like watershed association or coalition for the purpose of developing and carrying out a watershed restoration and management plan. Usually an advisory group is formed from the larger group of stakeholders to carry out planning activities, coordinate plan implementation, identify and represent stakeholder interests in the restoration process, and provide consensus-based recommendations to decision makers based upon information from the technical teams and input from all participants.

A technical team of experts with backgrounds in the disciplines of aquatic and terrestrial ecology, hydrology and hydraulics, and geomorphology is essential to the success of the project. A facilitator may be consulted to bring all the interested parties together, to oversee the logistics of the process, to assemble the technical team, to help the group define their overall goals and objectives, to establish and maintain communication between participants, and to identify funding sources.

4.2.2 – Assessment

Documentation of the existing conditions in the watershed is absolutely essential, and is accomplished through a process known as watershed assessment. The major components of a typical watershed assessment include watershed characterization, morphologic stream assessment, biological stream assessment, water quality assessment, and problem identification.

4.2.2.1 – Watershed Characterization

Watershed characterization involves analysis of the physical characteristics of the watershed, including its climate, basin morphometry, geology and soils, land use and land cover, and hydrology. Sources of this information include regional weather data, GIS databases, topographic maps, soil surveys and maps, geologic reports and maps, land
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use/land cover maps and historical records on land use activities, and historic and recent aerial photography, and hydrologic databases and technical reports.

4.2.2.2 – Morphologic Stream Assessment

*Morphologic stream assessment* involves field reconnaissance and field surveys. Data on the existing hydrology and channel morphology of the streams in the study area are collected and analyzed. The existing morphologic features of those streams are then measured, surveyed and mapped. From this information the existing stream channel conditions can be assessed.

4.2.2.3 – Biological Stream Assessment

*Biological stream assessment* typically focuses on the collection, identification, and analysis of benthic macroinvertebrates and fish. These are not the only organisms that are important to the health of a stream, but they are the most readily sampled and the most widely researched. The presence and relative abundance of certain types of organisms is indicative of the quality of the water and the in-stream habitat.

4.2.2.4 – Water Quality Assessment

*Water quality assessment* can be simple or comprehensive, depending upon the objectives of the stakeholders. At a minimum, physical and chemical parameters such as temperature, pH, dissolved oxygen, turbidity, and conductivity are measured to evaluate the quality of the in-stream habitat. Measurements of other parameters, such as nutrient, sediment, and levels of toxic compounds may be indicated in some watersheds.

4.2.2.5 – Problem Identification

*Problem identification* results from an integration of the findings of the watershed characterization and stream assessments that were conducted. These problems may include, but are not limited to, channel instability, degradation of aquatic habitat, altered hydrologic and sediment regimes, and impaired water quality.

4.2.3 – Planning

Once the existing conditions and problems in the watershed have been identified, the goals of the watershed restoration and management effort can be formulated. Goals typically fall into three categories:

- Maintain high quality, stable resources in their current condition;
- Protect resources from degradation; and/or
- Restore degraded or unstable resources to a desired condition.
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Formulation of goals and objectives requires the prioritization of the problems by their severity, complexity, natural recovery potential, cost effectiveness, and a logical assessment of the order in which the problems should be addressed.

After the problems have been prioritized, a set of alternative approaches to solving the problems can be developed. Alternatives are evaluated based on technical feasibility, cost and funding availability, and stakeholder support. Potential restoration or management projects can then be identified and designed.

4.2.4 – Implementation

Implementation of all restoration and management projects should begin with the development of a detailed scope of work. Some projects will entail a “hands off” approach or minimal active intervention. At the other end of the spectrum are projects which involve complete channel reconstruction. Construction projects are logistically more complex to implement, and include the following additional steps:

- Obtaining the necessary permits from federal, state, and local regulatory agencies
- Solicitation of bids
- Securing of any additional funding required
- Securing site access
- Locating existing site constraints (such as utility lines)
- Confirming the sources of materials and ensuring the standards of those materials
- Construction of the project according to the design plan

Regardless of their scope, all actions which are undertaken to solve watershed and stream problems must be carefully planned and thoughtfully carried out, and require a commitment to long-term success from everyone who is involved.

4.2.5 – Monitoring

Monitoring a restoration and management project entails assessing the watershed and stream conditions at prescribed intervals after the project has been implemented, to determine the effect(s) that the project has had on the conditions, which it was intended to rectify. Monitoring should involve the same efforts that were undertaken in the assessment phase.

4.2.6 – Evaluation

A final evaluation of the project after a certain time period will help to determine whether the goals and objectives of the watershed restoration effort were met. This may be a conclusion and summation of periodic monitoring that took place, or it may be a subjective review of how the post-project conditions compare to the conditions that prompted the initiation of the watershed management effort. Photographic comparison of “before” and “after” conditions can be extremely useful.
4.3 – Reach Level Restoration

You may be designing a restoration project because you are a consulting engineer whose client is a developer with mitigation requirements to satisfy. State and Federal permitting agencies routinely require mitigation for unavoidable impacts to streams and wetlands. Stream restoration has become a standard component of these mitigation requirements. Moreover many agencies are requiring that stream restoration projects utilize a geomorphic or natural channel design approach.

Perhaps you are a maintenance supervisor for a power company watching with concern as the stream along your power lines erodes laterally toward the locations of several transmission towers. You stabilized some of those stream banks several years ago with gabions. Unfortunately, the gabions are currently failing and the channel adjustments have initiated problems in other areas. You know you will be designing, permitting and implementing another stabilization project in the near future.

Or you may be a City Public Works engineer dealing with sanitary sewer lines exposed by stream channel erosion, scour and/or deposition problems at culverts and bridges, and complaints from streamside neighborhoods that periodically flood.

To a greater or lesser degree each of you is all dealing with the same issues. You must solve a problem that focuses on a stream channel and the processes that maintain it. You want any solutions you develop to be effective in both the short-term and long-term, to limit the need for future maintenance, and be readily permitted under current local, state and federal regulatory requirements. How do you go about correcting your stream channel stability problems utilizing a geomorphic or natural channel design approach?

Although the scale is very different at the reach level, the restoration process involves the same series of steps we discussed above: organization, assessment, planning, implementation, monitoring and evaluation.

4.3.1 – Organizing Your Team and Enlisting Technical Expertise

Your core team will probably include other engineers, planners, or supervisors with whom you routinely work. However, determining the nature and cause (assessment) of your stream problem and developing a viable solution (design), will require technical assistance from a civil engineer, hydrologist, geomorphologist, landscape architect, or other natural resource specialist trained and experienced in the application of geomorphic assessment and natural channel design.

Whether you choose to work with professionals associated with universities, consulting firms, or government agencies will depend on your in-house expertise, the expertise locally available and the amount of funding your group can afford. In deciding where to go for assistance, evaluate an organization or company’s level of training and experience with designing and implementing restoration projects. Look for an organization or
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company that utilizes an interdisciplinary team approach to the assessment and design process. Ask for references that document successful implementation of similar projects. Solicitations for proposals from private consultants should include:

- Project Description
- Project Objectives
- Project Proponent
- Scope of Services
- Program Constraints (e.g., funding, schedules, etc.)
- Selection Process
- Evaluation Criteria

4.3.2 – Developing a Project Budget

The costs of environmental restoration can be high. This is especially true of large-scale stream restoration projects. These costs include the assessment, design, construction, and monitoring phases of the project. Long-term planning efforts require that we have good information on what it will cost to accomplish our restoration objectives. Having this information can also assist us in evaluating our restoration programs from cost-benefit perspective.

Attempts have been made to assign standard (e.g., per linear foot) cost to stream restoration projects. However, it is important to realize that overall project costs can be highly variable. The severity of the problems and level of intervention required to correct those problems can significantly affect the costs of a project. Some unstable stream reaches may need only minor bank stabilization over a short length or would benefit significantly from changes in land management practices that would allow the channel to evolve to a more stable form. In general, these types of projects may face fewer obstacles and cost less. Conversely, projects involving significant channel reconfiguration over a considerable stream length or requiring extensive alteration of land management practices are likely to have more constraints and be more costly.

As a consequence, it is often difficult to develop reliable cost estimates for all phases of a restoration project early in the planning process. After conducting a preliminary reconnaissance of the project site, an experienced restorationist can provide good cost estimates for the assessment and design phases. Reliable estimates for construction costs are difficult to prepare until after an assessment has been conducted to determine the nature and cause of the problem and viable restoration concepts have been developed. The reliability of overall project cost estimates does increase as the project work progresses and more information becomes available. Although estimates of overall project costs are usually required early in the planning process so that funding can be secured, it is important to realize that preliminary construction cost estimates are less reliable. Final project costs may differ from the original estimates.

When you begin planning your stream restoration project budget you should consider the following typical work components:
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4.3.2.1 – Professional Consulting Services

- Assessment
  - Assembly and analysis of existing data
  - Field Reconnaissance
  - Topographic survey and existing conditions base maps
  - Stream gage calibration surveys
  - Assessment and documentation of project reach conditions
  - Departure from potential analysis
  - Level of intervention needed to correct the problem(s)
  - Identification and survey a reference reach
  - Existing conditions hydrologic and hydraulic analysis (H & H)
  - Report of Findings and Restoration Recommendations/Concepts
  - Coordination meetings between client and consultant

- Design and Permitting
  - Agency field meetings
  - Permit applications and supporting documentation
  - Final design drawings and construction documents
  - Proposed conditions hydraulic analysis
  - Engineer’s review and certification

The cost of assessment and design can vary considerably from project to project. The differences are generally due to differences in availability of existing data, the amount of assessment work required, the size of the project, the severity of the problems and the level of intervention required to correct those problems, site constraints that limit implementation of design criteria, and how much of the work is done in-house.

- Construction Management Services
  - Pre-bid meeting and bid specification addendum
  - Pre-construction meeting
  - Construction management or inspection

One method for increasing the likelihood that your stream restoration project will be successful is to have the project designer provide on-site construction management. At a minimum the project designer should provide periodic construction inspections to confirm that the construction contractor is implementing the project in accordance with the restoration design plans and specifications.

4.3.2.2 – Construction Contractor Services

- Mobilize equipment and materials
- Construction stakeout
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- Traffic maintenance
- Sediment and erosion control measures
- Clear and grub construction site
- Grade site and excavate channel
- Check line and grade
- Furnish and install grade control and flow diverting structures
- Furnish and install bank stabilization structures
- Furnish and install live plant material
- Clean up and debris disposal
- Soil preparation, seed and mulch
- As-built survey

Construction costs vary from region to region. Sources of information for developing cost estimates include: Means Site Work and Landscape Cost Data; Kerr’s Cost Data for Landscape Construction; government agencies that are routinely involved in construction projects, such as the North Carolina Wildlife Resources Commission, Stream Restoration Institute at North Carolina State University, the USDA Natural Resource Conservation Service, the North Carolina Department of Transportation, and private construction contractors.

These sources will also be helpful in sorting out the various work item categories used in the construction trades for developing bid specification packages. For example, in Maryland there are several categories of grading and excavation. Those most commonly associated with restoration projects include Class 1 excavation, which is general site grading, and Class 2 excavation, which is the more detail-oriented work associated with channel excavation and grading. The cost of Class 1 excavation ranges from $2 to $6 per cubic yard. The cost of Class 2 excavation ranges from $5 to $12 per cubic yard.

Nowhere is the old adage “you get what you pay for” more appropriate than in selecting a construction contractor to implement your restoration project. Although there are a large number of heavy equipment operators, there are relative few with experience in successfully implementing a natural channel design stream restoration project. Going with the low bidder has the same inherent risk in stream restoration work has it does in other types of construction projects. Use the same caution in selecting a construction contractor that you did in picking a design consultant. The contractor you select should have successfully completed a minimum of three (3) stream restoration projects. These projects should have involved channel reconstruction or relocation utilizing geomorphic designs, channel stabilization techniques such as installation of cross vanes, rock vanes, rootwads, and bio-engineering stabilization techniques such as installation of soil fabric lifts, live crib walls, live branch packing.

4.3.2.3 – Materials

- Structural components - boulders, rootwads, stone, timbers for cribwalls, coconut fiber blankets, etc.
- Non-structural components - plant materials, topsoil, fertilizer, grass seed, mulch
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- Ancillary components – silt fence, erosion control matting, stakes, fabric staples

Material costs may vary significantly from region to region. On the other hand, the distributors of some materials, such as the coconut fiber blankets used with soil fabric lifts, provide service nationwide. This market is becoming more competitive as more firms get into the business. Obviously, availability affects the cost of materials.

The Department of Environmental Protection and Resource Management in Baltimore County, Maryland has used a variety of approaches to ensure availability of materials and to reduce the cost of its restoration projects. An example is obtaining trees to be used as rootwads from land being cleared by the Department of Recreation and Parks for the expansion of an existing County golf course. The County has notified developers and contractors that it will provide disposal sites for excess rock encountered during the construction of residential and commercial developments. Utilizing this approach, it has been possible to stockpile sufficient quantities of material on public land to supply two or three small to medium sized restoration projects or one large project.

To develop realistic cost estimates for projects, it is a good idea to begin contacting contractors and suppliers well in advance of construction to begin pricing materials and current construction rates.

### 4.3.3 – Securing Funding

Project funding is a critical issue. Local jurisdictions in particular, have had to work diligently to secure funding for these types of projects, often seeking creative solutions to meet their objectives. For example, in addition to capital improvement funds and state and federal grants, many jurisdictions are increasingly relying on cooperative agreements with other local or state agencies, or in some cases private developers.

Public and private mitigation obligations, stemming from federal permits that involved wetland and stream impacts, have become another source of funding to accomplish comprehensive restoration objectives. Sharing information on funding sources and alternative funding mechanisms is becoming more critical under current budgetary constraints.

A number of state and federal programs are available to fund stream restoration projects. For example, the North Carolina Clean Water Management Trust Fund has provided numerous grants funding watershed assessment and stream restoration projects throughout the state. The USDA-NRCS Wetlands Reserve Program as well as the North Carolina Wetlands Restoration Program (WRP) provide grants to restore aquatic and wetland resources. The Soil and Water Conservation Districts administer landowner cost-share programs that partially fund the installation of streambank stabilization and riparian reforestation projects on agricultural lands. Although the cost-share programs administered by the Districts are restricted to problems on agricultural lands, technical assistance is available to all landowners.
4.3.4 – Stream Assessment

Even though your project is focused on a particular reach of stream, it is important to have some understanding of the nature and cause of the stability problems. This requires an evaluation of the general conditions in the watershed, as well reaches upstream and downstream of the project, and understanding how those conditions may be contributing to the problems in your reach.

4.3.4.1 – Data Assembly and Analysis

The first place you and/or your consultant should start is with an analysis of existing data and information. The types of data collected and compiled for review and evaluation include: regional weather data, existing GIS databases, topographic maps, soils, geology, land use maps, hydrologic and hydraulic data, historic and recent aerial photography, as well as published and unpublished technical reports and management plans.

The intent of this task is to collect, compile, review and evaluate existing information to provide an understanding of how regional weather patterns, natural watershed characteristics, historic and current land use practices may have affected or are affecting the hydrologic and sediment regime of the your watershed and the water quality, habitat and channel stability of your project reach.

4.3.4.2 – Field Reconnaissance

This preliminary field investigation of the watershed, upstream and downstream reaches, and project reach allows verification of information obtained from mapped resources. The visual observations, coupled with the initial analysis of maps and aerial photos, will help identify problem areas and develop a broad understanding of the general conditions within your watershed and along its stream system. In addition, specific activities or areas within the watershed that have a significant influence on stream flow, sediment supply, and channel stability can be identified.

During the field reconnaissance, evaluate and photographically document general conditions in upland and riparian areas and along the stream channels, identify sources of sediment (e.g., unstable hillslopes, unstable channel reaches, etc.), and identify stable reaches for further evaluation as potential reference reaches.

4.3.4.3 – Existing Conditions Survey and Base Map Preparation

An Existing Conditions Survey is conducted for the project study area. The survey extends some distance from the top-of-bank on either side of the channel. Vertical and horizontal controls are set. The survey includes:

- Topography at one foot contour intervals
- An offset baseline surveyed along the left or right floodplain/terrace running parallel with the stream along the length of the project area
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- Locations and elevations of all utilities
- Existing structures, such as roads and trails, drainage pipes, box culverts, and bridges
- Major stream features (e.g., point bars, depositional areas, rock outcrops, etc.)
- Survey of channel thalweg
- Cross-sections established off the baseline to pick-up key features along the channel and at the culverts and bridges
- Location of permanent bench marks for monitoring and construction stakeout
- Locations of significant vegetation

4.3.4.4 – Gage Calibration Survey

If existing regional curves are not available, a field calibration of the bankfull discharge and bankfull channel field indicators should be conducted at USGS gaging stations. These gage sites should be selected from among sites in the same physiographic region as the project. The intent should be to select gage sites that represent watersheds with similar land use characteristics as the project watershed. This field exercise is critical for gaining experience in identifying regional field indicators associated with the bankfull channel and for developing regional relationships between drainage area and discharge and drainage area and bankfull channel dimensions. Information gathered in this exercise will be used in conducting the geomorphic stream assessment. It will also be utilized as one method for developing design discharge(s).

4.3.4.5 – Reach Classification and Evaluation of Existing Channel Condition

Stream classification is the process of subdividing or categorizing stream systems, stream segments, or stream reaches into groups or sets on the basis of their similarities or relationships. For example, streams may be classified as perennial, intermittent, or ephemeral based on their flow characteristics.

Rosgen (1985, 1994, and 1996) developed a reach classification and channel stability assessment methodology for use with natural streams. His assessment methodology provides a basis for analyzing and interpreting data on stream channel form (i.e., cross-section, profile, and meander geometry), existing condition (i.e., later and vertical stability and sediment supply), and factors, which influence channel morphology (e.g., bank erosion potential, streambank and riparian vegetation, debris and channel obstructions, etc.). In addition, it provides insight into how a stream might respond to direct channel or floodplain alterations and/or indirect changes in watershed hydrologic and sediment regime. The methodology includes increasingly specific levels of assessment from broad inventory type evaluations to very detailed, data intensive assessments.

At the broad inventory level of the Rosgen assessment methodology, stream reaches are classified based on valley morphology, channel relief, pattern, shape, and dimension. These generalized categories of stream types can be delineated using aerial photographs and topographic maps. At the more detailed, descriptive level of assessment the Rosgen
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System classifies or categorizes stream channel reaches into morphologically similar stream types based on measurable morphological characteristics, such as entrenchment ratio, width/depth ratio, slope, sinuosity, and the particle size of streambed and bank material (Fig. 4-6). This level of assessment involves field measurements of the bankfull channel and provides a morphological description of the reach.

Figure 4-6. Classification criteria used at the descriptive level of assessment (Rosgen, 1996).

At the most detailed level of assessment, additional parameters are utilized to characterize the existing stream channel condition beyond the basic morphological description and to evaluate channel stability. This level of assessment involves field measurements of bankfull channel characteristics. The parameters include bank height ratio, sediment transport competence, width/depth ratio, depositional pattern, meander pattern, bank erosion potential, sediment supply, riparian vegetation, debris and channel obstructions, and channel alterations. Each of these parameters exerts a strong influence on existing channel conditions and relates to future potential conditions.

The Rosgen methodology has direct application to evaluating existing channel conditions, determining potential stable form, identifying appropriate reference reaches, analyzing departure from the potential stable form, and developing a natural channel design.
4.3.4.6 – Departure from Potential Analysis

Stream stability is defined as “the ability of a stream to maintain over time, its dimension, pattern, and profile in such a manner that it is neither aggrading or degrading and is able to effectively transport the flows and sediment delivered to it by its watershed”.

Morphological stability permits the full expression of natural stream characteristics. As a consequence, when a stream reach is functioning at full potential it exhibits its best morphologic condition. This morphologic condition includes a set of desired or preferred characteristics that can be quantitatively described relative to channel size (moderate-low width/depth ratio) and shape (symmetric in crossover reaches, asymmetric in meander bends), streamed stability (neither aggrading or degrading), stream bank stability (low bank erosion potential and low lateral migration rates), and sediment supply (comparatively low rates).

Conducting a detailed field survey of your project reach allows classification of the project reach by Rosgen stream type, characterization of the existing channel conditions relative to cross-sectional geometry, longitudinal profile, meander geometry, particle size distribution of the bed material, bank stability, bed stability, sediment supply, bank and riparian vegetation, debris and channel obstructions, and channel alterations.

The existing conditions data from your project reach can be compared to data collected from stable reference reaches of the same Rosgen stream type functioning at full potential. This comparison allows you to determine the degree to which the existing conditions in your project reach differ from those morphological values exhibited by the stable reference reach. This departure from potential analysis can be conducted by comparing the project reach to: a geomorphologic database for reference reaches of similar stream types, historical photography or surveys of the same reach, surveys of stable reaches of the same stream type at different points in your watershed or adjacent watersheds.

4.3.4.7 – Level of Intervention

When planning a reach level restoration project it is critical to determine the level of intervention required to correct existing stability problems. The level of intervention required is dictated by the severity of the problems. The severity of the problems is determined by the degree to which the existing conditions differ or have departed from a potential stable form. Therefore, the level of intervention is a function of the effort required to reestablish the best morphological conditions possible for your project reach.

The level of intervention dictates the scale or magnitude of a restoration project. Some unstable stream reaches may need only minor bank stabilization over a short length or would benefit significantly from changes in management practices that would allow the channel to evolve, on its own, toward a more stable form. In general, these types of projects face few obstacles, cost less, and have a higher potential for long-term success.
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Conversely, projects which involve significant channel reconfiguration over a considerable stream length or require extensive alteration of land management practices are likely to have more constraints, be more costly, and have a greater level of associated risk.

- Natural Recovery

At the lowest level of intervention, restoration may involve simply eliminating the impacting activity and allowing natural recovery to proceed. For example, unstable conditions may be corrected in rural areas by eliminating livestock grazing impacts. Installing fencing, providing alternative water sources, installing livestock crossings and allowing natural recovery processes to occur eliminates the need for costly restoration projects (Figures 4-7 and 4-8).

In suburban and urban areas, vegetation is routinely maintained by mechanical removal and/or spraying along power line rights-of-way and in public parks, particularly adjacent to athletic fields. In many cases simply modifying vegetation management practices to allow woody vegetation to grow along the stream banks would reduce the need for more costly maintenance caused by channel instability and lateral erosion. Homeowners who mow right up to the top of their stream banks are essentially perpetuating the same conditions that result in channel instability (Figures 4-9 and 4-10).

- Stabilization

As we discussed in the Watersheds and Streams Section, streams are dynamic and changes in channel morphology and stability usually occur gradually over time. For a stream reach that is in the very early stages of developing stability problems, installation of localized stabilization measures to restore lateral stability or streambed stability may correct the problems before they become more severe (Figures 4-11 and 4-12).

- Restoration

For stream reaches that have evolved to a condition of greater instability, it may be necessary to adjust the channel’s geometry (Figures 4-13 and 4-15). This may involve minor adjustments such as narrowing the channel cross-section and stabilizing the eroding stream banks. At the opposite end of the intervention scale, extremely unstable conditions with poor potential for natural recovery may require complete reconstruction of the stream channel to provide a stable channel pattern, profile, and cross-section and the utilization of bank stabilization techniques, and installation of flow diverting and grade control structures. For some stream reaches restoration may not be a realistic goal without intervention at the watershed level first.
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Figure 4-7. Stream in a rural watershed impacted by livestock grazing.

Figure 4-8. Same stream after fencing installed to limit livestock access.
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Figure 4-9. Stream in a residential area where landowner mowed to top of streambanks.

Source: R. Powell, 1995

Figure 4-10. Same stream two growing seasons after mowing practices were modified.

Source: R. Powell, 1997
Figure 4-11. Stream reach with bank erosion and lateral stability problems.

Figure 4-12. Same stream reach after installation of toe benches.
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Figure 4-13. This braided channel has poor natural recovery potential and requires complete restoration and changes in riparian land use practices.

Figure 4-14. This deeply incised channel has poor natural recovery potential and requires complete restoration and stormwater retrofitting to stabilize hydrologic regime.
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4.3.5 – Channel Design Principles

4.3.5.1 – Empirical Relationships

Early studies in fluvial geomorphology established that relationships exist between various stream characteristics (i.e., channel width and meander geometry, meander geometry and longitudinal profile) and that streams respond in a predictable manner to changes in one or more of these characteristics.

4.3.5.2 – Channel Evolution and the Reference Reach Concept

Some studies in fluvial geomorphology have focused on developing models that could explain the various stages or channel forms that develop as a stream reach evolves from a stable form to an unstable form (following some type of disturbance) and back to a stable form again (via natural recovery processes).

Figure 4-15. Channel evolution model developed by Simon (1989)
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In theory a stream that has evolved to a stable form by adjusting its channel geometry to accommodate the range of flows and sediment load delivered to it by its watershed and has remained stable over time provides an excellent model for how we want our project reach to look and function. Because these channel characteristics can be measured in the field, the goal of restoration design is to simulate or recreate the appropriate stream channel features, utilizing data gathered from stable reference streams (same stream type) in similar geomorphologic and hydrologic settings.

Knowing the current channel conditions, how the channel will adjust, and what the most likely form (i.e., most probable stable form) the unstable channel will evolve toward allows us to direct our restoration efforts toward recreating the most probable end product of that process.

Figure 4 -16. This figure, developed by Rosgen and Silvey (1996), depicts one possible outcome of the channel evolution process for a previously stable E4 stream type impacted by the removal of riparian vegetation.

4.3.6 – Channel Design Procedures

After the most probable stable channel form has been identified, the design of the stable channel form (cross-section, pattern, and profile) is developed.

4.3.6.1 – Design Discharge

Discharge estimates for the range of flows that the restored channel will convey including bankfull and flood flow discharges can be developed utilizing several methods. These methods include 1) Manning’s equation with data from field measurements, 2) flow records from stream gages (when available), 3) regional regression equations developed from stream gages in the same or other watersheds in the same physiographic region, and 4) hydrologic modeling.
4.3.6.2 – Stable Channel Geometry

As noted previously, early studies in fluvial geomorphology established that relationships exist between various stream characteristics (i.e., channel width and meander geometry, meander geometry and longitudinal profile) and that streams respond in a predictable manner to changes in one or more of these characteristics. These early studies also demonstrated that natural channel characteristics (e.g., width, depth, cross-sectional area, and velocity) could be described as functions of stream discharge.

These relationships can be described by the use of regime equations. In fact, the use of regime equations developed from empirical data has historically been used to design channels. While this approach has merit, it does not consider the natural variability that exists between streams in geographic areas with differing hydrologic and physiographic characteristics and between streams in differing landscape settings.

The natural channel design approach is based on the concept that dimensionless ratios developed from morphological data (see Table 4-1) collected from a stable reference reach of the same stream type in the same physiographic region can be utilized to establish design criteria for the cross-sectional geometry, meander pattern, profile, and other morphologic features of an unstable stream reach. The use of empirical relations developed from streams in similar geographic areas (i.e., physiographic regions) and similar landscape settings (i.e., valley and stream types) capitalizes on the fact that these relations exist yet reduces the error inherent in the historic regime equations.

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<td>Bankfull Max Depth</td>
<td>Riffle Slope</td>
<td>Ratio Lm/Wbkf</td>
<td>Riffle Subpavement Particle Size Distribution</td>
</tr>
<tr>
<td>Bankfull Cross-sectional Area</td>
<td>Ratio Riffle Slope/ Ave Slope</td>
<td>Radius Curvature (Rc)</td>
<td>Bankfull Discharge</td>
</tr>
<tr>
<td>Width/Depth Ratio</td>
<td>Pool Slope</td>
<td>Ratio Rc/Wbkf</td>
<td>Bankfull Velocity</td>
</tr>
<tr>
<td>Floodprone Width</td>
<td>Ratio Pool Slope/ Ave Slope</td>
<td>Belt Width (Wblt)</td>
<td>Drainage Area</td>
</tr>
<tr>
<td>Entrenchment Ratio</td>
<td>Run Slope</td>
<td>MWR Ratio</td>
<td>Stream Type</td>
</tr>
<tr>
<td>Pool Width</td>
<td>Glide Slope</td>
<td>Wblt/Wbkf</td>
<td>Bank Height Ratio</td>
</tr>
<tr>
<td>Pool Depth</td>
<td></td>
<td></td>
<td>Sediment Supply</td>
</tr>
<tr>
<td>Ratio Pool Depth/ Max Depth</td>
<td></td>
<td></td>
<td>Depositional Pattern</td>
</tr>
<tr>
<td>Run Depth</td>
<td></td>
<td></td>
<td>Bank Erodibility Hazard Index (BEHI)</td>
</tr>
<tr>
<td>Glide Depth</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 4-1. Typical morphological data and dimensionless ratios developed from a reference reach for use in natural channel design


**SECTION FOUR**

4.3.6.3 – Sediment Entrainment Analysis

A critical step in the design process is confirming that the proposed channel will be competent to transport the sediment conveyed from upstream reaches. This involves conducting a Wolman Pebble Count to determine the D\textsubscript{50} of the bed material in the riffles and analyzing sediment samples collected from the lower third of a point bar or the subpavement of those same riffles to determine the D\textsubscript{max} and D\textsubscript{50} of those samples. Utilizing this sediment data and the slope and mean depth of the proposed channel entrainment computations are performed to confirm that the proposed channel will generate sufficient shear stress to mobilize and transport the largest size sediment (D\textsubscript{max}) moving through the project reach under bankfull flow conditions.

4.3.6.4 – Hydraulic Modeling

Modeling of the proposed channel and floodplain under a variety of discharge conditions allows confirmation that the proposed channel modifications will not increase flood stage or create unstable channel conditions.

The HEC-RAS computer program develop by the U.S. Army Corps of Engineers is the most commonly used method for modeling pre and post-construction channel and floodplain conditions. Channel hydraulics should be modeled for the 10-, 50-, 100- year and bankfull events. In particular, the hydraulic analysis allows modeling of changes in the 50- and 100-year water surface elevations associated with the proposed channel modifications. This analysis is especially critical if an area has documented flooding problems.

4.3.6.5 –Design Adjustments to Accommodate Site Constraints

It may be necessary to adjust the design to accommodate site constraints that do not allow full application of the desired design criteria. This is particularly an issue when working with streams in urban settings where buildings, parking lots, athletic fields, and utilities are often located in the floodplain and may be immediately adjacent to the stream channel. Working around sanitary sewer lines can be especially difficult. Knowing which design criteria can be modified and how much requires a thorough understanding of the natural channel design process.

For example, a stream reach being evaluated for restoration has been classified as an F4 stream type. The wide valley width and relatively gentle longitudinal gradient indicate that the F4 was historically a C4 channel. Public records indicate that channel maintenance activities focused on flood control straightened, widened and deepened the channel. Unconstrained, this channel ultimately would adjust to form a C4 stream type. An examination of historic aerials and topographic maps and the surrounding area indicates that at about the time the F4 channel was created, construction of a road and several residences encroached on the floodplain. The road cannot be relocated and the property owners are unwilling to sell their homes. As a consequence, it is not possible to provide the required sinuosity and meander belt width to design a stable C4 channel.
However, the sinuosity and meander belt width requirements for a B4c channel can be met. In this case designing a B4c stream type is an acceptable alternative that accommodates the existing constraints.

4.3.7 – Channel Stabilization Techniques

The stream channel stabilization and flow diverting techniques utilized should complement the restored stable channel form, emphasize stability, habitat and aesthetics.

4.3.7.1 – Grade Control

Streambed stability can be maintained by incorporating grade control structures into the proposed channel design. Grade control can be provided by the installation of cross vanes, boulder drop structures, boulder steps, or rock sills at appropriate locations along the restored reaches.

Construction of these features is in no way similar to weirs or check dams utilized in a standard engineered channel. The features have very specific design criteria including site location, plan form, cross-section and profile. When appropriately installed some of these structures also function to slow and divert the flow away from the banks and into deep water or the center of the channel.

4.3.7.2 – Streambank Stabilization and Flow Diverting Techniques

For most natural stream channels the hydraulic and gravitational forces exerted on the stream banks are greatest along the outside of meander bends. In constructing the restored stream channel it is important to provide structural stability in these areas. This can be accomplished by protecting the banks utilizing a variety of stabilization and flow diverting techniques that resist and/or deflect the hydraulic forces away from the banks.

Techniques that utilize rootwad and boulder revetment, cross vanes, rock vanes, boulder-drop structures, and boulder step-pools, look natural and are especially effective at providing structural stability. These techniques are equally effective on high, moderate or low gradient streams. On moderate and lower gradient streams, these techniques are supplemented by a variety of other innovative approaches (e.g., rock vanes; J-hook vanes; W-weirs; and toe benches with sod or willow mats, fascines, brush mattresses, live stakes, crib walls, and soil/fabric lifts).

The objective of installing flow diverting structures is to reduce the shear stress on the stream banks by slowing and diverting the flow away from the banks and into deep water on bends or the center of the channel in crossover reaches.

4.3.7.2 – Streambank Stabilization and Riparian Vegetation

Reestablishing good vegetative cover along the stream banks and in the adjacent riparian zone is critical to the long-term stability of the restored channel.
Bioengineering techniques provide an ecologically, aesthetically and economically desirable alternative to traditional engineering solutions, such as riprap, gabions, and concrete. As used here, bioengineering means: utilizing live plants and plant parts for soil reinforcement (i.e., soil bioengineering) and utilizing living vegetation with inert structural components (e.g., boulders, logs, root wads) to reinforce soil (i.e., biotechnical slope protection).

Numerous bioengineering techniques utilize dormant cuttings of indigenous plant materials. Species that root easily from cuttings, such as dogwood, viburnum, willow, and elderberry, are used and can be harvested from local sources. Soil bioengineering techniques include live staking, brush mattress, branch packing, and live fascines.

Biotechnical slope protection involves the use of boulders, logs, root wads, geogrid, and fiber blankets in conjunction with plantings of live vegetation. Biotechnical slope protection techniques include live crib walls, soil/fabric lifts, toe benches with willow matting, and root wad revetment.

Bioengineering applications require an on-site assessment to determine which technique is suitable to the particular problem. This involves:

- Evaluating soils, hydrology, geology, and climate. Using plant materials appropriate for the site’s soil and hydrologic conditions, and adapted to the regional weather extremes is key to the long-term success of the project. Local or regional suppliers of native plants will be the best source of materials.

- Determining the cause of the bank stability problems such as natural processes (i.e. geotechnical failure, hydraulic failure, or a combination) or land use activities (e.g., livestock grazing, channelization and berming, and changes in soil moisture conditions due to drainage systems, etc.).

- It is critical to calculate the expected shear stress in the near bank region for the restored stable channel form and compare this estimate to the critical shear stress rating for the techniques being considered.

Riparian functions, and terrestrial and aquatic habitat considerations should be included in the design concept when selecting the plant material and the structural components.

4.3.8 – Floodplain and Wetland Restoration

Restoration objectives can include floodplain and wetland restoration focused on reducing the flow velocity of floodwaters along the banks and across the floodplain, providing additional storage of floodwaters to reduce the flood peak and extend the time of concentration for downstream reaches, filtering pollutants to improve water quality, and restoring riparian habitat.
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Many of the natural drainage ways in a floodplain are relic channels or backwater areas that currently or historically supported wetland conditions. To the extent practical these areas should be maintained or enhanced to encourage detention of floodwaters. To increase flood storage some areas can be excavated and/or expanded depending on landowner acceptance. Water quality in urban watersheds can be greatly improved by incorporating into the design constructed storm water wetland systems through which runoff from unmanaged subwatersheds can be routed. Incorporating into the design riparian reforestation with native plant species can restore riparian habitat.

4.3.9 – Other Design Considerations

- Locating Utilities

Locating underground services (e.g., sewer, water, and natural gas lines, power and communication cables, wells, septic tanks and drainfields), which could be damaged by construction activities, or could prevent full application of the design criteria should be completed early in the design process.

- Identifying Access and Staging Areas

Ingress and egress points from public roads to the site, construction access points along the project reach, and equipment and materials staging areas should be identified and their suitability confirmed early in the design process. Any site modifications necessary to accommodate access of heavy equipment should be incorporated into the design and construction sequence.

- Defining the Limits of Disturbance

Areas to be cleared and graded should be clearly shown on the design drawings. Areas with significant vegetation and other sensitive areas (e.g., wetlands, riparian buffers, historic or archeological sites) should be shown on the drawings and any protective measures (e.g., orange safety fence) that will be utilized should be clearly described in the special provisions and on the drawings.

4.3.10 – Securing Easements

Restoration projects implemented on public land generally do not require easements. However, where projects involve private land some type of easement will be required. An easement may be fairly straightforward, including language that allows temporary access for construction or it may be complicated requiring language that restricts post-construction access and use by the landowner, as well as future owners of the property. If multiple landowners are involved securing easements or rights-of-way can become quite involved and take a considerable time period to resolve.
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In order to avoid project delays, work to secure any easements necessary for project implementation should begin immediately after the design concept has been developed and the project limits clearly defined.

4.3.11 – Obtaining Permits

If you are planning a project that involves streambank stabilization, in-stream habitat improvements, stream reach restoration or relocation, you will probably need a state and federal permits.

As discussed in the Stream Management Section, permits are required from the U.S. Army Corps of Engineers (USACOE) and the North Carolina Department of Environment and Natural Resources, Division of Water Quality (DWQ) before any fill or dredge activities can occur within waters of the U.S. including lakes, rivers, streams, natural ponds, and wetlands. The USACOE is the lead regulatory agency. The DWQ issues a corresponding Certification (General or Individual), but cannot tell you which 401 Certification will apply until the 404 Permit type has been determined by the USACOE.

If your project is relatively small and/or has little potential to adversely impact aquatic or wetland resources, it probably qualifies for one of the USACOE Nationwide, Regional or General Permits. It would also qualify for DWQ’s associated General 401 Water Quality Certifications. To obtain one of these permits you are required to submit a Pre-Construction Notification (PCN) Application Form. The PCN application form is available online. Larger, more complex projects with potentially greater impacts to aquatic and wetland resources may require an Individual 404 Permit or Individual 401 Water Quality Certification. The USACOE Individual Permit application form is also available online.

To review the requirements for the use of Nationwide, Regional or General permits, and to determine which permit applies to your project, you can go to the USACOE website or contact your regional field office listed at the end of this section.

You may want to visit the DWQ's 401/Wetlands Unit website to read about current requirements for the 401 Water Quality Certification Program and to determine whether or not Riparian Buffer Rules are applicable. If you do not have access to the Internet contact DWQ's Central Office in Raleigh (see Contact List at end of section).

It is also a good idea to coordinate with the United States Fish and Wildlife Service (USF&WS) to ensure that your project will have no impact upon any endangered or threatened species or critical habitat as regulated by the Endangered Species Act, and the State Historic Preservation Office, North Carolina Department of Cultural Resources to ensure that the proposed project will have no impact upon any properties listed or eligible for listing on the National Register of Historic Places. Compliance with these regulations is required to be eligible for any Department of the Army permit. The addresses for both agencies are listed at the end of this section.
4.3.12 – Pre-Construction Meeting

Prior to beginning mobilization and construction, the Construction Contractor and technical advisor/project designer should walk the site with the design plans and discuss construction plan details, construction sequencing, final project schedules, special equipment needs, access and staging areas, other special provisions, and any changes the Contractor may recommend. This on-site meeting will minimize problems during construction and prevent delays in the construction process.

4.3.13 – Construction

4.3.13.1 – Site Preparation

Site preparation is the first step in the construction process. Preparing the site requires that the following actions be taken.

- Marking Limits of Disturbance and Work Zones

The area in which the restoration project will be implemented is defined by the project design and a variety of other factors including property boundaries, permit requirements, natural features of significance, and manmade constraints (e.g., utility lines, culverts and bridges, athletic fields, etc.). The project area limits should be clearly delimited on the design plans and marked with stakes and flagging in the field. In addition, key work zones such as equipment access, staging and stockpile areas should marked in the field. Areas that were identified for special protective measures, such as “Tree Save Areas”, vehicular or pedestrian detours should be clearly marked with orange safety fence.

- Installing Sediment and Erosion Control Measures

Control of sediment production and its introduction to the watercourse should be prevented or minimized during all construction operations. Prior to disturbing significant areas of the site, sediment and erosion control measures, such as, stabilized construction entrances, silt fences, diversion berms and sediment traps should be setup and/or installed.

In order to meet the requirements of state and federal regulatory agencies, stream channel construction generally requires that work be completed in a dry channel condition. During construction, various techniques ranging from construction of passive by-pass channels to installation of pump diversions, are utilized to divert stream flow around the work area. Traditional riprap projects generally allow for partial channel dewatering by diverting the flow to one side of the existing channel. However, geomorphic-based restoration often involves significant channel reconstruction requiring stream flows to be diverted completely around the project. This work includes the installation of a system of pumps and pipes/hoses designed to convey baseflow pumped from an in-stream cofferdam at the upstream of the construction area to an outfall-point downstream of the construction area for the purpose of dewatering the construction area.
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Temporary mulching may be required when permanent vegetated stabilization of the disturbed areas is delayed or when stockpiles of topsoil and fill will not be used for an extended period of time.

Additional measures can be installed on an as needed basis. For example, erosion control blankets should be utilized if it is determined they are necessary to maintain the stability of the graded slopes.

- Preparing Access and Staging Areas

In laying out these key work zones, care should be taken to minimize the total area disturbed and areas that are especially sensitive to disturbance. Limit the number of access points. Avoid crossing the stream where possible. If crossings are unavoidable use temporary bridges or culverts as opposed to ford crossings. Avoid steep, erodible slopes and wetlands areas. Keep access road gradients as flat as possible.

Place equipment storage areas back from the stream to avoid contamination due to fuel or oil leaks. Staging and equipment storage areas should be out of view of public roads to increase security.

- Clearing and Grubbing

Clearing within the construction area includes removing and disposing of trees, brush, shrubs, vegetation, rotten wood, and rubbish for removal and disposal. Grubbing includes removing from the ground and disposing of all stumps, roots, and brush and debris.

In order to minimize the potential for erosion, sedimentation and the degradation of water quality, clearing and grubbing will be conducted in stages. The area cleared and grubbed at any one time should be limited to the area of active construction work.

The Contractor should be held responsible for any damage to trees, shrubs, or turf located beyond the limits of disturbance that occurs from his operations during the life of the Contract.

- Construction Stakeout

Utilizing a surveyed baseline and the design plans, the project designer or construction contractor should set stakes at key points along the floodplain/terrace adjacent to the project reach. These stakes are usually marked with the thalweg station and denote the bed feature or structure associated with that stationing. The stakes are utilized during construction to verify stationing of bed and structural features (i.e., top and bottom of riffles, runs and pools; and log and rock sills, cross vane sills and cross vane arm tie-in points, steps and pools, etc.).
4.3.13.2 – Construction and Installation

- Site Grading

In restoration projects that include reestablishing natural floodplain features and/or wetland creation, focus is placed on reconnecting the channel and floodplain and reestablishing hydrology to support the created wetland system. Excavation and rough grading of the surrounding floodplain reduces entrenchment, increases out of bank flows and reduces the depth to groundwater. Fine grading can establish micro-topography and produce a variety of hydrologic regimes within the wetland.

- Channel Excavation and Bank Contouring

In natural channel restoration projects, primary focus is placed on excavation and grading to produce a stream channel with correct geomorphic features. During the implementation of the project, excavation and fill is required to restore a stable plan form and channel cross-section. Excavation also focuses on the development of a stable streambed profile and requires the construction of riffle-pool or step-pool complexes. Grading and reshaping existing stream banks can provide a more stable angle of repose.

- Installation of Grade Control, Flow Diverting, and Bank Stabilization Structures

Streambed stability can be maintained by incorporating grade control structures into the proposed channel design. Grade control can be provided by the installation of cross vanes, boulder drop structures, boulder steps, or rock sills at appropriate locations along the restored reaches.

The hydraulic and gravitational forces exerted on the stream banks are greatest along the outside of meander bends. In constructing the restored stream channel it is important to provide structural stability in these areas. This can be accomplished by protecting the banks utilizing a variety of stabilization and flow diverting techniques that resist and/or deflect the hydraulic forces away from the banks.

The objective of installing flow diverting structures is to reduce the shear stress on the stream banks by slowing and diverting the flow away from the banks and into deep water on bends or the center of the channel in crossover reaches.

Techniques that utilize rootwad and boulder revetment, cross vanes, rock vanes, boulder-drop structures, and boulder step-pools are effective at providing structural stability. As previously pointed out, construction of these features is in no way similar to weirs or check dams utilized in a standard engineered channel. These features have very specific design criteria including size and shape of rock utilized, angle and slope of structures, and installation location relative to channel plan form, cross-section and profile.
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• Installation of Bioengineering Measures

Bioengineering involves the use of live plants and plant parts for soil reinforcement (i.e., soil bioengineering) and utilizing living vegetation with inert structural components (e.g., boulders, logs, root wads) to reinforce soil (i.e., biotechnical slope protection).

Numerous bioengineering techniques utilize dormant cuttings of indigenous plant materials. Species that root easily from cuttings, such as dogwood, viburnum, willow, and elderberry, are used and can be harvested from local sources.

Soil bioengineering techniques include live staking, brush mattress, branch packing, and live fascines. Biotechnical slope protection involves the use of boulders, logs, root wads, geogrid, and fiber blankets in conjunction with plantings of live vegetation. Biotechnical slope protection techniques include live crib walls, soil/fabric lifts, toe benches with willow matting, and root wad revetment.

Key to the success of these bioengineering measures is an on-site assessment to determine which technique is suitable to the particular problem, the selection of appropriate live plant material for the site conditions, and proper installation. The timing of and manner in which the live material is harvested, transported, installed, and maintained is equally critical. Proper selection and handling of live cuttings used for bioengineering techniques is discussed in more detail below.

4.3.13.3 – Planting Woody Vegetation

• Timing

The optimum conditions for successful planting vary from region to region. For the highest rate of survival transporting, and installation of plant material should take place when plants are dormant. In North Carolina December 1 through April 1 is ideal.

• Acquisition

Generally, it is preferred that plant material utilized in restoration projects be native to the region in which the project is located. It is also preferred that the plants be obtained from stock grown in the region and thereby adapted to regional climatic conditions. Regardless, all plant material should conform to the most current issue of the American Standard for Nursery Stock published by the American Association of Nurserymen. Plant materials should be selected from certified nurseries that have been inspected by state and/or federal agencies. Although exceptions can be made, in general plant material should not be collected from the “wild”.

• Transport and Storage

Live plant materials should be protected against drying out and overheating before and during transport and on-site prior to installation. Cuttings, bareroot, and containerized
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plants can be protected from drying by moistening and covering the materials and transporting in unheated or refrigerated vehicles. Cuttings and bareroot stock should be kept in soak pits, stored in shade and covered with evergreen branches or plastic, and sprayed with anti-transpirant chemicals until ready for installation. All containerized plants should be grouped and watered daily until they are planted.

• Planting

The specific types of plants, plant spacing and installation techniques are generally specified in the design plans and were determined long before implementation. The project manager or site foreman should know the basic installation principles and techniques.

4.3.13.4 – Seeding and Mulching

Seeding and mulching is used to provide permanent or temporary stabilization to areas of disturbance. This operation consists of site preparation, soil amendments, seedbed preparation, seeding and mulching.

• Timing

As a general rule, temperature, moisture, and sunlight must be adequate for germination and establishment. With the exception of mid-December through mid-February, in Forsyth County these conditions are met most years. Even during these months seed mixtures that include cold-hardy annuals, such as winter rye, will germinate and provide temporary stabilization until the weather warms and the other seeds in the mixture germinate.

• Soil Preparation

For many restoration sites, the existing soil conditions were suitable for establishment of woody vegetation, as well as ground cover. Therefore, stockpiled topsoil can be spread back over the site to provide the growth medium for your plants. However, part of the rehabilitation of a severely disturbed site might include removal of existing soil and/or transport and application of new topsoil.

After the topsoil as been applied it may be appropriate to apply soil amendments to enhance existing soil conditions and increase the survival potential of your plants. Fertilizer composition and application rates are usually specified in the construction documents. Fertilizers should be delivered to the site in the manufacturer’s packaging and meet all applicable state or federal laws related to labeling. When lime is required, the materials should be ground limestone, hydrated lime or burnt lime. Lime should be incorporated into the top 3 – 6 inches of soil by diskng or other suitable methods. Application rates are usually specified in the construction documents.
Prior to seeding, the seedbed should be prepared by loosening the soil to a depth of 3 – 6 inches by means of suitable equipment. The area shall not be rolled or smoothed. On slopes greater than 3:1, the surface should be tracked with heavy equipment such that the surface is irregular with track ridges running parallel to the slope contour.

- **Seed Mixes and Seeding Techniques**

Species selection is usually considered well before project implementation. Because single species plantings are more susceptible to damage from disease, insects, and weather extremes, most planting plans call for seed mixtures. Seed mixtures usually include annuals, which germinate and establish quickly, providing temporary stabilization, and slower growing perennials that provide the permanent cover. These stands of perennials will persist indefinitely with proper management and environmental conditions. Plant species and application rates for seed mixtures are specified in the design plans and construction documents.

The most commonly used methods of seeding include hydro-seeding, which involves the application of a combination of seed, fertilizer, and mulch in a slurry mixture, and dry-seeding, which includes the use of conventional drop or broadcast spreaders.

Drill/Cultipacker seeding involves the use of mechanized spreaders that apply and cover seed with soil. This method is most often used for reestablishing native grasses because the cultipacker readily buries the seed at the depth specified by the supplier.

- **Mulches and Mulching Techniques**

Mulching limits surface erosion, suppresses weeds, retains soil moisture, and adds organic material to the soil following decomposition. All disturbed areas should be mulched immediately upon completion of the seeding operations. Mulch should be applied so as to provide a uniform cover on all seeded areas.

A variety of mulches are available with different benefits and limitations. Because it is readily available, inexpensive and easily applied, straw is the most commonly used mulch. When straw mulch is specified, the Contractor should provide for anchoring of the mulch. Anchoring may be accomplished by mechanical equipment designed to punch and anchor mulch. The next most commonly used mulch is hydraulic mulch, which includes wood or paper fibers applied with a tackifier or liquid binder. These are not as effective as straw mulch. When liquid binders are used, they should be applied at a uniform rate as provided for in the manufacturer’s directions. Mulch application rates are specified in the construction documents.

4.3.13.5 – Site Cleanup

Final cleanup is the responsibility of the Contractor and consists of removing all trash, debris, and materials incidental to the project and disposing of them off-site.
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4.3.13.6 – Construction Inspections

Throughout construction all installation activities should be routinely monitored to ensure that the contractor completes work in accordance with the design plans and specifications. Ideally the project designer is providing on-site construction management and inspection services. Alternatively, the project designer provides periodic inspections at critical points during construction. The inspector should develop comprehensive documentation of key construction components as they are completed.

A final inspection after construction determines whether all components of the project have been completed in accordance with the design plans, construction specification documents and the contract. Because this also determines the conditions under which the contractor can be paid it must occur promptly.

The final inspection should occur with representatives of the client, design team, and contractor present after the completion of all required work and after site cleanup. A written report should outline any outstanding issues, such as problem areas that developed during or immediately after installation, removal of erosion control measures no longer needed, or trash and debris not removed during cleanup. A schedule should be set for completion of the items in report and follow-up inspection.

4.3.14 – Post-Construction Monitoring

Planning for successful restoration projects should always include a long-term monitoring program to evaluate the performance of the project over a period of many months and years. This monitoring program will generally require a separate budget item that must be anticipated during the early planning stages.

4.3.14.1 – General Inspection

After construction is completed and the site has been stabilized, general conditions along the entire project area should be photographically documented from permanently established viewpoints. The viewpoints should be recorded on a sketch plan or plan view survey map of the site.

The entire project area should be inspected annually to identify problem areas, such as bank erosion; debris accumulation; sediment deposition; and/or damage to bioengineering measures, grade control/flow diverting structures, and bank and riparian vegetation. Observations should be recorded and photographically documented.

Best management practices (e.g., water quality inlets and ponds, stabilized storm drain outfalls, culverts retrofitted for fish passage, fencing and signage to control access, etc.) that were implemented as part of the project should be evaluated to verify that they are being maintained and functioning as intended. Lack of compliance with agreed upon management practices should be noted and photographically documented.
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4.3.14.2 – As-Built Survey and Stability Assessment

A certified as-built survey of the stream geometry (i.e., cross-sectional, plan form and profile) should be completed for the project reach immediately following construction. The as-built survey should be plotted at the same scale as the design plans to allow overlays.

Permanent monumented cross-sections should be installed and included with the as-built survey. These monumented sections should be located at the same location as the design sections and other key points along the length of the project. Cross-sections should be in crossover reaches and at the entrance, apex, and exit of meander bends. The number of monumented sections to include is a judgement call. It is important to establish enough sections to provide representation over the complete length of the project. However, do not establish so many that cost becomes an issue or the likelihood of follow-up is diminished because of the work effort involved. One effective approach would involve locating sections in randomly selected reaches with the objective of a certain percent coverage of the total. Sections should definitely be located in areas where design constraints have predisposed the reach to potential problems.

The as-built survey should document the channel plan form with a detailed topographic survey of the entire project. Include thalweg alignment, right and left edge of water, bankfull and top of bank. Pick up key features including riffles, runs, pools and glides, as well as all grade control and flow diverting structures. Survey the longitudinal profile along the thalweg, water surface, bankfull, and top of bank elevation. Make sure to pick up the elevations and locations of key features including top of riffles, the point of maximum depth in pools, top and bottom of steps, grade control and flow diverting structures. Tie-in the sections to the longitudinal profile.

If the annual inspections intact possible problems with sediment transport (e.g., aggradation or degradation) and evaluation of sediment transport competency should be conducted. This can be accomplished by collecting and analyzing bulk sediment samples of bed material from riffles along the areas of concern. Determine the particle size distribution of riffle pavement and subpavement material. Utilizing the data collected, conduct a sediment entrainment analysis to verify that the restored channel is neither aggrading nor degrading. The monumented cross-sections should be resurveyed annually. The entire project should be resurveyed at intervals of 1 year, 2 years, 5 years, and 10 years after implementation.

4.3.14.3 – Grade Control and Flow Diverting Structures

Visual inspections should be conducted as part of the annual inspections and following high flows to evaluate the condition of grade control and flow diverting structures (e.g., (e.g., cross vanes, rock vanes, j-hook vanes, w-weirs, boulder drop structures, rock or log sills, step-pools, etc.). Observations should be recorded and photographically documented.
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The evaluation should focus on the stability and general condition of structural components. Undercutting, lateral short-circuiting or general failure of structures should be noted and photographically documented. If the visual inspections indicate substantial change has occurred, then additional survey work should be conducted to document the change and assist in determining if remedial measures will be necessary.

4.3.14.4 – Bioengineering Measures

Visual inspections should be conducted as part of the annual inspection to identify problems with bioengineering bank stabilization techniques such as rootwads, live cribwalls, brush layering, fascines, fiber blankets, coir logs, toe boulders, etc.). Evidence of tearing or deterioration in fabric; mortality in live cuttings; loosening, shifting or dislodging of rootwads, cribwalls, coir logs, toe boulders should be noted and photographically documented. If the visual inspections indicate substantial change has occurred, then additional survey work should be conducted to document the change and assist in determining if remedial measures will be necessary.

4.3.14.5 – Streambank and Riparian Vegetation

For the first five years after implementation, plantings should be evaluated annually for evidence of insect infestation, disease, weed competition, animal browsing, damage due to careless maintenance practices, and mortality. At the end of a 2-year period, 50 percent or more of the originally installed plant material should be healthy and growing well. The condition of vegetation should be photographically documented.

4.3.15 – Maintenance

Maintenance includes remedial measures that are initiated as a result of problems identified during the annual inspections, are part of regularly scheduled upkeep, or arise on an emergency basis.

4.3.15.1 – Remedial

Remedial maintenance is initiated as a result of problems identified during annual inspections. These include the types of repairs that are not normally addressed as part of regularly scheduled maintenance and if left unattended could develop into more serious problems. For example, resetting loose or partially dislodged logs or rocks from bank stabilization or flow diverting structures would be remedial maintenance.

4.3.15.2 – Scheduled

Scheduled maintenance is performed at intervals that are prescribed during the planning and design phases or based on project-specific needs. Such maintenance activities as clearing debris and sediment from culverts, spraying and/or mechanical removal of invasive weeds (e.g., kudzu) can be anticipated, scheduled, and funded well in advance.
4.3.15.3 – Emergency

Emergency maintenance requires immediate mobilization to repair or prevent damage. It may include measures such as replacing or reconstructing a failed bank stabilization, grade control, or flow diverting structure, excavating pools that were partially or completely filled, or other damage associated with a recent, high flow event.

For higher risk projects, where there is a reasonable probability that some replacement or reconstruction work will be required, sources of funding, labor, and materials should be identified in advance as part of the planning process. There should be a general strategy for allowing rapid response to an emergency.
For most natural stream channels the hydraulic and gravitational forces exerted on the stream banks are greatest along the outside of meander bends. In constructing the restored stream channel it is important to provide structural stability in these areas. This can be accomplished by protecting the banks utilizing a variety of stabilization and flow diverting techniques that resist and/or deflect the hydraulic forces away from the banks.

Techniques that utilize rootwad and boulder revetment, cross vanes, rock vanes, boulder-drop structures, and boulder step-pools, look natural and are especially effective at providing structural stability. These techniques are equally effective on high, moderate or low gradient streams. On moderate and lower gradient streams, these techniques are supplemented by a variety of other innovative approaches (e.g., rock vanes; J-hook vanes; W-weirs; and toe benches with sod or willow mats, fascines, brush mattresses, live stakes, crib walls, and soil/fabric lifts).

The objective of installing flow diverting structures is to reduce the shear stress on the stream banks by slowing and diverting the flow away from the banks and into deep water on bends or the center of the channel in crossover reaches.

Streambed stability can be maintained by incorporating grade control structures into the proposed channel design. Grade control can be provided by the installation of cross vanes, boulder drop structures, boulder steps, or rock sills at appropriate locations along the restored reaches.

The following fact sheets are intended to provide information on some of the more common techniques utilized to provide grade control, divert and direct streamflow and stabilize streambanks.

*The stream channel stabilization and flow diverting techniques utilized should complement the restored stable channel form, emphasize stability, habitat and aesthetics.*
SECTION FOUR

Cross Vanes

*Cross vanes* are in-stream structures constructed with native/natural materials (i.e., boulders and/or logs) that are typically installed at the upstream end of a riffle. In this location they serve to divert stream flow away from banks and towards the center of the channel as it leaves the pool in the meander bend and enters the riffle in the crossover reach. In addition, these structures provide grade control by preventing riffles from eroding headward into the upstream pools. The plunge pools associated with these structures also provide excellent habitat for fish.

PLAN

Source: Powell, 2003
RESTORATION

Source: Powell, 2003
SECTION FOUR

Cross Vane sill under baseflow conditions

Source: Powell, 1999

Cross Vane under baseflow conditions

Source: Powell, 1999
RESTORATION

Source: Powell, 2001

Cross Vane under bankfull flow conditions. Note high velocity flow diverted to center of channel with low velocity flow along streambank.
SECTION FOUR

Rock Vane

Rock vanes are in-stream structures constructed with native/natural materials (i.e., boulders) that are typically installed along the channel margin in meander bends. In this location they serve to divert stream flow away from banks and towards the center of the channel as it flows from the run at the upstream end, through the pool, and out the glide at the downstream end of the meander bend. In addition, these structures maintain the thalweg offset from the bank and create back-eddies along the channel margin that encourage the deposition of material along the toe of the bank as well as provide excellent habitat for fish.

Source: Powell, 2003
RESTORATION

Source: Powell, 2003
SECTION FOUR

Rock Vane under baseflow conditions

Source: Powell, 1999

Rock Vane under bankfull flow conditions. Note high velocity flow diverted to center of channel with dead water (low velocity flow) along streambank.

Source: Powell, 2001
RESTORATION

Rock Vane under baseflow conditions

Source: Powell, 1996

Rock Vane under baseflow conditions

Source: Powell, 1996
SECTION FOUR

J-Hook Vane

_J-hook vanes_ are in-stream structures constructed with native/natural materials (i.e., boulders) that are essentially rock vanes with a hook added to the upstream end of the vane arm. They are typically installed along the channel margin, where they serve to divert stream flow away from banks and towards the center of the channel. The added feature of the hook serves to create and maintain a scour pool, thereby providing excellent habitat for fish. In addition, these structures maintain the thalweg off-set from the bank and create back-eddies along the channel margin that encourage the deposition of material along the toe of the bank.

Source: Powell, 2003

PLAN
RESTORATION

Source: Powell, 2003
J-Hook Vane under baseflow conditions. Note flow dropping across hook.

A series of J-Hook Vanes installed to enhance habitat.
RESTORATION

Log/Boulder Step-Pools

Step pool structures are streambed features composed of logs and boulders constructed in steep stream reaches to provide grade control for actively eroding channels as well as energy dissipation during bankfull flow events. They are most effective when installed during restoration of unstable A and B stream types, as well as conversions from G to B stream types.

SECTION FOUR

Log/Boulder Step-Pools immediately after installation

Source: Powell, 1999

Log/Boulder Step-Pools immediately after installation

Source: Powell, 1999
RESTORATION

Log/Boulder Step-Pools 2 years after installation

Source: Powell, 2001

Log/Boulder Step-Pools 2 years after installation

Source: Powell, 2001
SECTION FOUR

Toe Benches

Stream bank failure results from three principal mechanisms: tractive erosion caused by hydraulic forces that remove erodible bank and bed material, gravitational erosion caused by geotechnical instability, and a combination of tractive and gravitational forces acting to cause the failure. For most natural stream channels the hydraulic and gravitational forces exerted on the stream banks are greatest along the outside of meander bends. In constructing the restored stream channel it is important to provide structural stability in these areas. This can be accomplished by protecting the toe of the banks utilizing a variety of stabilization and flow diverting techniques that resist and/or deflect the hydraulic forces away from the bank. In addition, the new banks should be constructed with an angle of repose that minimizes the potential for gravitational failures. Toe benches are a particularly effective method for addressing both concerns.

Source: Powell, 1997
Unstable streambank prior to stabilization.

Source: Powell, 1998
A view of the same streambank after stabilization with a toe bench. Note that the trees along the streambank were not disturbed.

Source: Powell, 1999
RESTORATION

Rootwads

Rootwads are a channel stabilization technique that uses native/natural materials (i.e., logs and boulders) to provide short-term (5 –10 years) protection of stream banks that allows the establishment of deep-rooted woody vegetation (i.e., trees and shrubs) planted on the banks. When installed in a stream bank with the root mass pointing upstream, rootwads deflect stream flows away from banks, encourage scour and maintenance of pools on meander bends, and provide overhead cover for fish.

Source: Powell, 1999
Looking downstream at rootwads installed in left bank

Source: Powell, 1999

Source: Powell, 1991
RESTORATION

Rootwad bank stabilization immediately after installation

Source: S. McGill, 1997

Rootwad bank stabilization one year after installation

Source: S. McGill, 1998
SECTION FOUR

Soil Fabric Lifts

*Soil fabric lifts* consist of alternating layers of live branches and compacted soil wrapped in natural biodegradable organic (e.g., coconut fiber, straw, etc.) or synthetic geotextile fabric. Provide immediate reinforcement for newly constructed streambanks until vegetation can become established. Live branches produce rapidly vegetated banks. Can be used above or below bankfull elevations. Can be placed on 1:1 slopes or steeper.

Source: USDA, Natural Resources Conservation Service, 1996
New stream banks constructed utilizing soil fabric lifts.

View of restored channel from similar perspective 17 months after project completion
New stream banks constructed utilizing soil fabric lifts.

View of restored channel from same perspective, 17 months after project completion
RESTORATION

Source: R. Powell, 2000

Close-up photograph of recently installed soil fabric lifts. Note live branch cuttings sticking from between successive lifts.
SECTION FOUR

Live Crib Walls

A vegetated crib wall is composed of a box–like interlocking arrangement of untreated structural beams (i.e., logs or timbers) filled with layers of a suitable backfill material and layers of live branch cuttings that root inside the crib structure and extend into the existing slope. Once the live cuttings root and become established, the vegetation gradually takes over the structural function of the structural beams. The structural components of crib walls provide immediate protection from erosion, while the established vegetation provides long-term stability. They function well at the base of slopes, where low walls can stabilize the toe and serve to reduce the angle of repose. Crib walls are especially useful where space is limited and a more vertical structure is required. They are effective on the outside of meander bends and are appropriate above and below water when the streambed is stable.

Source: USDA, Natural Resources Conservation Service, 1996
RESTORATION

Installation of crib wall structural components

Same crib wall immediately after installation
Same crib wall 17 months after project completion.

Source: R. Powell, 2000
RESTORATION

Live Branch Packing

*Branch packing* consists of alternating layers of live branches and compacted backfill utilized to repair small, localized slumps and scour holes in streambanks. Branch packing provides immediate soil reinforcement and rapidly establishes vegetated streambanks. This technique is effective and inexpensive.

Source: USDA, Natural Resources Conservation Service, 1996
SECTION FOUR

Live Fascines

*Live fascines* are long bundles of branch cuttings bound together in cylindrical structures that are installed in shallow trenches cut across slopes to reduce erosion and shallow sliding. This technique is effective for stabilizing streambanks and offer immediate protection from surface erosion. Generally installed above bankfull elevation.

Source: USDA, Natural Resources Conservation Service, 1996
RESTORATION

Live Stakes

*Live staking* involves the insertion and tamping of live, rootable vegetative cuttings into the ground. A system of stakes creates a living root mat that stabilizes the soil by reinforcing and binding soil particles together and by extracting excess soil moisture. This technique is effective for streambank protection where site conditions are uncomplicated, construction time is limited, and an inexpensive method is needed. It is often utilized in conjunction with other bioengineering techniques, such as fascines.

Source: USDA, Natural Resources Conservation Service, 1996
A brush mattress is a combination of live stakes, live fascines, and branch cuttings installed to cover and stabilize streambanks. It forms an immediate protective cover over the streambank and rapidly establishes steambank and riparian vegetation. Generally installed above bankfull elevation.

Source: USDA, Natural Resources Conservation Service, 1996
4.5 – Streambank Stabilization and Riparian Vegetation

Reestablishing good vegetative cover along the stream banks and in the adjacent riparian zone is critical to the long-term stability of the restored channel.

Bioengineering techniques provide an ecologically, aesthetically and economically desirable alternative to traditional engineering solutions, such as riprap, gabions, and concrete. Bioengineering means: utilizing live plants and plant parts for soil reinforcement (i.e., soil bioengineering) and utilizing living vegetation with inert structural components (e.g., boulders, logs, root wads) to reinforce soil (i.e., biotechnical slope protection).

Numerous bioengineering techniques utilize dormant cuttings of indigenous plant materials. Species that root easily from cuttings, such as dogwood, viburnum, willow, and elderberry, are used and can be harvested from local sources. Soil bioengineering techniques include live staking, brush mattress, branch packing, and live fascines.

Biotechnical slope protection involves the use of boulders, logs, root wads, geogrid, and fiber blankets in conjunction with plantings of live vegetation. Biotechnical slope protection techniques include live crib walls, soil/fabric lifts, toe benches with willow matting, and root wad revetment.

Bioengineering applications require an on-site assessment to determine which technique is suitable to the particular problem. This involves:

- Evaluating soils, hydrology, geology, and climate. Using plant materials appropriate for the site’s soil and hydrologic conditions, and adapted to the regional weather extremes is key to the long-term success of the project. Local or regional suppliers of native plants will be the best source of materials.

- Determining the cause of the bank stability problems such as natural processes (i.e. geotechnical failure, hydraulic failure, or a combination) or land use activities (e.g., livestock grazing, channelization and berming, and changes in soil moisture conditions due to drainage systems, etc.).

- It is critical to calculate the expected shear stress in the near bank region for the restored stable channel form and compare this estimate to the critical shear stress rating for the techniques being considered.

Riparian functions, and terrestrial and aquatic habitat considerations should be included in the design concept when selecting the plant material and the structural components.
## Table 4.5 – Recommended Native Trees and Shrubs for Stream Bank Stabilization and Riparian Area Plantings

<table>
<thead>
<tr>
<th>Common Name (Scientific Name)</th>
<th>Availability</th>
<th>Size/Form</th>
<th>Exposure &amp; Soils</th>
<th>Habitat Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Gum (Nyssa sylvatica)</td>
<td>Very Common</td>
<td>Tree</td>
<td>Sun – partial shade, moist</td>
<td>High, songbirds</td>
<td></td>
</tr>
<tr>
<td>Sycamore (Platanus occidentalis)</td>
<td>Very Common</td>
<td>Tree</td>
<td>Sun, adapts</td>
<td>Low, cavity nesters</td>
<td>Transplants well, rapid growth</td>
</tr>
<tr>
<td>Black Willow (Salix nigra)</td>
<td>Very Common</td>
<td>Shrub &amp; Tree</td>
<td>Sun, moist</td>
<td>Nesting</td>
<td>Rapid growth, good bank stabilizer</td>
</tr>
<tr>
<td>Red Maple (Acer rubrum)</td>
<td>Very Common</td>
<td>Tree</td>
<td>Sun – shade, adapts</td>
<td>High, seeds and browse</td>
<td>Rapid growth</td>
</tr>
<tr>
<td>Smooth Alder (Alnus serrulata)</td>
<td>Common</td>
<td>Shrub</td>
<td>Sun, moist</td>
<td>Mod, cover</td>
<td>Rapid growth, good bank stabilizer</td>
</tr>
<tr>
<td>River Birch (Betula nigra)</td>
<td>Very Common</td>
<td>Tree</td>
<td>Sun, moist</td>
<td>Good for cavity nester</td>
<td></td>
</tr>
<tr>
<td>Serviceberry (Amelanchier arborea)</td>
<td>Common</td>
<td>Shrub</td>
<td>Shade, moist</td>
<td>High, songbirds, mammals</td>
<td>Well drained sites</td>
</tr>
<tr>
<td>Silky Dogwood (Cornus amomum)</td>
<td>Very Common</td>
<td>Shrub</td>
<td>Sun – shade, moist</td>
<td>High, songbirds, mammals</td>
<td>Drought tolerant, Good bank stabilizer</td>
</tr>
<tr>
<td>Alternate Leaf Dogwood (Cornus alternifolia)</td>
<td>Common</td>
<td>Shrub</td>
<td>Sun – shade, moist</td>
<td>High</td>
<td>Good bank stabilizer</td>
</tr>
<tr>
<td>Spicebush (Lindera benzoin)</td>
<td>Very Common</td>
<td>Shrub</td>
<td>Shade, moist rich</td>
<td>Mod, songbirds</td>
<td>Acidic soils, good understory</td>
</tr>
<tr>
<td>Elderberry (Sambucus canadensis)</td>
<td>Common</td>
<td>Shrub</td>
<td>Sun – partial shade, moist</td>
<td>Very high food, cover</td>
<td>Well drained sites</td>
</tr>
<tr>
<td>Sugarberry (Celtis laevigata)</td>
<td>Common</td>
<td>Tree</td>
<td>Partial shade, moist</td>
<td>High, food &amp; cover</td>
<td></td>
</tr>
<tr>
<td>Hackberry (Celtis occidentalis)</td>
<td>Common</td>
<td>Tree</td>
<td>Sun – partial shade, adapts</td>
<td>High</td>
<td>Excellent shade tree, drought resistant</td>
</tr>
<tr>
<td>Winterberry (Ilex verticillata)</td>
<td>Very Common</td>
<td>Shrub</td>
<td>Sun – partial shade, adapts</td>
<td>High, cover &amp; fruit for birds</td>
<td>Tolerates flooding, holds berries in winter</td>
</tr>
<tr>
<td>Willow Oak (Quercus phellos)</td>
<td>Very Common</td>
<td>Tree</td>
<td>Sun – partial shade, adapts</td>
<td>High, mast</td>
<td></td>
</tr>
<tr>
<td>Shumard Oak (Quercus shumardii)</td>
<td>Very Common</td>
<td>Tree</td>
<td>Sun, adapts</td>
<td>High</td>
<td>Good shade tree</td>
</tr>
<tr>
<td>Green Ash (Fraxinus pennsylvanica)</td>
<td>Very Common</td>
<td>Tree</td>
<td>Sun, adapts</td>
<td>Mod, songbirds</td>
<td>Rapid growth, good bank stabilizer</td>
</tr>
<tr>
<td>Silky Willow (Salix sericea)</td>
<td>Common</td>
<td>Shrub</td>
<td>Sun, moist</td>
<td>High</td>
<td>Rapid growth, good bank stabilizer</td>
</tr>
<tr>
<td>Southern Arrowwood (Viburnum dentatum)</td>
<td>Common</td>
<td>Shrub</td>
<td>Partial shade, adapts</td>
<td>Good</td>
<td>Forms colonies</td>
</tr>
<tr>
<td>Black Walnut (Juglans nigra)</td>
<td>Very Common</td>
<td>Tree</td>
<td>Sun, moist rich</td>
<td>Good</td>
<td>Temporarily flooded wetlands along floodplain</td>
</tr>
<tr>
<td>Witch Hazel (Hamamelis virginiana)</td>
<td>Very Common</td>
<td>Shrub/Small Tree</td>
<td>Shade, moist</td>
<td>Low</td>
<td>Well drained sites</td>
</tr>
<tr>
<td>Purple Osier Willow (Salix purpurea)</td>
<td>Very Common</td>
<td>Shrub</td>
<td>Sun, moist</td>
<td>Very good</td>
<td>Rapid growth, good bank stabilizer</td>
</tr>
<tr>
<td>Possumhaw (Ilex decidua)</td>
<td>Common</td>
<td>Shrub</td>
<td>Sun – shade, moist</td>
<td>High, food, nest sites</td>
<td></td>
</tr>
</tbody>
</table>
Approval Process for Stream Work in North Carolina

Applicant/Consultant Identifies Project Site

Applicant/Consultant Identifies Potential Impacts & Identifies Required Permit/Certification/Approvals\(^1\) Needed For Project

If Required Applicant/Consultant Submits Pre-Construction Notification to USACOE and DWQ & Coordinates with DLR and City of Winston-Salem Sediment and Erosion Control Program

Smaller Impacts:

- Nationwide or Regional General Permit
- General Certification

Larger Impacts:

- Individual Permit
- Public Notice
- Individual Certification

Review by DWQ/USACOE for Avoidance/Minimization of Impacts, Need for Project Mitigation, Etc

Issue or Deny 404 Permit and 401 Certification\(^2\)

Submit Sediment and Erosion Control Plan to DLR City of Winston-Salem Sediment and Erosion Control Program

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1. May require permits/certifications/approvals from USACOE, DWQ, DLR, DCM, various local programs, WRC, DCR, FERC, FEMA, as well as other agencies depending on site conditions. The applicant/consultant should identify other applicable rules, including but not limited to, rules that require buffers. Some Projects require environmental documentation (NEPA/SEPA).

2. Both Individual and General Permits and Certifications may have conditions that must be met prior to impacts.
SECTION FOUR

Permitting Contacts:

U. S. Army Corps of Engineers
Raleigh Regulatory Office
6508 Falls of Neuse Road, Suite 120
Raleigh, NC 27615
(919) 876-8441

North Carolina Department of Environment and Natural Resources
Division of Water Quality, Water Quality Section
585 Waughtown Street
Winston-Salem, NC 27107
(336) 771-4600

North Carolina Department of Environment and Natural Resources
Division of Land Resources, Land Quality Section
585 Waughtown Street
Winston-Salem, NC 27107
(336) 771-4600
CASE STUDIES

Introduction

The City of Winston-Salem faces the challenge of maintaining public infrastructure (e.g., water and sewer lines, storm drains, roads, culverts and bridges) while minimizing the potential impacts to our natural resources. For example, the majority of the sewer network in Winston-Salem is a gravity feed system. These sewer lines follow the natural topography of the land, flowing to a treatment system located at a low point in the area. Unfortunately with this type of system, sewer lines are often placed adjacent to intermittent and perennial streams. When these streams adjust to changes in the watershed, the utilities are often adversely affected. The following case studies were developed to demonstrate how public infrastructure could be protected and maintained while minimizing adverse impacts to streams. They are presented as one possible approach to correcting the problems that exist at the case study sites.

Please note that the field and office work conducted to develop the stabilization concepts for the case studies did not include the detailed survey and analyses required to develop final designs suitable for construction. The following stabilization concepts were developed for demonstration purposes only!
CASE STUDIES

Case Study #1 – Regency Drive

Background Information

This case study involves the protection of an exposed sanitary sewer line located at the dead end of Regency Drive near the headwaters of Silas Creek. The watershed area draining to this point is approximately 210 acres that includes multifamily residential and commercial land uses. Because of high impervious acreage draining to this site, storm flows have increased significantly with subsequent streambed and stream bank erosion occurring. A bedrock ledge in the middle of the project reach halted this channel incision at some time in the past. Although the right bank was armored with riprap, the entrenchment resulting from the initial lowering of the streambed has increased bank heights and increased the stress on the banks under storm flow conditions. As a consequence, the left stream bank has eroded laterally exposing the sewer line that parallels the channel along this bank (Fig. 1). In a relatively brief period of time the sewer line has become unstable. Intervention will be required to stabilize the bank, divert storm flows away from the stream banks, and protect the sewer line. Stabilizing this channel reach will also reduce sediment loading to Silas Creek.

Fig. 1 – Photo taken looking downstream toward sanitary sewer manhole. Arrow indicates area of exposed sewer line along left bank

Study Area

The study area for this study project includes the reach located at the dead end of Regency Drive (Fig. 2).
CASE STUDIES

Fig. 2 – Regency Drive Study Area

Methods

The stabilization design concepts were prepared based on observations made during a preliminary site visit and in-office analysis. The analysis and plan development involved:

1) Review of recent (2000) aerial photographs and topographic maps provided by the City;
2) Review of drainage area information derived by the City;
3) Entering field data for cross-sections surveyed by the City into a data analysis spreadsheet;
4) Computation of predicted bankfull channel dimensions and bankfull discharge utilizing the Bankfull Regional Curves for the Rural Piedmont of North Carolina (NRCS and NCS University, 1999) and Bankfull Regional Curves for the Urban Piedmont of North Carolina (Wilkerson, et. al., 1998);
5) Computation of bankfull channel dimensions and bankfull discharge for the project reach utilizing the survey data provided by the City and comparison to the predicted values from the regional curves;
6) Plotting of cross-sections for use in developing design cross-section plans;
7) Preparation of plan view design base map utilizing hand drawn sketches developed during the preliminary site visit; and
8) Layout of stabilization design concept plans based on information derived from the preliminary site visit and data analysis, and utilizing the geomorphic

Prior to developing final design plans a geomorphic assessment and detailed field surveys should be conducted along the project reach. Conducting a detailed survey will allow, among other things, verification of the bankfull channel and floodprone area, characterization of existing conditions, and confirmation that the concept represents the appropriate restoration approach for this site. In particular, the information obtained from the fieldwork will provide the design dimensions for the restored channel.

<table>
<thead>
<tr>
<th>Computational Method</th>
<th>Bankfull Cross-Sectional Area (ft²)</th>
<th>Bankfull Discharge (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural Regional Curve</td>
<td>10.0</td>
<td>24.7</td>
</tr>
<tr>
<td>Urban Regional Curve</td>
<td>31.0</td>
<td>185.7</td>
</tr>
<tr>
<td>Plotted Field Data and Mann’s Equation</td>
<td>37.35</td>
<td>187.8</td>
</tr>
<tr>
<td></td>
<td>(36.5 – 38.2)</td>
<td>(182.6 – 193.0)</td>
</tr>
</tbody>
</table>

Table 1. Computational methods used to estimate bankfull channel dimensions and bankfull discharge.

Restoration Approach

Changes in watershed hydrology and historic channelization have increased the shear stress associated with storm flows. Initially this increased shear stress caused the channel to incise with a subsequent lowering of the bed elevation. Lowering of the streambed increased bank height, confined the channel and placed additional stress on the banks. Although a bedrock ledge in the middle of the project reach halted the channel incision, hydraulic forces eroding the toe of the banks resulted in steeper bank angles with increased susceptibility to gravitational failures. As these failures became common the channel adjusted laterally. Due to the high erosion potential of the banks and a lack of mature trees to provide lateral control, lateral migration rates will accelerate as meander development progresses. Currently the project reach is a G stream type (i.e., low width/depth ratio, and low entrenchment ratio). Left unchecked this condition will cause damage to the sewer line that parallels the channel along the left bank.

Therefore, the long-term stabilization objectives for this reach of Silas Creek include:

1. Convert the unstable G channel into a stable B channel by excavating/constructing bankfull benches and grading both banks to create additional floodprone area;

2. Install a cross vane to divert storm flows into the center of the channel, away from the banks and the manhole;
CASE STUDIES

3. Protect the exposed sewer line by burying it beneath the bankfull bench and left arm of the cross vane;

4. Provide long-term bank stabilization and lateral control by establishing native grasses and shrubs along both banks.

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Regency Drive
Sanitary Sewer Stabilization
Plan View
CASE STUDIES

Regency Drive
Sanitary Sewer Stabilization
Cross Section 1

Regency Drive
Sanitary Sewer Stabilization
Cross Section 2
CASE STUDIES

Case Study #2 – Natalie Drive

Background Information

This case study involves the protection of an exposed sanitary sewer line located along a tributary to Muddy Creek downstream of Natalie Drive. The watershed area draining to this point is approximately 142 acres that includes predominantly single-family residential land uses. Recent residential development and additional storm drainage conveyances to the stream have caused instability of this channel. In recent years, the channel has deepened and widened to accommodate increased storm flows. Lateral migration and scour of the channel has exposed a sanitary sewer line that was originally installed beneath the streambed (Fig. 3). Currently the project reach is a G stream type (i.e., low width/depth ratio, and low entrenchment ratio). Intervention will be required to stabilize the banks and protect the sewer line. Stabilizing this channel reach will also reduce sediment loading to Muddy Creek.

Fig. 3 – Photo taken looking downstream. Arrow indicates area of exposed sewer line along left bank.
CASE STUDIES

Study Area

The study area for this study project includes the reach located downstream of Natalie Drive (Fig. 4).

Fig. 4 – Natalie Drive Study Area

Methods

The stabilization design concepts were prepared based on observations made during a preliminary site visit and in-office analysis. The analysis and plan development involved:

1. Review of recent (2000) aerial photographs and topographic maps provided by the City;
2. Review of drainage area information derived by the City;
3. Entering field data for cross-sections surveyed by the City into a data analysis spreadsheet;
4. Computation of predicted bankfull channel dimensions and bankfull discharge utilizing the Bankfull Regional Curves for the Rural Piedmont of North Carolina (NRCS and NCS University, 1999) and Bankfull Regional Curves for the Urban Piedmont of North Carolina (Wilkerson, et. al., 1998);
5. Computation of bankfull channel dimensions and bankfull discharge for the project reach utilizing the survey data provided by the City and comparison to the predicted values from the regional curves;
6. Plotting of cross-sections for use in developing design cross-section plans;
CASE STUDIES

7. Preparation of plan view design base map utilizing hand drawn sketches developed during the preliminary site visit; and
8. Layout of stabilization design concept plans based on information derived from the preliminary site visit and data analysis, and utilizing the geomorphic principles set forth in the Natural Channel Design Approach to Stream Restoration (Rosgen, 1996).

Prior to developing final design plans a geomorphic assessment and detailed field surveys should be conducted along the project reach. Conducting a detailed survey will allow, among other things, verification of the bankfull channel and flood prone area, characterization of existing conditions, and confirmation that the concept represents the appropriate restoration approach for this site. In particular, the information obtained from the fieldwork will provide the design dimensions for the restored channel.

<table>
<thead>
<tr>
<th>Computational Method</th>
<th>Bankfull Cross-Sectional Area (ft²)</th>
<th>Bankfull Discharge (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural Regional Curve</td>
<td>7.7</td>
<td>17.4</td>
</tr>
<tr>
<td>Urban Regional Curve</td>
<td>24.3</td>
<td>148.9</td>
</tr>
<tr>
<td>Plotted Field Data and Mannings’ Equation</td>
<td>31.35</td>
<td>141.1</td>
</tr>
<tr>
<td></td>
<td>(29.9 – 32.8)</td>
<td>(137.3 – 144.8)</td>
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</tbody>
</table>

Table 1. Computational methods used to estimate bankfull channel dimensions and bankfull discharge.

Restoration Approach

Changes in watershed hydrology have increased the shear stress associated with storm flows. Initially this increased shear stress caused the channel to incise with a subsequent lowering of the bed elevation. Lowering of the streambed increased bank height, confined the channel and placed additional stress on the banks. Hydraulic forces eroding the toe of the banks resulted in steeper bank angles with increased susceptibility to gravitational failures. As these failures became common the channel adjusted laterally. Due to the high erosion potential of the banks, lateral migration rates will accelerate as meander development progresses. Currently the project reach is a G stream type (i.e., low width/depth ratio, and low entrenchment ratio). Left unchecked this condition will cause damage to the sewer line that parallels and crosses the channel in this reach.

Therefore, the long-term stabilization objectives for this reach of the Muddy Creek Tributary include:

1. Convert the unstable G channel into a stable B channel by excavating/constructing bankfull benches and grading both banks to create additional flood prone area;

2. Protect the exposed sewer line by burying it beneath the bankfull bench and shifting the thalweg;

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CASE STUDIES

3. Provide long-term bank stabilization and lateral control by establishing native grasses and shrubs along both banks.
CASE STUDIES

Natalie Drive
Sanitary Sewer Stabilization
Cross Section 1

Natalie Drive
Sanitary Sewer Stabilization
Cross Section 2
CASE STUDIES

Case Study #3 – Club Park Drive

Background Information

This case study involves the protection of an exposed sanitary sewer line located along Buena Vista Branch, a tributary to Silas Creek. The watershed area draining to this point is approximately 350 acres that includes single family and multifamily residential, institutional (i.e., schools) and commercial land uses. As with the other case study sites, increased storm flows have caused the stream channel to deepen and widen. The most significant problem associated with these channel adjustments has been damage to an eight-inch sewer line crossing encased in ductile iron (Fig. 5). As the streambed incised, the support structures for the pipe were undermined and became unstable. This in turn lowered the elevation of the pipe making gravity flow through the sewer line ineffective. A storm drain outfall that discharges into the channel just upstream from the sewer line crossing exacerbates the situation. The storm drain has no energy dissipation at its outlet and is contributing to the undermining of the structural supports. Currently the project reach is a G stream type (i.e., low width/depth ratio, and low entrenchment ratio). Left unchecked this condition will cause additional damage to the sewer line.

Fig. 5 – Photo taken looking downstream.
CASE STUDIES

Study Area

The study area for this study project includes the reach located downstream of Club Park Road (Fig. 6).

Methods

The stabilization design concepts were prepared based on observations made during a preliminary site visit and in-office analysis. The analysis and plan development involved:

1. Review of recent (2000) aerial photographs and topographic maps provided by the City;
2. Review of drainage area information derived by the City;
3. Entering field data for cross-sections surveyed by the City into a data analysis spreadsheet;
4. Computation of predicted bankfull channel dimensions and bankfull discharge utilizing the Bankfull Regional Curves for the Rural Piedmont of North Carolina (NRCS and NCS University, 1999) and Bankfull Regional Curves for the Urban Piedmont of North Carolina (Wilkerson, et. al., 1998);
5. Computation of bankfull channel dimensions and bankfull discharge for the project reach utilizing the survey data provided by the City and comparison to the predicted values from the regional curves;
6. Plotting of cross-sections for use in developing design cross-section plans;
CASE STUDIES

7. Preparation of plan view design base map utilizing hand drawn sketches developed during the preliminary site visit; and
8. Layout of stabilization design concept plans based on information derived from the preliminary site visit and data analysis, and utilizing the geomorphic principles set forth in the Natural Channel Design Approach to Stream Restoration (Rosgen, 1996).

Prior to developing final design plans a geomorphic assessment and detailed field surveys should be conducted along the project reach. Conducting a detailed survey will allow, among other things, verification of the bankfull channel and floodprone area, characterization of existing conditions, and confirmation that the concept represents the appropriate restoration approach for this site. In particular, the information obtained from the fieldwork will provide the design dimensions for the restored channel.

<table>
<thead>
<tr>
<th>Computational Method</th>
<th>Bankfull Cross-Sectional Area (ft²)</th>
<th>Bankfull Discharge (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural Regional Curve</td>
<td>14.3</td>
<td>39.1</td>
</tr>
<tr>
<td>Urban Regional Curve</td>
<td>42.95</td>
<td>248.7</td>
</tr>
<tr>
<td>Plotted Field Data and Manning’s Equation</td>
<td>63 (61.6 – 64.4)</td>
<td>260.3 (258.6 – 261.9)</td>
</tr>
</tbody>
</table>

Table 1. Computational methods used to estimate bankfull channel dimensions and bankfull discharge.

Restoration Approach

Typical of urban watersheds, changes in watershed hydrology have increased the shear stress associated with storm flows. Initially this increased shear stress caused the channel to incise with a subsequent lowering of the bed elevation. Lowering of the streambed increased bank height, confined the channel and placed additional stress on the banks. Hydraulic forces eroding the toe of the banks have resulted in lateral migration and steeper bank angles. These vertical and lateral adjustments have damaged the support structures for an eight-inch sewer line crossing. In addition, a storm drain outfall that discharges into the channel just upstream from the sewer line crossing is contributing to the undermining of the structural supports. Currently the project reach is a G stream type (i.e., low width/depth ratio, and low entrenchment ratio). Left unchecked this condition will cause additional damage to the sewer line.

Therefore, the long-term stabilization objectives for this reach of the Buena Vista Branch include:

1. Convert the unstable G channel into a stable B channel by excavating/constructing bankfull benches and grading both banks to create additional floodprone area;
CASE STUDIES

2. Install a cross vane to raise the streambed so that storm flows are conveyed over the sewer line and its support structures, provide grade control, dissipate energy, and divert storm flows into the center of the channel away from the banks;

3. Protect the exposed sewer line by burying it beneath the bankfull bench and in the sill of the cross vane;

4. Relocated and stabilize the storm drain outfall, such that it discharges over the right arm of the cross vane;

5. Provide long-term bank stabilization and lateral control by establishing native grasses and shrubs along both banks.
CASE STUDIES

Existing

Sanitary Sewer

Proposed

Cross Vane

Club Park Road
Sanitary Sewer Stabilization
Cross Section 1

Existing

Plunge Pool

Proposed

Club Park Road
Sanitary Sewer Stabilization
Cross Section 2
CASE STUDIES

Existing

Proposed

Club Park Road
Sanitary Sewer Stabilization
Longitudinal Profile
CASE STUDIES

Case Study #4 – Crafton Street Bridge

Background Information

This case study involves the stabilization of failing stream banks and the protection of a commercial property along Peters Creek, downstream from the Crafton Street Bridge. Peters Creek, a major tributary to Salem Creek, is highly urbanized from its headwaters to its confluence with Salem Creek. The watershed area draining to this point is 4.76 square miles. The reach down stream from the Crafton Street Bridge has developed very steep, vertical banks, which results in mass wasting during storm events. A building located just off the right bank of the stream has foundation damage due to the failure of the stream bank and owners of the property have dumped broken pieces of concrete onto the bank to prevent further damage (Figs. 7 - 9). Currently the project reach is an F stream type (i.e., high width/depth ratio, and low entrenchment ratio). Left uncorrected this condition will worsen and cause additional damage to the building. Intervention will be required to stabilize the banks and protect the building. Stabilizing this channel reach will also reduce sediment loading to Peters Creek and Salem Creek.

Fig. 7 – Photo looking upstream at the Crafton Street Bridge.
CASE STUDIES

Fig. 8 – View looking downstream from bridge. Note concrete rubble revetment along right bank and building at top of bank.

Fig. 9 – View looking downstream from bridge. The severely undercut left bank is obscured by the thick cover of Kudzu, which provides no protection for the bank.
CASE STUDIES

Study Area

The study area for this study project includes the reach located downstream of the Crafton Street Bridge (Fig. 10).

![Fig. 10 – Crafton Street Bridge Study Area.]

Methods

The stabilization design concepts were prepared based on observations made during a preliminary site visit and in-office analysis. The analysis and plan development involved:

1. Review of recent (2000) aerial photographs and topographic maps provided by the City;
2. Review of drainage area information derived by the City;
3. Entering field data for cross-sections surveyed by the City into a data analysis spreadsheet;
4. Computation of predicted bankfull channel dimensions and bankfull discharge utilizing the Bankfull Regional Curves for the Rural Piedmont of North Carolina (NRCS and NCS University, 1999) and Bankfull Regional Curves for the Urban Piedmont of North Carolina (Wilkerson, et. al., 1998);
5. Computation of bankfull channel dimensions and bankfull discharge for the project reach utilizing the survey data provided by the City and comparison to the predicted values from the regional curves;
6. Plotting of cross-sections for use in developing design cross-section plans;
7. Preparation of plan view design base map utilizing hand drawn sketches developed during the preliminary site visit; and
8. Layout of stabilization design concept plans based on information derived from the preliminary site visit and data analysis, and utilizing the geomorphic principles set forth in the Natural Channel Design Approach to Stream Restoration (Rosgen, 1996).

Prior to developing final design plans a geomorphic assessment and detailed field surveys should be conducted along the project reach. Conducting a detailed survey will allow, among other things, verification of the bankfull channel and floodprone area, characterization of existing conditions, and confirmation that the concept represents the appropriate restoration approach for this site. In particular, the information obtained from the fieldwork will provide the design dimensions for the restored channel.

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<tr>
<th>Computational Method</th>
<th>Bankfull Cross-Sectional Area (ft²)</th>
<th>Bankfull Discharge (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural Regional Curve</td>
<td>61.9</td>
<td>266.9</td>
</tr>
<tr>
<td>Urban Regional Curve</td>
<td>168.6</td>
<td>841.7</td>
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<tr>
<td>Plotted Field Data and Manning’s Equation</td>
<td>143.7</td>
<td>880.2</td>
</tr>
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</table>

Table 1. Computational methods used to estimate bankfull channel dimensions and bankfull discharge.

**Restoration Approach**

Historical changes in watershed hydrology have increased the shear stress associated with storm flows. This increased shear stress initially caused the channel to incise with a subsequent lowering of the bed elevation. Lowering of the streambed increased bank height, confined the channel and placed additional stress on the banks. Hydraulic forces eroding the toe of the banks have resulted in lateral migration and steeper bank angles, making them susceptible to gravitational failure. The building located adjacent to the right stream bank has foundation damage due to the failure of the stream bank and the property owners have dumped broken pieces of concrete onto the bank to prevent further damage. Currently the project reach is an F stream type (i.e., high width/depth ratio, and low entrenchment ratio). Left uncorrected this condition will worsen and cause additional damage to the building.

Therefore, the long-term stabilization objectives for this reach of Peters Creek include:
CASE STUDIES

1. Convert the unstable F channel into a stable B channel by excavating/constructing bankfull benches and grading both banks to create additional flood-prone area;

2. Remove the concrete rubble and grade the stream banks to create a more stable angle of repose;

3. Install a cross vane downstream of the bridge to divert storm flows into the center of the channel and away from the banks;

4. Provide long-term bank stabilization and lateral control by establishing native grasses and shrubs along both banks.
CASE STUDIES

Existing

Proposed

Crafton Street Bridge
Slope Stabilization
Cross Section
REFERENCES


13. Klein, R.D., 1985. Effects of Urbanization on Aquatic Resources. Tidewater Administration, Maryland Department of Natural Resources.


15. Legacy Citizens Steering Committee, 1999. The Legacy Comprehensive Plan, City-County Planning Board of Forsyth County and Winston-Salem, North Carolina
REFERENCES


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