Appendix 6-B

Stormwater Design Guidelines for Karst Terrain in Virginia

Adapted from CSN Technical Bulletin No. 1
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Developed by the CSN Karst Working Group

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by the Virginia Department of Conservation and Recreation

Appendix 6-B
Stormwater Design Guidelines for Karst Terrain in Virginia

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6-B.1.0. INTRODUCTION

This Appendix has been prepared for engineers, plan reviewers, and public works officials to guide better stormwater decisions when land is developed in karst regions of Virginia. Until now, available local and state guidance on this topic has been uneven, sometimes conflicting and certainly not comprehensive. An informal working group of the Chesapeake Stormwater Network (CSN) developed the guidance from which this Appendix was adapted.

This Appendix can be incorporated directly or by reference into local and state land development codes, ordinances, regulations, permits, and engineering manuals that govern how stormwater is managed in karst terrain. The Appendix has been designed as an evolving document so that it can be updated over time to reflect new research, experience and project implementation.

Several important caveats apply to this guidance. First, the effect of land development on karst terrain is complex and hard to predict, and it requires professional analysis to reduce the risk of geological hazards, damage to infrastructure, and groundwater contamination. Second, this guidance was produced to respond to the recent growth pressures in many small communities in the Ridge and Valley region of Virginia. There is concern that past approaches to stormwater and land development in karst terrain have been inadequate to safeguard the public and the environment.

While communities that incorporate this guidance into their development review process can reduce the incidence of infrastructure damage and groundwater contamination, there is always some inherent risk when development occurs on this sensitive terrain. Consequently, the best local approach is to craft stronger local comprehensive land use plans that direct new growth away from karst areas to more appropriate locations (although it is recognized that this will be challenging for communities that are completely underlain by karst).

The following references are excellent sources of information for developers, local governments or citizens living or working in areas underlain by karst topography: *Living On Karst: A reference guide for landowners in limestone regions*, 1997, by the Cave Conservancy of the Virginias, and *Living With Karst: A Fragile Foundation*, by the American Geological Institute, 2001. Definitions of unfamiliar words, terms and acronyms in this Appendix can be found in this Handbook glossary, which is an Appendix of Chapter 1 of this Handbook.

6-B.2.0. WHY IS KARST TERRAIN DIFFERENT?

Two of Virginia's major tributaries B the Potomac and the James Rivers B flow through karst country. This band of karst terrain runs through the Bay watershed, and encompasses portions of Maryland, Pennsylvania, Virginia and West Virginia (**Figure 6-B.1** below). (A Virginia-specific map can be found in **Section 6.7.1** of this Chapter.) Karst in Virginia is a dynamic landscape characterized by sinkholes, springs, caves, and a pinnacled, highly irregular soil-rock interface that is a consequence of the presence of underlying carbonate rocks such as limestone, dolomite and marble (Denton, 2008).

Karst is often referred to as a dissolving landscape. However, karst rarely develops from bedrock dissolution on human timescales, except where salt or other evaporites occur in the subsurface. However, bedrock can dissolve over geologic time to result in hidden voids in the subsurface, susceptible to soil cover collapse into these voids. So when building in a karst environment, the watchword is to *live lightly on the land.*

The karst terrain in Virginia is distinct from some other regions (e.g., Florida) in that the bedrock is very ancient and, in many areas, is deeply buried by residual soils. Consequently, many sinkholes form due to the collapse of surface sediments, which is typically caused by the intrusion of stormwater from the surface into deep, underlying voids.

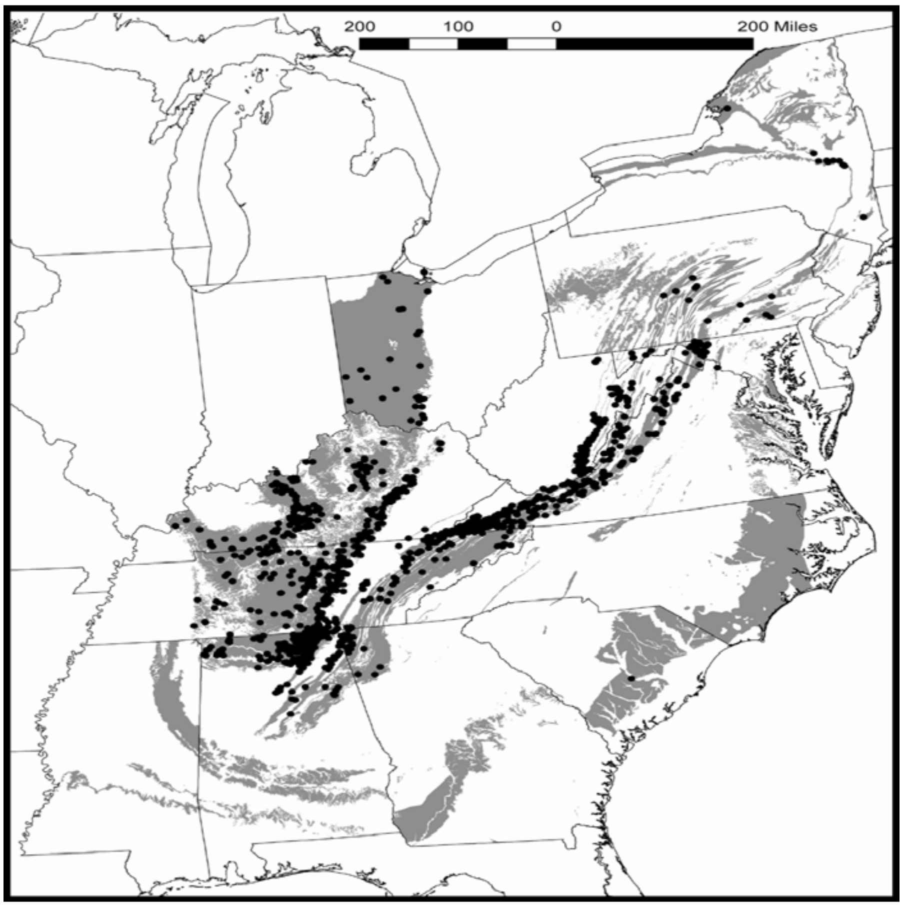

Figure 6-B.1. Karst Distribution in the Bay States
Note: grey = karst; black = caves (Source: Weary, 2005)

The presence of karst terrain within the Ridge and Valley Province (and select portions of the Piedmont Province) complicates the land development process and requires a unique approach to stormwater design. Significant cut and fill can aggravate karst issues. Some of the important considerations include the following.

Post Development Runoff Rates are Greatly Increased. In an undeveloped state, karst terrain produces about two-thirds less stormwater runoff than the Piedmont or Coastal plain (VA DCR, 1999). Even less runoff is produced if the site discharges into an existing sinkhole. As land is developed, however, the paved surfaces and compacted soils produce a much greater rate and volume of runoff. Three important consequences arise due to the increased runoff:

- More runoff is conveyed into a poorly defined surface drainage system that often lacks the capacity to handle it.
- More runoff greatly increases the risk of new sinkhole formation (e.g., collapse or subsidence), particularly if runoff is allowed to pond in the landscape. The increased risk for sinkholes may apply to the development site or to down-gradient off-site areas.
- Development-related changes that increase surface runoff could deprive the karst system of recharge, thereby causing a lowering of the water table and diminished spring flows. These changes can profoundly alter the hydrology of surface streams.

The implications of these risks are that highly distributed infiltration is preferred over focused infiltration, such as might occur in a large stormwater retention basin. Large basins and associated conveyances can be a problem in karst, but small ponds present much less risk. However, rain gardens and other small, distributed infiltration practices are best.

Highly Variable Subsurface Conditions. Karst terrain is notorious for its spatial variability, meaning that subsurface conditions and the consequent risk of sinkhole formation can change within a matter of yards across a development site. As a result, a sequence of karst feature analyses, geotechnical investigations and borings must be performed prior to site layout and the design of any stormwater practice to minimize the risk of a failure or other unintended consequences.

Surface/Subsurface Drainage Patterns are Poorly Understood. Drainage patterns are highly dynamic in karst terrain and involve a great deal of interaction between surface water and groundwater (see **Figures 6-B.2 and 6-B.3** below). Often, there is not a well-defined stream network that moves water to a downstream point. Furthermore, subsurface conduits commonly convey their flow in different directions than the overlying surface streams, in some cases crossing beneath topographical divides.

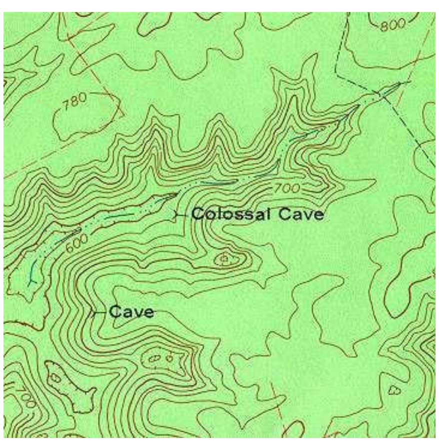

Figure 6-B.2. Typical Karst Topography

Figure 6-B.3. Typical Spring-Fed Stream

Site designers working in karst terrain face a confusing surface drainage pattern, full of losing streams, estravelles, turloughs, swallets and insurgences, which makes it hard to predict exact discharge points for runoff and groundwater. Therefore, designers need to think in three dimensions, rather than just two.

Lower Stream Density and More Karst Swales. Karst landscapes also have less perennial stream mileage per unit area than other physiographic regions. Consequently, many development sites in karst regions cannot discharge to the stream network within their property boundaries. This is a particular regulatory concern in Virginia, which requires that stormwater must discharge to an *adequate channel* (with defined bed and banks), a feature that may not be present at many sites in karst terrain (VA DCR, 1999).

Instead, much of the length of the headwater stream network in karst terrain is composed of karst swales, which appear as wide, shallow parabolic swales (Fennessey, 2003). Karst swales lack defined channels beds or banks, and may only briefly hold water during extreme storm events. Nevertheless, karst swales are an integral element of the natural drainage system and often exhibit significant infiltration capacity (SEA, 2000). The protection of natural karst swales is an important element of effective stormwater design in karst regions. However, soil and vegetation types common in karst swales, or other tell-tale signs, are rarely defined or delineated on soil or geology maps. Thus, where karst swales are suspected, their accurate delineation requires site-specific investigations by a professional geologist or soil scientist familiar with karst.

Rural Development Patterns and Growth Pressures. The karst region of Virginia has experienced primarily rapid, low-density growth in recent decades, and this trend is projected to continue in the future. The common rural development pattern involves large lot residential development and also many small lots or subdivisions constructed outside of water and sewer service areas. Consequently, many communities in karst terrain rely mainly on public or private wells to provide drinking water and septic systems to dispose of wastewater. Rural land development increases the demand on groundwater resources which, in times of drought, lowers the water table and causes wells to dry up. These problems are made worse when poorly designed stormwater management also reduces groundwater recharge within the same development.

Groundwater Contamination Risks. In karst terrain, contaminants in polluted runoff and spills often pass rapidly from the surface into groundwater, with little or no filtration or modification. In other cases, contaminants are "hung up" above the water table in the epikarst, releasing toxins into groundwater more gradually. The strong interaction between surface runoff and groundwater poses risks to the drinking water quality, upon which residents in karst terrain rely. Once an aquifer becomes contaminated, it is likely to be useless for a lifetime for consumption by humans and farm animals. As a result, designers need to consider groundwater protection as a first priority when they are considering how to dispose of stormwater, since there is always a risk that it will end up in the groundwater system.

Increased Sinkhole Formation **(Figures 6-B.4** and **6-B.5 below).** The increased rate of sinkhole formation caused by increased runoff from land development can result in damage to public infrastructure, roads and buildings. In addition, the existing drainage system may be further modified by land development, and then sinkholes may cause larger centralized stormwater practices to fail. Consequently, designers need to carefully assess the entire stormwater conveyance and treatment system at the site to minimize the risk of sinkhole formation. In most cases, this means installing a series of small, shallow runoff reduction practices across the site, rather than using the traditional pipe-to-pond approach.

Endangered Species. In some cases, development sites may have a subsurface discharge to caves, springs and surface streams that are home to rare, threatened or endangered species that are legally protected or otherwise merit special protection (e.g., cave-obligate aquatic and terrestrial invertebrates, bats and aquatic fauna in surface streams). Designers are required by federal law to screen for the presence of rare, threatened or endangered species to minimize project impact to habitat and ensure the project complies with the legal protections afforded under the Endangered Species Act. Designers should consult the Virginia Department of Conservation and Recreation's (DCR) Division of Natural Heritage for assistance with screening for threatened or endangered species.

Figure 6-B.4. A House Destroyed by a Sinkhole.

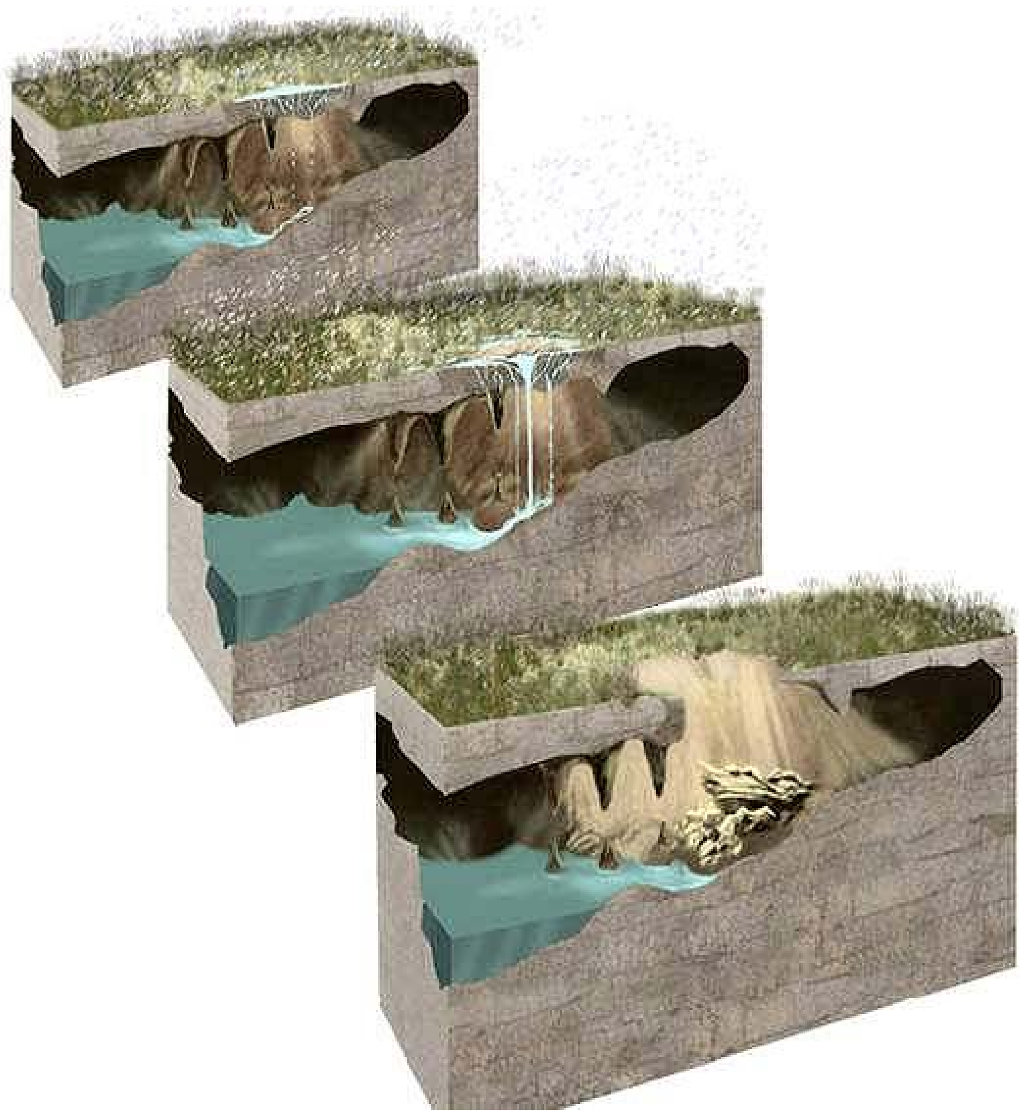

Figure 6-B.5. Schematic of Sinkhole Formation

6-B.3.0. A UNIFIED APPROACH FOR STORMWATER DESIGN IN KARST TERRAIN

This Appendix outlines a sequence of investigations to provide an adequate basis for stormwater design for any site underlain by limestone, dolomite and marble. These special studies are organized in the flow chart on the next page. The flow chart outlines a series of questions about the nature of the development. Based on the answers, designers can determine whether a special analysis is needed, and in which section of this Appendix they can find more information about it. The flow chart in **Figure 6-B.6** below was synthesized from several sources, including the Minnesota Stormwater Manual (2006), VA DCR (1999), CCDP (2007), MDE (2000) and PADEP (2006). It is important to note that flow chart is intended solely as a guide for stormwater management design; it is not meant to be used as a prescriptive process for local stormwater plan review.

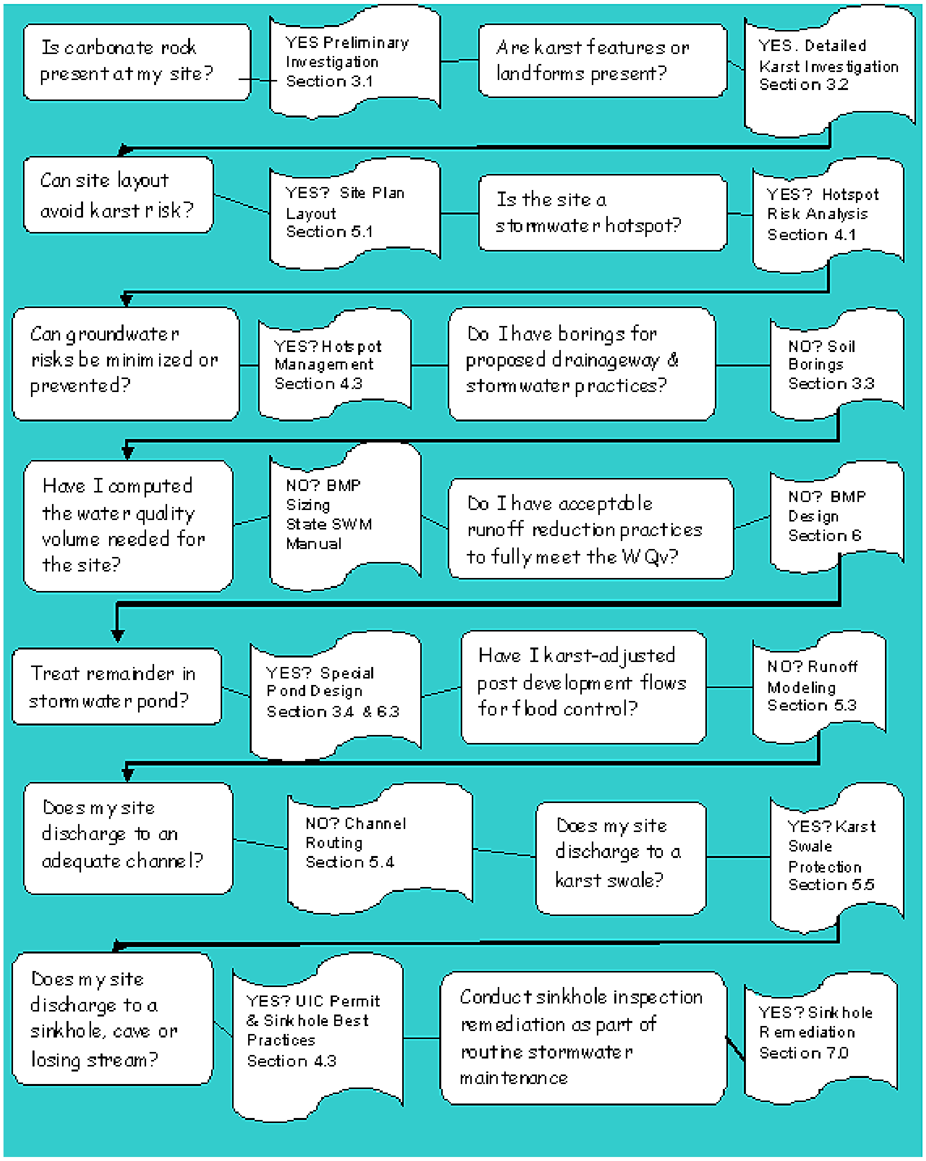

Figure 6-B.6 Flow Chart for Stormwater Design in Karst Terrain

6-B.4.0. PRELIMINARY AND DETAILED SITE INVESTIGATIONS FOR KARST

6-B.4.1. Introduction

Percolation of surface water can cause a migration of soil into solution cavities, forming "sinkholes" at the surface. Sinkholes cause instability of the land surface and must be given serious consideration in the development of erosion and sediment (E&S) control and stormwater management (SWM) plans. Sinkhole formation is often accelerated by construction activities that modify a site's hydrology or disturb existing soil and bedrock conditions. Ground failure in karst areas is most often caused by the alteration of drainage patterns, construction of impervious coverage, excessive grading, and the increased weight of site improvements.

An awareness of the limitations to site development posed by karst features can prevent problems, including damage to property, structures and life, and contamination of ground water. Appropriate site testing, planning, design, and remediation helps to prevent sinkhole formation during site development. Conventional methods of design and engineering may be inappropriate for karst areas. Often minor modifications in the approach to site testing and design can prevent persistent and costly post-development problems.

6-B.4.2. Preliminary Site Investigation

Site evaluation for karst features is usually carried out in two phases: (1) a *preliminary site investigation*, done prior to site design and development, and (2) a *site-specific investigation*, conducted once the decision is made to design a site plan and proceed with development.

Developers need to undertake a ***preliminary site investigation*** prior to conducting any design work for projects or building in areas known to be prone to karst. The level of investigation depends on the probability of karst being present and the local regulatory requirements. The purpose of the preliminary investigation is to identify areas of concern that may require additional investigation, and to review the preliminary site design in relationship to potential problem areas. The preliminary site investigation will often result in immediate changes to the site layout to avoid future problems.

Various methods are available to collect information about the bedrock and soil conditions at a proposed development site. The preliminary site investigation involves analysis of easily obtainable geological maps, topographic maps, soil surveys, and aerial photography.

Geologic maps contain information on the physical characteristics and distribution of the bedrock and/or unconsolidated surficial deposits in an area. Geologic features such as the strike and dip of strata, joints, fractures, folds, and faults are usually depicted. The orientation of strata and geologic structures generally controls the location and orientation of solution features in carbonate rock. Geologic contacts, faults, and certain fractures sets may be more prone to solution than others. The relationship between topography and the distribution of geologic units may reveal clues about the solubility of the specific rock units. Geologic maps are often available at various scales, the most common being 1:24,000. Digital geologic data may be available as well. Geologic maps can be obtained from the Virginia Department of Mines, Minerals and Energy, Division of Mineral Resources.

*Topographic map*s contain information about the relative positions and elevations of natural or man-made features of an area (e.g., buildings, roads, plains, hills, mountains, degree of relief, steepness of slopes and other physiographic features) related to the contours and configuration of the earth's surface. Topographic maps are typically available at architectural/engineering supply, reprographic, and outdoor supply businesses. Topographic maps are also available at various scales, the most common being 1:24,000.

County soil surveys show the distribution of soil types or other soil mapping units in relation to the prominent physical and cultural features of the Earth's surface. Soil surveys can be obtained from the local office of the U.S. Department of Agriculture of the local Soil and Water

Conservation District. USDA and Virginia Soil Survey soils maps commonly indicate sinkholes and other karst features, even if in cases where such features are too small to be visible on a 1:24,000 topographic map.

Aerial photographs provide a simple, quick method of site reconnaissance. Most localities have access to the 2002 and 2006-7 Virginia Geographic Information Network (VGIN) photographs at scales ranging from 1:100 for urban areas to 1:400 for rural areas. Google Earth is also a valuable tool for picking up landscape features that may not be visible on topographic maps. Inspection of photos can quickly reveal vegetation and moisture patterns that provide indirect evidence of the presence of cavernous bedrock. Piles of rock or small groups of brush or trees in otherwise open fields can indicate active sinkholes or rock pinnacles protruding above the ground surface. Circular and linear depressions associated with sinkholes, and linear solution features and bedrock exposures are often visible when viewed using stereo imagery. Inspecting photos taken on more than one date can be especially valuable in revealing changes that take place over time. Images defined at wavelengths other than visible light can be useful in detecting vegetative or moisture contrasts. Aerial photography is available from various state and federal agencies as well as from some private vendors.

LIDAR and other high resolution remote sensing data. Many Virginia localities have LIDAR (Light detecting and ranging) digital elevation maps with sub-meter vertical resolution. This data allows for very fine delineation of surface topographic features, including karst features such as sinkholes, as well as the watersheds draining to individual features.

The preliminary site investigation should also include screening for proximity to known caves. This can be accomplished through inquiries to DCR's Division of Natural or by directly searching relevant state cave surveys.

The ***site-specific investigation*** includes collecting subsurface information at sites identified during the preliminary investigation as potential problem areas. During the site-specific investigation process, the experienced professional studies the site terrain in an effort to detect the signs of ground subsidence and to locate any obvious karst features, such as rock outcrops, sinkholes, springs, caves, etc. An on-site reconnaissance is an inexpensive, important step in finding potential site constraints.

Although many karst features are obvious to the eye, it is an advantage to conduct the site visit with an individual knowledgeable about karst geology. Prior to the site visit, field personnel should have reviewed the relevant resources described above to identify where problems might be found. It is important to review drainage patterns, vegetation changes, depressions, and bedrock outcrops to find evidence of ground subsidence. Sinkholes in subdued topography can often only be seen at close range. Disappearing streams are common in karst areas, and bedrock pinnacles that can be a problem in the subsurface will often protrude above the ground surface.

A simple and effective but often overlooked source of information during the site visit is an interview of the property owner. Often property owners can recount a history of problems with ground failure that may not be evident at the time of the site evaluation.

The product of the preliminary site investigation is usually a site map, which shows the location of any known or suspected karst features for later reference. These can be compared to other information collected to assess the potential risk of karst-related problems. It is important to understand that the while the presence of sinkholes or caves indicates the presence of karst, their absence does not necessarily mean that karst will not cause problems at the site (Hubbard 2004).

6-B.4.3. Detailed Site Investigation

Detailed site investigations are required in the design of all buildings, roads, stormwater conveyances and centralized stormwater facilities proposed within karst areas. The purpose of the investigation is to develop a **karst feature plan** that identifies the location and elevation of subsurface voids, cavities, fractures and discontinuities. The presence of any of these features could pose a danger to groundwater quality, a construction hazard, or an increased risk of sinkhole formation at a proposed centralized stormwater facility.

The scope of the geotechnical investigation should reflect the size and complexity of the development project. No single investigative approach works in every location. The sequence begins with a visual assessment of diagnostic karst features, and analysis of subsurface heterogeneity through geophysical investigation and/or excavation. Based on this information and the preliminary site plan, the number and pattern of test pits, test probes, soil borings, geophysical instruments or other observations needed to adequately characterize subsurface conditions can be determined by the geotechnical consultant and the requirements of the local reviewing authority. The following are some of the techniques that can be used in the detailed site investigation.

Test pit excavations are a simple, direct way to view the condition of soils that may reveal the potential for ground subsidence, and to inspect the condition and variability of the limestone bedrock surface where bedrock is sufficiently shallow. Soil texture is an important indicator of soil strength and, therefore, the ability of soils to bridge voids. An inspector should look for evidence of slumping soils, former topsoil horizons, and fill material (including surface boulders, organic debris, and other foreign objects) in the test pit. Voids in the soil or underlying bedrock can be revealed. The presence of organic soils at depth is an indicator of potentially active sinkhole sites. Leached or loose soils may also indicate areas of existing or potential ground subsidence. Observations of this type should be recorded in the soil log.

Test probes are performed by advancing a steel drill bit into the ground using an air-percussion-drilling rig. Probes can be installed rapidly and are an effective way to quickly test subsurface conditions. Penetration depths are usually less than 50 feet. During the installation of a test probe the inspector should be aware of the rate of advance of the drill bit, sudden loss of air pressure, soft zones, free-fall of the bit, and resistant zones. These observations can provide clues to the competency of the bedrock and the presence of cavities in soil or bedrock. The volume of fluid cement grout needed to backfill the probe hole can yield a measure of the size of subsurface voids encountered during drilling.

Soil borings can yield virtually complete and relatively undisturbed soil and rock samples. Borings may provide direct evidence of the presence and orientation of fractures, weathering, fracture fillings, and the vertical dimensions of cavities. They provide undisturbed samples that can be subjected to laboratory testing. However, it is possible that a set of borings could be located so that they miss key subsurface features and, therefore, do not accurately represent karst features under the surface. Soil borings can also create the conditions for surface collapses if they are not properly filled and sealed.

Use of a split inner core barrel in rock coring provides the most meaningful results, because this method collects a relatively undisturbed sample in the core barrel. Losses of drilling fluid can indicate the presence of soil or rock cavities. As with test probes, the volume of fluid cement grout placed to seal the drill hole can also yield a measure of the size of openings in the subsurface.

Once the general character of the surface cover is understood, borings are used to reveal its characteristics at specific locations at the site where construction is planned. The extreme spatial variability in subsurface conditions cannot be over-emphasized, with major differences seen a few feet away. Therefore, the consultant should obtain borings:

- Into suspected zones of bedrock solution;
- Adjacent to sinkholes or related karst features at the site;
- Along known zones of bedrock solution, or along known zones of geologic weakness, such as faults or fracture traces, including alignment of sinkholes;
- Adjacent to bedrock outcrop areas;
- Within the planned boundaries of any centralized stormwater facility;
- Through surficial materials to determine depth to bedrock; and
- Near any areas identified as anomalies from prior geophysical or subsurface studies.

The number and depth of borings at the site will depend entirely on the results of the subsurface investigations, the experience of the geotechnical consultant and the requirements of the local review authority. All borings or excavations should include the following:

- Descriptions, logged data and samples over the entire depth of the boring;
- Descriptions of any stains, odors, or other indications of environmental degradation;
- A minimum laboratory analysis of two soil samples representative of the material penetrated, including potential limiting horizons, with the results compared to field descriptions;
    - Minimum identified characteristics should include color, mineral composition, grain size, shape, sorting and degree of saturation;
- Any indications of water saturation should be carefully logged to include both perched and ground water table levels, and descriptions of soils that are mottled and gleyed. Note that groundwater levels in karst terrain can change dramatically in a short period of time and will not always leave evidence of mottling or gleying;
- Water levels in all borings should be fully open to a total depth that reflects seasonal variations in water level fluctuations; and
- A record of the estimates of soil engineering characteristics, including “N” or the estimated unconfined compressive strength, from a standard penetration test.

At the locations of centralized stormwater management facilities, the density of soil borings must result in a representative sampling over the area of the proposed facility. In general, a minimum of five borings must be taken for each centralized stormwater facility (or five per acre, whichever is greater), with at least one on the centerline of the proposed embankment and the reminder within the proposed impoundment area. For carbonate rocks, borings should extend at least 20 feet below the bottom elevation of the proposed centralized stormwater facility. Where refusal is encountered, the boring may either be extended by rock coring or moving to an adjacent location within 10 linear feet of the original boring site, in order to attain the 20 foot minimum depth. Upon completion, the boring should be backfilled with an impermeable plugging material such as grout mixed with bentonite, particularly when the boring intercepts subsurface voids.

Geophysical methods can serve as a rapid reconnaissance tool to detect physical anomalies in the subsurface that may be caused by karst features. Geophysical evaluations are often preferred over exclusive soil borings. There are many different techniques to reveal the nature of subsurface conditions in karst terrain, including:

- Electric resistivity tomography
- Seismic refraction
- Gravity surveys
- Electromagnetic (EM) inductance/conductivity surveys

These methods are especially suited to surveying linear corridors, and they are non-disruptive to the land. Geophysical data are often useful for extrapolating between locations where different sampling methods are used. Generally it is advisable to apply more than one geophysical technique, owing to the variability in physical properties of karst terrain. Geophysical methods require an experienced professional to interpret the data collected. The properties of weathered limestone, including a highly variable bedrock surface and soils with high clay content, often hinders the depth of penetration and resolution of geophysical signals, which can compromise the effectiveness of geophysical surveys. Despite these limitations, geophysics can sometimes provide a cost-effective, relatively rapid means of determining the potential for problems with karst features, including the location of shallow bedrock and significant cavities in the soil or bedrock. Geophysical anomalies should be targeted for additional direct testing procedures.

Electric resistivity tomography (see **Figure 6-B.7** below) has proven to be a particularly useful technique to identify subsurface anomalies at a scale that impacts stormwater design. This method allows high resolution imaging of features in the shallow subsurface. These surveys provide a qualitative evaluation of the site area and may identify “suspect areas” to be further evaluated by borings. The use of these surveys may reduce the total number of soil borings by narrowing down the locations of suspect areas at the site.

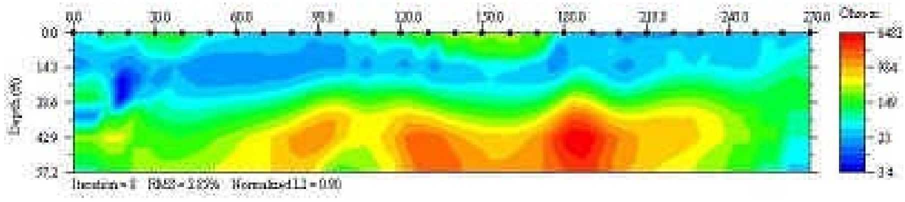

Figure 6-B.7. An Electric Resistivity Tomography Printout

Dye tracing. If karst features are expected to receive additional runoff after land development, it is advisable to conduct dye tracing to determine the flow direction of water entering the subsurface and the distance the water travels within the subsurface feature. Stormwater designers should retain the services of a qualified karst hydrologist or hydro-geologist to perform the trace. Also, designers are advised to coordinate with state natural resource agencies prior to initiating a trace to acquire pre-existing information on karst hydrology in the area and avoid potential cross-contamination with dyes from other investigations. Lastly, designers should notify local emergency response staff prior to introducing dye into the aquifer.

6-B.4.4. Specific Site Data To Be Obtained

Site and stormwater designers should retain the services of a qualified consultant experienced in working in karst landscapes. The investigation should determine the nature and thickness of subsurface materials including the depth to bedrock and the water table in area of the site where construction is planned. The investigation is an iterative process that may need to be expanded until the desired amount of detailed knowledge of the site is collected and fully understood. Pertinent site data to be obtained includes the following:

- The locations and descriptions of sinkholes, closed depressions, grikes and solution-enlarged voids. Note the dimensions of sinkholes, voids, and closed depressions (approximate depth, width, length). Descriptions of closed depressions should include other notes, such as cover collapse, open throat, bedrock or soil throat, ponding, rock collapse, rock fill, or other types of improvements.
- Bedrock characteristics (e.g., type, geologic contacts, faults, geologic structure).
- Overlying soil characteristics (type, thickness, spatial variability, mapped unit, geologic parent/history, infiltration rate, depth to seasonally high water table).
- Identification/verification of geological contacts if present, especially between karst and non-karst formations.
- A photo-geologic fracture trace map.
- The locations of bedrock outcrop areas.
- The locations of cave openings.
- The locations of springs.
- The locations of perennial, intermittent and ephemeral streams and their flow behavior and surface or subsurface discharge points (e.g., losing or gaining streams), channels and surface drainage network.
- The locations of site-scale watershed or drainage area boundaries based on large scale site topography (i.e., one foot or less contour intervals).

- The locations of public and private wells, at a minimum, within 1/4-mile of the site. However, to be thorough, wells within up to 10 miles (reflective of the direction of subsurface flow and the distance of the discharge's flow) of the site should be located because they could very well be at risk.
- The layout of proposed buildings, roads, and stormwater management structures (and estimated locations and areas of site impervious and turf cover).
- The existing stormwater flow pattern.

The record of findings during this phase of the investigation includes logs of test pits, probes and borings, notes about evidence of cavities in soil and rock, loss of air pressure or drilling fluid during drilling, and the condition of soil and bedrock determined from samples collected. If unstable subsurface conditions are encountered, a decision can be made to (1) remediate the instability prior to construction or (2) to modify the site layout to avoid problem area(s).

6-B.4.5. Plan Submission

Consultants should identify and locate karst features, including suspected areas of ground subsidence, and submit these with both the development and stormwater management plan for the proposed site. Any existing sinkholes should be surveyed and permanently recorded on the property deed. Where these exist, an easement, buffer or reserve area should be identified on the development plat for the project so that all future landowners are aware of the presence of sinkholes on their property.

These findings should be compared to the proposed layout of site facilities and the site plan adjusted, wherever feasible, so that facilities are sited to avoid suspected areas of potential ground subsidence or sinkholes. Ideally, the site plan should minimize major site disturbance, especially cuts and fills. The amount of impervious cover on the site should be minimized to reduce stormwater runoff. Wells and septic systems should be located sensibly.

Alteration of drainage patterns should also be avoided, or at least minimized, to protect existing flow paths (such as karst swales). Where relocation of facilities is not practical, remedial measures and design standards can be employed to minimize the likelihood of failure. Remedial sealing of voids in the soil or bedrock and/or compaction of soil and rock voids may be viable measures in some areas.

At least one subsurface cross-section should be submitted with the stormwater plan, showing confining layers and depth to bedrock and the water table, if encountered. The cross-section should extend through the center-line of the proposed centralized stormwater facility, using actual geophysical and boring data. A sketch map or construction drawing indicating the location and dimension of the proposed facility should be included for reference to the identified subsurface conditions.

6-B.5.0. ASSESS FUTURE RISK OF GROUNDWATER CONTAMINATION

6-B.5.1. Designation of Stormwater Hotspots

Another key task in karst terrain is to assess whether the proposed operation or activity being built has a significant risk of becoming a future stormwater hotspot. Stormwater hotspots are operations or activities that are known to produce higher concentrations of stormwater pollutants and/or have a greater risk for spills, leaks or illicit discharges. **Table 6-B.1** presents a list of potential land uses or operations that may be designated as stormwater hotspots. It is important to understand that the actual hotspot generating area may only occupy a portion of the entire drainage area, and that some "clean" areas (such as rooftops or buffer areas) can be diverted away to another infiltration or runoff reduction practice. Communities should carefully review development proposals to determine if any future operation, on all or part of the site, should be designated as a stormwater hotspot. Also, it is important to note that practices that qualify as "injection wells" (see **Section 6-B.5.3** below) create potentially severe hotspot risks for groundwater resources and drinking water contamination.

Table 6-B.1. Potential Stormwater Hotspot and Site Design Responses

Potential Stormwater Hotspot Operation [1]	**SWPP Required?**	**Restricted Infiltration**	**No Infiltration**
Facilities w/NPDES Industrial permits	Yes	■	■
Public works yard	Yes		●
Ports, shipyards and boat/ship repair facilities	Yes		●
Railroads and railroad equipment storage	Yes		●
Auto and metal recyclers/scrap yards	Yes		●
Petroleum storage facilities	Yes		●
Highway maintenance facilities	Yes		●
Wastewater, solid waste, composting facilities	Yes		●
Industrial machinery and equipment	Yes	●	
Trucks and trailers	Yes	●	
Aircraft maintenance areas	Yes		●
Fleet storage areas	Yes		●
Parking lots (40 or more parking spaces)	No	●	
Gas stations	No		●
Highways (2500 ADT)	No	●	
Construction business (paving, heavy equipment storage and maintenance)	No	●	
Retail/wholesale vehicle/ equipment dealers	No	●	
Convenience stores/fast food restaurants	No	●	
Vehicle maintenance facilities	No		●
Car washes (unless discharged to sanitary sewer)	No		●
Nurseries and garden centers	No	●	
Golf courses	No	●	

Key: ■ Depends on facility ● Definitely restricted

The shaded Area highlights commercial facilities or operations not technically required to have NPDES permits, but can be designated as potential stormwater hotspots by the local review authority, as part of their local stormwater management ordinance.

[1] For a full list of potential stormwater hotspots, consult Schueler et al (2004).

Designation of a site as a hotspot influences how much runoff must be treated and whether it can be infiltrated or discharged to a sinkhole. A range of stormwater treatment and pollution prevention practices can be applied to prevent contamination of surface runoff or groundwater, particularly when the hotspot discharges to a community drinking water supply or wellhead protection area. Depending on the severity of the hotspot discharge, one or more of the management strategies outlined in **Section 5.2** of this Appendix may be required by the local review authority.

6-B.5.2. Management Strategies for Stormwater Hotspots in Karst Areas

As shown in **Table 6-B.1**, if a future operation at a proposed development project is designated as a stormwater hotspot, then one or more of the following management actions are required.

- **Stormwater Pollution Prevention Plan (SWPPP)**. This plan is required as part of an industrial, municipal, or general construction stormwater permit. It outlines pollution prevention and treatment practices that will be implemented to minimize polluted discharges from the site. Other facilities or operations are not technically required to have NPDES permits (shown in the shaded areas of **Table 6-B.1** above), but can be designated in the local stormwater management ordinance as potential stormwater hotspots. An addendum should be included in the stormwater management plan for each designated hotspot facility to provide details regarding the pollution prevention practices and employee training measures that will be used to reduce contact of pollutants with rainfall or snowmelt.
- **Restricted Infiltration**. A minimum of 50% of the total Treatment Volume (T_v) must be treated by a filtering or bioretention practice ***prior*** to any infiltration. Runoff from portions of the site that are not associated with the hotspot generating area should be diverted away and treated by an appropriate stormwater practice.
- **Infiltration Prohibition.** If a site is classified as a potentially severe hotspot, the risk of groundwater contamination is so great that infiltration of stormwater must be ***prohibited*.** In these cases, an alternative stormwater management practice, such as a closed bioretention facility, a sand filter, or a constructed wetland must be used to filter the entire T_v before it is discharged to surface water or reaches the groundwater.

6-B.5.3. Underground Injection Control Permits

The Safe Drinking Water Act regulates the infiltration of stormwater in certain situations pursuant to the Underground Injection Control (UIC) Program. The UIC regulations are intended to protect underground sources of drinking water from potential contamination. Depending on their design, some stormwater infiltration practices and ***all*** improved sinkholes can be potentially regulated as “Class V” underground injection wells. In Virginia, the UIC Program is administered by the USEPA, Region III (Philadelphia). Where the EPA administers the UIC program, Class V wells are “rule- authorized”, meaning that they do not require a permit, but the operator must contact the agency to provide an inventory of their well. Consult **Section 11** of this Appendix for more specific contact information.

Typically, Class V wells are shallow wells used to place a variety of fluids directly below the land surface. By definition, a well is “any bored, drilled, or driven shaft, or dug hole that is ***deeper than its widest surface dimension***, or an improved sinkhole, or a subsurface fluid distribution system.”

In karst terrain, improved sinkholes are the most common type of Class V well that will be encountered, although some infiltration practices may also qualify. Injection wells located in karst topography create a significant risk of groundwater contamination.

Federal regulations require all owners and operators of Class V wells to submit information to the appropriate state or federal authority. This includes the facility name and location, the name and address of a legal contact, ownership of the property, the nature and type of injection well(s), and the operating status of the injection well. Additional information on Class V well requirements can be accessed online at:

http://water.epa.gov/type/groundwater/uic/class5/regulations.cfm

The applicable regulatory authority then reviews this inventory data and may (1) determine the injection is authorized, (2) require more information, (3) issue a UIC permit with best management practice requirements, or (4) order the well closed. Given the risk of groundwater contamination, the locations of public and private wells should be identified, at a minimum, within 1/4-mile of the site. However, to be thorough, wells within up to 10 miles of the site (reflective of the direction of subsurface flow and the distance of the discharge's flow) should be located because they could very well be at risk.

Class V well requirements are primarily triggered by two conditions in karst terrain. The first and most serious condition is when increased post-development runoff is directed to an ***"improved sinkhole."*** The EPA defines an "improved sinkhole" as a naturally occurring karst depression or other natural crevice, which has been modified by a man-made structure to direct fluids into the subsurface. The EPA defines man-made structures to include pipes, swales, ditches, excavations, drains, graded slopes, or any other device that is intended to channel fluids toward or into a sinkhole

In Virginia, this definition would also include directing increased stormwater runoff volumes into an existing sinkhole from new upland development. The act of directing increased stormwater runoff from developed land into a sinkhole or other karst feature constitutes a "modification" and as such, becomes a de facto *improved* sinkhole requiring that the developer or owner obtain an EPA authorization and provide the required inventory of the facility. This is even true if the improved sinkhole is downstream of stormwater treatment practices, either on the site of off-site. Discharges to improved sinkholes on adjacent downstream properties are only allowed when appropriate legal agreements are made with the owner(s) of the property where the improved sinkhole is located. Since guidance on this matter is thin (i.e., what is the reasonable proximity between a discharge and a receiving sinkhole to result in the sinkhole being declared "improved?"), when in doubt, the developer should coordinate with the EPA and let the EPA make the call.

The second situation where a UIC authorization may be required is for certain "dug-out" stormwater practices that infiltrate runoff into the subsurface, or have a subsurface fluid distribution system. The specifications for the stormwater practices referred to in this Appendix have been created to avoid classification as Class V injection wells. The new Virginia stormwater management BMP design specifications include criteria regarding minimum geometric dimensions, surface pre-treatment, soil filtering, and design of "closed practices" that have filter fabric or under drains which daylight to the surface. These design specifications can be found on the Virginia Stormwater BMP Clearinghouse web site at:

http://www.vwrrc.vt.edu/swc/NonProprietaryBMPs.html

6-B.5.4. Stormwater Discharges to Improved Sinkholes

Under some circumstances, post-development stormwater must be discharged into an existing sinkhole or other karst feature. This may occur where significant portions of a site are internally drained and/or the majority of a site is underlain by karst. In other cases, it may be desirable to maintain pre-development flows to the existing sinkhole in order to maintain the subsurface hydrology. In either case, the following rules apply:

- The design goals are (1) to prevent *increased* runoff volumes from discharging to the sinkhole, but (2) to maintain the discharge at the level of the pre-development runoff volume, in order to maintain groundwater recharge.
- The applicant should ensure that known carcinogens, neurotoxins, drinking water pollutants and substances otherwise known to harmful to the health of humans, livestock and poultry will not be funneled underground into an aquifer.
- The sinkhole or karst feature receiving post-development stormwater runoff must be registered as a Class V Injection Well.
- The designer should conduct a survey to identify public or private drinking water wells within, at a minimum, 1,500 feet of the improved sinkhole. However, to be thorough, wells within up to 10 miles of the site (reflective of the direction of subsurface flow and the distance of the discharge’s flow) should be located because they could very well be at risk.
- As such, the designer must notify the USEPA Region III office and must submit data on any drinking water wells identified in the survey. Keep in mind that an underground injection well authorization will be extremely difficult to obtain if the proposed land use or operation at the site is designated as a severe stormwater hotspot.
- DEQ strongly recommends that a dye trace be performed to understand in what direction and how far additional stormwater flows will move through the groundwater, particularly if drinking water wells are located nearby.
- The designer should maintain both the quality and quantity of runoff at pre-development levels prior to discharge into an existing sinkhole. Operationally, this means that the designer must treat the full Treatment Volume (produced by 1 inch of rainfall) in an acceptable runoff reduction practice before discharging to a sinkhole.
- A commitment to the operation and maintenance of stormwater practices (e.g., a maintenance agreement) must be included as a condition of the required underground injection authorization issued by the USEPA, Region III.

6-B.6.0. GENERAL STORMWATER DESIGN PRINCIPLES IN KARST AREAS

The following are general principles that should be considered in site layout and the design of stormwater management systems.

6-B.6.1. Site Design

Site design and construction procedures can be important in reducing the risk of sinkhole development. Sinkholes most often form in areas where storm-water runoff is concentrated, where bearing loads are concentrated, and where ground water is pumped out in large volumes. When development is proposed, consideration should be given to the following general guidelines to minimize the risk of ground failure:

- Designers should perform the preliminary and detailed site investigations prior to beginning site and stormwater design to fully understand the subsurface conditions, assess karst vulnerability, and define the actual drainage pattern present at the site.
- Any existing sinkholes and karst swales should be surveyed and permanently recorded on the property deed or plat. In addition, an easement, buffer or reserve area should be identified on the development plat for the project so that all future landowners are aware of the presence of these features.
- Minimize site disturbance and changes to soil profile, including cuts, fills, excavation and drainage alteration, near karst features.
- Require notification procedures on the design plans for both erosion and sediment control and stormwater management.
- Increase setbacks from building and other infrastructure.
- Minimize the amount of impervious cover created at the site so as to reduce the volume and velocity of stormwater runoff generated.
- Employ storm-water management measures that minimize flow velocities and ponding to avoid erosion of over-saturated of soils.
- Take advantage of subsurface conditions when locating building pads and place foundations on sound bedrock. To ensure this, take soil borings at key locations near buildings, roads, conveyances and at centralized stormwater management facilities. The number and depth of borings depends on the karst feature plans and local requirements.
- The location of new or replacement septic systems near improved sinkholes may be regulated by the local public health authority associated with the Virginia Department of Health. It is typically recommended that septic systems should be located at least 100 feet away from the base of an existing or remediated sinkhole.
- Designers should place a high priority on preserving as much of the length of natural karst swales present on the site as is feasible, in order to increase infiltration and accommodate flows from extreme storms

6-B.6.2. Erosion and Sediment Control Principles for Karst Areas

The selection, design, and implementation of E&S Control practices in karst areas should be guided by the following objectives and should incorporate the following design elements:

- The site should be designed to take maximum advantage of topography. Modifications of site topography should be minimized.
- Changes to the existing soil profile, including cuts, fills, and excavations, should be minimized.

- Where practical, drainage facilities should consist of embankments at or above grade. Excavation into the existing soil profile to construct swales and basins should be minimized to the degree possible.
- Temporary and final grading of the site should provide for drainage of storm-water runoff away from structures.
- All SWM facilities, including grassed waterways, diversions and lined waterways, should be designed to disperse the flows across the broadest channel area possible. This reduces the level of soil saturation and reduces the potential for soil movement. Shallow trapezoidal channel cross-sections are preferred over parabolic or V-shaped channels.
- Sediment traps and basins should only be used as a last resort for sediment control in karst areas, after all other erosion and sediment control options have been considered and determined to be inadequate. In the rare instance they are employed, they should serve small drainage areas (2 acres or less) and be located away from known karst features. The ESC plan should attempt to minimize drainage area sizes and therefore the need for basins or large traps.
- Vegetative cover should be established as rapidly as possible over exposed areas of soil. Construction scheduling should strive to minimize the time that soil excavations are open and non-vegetated. This reduces the time that the site is exposed to periods of concentrated flows as well as preventing excessive drying of soils.
- Utility trenches should be back-filled with in-situ soils or low permeability fill material, in order to discourage sub-surface water flow along the trench. Clay dams should be used at intervals along the trench excavation to impede subsurface flow along the trench. Trench backfill should be compacted to prevent future settlement and ponding. Backfill densities for open areas should exceed 90% of ASTM D-1557 maxima. Densities for areas supporting structures such as roadways should equal or exceed 95% ASTM D-1557 maxima.
- All underground piping should be waterproof and have water-tight fittings to minimize underground leaks. Leaks weaken and erode soils around underground conduits. The piping should be designed to withstand some limited displacement due to the probable ground settling and/or downward migration of trench bedding material into solution features.

6-B.6.3. Response to/Remediation of Sinkholes Occurring During Construction

It is possible for sinkholes to form during construction of a project (**Figure 6-B.8**). Sinkholes that occur during construction should be repaired immediately to prevent their enlargement and associated adverse impacts.

When sinkholes occur during construction, the site superintendant should take the following steps:

- Report the occurrence to the local plan approving authority within twenty-four (24) hours of discovery.
- Halt construction activities in the immediate area of the sinkhole until it is stabilized. Secure the sinkhole area.
- Direct the surface water away from the sinkhole area, if possible, to a suitable storm drainage system.

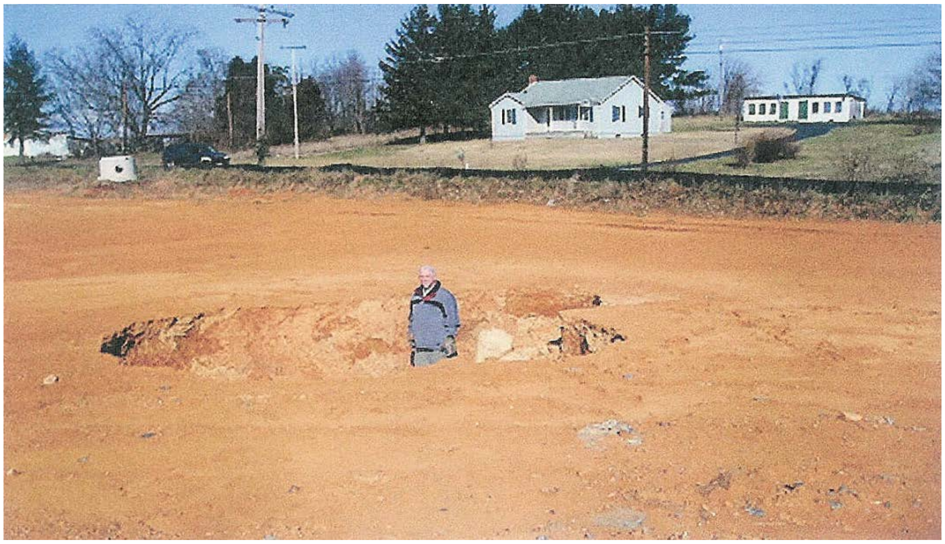

Figure 6-B.8. Sinkhole at a Construction Site

- Communicate the proposed remediation plan to the local plan approving authority. Some jurisdictions may have local requirements for notification and review as well.
- Repair any damage to E&S Control measures and restore ground cover and landscaping.
- In those cases where the hazard cannot be repaired without adversely affecting the E&S Control design, the applicant should submit contact the local plan approving authority for approval of changes to the plan.

The type of repair chosen for any sinkhole depends on its location, the extent and size of the void, and the type of infrastructure planned for the sinkhole area. Sinkhole sealing methods can include the use of available on-site materials, dry or wet grout, filter material, and geotextiles (see **Figure 6-B.9** below). General recommendations and references are available from Karst Program staff of the DCR Division of Natural Heritage, upon request.

All sinkhole remediation activities should be under the direct supervision of a geologist or geotechnical engineer with experience in limestone investigations and remediation practices. A certified professional should perform all borings. Also see related information in **Section 6-C.8.0** of this Appendix.

6-B.6.4. Stormwater Design Principles for Karst Areas

The following are important stormwater management design principles for karst areas:
- Treat runoff as sheet flow in a series of small runoff reduction practices before it becomes concentrated. Practices should be designed to disperse flows over the broadest area possible to avoid ponding, concentration or soil saturation.

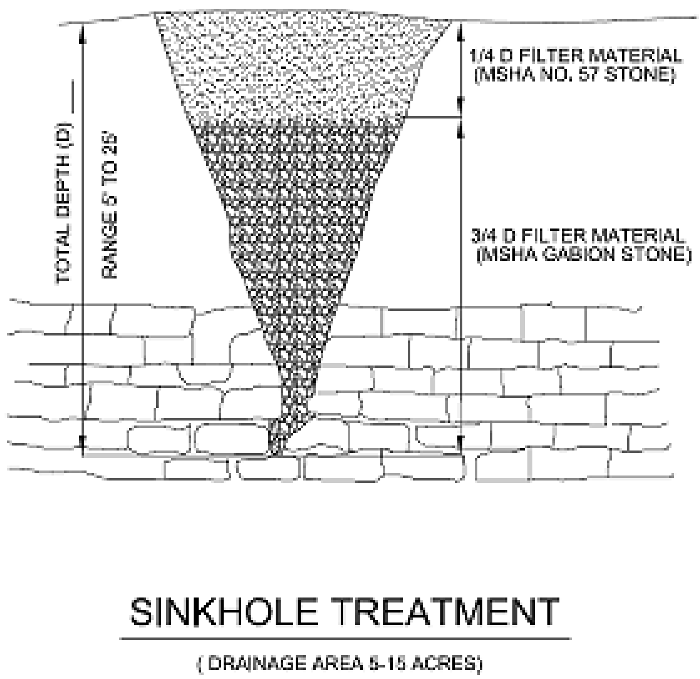

Figure 6-B.9. Typical Sinkhole Remediation (Similar to a Bioretention Cross-Section)
Source: MDE (2000)

- Small-scale low impact design (LID) types of practices work well in karst areas, although they should be shallow and sometimes use perforated under drains to prevent groundwater interaction. For example, micro-bioretention and infiltration practices can be a key part of the treatment train.
- Distributed treatment is recommended over centralized stormwater facilities, which are defined as any practice that treats runoff from a contributing drainage area greater than 20,000 square feet of impervious cover and/or has a surface ponding depth greater than 3 feet (e.g., wet ponds, extended detention (ED) ponds, and infiltration basins).
- The use of centralized stormwater practices with large drainage areas is strongly discouraged even when liners are used. Centralized treatment practices require more costly geotechnical investigations and design features than smaller, shallower distributed LID practices. In addition, distributed LID practices generally eliminate the need to obtain an underground injection well authorization from the EPA.
- Designers should refer to the list of preferred and acceptable stormwater practices as outlined in **Table 6-B.2** and discussed further in **Section 7** below.
- Designers must address both the flooding and water quality aspects of post-development stormwater runoff. In most localities, the sequence of stormwater practices should have the capacity to safely convey or bypass the 2- and 10-year design storm, following the methods outlined in **Section 6.5** below.
- Designers should maintain both the quality and quantity of runoff at pre-development levels and minimize rerouting of stormwater from existing drainage.
- As a general rule, the stormwater system should avoid large contributing drainage areas, deep excavation, or pools of standing water.

- o In fact, use of larger ponds is highly discouraged in karst areas – especially wet ponds.
- o Temporary detention water depths should not exceed six feet.
- o Liners are required for ponds (see **Table 6-B.6** later in this document), with the thickness and material based on the proximity to bedrock or groundwater access.
- o Where ponds are employed, a rigid maintenance protocol with routine inspections is necessary, with immediate remediation of sinkholes that occur within basins.

- The potential hotspot status of the proposed development should be evaluated prior to design. If the site is likely to be designated as a stormwater hotspot, full water quality treatment must be provided prior to any discharge to groundwater.
- When existing or new sinkholes are determined to require remediation, the repair will use appropriate techniques [reference WVDEP (2004), MDE (2000) or CCDP (2007)]. These techniques are related to the size of the sinkhole, and are summarized in **Section 8** below.

Table 6-B.2. Stormwater Practice Selection in Karst Regions

Stormwater Practice	Suitability in Karst Regions	Bay-wide Design Spec # [4]	UIC Permit?	Design and *Implementation Notes*
Closed Bioretention	Preferred	**9**	No	
Urban Bioretention [1]	Preferred	**9a**	No	
Rainwater Harvesting	Preferred	**6**	No	
Vegetated Roofs	Preferred	**5**	No	
Shallow Dry Swale	Preferred	**10**	No	Lined w/ underdrains
Filtering Practices	Preferred	**12**	No	Water-tight
Sheet Flow to a Filter Strip or Conserved Open Space	Adequate	**2**	No	Flow to karst swales
Grass Channel	Adequate	**3**	No	Compost amendments
Soil Compost Amendments	Adequate	**4**	No	
Small Scale Infiltration [2]	Adequate	**8**	No	Not at stormwater hotspots
Micro-bioretention	Adequate	**9**	No	Closed systems
Permeable Pavers	Adequate	**7**	No	
Constructed Wetlands	Adequate	**13**	Maybe	Use liner and linear cells
Rooftop Disconnection	Preferred	**1**	No	15 feet foundation setback
Wet Ponds	Discouraged	**14**	Maybe	Liner required
Dry ED Ponds	Discouraged	**15**	Maybe	Liner required
Open Bioretention	Discouraged	**9**	No	
Wet Swale	Prohibited	**13a**	No	Infeasible
Large Scale Infiltration[3]	Prohibited	**8**	Maybe	Use small-scale instead

[1] Closed, above-ground facilities with no groundwater interaction.
[2] See definitions and design requirements for micro- and small- scale infiltration in **Table 6-C.4**.
[3] Contributing drainage area of 20,000 sf of impervious cover or more.
[4] The most current version of the Virginia Stormwater Design Specifications can be downloaded from the Virginia Stormwater BMP Clearinghouse web site at http://www.vwrrc.vt.edu/swc/ .

6-B.6.5. Recommended Procedures for Conveying Runoff from Larger Storms

Karst areas often have no natural defined channels in or near small or moderate sized development sites. Instead, pre-development runoff typically flows in natural parabolic type swales (karst swales) across adjoining properties. New stormwater conveyance structures in karst areas should be designed in a manner that dissipates overland flow over the largest area possible. Every attempt should be made to avoid concentrated flows and ponding. Grass channels can be effective storm-water-diversion structures in karst areas. Particularly effective are waterway designs that are shallow and broad, providing maximum bottom width and wetted perimeter to disperse flow over the greatest area.

When developing a karst site, the peak storm runoff rate to these waterways must be restricted to the existing karst-adjusted peak runoff rate (see **Section 6.6** below) or the pre-development rate for good pasture (or better yet, forest cover), whichever is less. This is calculated by reducing the allowable peak flow rate resulting from the 24-hour storm events with return periods of 1-year, 2-years, and 10-years to levels that are less than or equal to the peak flow rates from the site for those storms, assuming the site was in a good pasture (or better yet, good forested) condition. This is typically achieved by multiplying the good pasture (or better yet, good forested) peak flow rate by a reduction factor [i.e., the runoff volume from the site when the site was in a good pasture condition (or, better yet, in a good forest condition) divided by the runoff volume from the site in its proposed condition].

6-B.6.6. Stormwater Modeling in Karst Areas

Karst loss is a term given to the loss of surface runoff into bedrock strata in areas underlain by limestone geologic formations. Unlike other calculation factors, such as curve numbers (which deal with characteristics of the land surface), a karst loss factor is intended to depict projected losses into bedrock.

The determination of karst potential in any given area may be simplified by the observation of noticeable indicators such as caves, crevices, limestone outcrops, sink holes, ponds that appear to lack sufficient contributing area, and disappearing streams. In other cases, karst infiltration areas may be difficult to identify, since definitive karst features are not always obvious. Generally, a lack of natural drainageway erosion or inadequately sized drainageways (in comparison to the size of the contributing area) may be clues to karst loss. Other observations may include undersized drainage conduits that never run full.

By accounting for karst loss through hydrologic modeling, the site designer can more accurately simulate actual conditions in deriving runoff rates. Mapping of a geographic area (when limited in size) may be productive in defining a karst loss zone (an area underlain by karst bedrock). However, the delineation of such zones is simply a method for *estimating* karst loss, not an accurate representation of the actual site-specific rate of karst loss. Accurate karst loss modeling requires an extensive field investigation at each site under consideration to obtain comprehensive information about subsurface strata. In many cases the cost to fully model a site is prohibitive. Therefore, as an alternative, karst runoff loss estimations may be comparatively simple but still reasonably accurate.

The premise behind karst runoff loss estimation and adjustment is to better approximate actual site conditions, which produce lower peak rates of runoff than those than would occur on a similar site where karst is not present. Typically, adjustment for karst loss is recommended only when analyzing *pre-development* site conditions. This is because once development occurs, karst features may become more obliterated from extensive site grading activity. Also, the addition of impervious cover and the construction of a surface drainage system may offset karst losses that may have existed prior to development.

Karst adjustment for post-development site conditions is typically *not* recommended, except for portions of the site that remained substantially undisturbed and uncompacted, during and subsequent to development. Furthermore, any runoff from the site draining to sinkholes subsequent to development must meet water quality and quantity standards. In any event, the adjustment factors shown in **Table 6-B.3** below apply only to pre-development runoff, and should never be used for post-development runoff computations.

Projecting karst loss in hydrologic modeling of limestone requires some specific examination (field inspection) of the subject area, along with a geologic examination of the underlying strata, in order to predict the extent of the karst loss zone. Many urban development sites of limited size will fall exclusively inside or outside of a karst loss zone. In such cases, the watershed does not need to be split into karst and non-karst areas.

Many of the traditional NRCS hydrologic models over-predict pre-development runoff from karst terrain, as a result of the high initial abstraction that occurs in karst areas, as well as the fact that concentrated storm flows are often rapidly converted to subsurface flows (Laughland, 2007). In general, over-predictions are more likely to occur when modeling the smaller storms and less likely to occur when modeling larger storm events, such as the 100-year storm. Consequently, designers must carefully modify their NRCS hydrologic and hydraulic computations to reflect the lower pre-development peak discharge rates. It is important to understand that more hydrologic monitoring and modeling research is needed to get predictions that are more reliable.

The following method for estimating stormwater runoff losses in karst settings is adapted from Laughland (2007), only one of many methods that can be used (some much more detailed than this). This method provides the multiplier factors (shown in **Table 6-B.3** below) used to adjust TR-55 and TR-20 pre-development rates, as follows.

1. Delineate the contributing drainage area or watershed to be studied.
2. Define any sinkhole areas within the contributing drainage area where surface drainage has no means of escaping offsite, other than downward through the karst strata (i.e. cracks, sinks, etc.). These areas can be assumed to contribute no surface discharge and can be subtracted from the contributing drainage area from Step 1.
3. Determine the amount of the contributing drainage area (from Step 2) underlain by karst strata (in percent).
4. Calculate the peak rate of runoff from the contributing drainage area using standard hydrologic methods, and reduce the calculated value by multiplying by the *Karst Loss Modification Value* (**Table 6-B.3**), based on the percent karst (% Karst) calculated in Step 3.

Table 6-B.3. Multipliers for Adjusting Predevelopment Runoff Quantities for Karst Impact

% of Drainage Area in Karst	Design Storm Return Frequency		
	2-year Storm	10-year Storm	100-year Storm
100	0.33	0.43	0.50
90	0.35	0.46	0.56
80	0.38	0.51	0.62
70	0.47	0.58	0.68
60	0.55	0.66	0.74
50	0.64	0.73	0.80
40	0.73	0.80	0.85
30	0.82	0.86	0.89
20	0.91	0.92	0.93
10	1.00	0.98	0.97
0	1.00	1.00	1.00

Source: Laughland,(2007) and VA DCR (1999)

Table 6-B.3 (developed using the *PSU-IV Program* by G. Aron et al) provides modifiers based on the percentage of the contributing drainage area that is underlain by karst strata. The modifiers are used to adjust the peak rate of runoff calculated using standard modeling techniques. For example, the calculated 2-year peak discharge of 12 cubic feet per second (cfs) from a drainage area that has been determined to be underlain by 80% karst zone (with no observed sinkhole areas) would be reduced as follows:

$$12\ cfs \times 0.38 = 4.5\ cfs$$

This represents a peak rate reduction of 62%. Note that as the storm frequency decreases (i.e. 2-year frequency to 10-year frequency storm), the multiplier may decrease and have less affect on the result. This is due to the fact that karst typically exerts less of an influence as the rainfall rate increases and underground voids fill with water. However, the change in infiltration capacity with storm frequency will vary between sites. Some sites may actually experience karst gain (a surcharge) in response to large flood events.

Other potential methods that can be used to model karst include applying a *TYPE I* rainfall distribution to a karst area that actually has a *TYPE II* rainfall distribution, or manipulating the Runoff Curve Number (RCN) or *Initial Abstraction* (Ia) values (when using NRCS methodology). However, each method of manipulation has both advantages and disadvantages in accurately representing the impacts of karst topography on runoff rates. However, more hydrologic monitoring and modeling research is needed to get predictions that are more reliable.

Local stormwater review authorities and state regulations may require management of different design storms for quantity control, including the following:

- Runoff reduction or detention of the 1-year storm event for downstream channel protection;
- Detention of the 10-year storm for safe conveyance; and
- Detention or floodplain control to manage the 100-year storm event.

Karst Surcharge. Sinkhole surcharge is a topic that is not frequently addressed in karst modeling methods. In this phenomenon, the opposite condition than that expected from karst loss occurs.

Rather than dampening the runoff peak, there can be depressed surface areas, or sinkholes, that experience surcharge (flooding) during rainfall events. This is due to the connectivity of the underground conveyance network. These natural runoff detention areas may or may not be significant in the overall hydrology of a watershed, but they may exert substantial impact on small sites, subjecting development in the area to inundation. A shift of detention catchment to other on-site or off-site karst areas is also possible when on-site development activity fills a sinkhole. Karst is unpredictable, and changes on the land surface may also result in subsurface hydrologic modifications. Due to the complexity of karst, sinkholes or surface depressions should *never* be filled unless a comprehensive valuation of the feature is completed first.

Additional guidance may be provided in the future to help identify the extent of karst loss.

6-B.6.7. Karst Swale Protection (KSP) for Stormwater Management

SEA(2000) proposed a Treatment Volume credit for protection of natural drainageways present on a karst development site. They define a karst swale protection area as being centered on the drainage-way or swale with a maximum width of 300 feet and a minimum width of 50 feet. However, the local review authority has some discretion to opt for a smaller width at small sites where natural land forms define an appropriate alternate width.

The credit is taken in the water quality or runoff reduction equation by reducing the area of site impervious cover draining to the karst swale by twice the KSP area. However, the maximum KSP credit may not to exceed 50% of the site impervious area. The rationale for the high credit is that the KSP area has proportionally higher infiltration capability than more upland areas at the site (Fennessey, 2003). SEA (2000) also recommends the following restrictions on the karst swale credit:

- The KSP area must be located on the development site.
- It is good practice to combine a KSP with an adjacent filter strip to accept off-site stormwater runoff.
- KSP areas must remain in an undisturbed condition during and after construction activity. There can be no construction activity within these areas, including temporary access roads or storage of equipment and materials. Temporary access for the construction of utilities crossing the KSP area may be permitted at the municipal engineer’s discretion, if the alignment of the crossing is perpendicular to the karst swale.
- KSP areas should be placed in a conservation easement or permanently preserved through a similarly enforceable agreement with the municipality.
- The limits of the undisturbed KSP area and conservation easement must be shown on all construction plans.

6-B.7.0. DESIGN CRITERIA FOR SPECIFIC STORMWATER CONTROL MEASURES

Stormwater management facilities are particularly vulnerable to collapse in karst areas because most are designed to concentrate and detain surface water runoff. Ponding and associated soil saturation occur where surface-runoff is concentrated. Saturation of fine-grained soils that develop on weathered limestone can cause a reduction in soil strength and erosion into bedrock voids.

One preventive strategy is to provide a pre-treatment method that does not use the detention of stormwater to settle out or filter pollutants. Consider manufactured water quality BMPs which can serve as pre-treatment devices or even spill containment BMPs for commercial/industrial development in karst areas. These structures will not eliminate the potential for karst collapse, but they do provide water quality treatment that helps to minimize the potential for the contamination of groundwater.

This section describes recommended design adaptations for stormwater practices installed in karst terrain. With reference to **Table 6-B.2** above**,** the base design specification for each practice can be found at the Virginia Stormwater BMP Clearinghouse web site at:

http://www.vwrrc.vt.edu/swc/.

6-B.7.1. Preferred Practices

Vegetated Roofs. Vegetated Roofs (Virginia Stormwater Design Specification No. 5 -- see **Figure 6-B.10** below) are a preferred treatment option in karst terrain for commercial, institutional and industrial sites. However, they may have somewhat limited application, given the forms and intensity of development in the Ridge and Valley Province. The overflow from the Vegetated Roof should extend at least 15 feet away from the building foundation.

Figure 6-B.10. Vegetated Roof

Rainwater Harvesting. Rainwater Harvesting (Virginia Stormwater Design Specification No. 6 – see **Figure 6-B.11** below) is a preferred practice in karst terrain, as long as the surface of the roof is not designated as a stormwater hotspot (based on the roofing material). Rainwater harvesting is also well-suited to provide an alternative water source in rural communities. Recommended design adaptations for karst areas are as follows:

Figure 6-B.11. Cistern to Harvest Rainwater

- Above ground tank designs are preferred to below ground tanks
- Tanks should be combined with automated irrigation, front-yard bioretention or other secondary practices to maximize their runoff reduction rates.
- The overflow from the rain tank should extend at least 15 feet away from the building foundation.

Bioretention (closed). Since bioretention (Virginia Stormwater Design Specification No. 9 – see **Figure 6-B.12** below) requires shallow ponding and treats runoff through a prepared soil media, it is generally appropriate for karst regions, provided that the following design modifications are made to reduce the risk of sinkhole formation or groundwater contamination:

Figure 6-B.12. Small Rain Garden

- Bioretention facilities in karst areas should be wide and shallow.
  - The minimum depth of the filter bed may be relaxed to 18 inches if the geotechnical investigation indicates that further excavation is likely to increase karst vulnerability.
  - Maximum depth of the filter bed should be 3 feet.

  - To reduce the vertical footprint, (1) to limit surface ponding to from 6 to 9 inches, and (2) save additional depth by shifting to turf rather than a mulch cover.
- If bedrock is within 3 feet of the bottom invert of a proposed bioretention area, it should be equipped with an underdrain to convey treated runoff to an appropriate discharge point. If groundwater contamination is a strong concern, the bottom of the facility should be lined with an impermeable filter fabric.
  - It is important to (1) maintain at least a 0.5% slope in the underdrain to ensure positive drainage, and (2) connect the underdrain to the ditch or conveyance system.
  - Add a sump stone layer below the underdrain to increase runoff volume reduction.
- The scale of the bioretention application is extremely important in karst terrain. Larger bioretention designs that rely on exfiltration of treated runoff into underlying soils are not recommended in karst regions.
- The Department recommends that the contributing area to individual bioretention areas be kept to less than 20,000 square feet of impervious cover. These micro-bioretention and small-scale bioretention practices are preferred over larger bioretention basins.
- The mix of plant species selected should reflect native plant communities present within the same physiographic region or eco-region, in order to be more tolerant of drought conditions.
- The standard setbacks from buildings, structures and roadways should be as described in **Table 6-B.4** below.

Table 6-B.4. The Three Design Scales for Bioretention Practices

Design Factor	Micro Bioretention (Rain Garden)	Small-Scale Bioretention	Bioretention Basins
Impervious Area Treated	250 to 2500 sq. ft.	2500 to 20,000 sq. ft.	20,000 to 200,000 sq. ft.
Type of Inflow	Sheetflow or roof leader	Shallow concentrated flow	Concentrated flow
Runoff Reduction Sizing	Minimum 0.1 inches over CDA	Minimum 0.3 inches over the CDA	Remaining T_V up to the full Cp_V
Observation Well/ Cleanout Pipes	No	No	Yes
Type of Pre-treatment	External (leaf screens, etc)	Filter strip or grass channel	Pre-treatment cell
Recommended Max. Filter Depth	Max 3 Foot Depth	Max 5 Foot Depth	Max. 6-foot depth
Media Source	Mixed On site	Obtained from an Approved Vendor	
Hydraulic Head Required	Nominal 1 to 3 feet	Moderate 1 to 5 feet	Moderate 2 to 6 feet
Building Setbacks	15 ft. down-gradient 25 ft. up-gradient	15 ft. down-gradient 50 ft. up-gradient	25 ft. down-gradient 100 ft. upgradient

Urban Bioretention (closed). Three forms of bioretention for highly urban areas (Virginia Stormwater Design Specification No. 9, Appendix A –**Figure 6-B.13**) can work acceptably within karst terrain. They are (1) stormwater curb extensions, (2) expanded tree planters, and (3) foundation planters, since each of these variants is enclosed in a concrete shell and does not interact with groundwater. Designers should consider the above-ground design variants, since they reduce excavation and also incorporate the general karst design modifications for regular bioretention described above.

Figure 6-B.13. Urban Bioretention

***Dry Swale (closed)*.** Shallow Dry Swales (Virginia Stormwater Design Specification No. 10 – see **Figure 6-B.14** below) work well in karst terrain when they use impermeable filter fabric liners and underdrains. Recommended design adaptations for karst areas are as follows:

- Try to locate Dry Swales in the pre-development flow paths.
- The invert of the Dry Swale must be located at least 2 feet above bedrock layers or pinnacles.
- If a Dry Swale facility is located in an area of sinkhole formation, standard setbacks to buildings and roads should be increased.
- The minimum depth of the filter bed may be relaxed to 18 inches or even less, if hydraulic head or water table conditions are problematic.
- A minimum underdrain slope of 0.5% slope must be maintained to ensure positive drainage and the underdrain must be connected to an adequate channel or discharge to a karst swale protection area.

Figure 6-B.14. Dry Swale

***Filtering Practices*.** Stormwater filters (Virginia Stormwater Design Specification No. 12 – see **Figure 6-B.15**) are a good option in karst terrain, since they are not connected to groundwater and therefore minimize the risk of sinkhole formation and groundwater contamination. They are highly recommended for the treatment of hotspot runoff. Recommended design adaptations for karst areas are as follows:

- Construction inspection should certify that the filter bottoms are closed and water tight.
- The bottom invert of the sand filter should be at least 2 feet above bedrock.
- The minimum depth of the sand filter bed may be reduced to from 18 to 24 inches.

Figure 6-B.15. Sand Filter

6-C.7.2. Adequate Practices

Rooftop Disconnection (Figure 6-B.16). Rooftop disconnection is an acceptable practice for most residential lots with areas of less than 6,000 square feet, particularly if it can be combined with a secondary micro-practice to increase runoff reduction and prevent seepage problems. (See Virginia Stormwater Design Specification No. 1 for the four primary micro-practice options.) The discharge point from the disconnection should extend at least 15 feet from any building foundations There should be at least 40 feet of disconnect if the discharge ultimately flows back onto an impervious surface or into a storm drainage system.

Figure 6-B.16. Rooftop Disconnection

Sheet Flow to Vegetated Filter Strips and Conserved Open Space. The use of conservation filter strips (Virginia Stormwater Design Specification No. 2 – see **Figure 6-B.17** below) is acceptable in karst areas, particularly when stormwater runoff discharges to the outer boundary of a karst swale protection area.

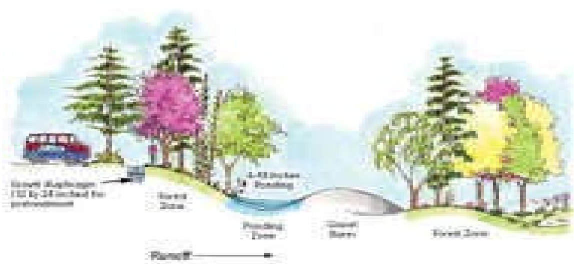

Figure 6-B.17. Sheet Flow to Filter Strips or Conserved Open Space

Conservation filter strips can also be used to treat runoff from small areas of impervious cover (e.g., less than 20,000 square feet). Some communities use wide grass filter strips to treat runoff in the roadway shoulder. Depending on flow conditions (i.e., sheet or concentrated), the strip must have a gravel diaphragm, pervious berm or engineered level spreader conforming to the new requirements outlined in this design specification, to help spread the runoff across the surface of the receiving filter area. Ideally, vegetation in the filter area should be native meadow or forest cover. Each individual filter strip should have a maximum area of 1/2-acre.

***Grass Channel*.** Grass Channels (Virginia Stormwater Design Specification No. 3 – see **Figure 6-B.18**) are an acceptable practice in karst terrain of Virginia, as long as they do not receive hotspot runoff. The following design adaptations apply to Grass Channels in karst terrain.

- Soil compost amendments can be incorporated into the bottom of a Grass Channel to improve its runoff reduction capability.
- Check dams are generally discouraged for Grass Channels in karst terrain, since they pond too much water. However, flow spreaders that are flush with ground surface may be useful in spreading flows more evenly across the channel width.
- The minimum depth to the bedrock layer may be 18 inches.
- A minimum slope of 0.5% must be maintained to ensure positive drainage.
- The Grass Channel may have off-line cells and should be connected to an adequate discharge point.

Figure 6-B.18. Grass Channel

Soil Compost Amendments. The incorporation of Soil Compost Amendments (Virginia Stormwater Design Specification No. 4) requires no special adaptations in karst terrain, but the designer should take soil tests to ensure that soil pH is adjusted to conform to pre-existing soil conditions.

Micro- and Small Scale Infiltration. The karst region is an acceptable environment for micro-infiltration and small-scale infiltration practices (see Virginia Stormwater Design Specification No. 8 – see **Figure 6-B.19** below). For definitions and design requirements, See **Table 6-B.5** below. Designers may choose to infiltrate less than the full Treatment Volume in a single practice (and use another runoff reduction practice to pre-treat or filter runoff before it reaches the infiltration facility.

Figure 6-B.19. Small-Scale Infiltration Trench

Table 6-B.5. The Three Design Scales for Infiltration Practices

Design Factor	Micro Infiltration	Small-Scale Infiltration	Large Scale Infiltration
Impervious Area Treated	250 to 2500 sq. ft.	2500 to 20,000 sq. ft.	20,000 to 100,000 sq. ft.
Typical Practices	Dry Well, French Drain, Paver Blocks	Infiltration Trench Permeable Paving	Infiltration Trench Infiltration Basin
Runoff Reduction Sizing	Minimum 0.1 inches over the CDA	Minimum 0.3 inches over the CDA	Remaining T_v up to the full Cp_v
Minimum Soil Infiltration Rate	0.5 inches per hour	1.0 inches per hour	1.0 inches per hour
Design Infililtraton Rate	50% of the measured rate for the soils in place		
Observation Well	No	Yes	Yes
Type of Pre-treatment	External (leaf screens, etc)	Filter strip or grass channel	Pre-treatment cell
Depth to Width	Max. 3 ft. deep Min. 10 ft. wide	Max. 5 ft. deep Min. 15 ft. wide	Max. 6 ft. deep Max. 20 ft. wide
Required Borings	One per practice	Two per practice	One per 500 sq. ft. of infiltration area
Building Setbacks	15 ft. down-gradient 25 ft. up-gradient	15 ft. down-gradient 50 ft. up-gradient	25 ft. down-gradient 100 ft. up-gradient

Some design modifications for small-scale infiltration in karst terrain include the following:

- The maximum CDA to the facility is 20,000 square feet.
- Designers should maximize the surface area of the infiltration practice and keep the depth of infiltration to less than 24 inches and the width wider than the depth.
- Soil borings must indicate that at least 3 feet of vertical separation exists between the bottom invert of the infiltration facility and the bedrock layer.
- Where soils are marginal, underdrains may be used.

- Setbacks to roads and buildings should be 15 feet down-gradient and 25 feet up-gradient.
- In many cases, bioretention is preferred over infiltration for stormwater management in karst areas.
- Infiltration is prohibited in karst areas if the contributing drainage area is classified as a severe stormwater hotspot.

Permeable Pavement. Permeable Pavement (Virginia Stormwater Design Specification No. 7 – **Figure 6-B.20** below) are an acceptable option in karst terrain if geotechnical investigations have eliminated concerns about the potential for sinkhole formation and groundwater contamination.

- Full infiltration from Permeable Pavement (i.e., the Level 2 design) is not recommended for large-scale pavement applications and is prohibited if the site (1) is designated as a severe stormwater hotspot, or (2) discharges to areas known to recharge to aquifers that are used for water supply.
- Permeable Pavement is acceptable when it is designed with an impermeable bottom liner and an underdrain. A minimum 0.5% underdrain slope must be maintained to ensure positive drainage.
- Carbonate rock should be used in the reservoir layer in order to provide extra water quality buffering capacity.

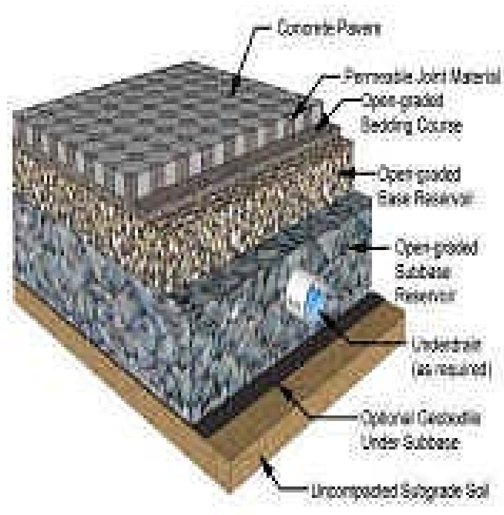

Figure 6-B.20. Profile Through Permeable Pavement

Constructed Wetlands (lined). Even shallow pools in karst terrain can increase the risk of sinkhole formation and groundwater contamination. Designers should always conduct geotechnical investigations in karst terrain during the planning stage to assess this risk. If Constructed Wetlands ((Virginia Stormwater Design Specification No. 13 – see **Figure 6-B.21** below) are employed, the designer should do the following:

- Use an impermeable liner and maintain at least 3 feet of vertical separation from the bottom of the wetland to the underlying bedrock.
- Shallow, linear and multiple cell wetland configurations are preferred.

Figure 6-B.21. Constructed Wetland

- Regenerative conveyance systems are worth testing (with sand and organic lenses).
- Ideally, constructed wetlands should be installed draining to or in close proximity to karst swale protection areas.
- Deeper basin configurations (e.g., the pond/wetland system and the extended detention wetland) have limited application in karst terrain.

6-B.7.3. Discouraged Practices

Dry Extended Detention (ED) Ponds and Wet Ponds. The use of either Wet Ponds (Virginia Stormwater Design Specification No. 14) dry or ED Ponds (Virginia Stormwater Design Specification No. 15) is highly restricted in karst terrain because of frequent and recurring failures due to sinkhole formation.

The sealing of the solution channels in bedrock beneath stormwater basins can reduce seepage and soil displacement into underlying voids. Traditional sealing methods include compaction, clay blankets, bentonite treatment and flexible membrane liners. Methods traditionally used to reduce or eliminate excessive seepage from an impounded area may have limited success in limestone areas.

Sinkholes undermine the beneficial effects of basins on water quality by allowing introduction of untreated surface runoff directly to ground water. Thus, sinkholes "short-circuit" the hydraulic benefits of basins by allowing outlet structures to be bypassed.

Stormwater management basin sites can be evaluated and facilities designed and retrofitted to guard against sinkhole formation and improve water quality treatment performance. If a basin is used in a karst area, the following criteria should be applied:

- Minimize the amount of impervious cover on the site, in order to be able to minimize the size of the basin.

- Investigate soils and bedrock below the basin for the presence of voids. Repair existing voids and/or perform preventative grouting of the basin substrate.
- A minimum of 6 feet of unconsolidated soil material exists between the bottom of the basin and the top of the bedrock layer.
- Basin profiles should be broad and flat to allow the maximum dispersion of detained flow.
- Basin bottoms should be smooth, to avoid ponding.
- A liner is installed that meets the requirements outlined in **Table 6-B.6** below.
- Maximum temporary or permanent water elevations within basins do not exceed 6 feet.
- Inlet and outlet structures should be designed to provide diffuse discharge of water; avoid concentration of flows. Underdrains are preferred, in order to provide gradual discharge of water and avoid prolonged ponding of water.
- Maintenance inspections must be conducted at least annually (ideally, twice a year) to detect sinkhole formation. Sinkholes that develop should be reported immediately to local and state officials (see **Section 8.1**) and should be repaired, abandoned, adapted or observed over time following the guidance prescribed by the appropriate local or state groundwater protection authority (see **Section 8**).

6-B.7.4. Prohibited Practices

Wet Swale. Wet Swales (Virginia Stormwater Design Specification No. 11), which are essentially linear wetlands, will often not work in karst terrain since the water table rarely reaches the land surface. (NOTE: In the Shenandoah Valley, numerous areas underlain by marl soils exist, indicating that many natural wet swales do exist in certain karst areas in Virginia. These areas result from the prolonged elevation of the water table above the land surface. If the soils are marly, a wet swale *may* be appropriate.)

Table 6-B.6. Required Groundwater Protection Liners for Ponds in Karst Terrain

Pond Position	Liner Material
The pond is excavated with at least 3 feet above bedrock	24 inches of soil with a maximum hydraulic conductivity of 1 x 10^{-5} cm/sec.
The pond is excavated within 3 feet of Bedrock	24 inches of clay [1] with a maximum hydraulic conductivity of 1 x 10^{-6} cm/sec.
The pond is excavated near bedrock within a wellhead protection area, in a recharge area for a domestic well or spring, or in an area with a high fracture density or significant geophysical anomalies	A synthetic liner with a minimum thickness of 60 mil

[1] Clay properties as follows:
Plasticity Index of Clay = Not less than 15% (ASTM D-423/424)
Liquid Limit of Clay = Not less than 30% (ASTM D-2216)
Clay Particles Passing = Not less than 30% (ASTM D-422)
Clay Compaction = 95% of standard proctor density (ASTM D-2216)

Source: WVDEP (2006) and VA DCR (1999)

Large-Scale Infiltration. Large-scale Infiltration (see Virginia Stormwater Design Specification No. 8) is defined as individual practices that infiltrate runoff from a contributing drainage area with 20,000 to 100,000 square feet of impervious cover. These practices ***should not be used*** in karst terrain due to concerns about sinkhole formation and groundwater contamination. Micro-infiltration and small scale infiltration or bioretention are preferred stormwater management alternatives in karst terrain.

6-B.8.0. SINKHOLE REMEDIATION IN STORMWATER CONTROL MEASURES

Since karst terrain is so dynamic, there is always some risk that sinkholes will be created in the conveyance system or with E&S Control or Stormwater Management practices. This section outlines a four-step process of sinkhole remediation, involving notification, investigation, stabilization and final grading. This process has been loosely adapted from CCDP (2007). The choice of sinkhole remediation techniques is contingent on the scope of the perceived problem, the nature of contributing land uses, and the cost and availability of equipment and materials.

6-B.8.1. Sinkhole Notification

The existence of a new sinkhole within a temporary erosion control practice, road right of way or stormwater management practice must be reported to the local stormwater review authority within 24 hours or on the next business day. In the meantime, halt construction activities in the immediate area of the sinkhole and secure the area until it is stabilized. A plan for investigation and stabilization must be coordinated with the local regulatory authority, and repairs must commence immediately after receiving design approval. Until repairs are completed, a temporary berm must be constructed to divert surface flow away from the sinkhole. Having a registered professional engineer provide certify documentation of sinkhole repairs will provide assurance to the local review authority that the repairs are correctly designed and completed.

6-B.8.2. Sinkhole Investigation

The investigation phase should determine the areal extent and depth of the new sinkhole, as well as the depth of bedrock pinnacles upon which sinkhole stabilization will be founded. The investigation may involve visual inspection, excavation, borings and/or geophysical studies, as described below.

Visual inspection is generally used for smaller sinkholes (i.e., less than 10 feet in diameter) where the bedrock throat of a sinkhole is entirely visible from the ground surface.

Excavation by backhoe is commonly used for small to moderate-sized sinkholes (i.e., up to 20 feet in diameter) when the throat of the sinkhole is not visible from the ground surface. Track hoes, clam shells or other excavating equipment are typically used when soil depths exceed about 20 feet. The equipment is used to remove soil and fill from the sinkhole until the bedrock pinnacles and/or throat of the sinkhole are clearly visible.

As a safety measure prior to bringing in heavy equipment, a geophysical resistivity survey should be conducted in an attempt to determine if any very large subsurface voids exist. There are numerous documented instances of large equipment being swallowed by collapse of what appeared at the surface to be a small hole, but in the subsurface was actually a very large void.

Soil borings may be taken using augers, coring devices, air track or other boring equipment at larger sinkholes, particularly when more extensive sinkhole development is anticipated and/or critical foundation structures are at risk (e.g., bridge abutments, major roads, load bearing structures, etc.). This investigation involves a program of closely spaced borings to determine the location and depth of bedrock pinnacles, cavities and sinkhole throats.

Geophysical studies may be needed in conjunction with more intrusive methods to further delineate the scope of sinkhole dimensions, using techniques such as electromagnetic terrain conductivity, seismic refraction, or resistivity.

6-B.8.3. Sinkhole Stabilization

Stabilize reverse-graded backfilling, grouting, or subsurface engineering structures, as follows:

- ***Reverse-graded backfilling*** **(Figure 6-B.22** below**)** is generally applied to small and moderately-sized sinkholes. Once the throat of the sinkhole is fully excavated, it is filled with clean, interlocking rock material. The stone diameter of the initial fill layer must generally be one-half the diameter of the throat or cutter width. Once the initial fill layer is placed, progressively smaller diameter clean rock fill is layered above, up to or near the ground surface. Compaction of each layer of rock fill is essential. In general, at least three gradation sizes of fill are needed for adequate stabilization.
- ***Grouting*** **(Figure 6-B.23)** is generally discouraged, unless it is combined with the graded filter within moderate to large sinkholes. Borings are placed in the ground adjacent to the sinkhole and a concrete (grout) mix is injected by pressure or gravity into the subsurface until the throat is sealed. Grouting may be used to remediate small diameter voids, such as test borings or abandoned wells.

Figure 6-B.22. Sinkhole Remediation

Figure 6-B.23. Grouting a Sinkhole

Engineered ***subsurface structures*** are used on larger sinkholes or where concentrated load-bearing structures are present. The technique involves creating a bridge between bedrock pinnacles to form a stable base, above which appropriate fill and construction may be completed.

The type of repair chosen for any sinkhole depends on its location, the extent and size of the void, and the type of infrastructure planned for the sinkhole area. Sinkhole sealing methods can include the use of available on-site materials, dry or wet grout, filter material, and geotextiles. A good general engineering specification for sinkhole repair is included in Virginia Department of Transportation *Instructional and Informational Memorandum 228: Sinkholes – Guidelines for the Discharge of Stormwater at Sinkholes*:

(http://www.virginiadot.org/business/resources/IIM228.pdf)

6-B.8.4. Final Grading

In order to provide permanent stabilization and prevent groundwater contamination, final grading at the repaired sinkhole must be completed to avoid excess infiltration from the ground surface. The final grading should include placement of low permeability topsoil or clay and a vegetative cover. A positive grade should also be maintained away from the sinkhole to avoid local ponding or infiltration. However, this is not always possible if the sinkhole forms within the stormwater conveyance system or a centralized pond.

6-B.9.0. ACKNOWLEDGEMENTS

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6-B.10.0. REFERENCES

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6-B.11.0. KARST-RELATED RESOURCES FOR VIRGINIA

6-B.11.1. Virginia Resources

USGS Geologic Quadrangles. http://www.usgs.gov/pubprod/

Virginia Department of Conservation and Recreation Karst Program:
- Conservation sites for Virginia's Significant Caves
- Karst Hydrology Atlas
- Statewide Karst Bedrock Coverage
- Access available to areas of interest by request; contact Karst Program staff at 540-394-2552.

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Department of Conservation and Recreation
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Richmond, VA 23219
http://www.dcr.virginia.gov/natural_heritage/cavehome.shtml
phone: (804) 786-7951
fax: (804) 371-2674
larry.smith@dcr.virginia.gov

Virginia Department of Mines, Minerals and Energy, Division of Mineral Resources:
- https://www.dmme.virginia.gov/commerce/
- Geologic Quadrangle Maps and Digital Data
- Karst Feature Maps
- Publications 44, 83, and 167
- Local Karst Maps
- Publications 102 (Clarke County) and 070 (Giles County)

Virginia DEQ Ground Water Characterization Program:
http://www.deq.virginia.gov/gwcharacterization/
Joel P. Maynard (Valley and Ridge contact)
4411 Early Road
P.O. Box 3000
Harrisonburg, VA 22801
Phone: (540) 574-7864
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6-B.11.2. Regional and National Resources

Digital Engineering Aspects of Karst Map: A GIS Version of Davies, W.E., Simpson, J.H., Ohlmacher, G.C., Kirk, W.S., and Newton, E.G. 1984. *Engineering Aspects of Ka*rst: U.S. Geological Survey, National Atlas of the United States of America, Scale 1:7,500,000.

http://pubs.usgs.gov/of/2004/1352/

Preliminary Map of Potentially Karstic Carbonate Rocks in the Central and Southern Appalachian States. 2008. D.J. Weary. Scale 1:250,000.

http://pubs.usgs.gov/of/2008/1154/

Geologic Framework of the Northern Shenandoah Valley Carbonate Aquifer System (in progress). Harlow, G., D. Nelms, M. Kozar. Scale 1:24,000.

http://geology.er.usgs.gov/eespteam/Karst/tasks/Shenandoah/shenandoah.htm

Digital Geologic Map and Database of the Frederick 30 x 60 Minute Quadrangle, Maryland, Virginia, and West Virginia. 2002. Scott Southworth, David K. Brezinski, Avery Ala Drake, Jr., William C. Burton, Randall C. Orndorff, and Albert J. Froelich. U.S. Geological Survey Open-File Report 02-437. Scale 1:100,000. Also includes 1:24,000 maps of certain quadrangles.

http://pubs.usgs.gov/of/2002/of02-437/

6-B.11.3. Other Karst Resources

Karst Environmental Education and Protection (KEEP): http://keepinc.org.

Karst Information Portal: www.karstportal.org.

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