Appendix B

Stormwater Design Guidelines for Karst Terrain

The effect of land development on karst terrain is complex, hard to predict, and requires professional analysis to reduce the risk of geological hazards, damage to infrastructure, 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 comprehensive land use plans that direct new growth away from karst areas to more appropriate locations (although it is recognized that this may be problematic for communities that are completely underlain by karst).

B.1 Why Karst Terrain is Different

Karst in Tennessee watersheds 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. The karst terrain in Tennessee is distinct from some other regions (e.g., Florida) in that the bedrock is very ancient and, in some areas, is deeply buried by residual soils and other areas on or near the surface. Consequently, many sinkholes form due to collapse of surface sediments caused by the intrusion of stormwater from the surface into deep, underlying voids. The presence of karst terrain within the Ridge and Valley and Interior Plateau regions of Tennessee complicates the land development process and requires a unique approach to stormwater design. Some of the important considerations include:

Post Development Runoff Rates are Greatly Increased: In an undeveloped state, karst terrain produces about two-thirds less stormwater runoff than in non-karst regions like the Mississippi Alluvial Plain region. 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 down-gradient off-site areas.
- More 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.

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 in 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 unintended consequences or failure.

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. 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. Designers face a confusing surface drainage pattern, full of **losing streams, estavelles, turloughs, swallets,** and **insurgences,** which makes it hard to predict exact discharges points for runoff and groundwater. Designers in karst terrain need to think in three dimensions rather than just two.

Lower Stream Density and More Karst Swales: Another characteristic of karst landscapes is they have less perennial stream mileage per unit area than other physiographic regions. Consequently, many development sites cannot discharge to the stream network within their property boundaries.

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.

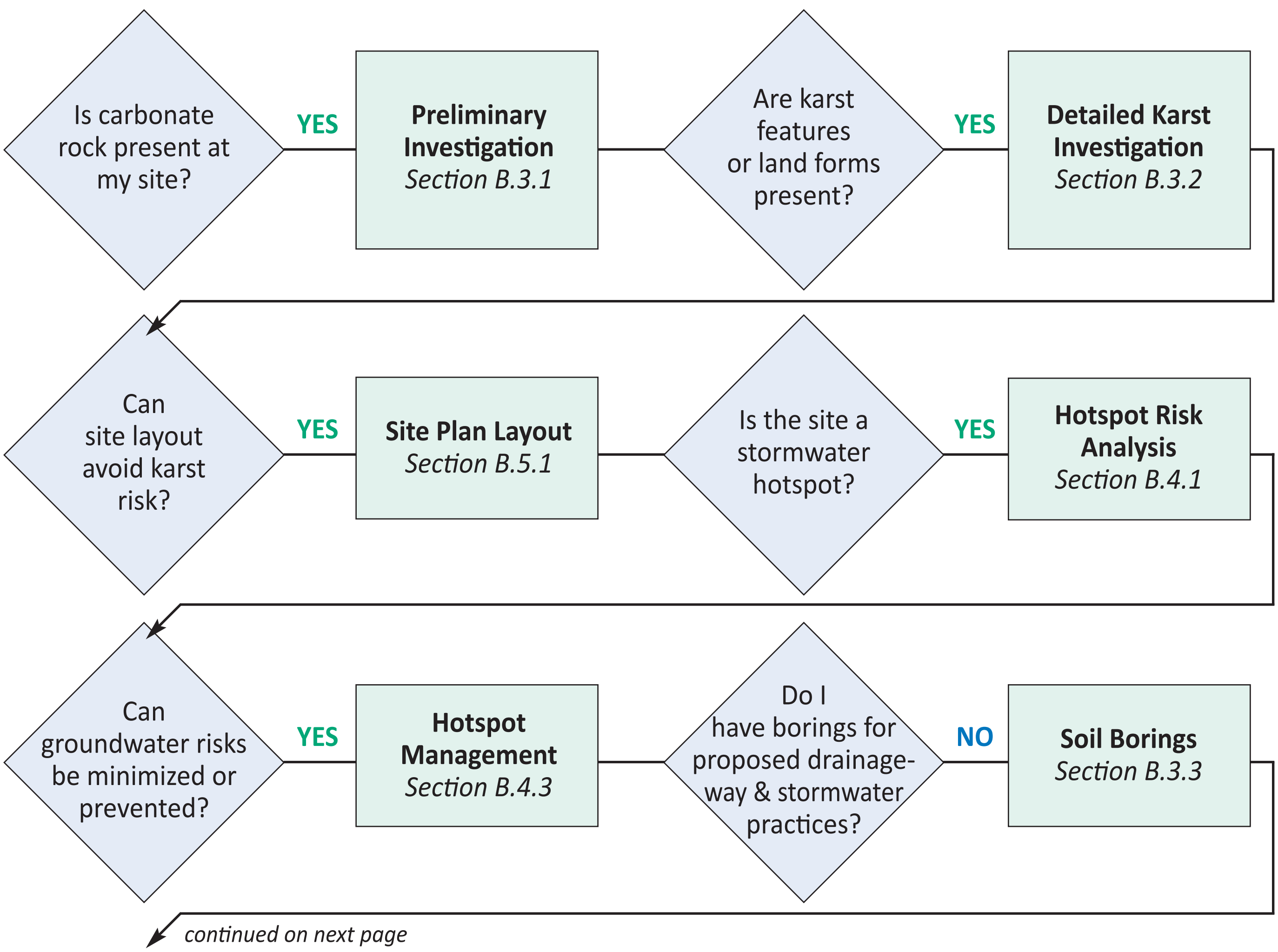
Groundwater Contamination Risks: In many cases, contaminants in polluted runoff and spills can pass rapidly from the surface into groundwater in karst terrain, with little or no filtration or modification. In other cases, contaminants are "hung up" above the water table in the **epikarst**, releasing toxins more gradually. The strong interaction between surface runoff and groundwater poses risks to the drinking water quality upon which residents in karst terrain rely. 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: The increased rate of sinkhole formation caused by increased runoff from land development can cause damage to public infrastructure, roads, and buildings. In addition, the existing drainage system can be further modified by land development, and larger centralized stormwater practices may 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 legally protected rare, threatened, or endangered species such as cave-obligate aquatic and terrestrial invertebrates, bats, and aquatic fauna in surface streams. Designers are encouraged 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. The specific agency that designers should consult will vary depending on the state: see Appendix A and B for some contact information.

B.2 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 and/or dolomite. 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.



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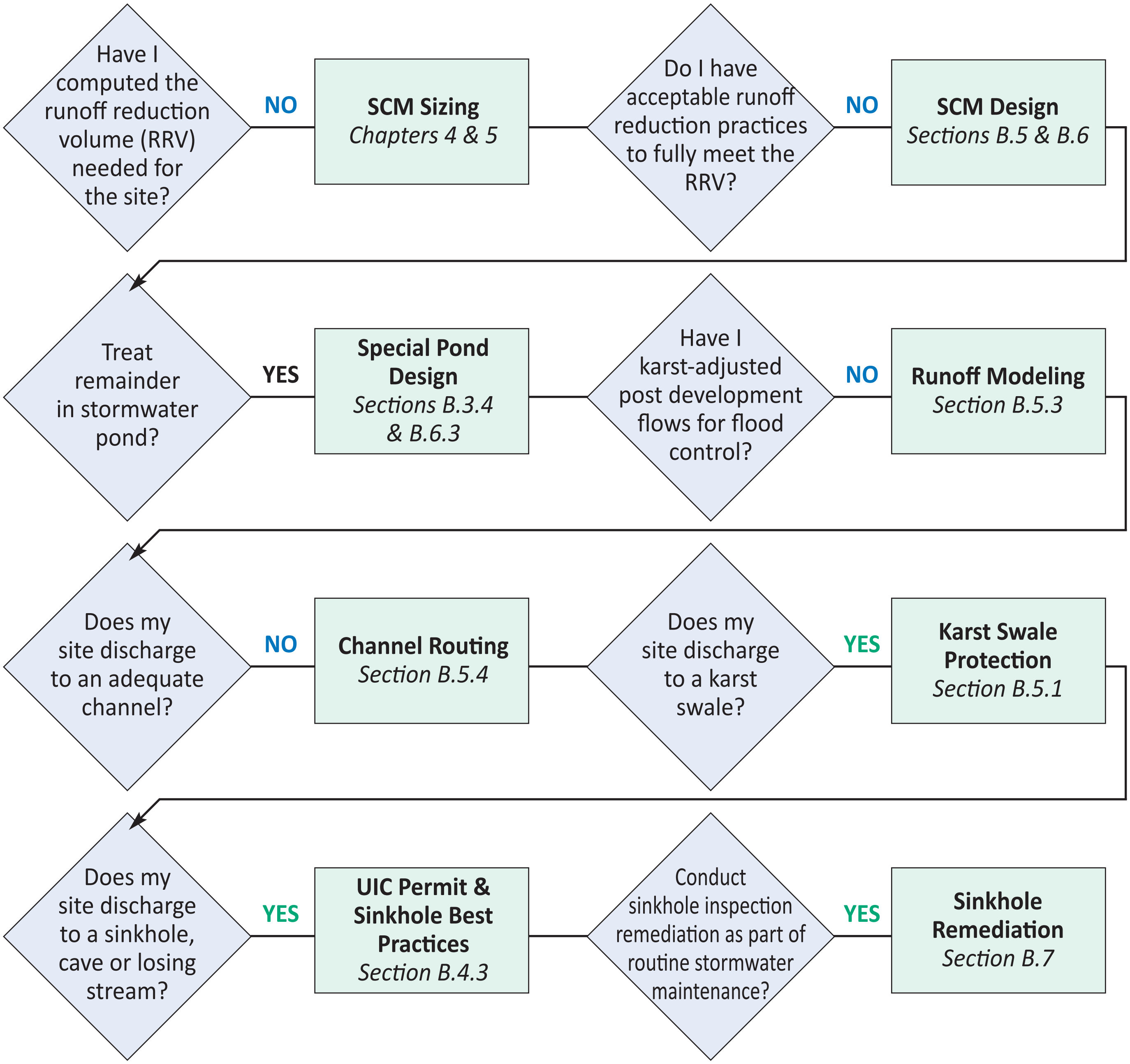

Figure B.1: Flow Chart for Stormwater Design in Karst Terrain.

The flow chart was synthesized from several sources, including the Minnesota Stormwater Manual (2005), VA DCR (1999), CCDP (2007), MDE (2000), and PADEP (2006). It is important to note that the flow chart is solely intended as a guide for stormwater design and is not meant to be used as a prescriptive process for local stormwater plan review.

B.3 Preliminary and Detailed Site Karst Investigations

B.3.1 Preliminary Site Investigations

Developers need to undertake a preliminary site investigation prior to 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 scope of the preliminary site investigation involves analysis of geological and topographic maps, aerial photography, and a site visit by an experienced professional knowledgeable in karst terrain. The preliminary site investigation should also include screening for proximity to known caves through the state natural resource agency or directly from the relevant state cave survey.

Various methods are available to collect information about the bedrock and soil conditions at a proposed development site. These can range from inspecting topographic and geologic maps and aerial photographs of the site, to drilling test borings at the location of planned facilities. Professionals involved with projects in karst areas should make a special effort to observe signs of ground subsidence during development.

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

Preliminary site investigation includes a review of topographic and geologic maps, soil surveys, aerial photography, and any previous technical reports prepared for the site. This phase of investigation should include a site visit, where the experienced professional studies the site terrain in an effort to locate any obvious features, such as rock outcrops, sinkholes, springs, caves, etc. 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.

Site-specific investigation includes collecting subsurface information at sites identified as potential problem areas during the preliminary investigation. During the site-specific investigation process the professional may examine subsurface soil and geologic conditions using test pits, test borings, and geophysical instruments to evaluate the stability of soil and rock at locations of proposed site facilities. If unstable subsurface conditions are encountered, a decision can be made to proceed to remediate prior to construction or to modify the site layout to avoid problem areas. The record of findings during this phase of the investigation includes logs of test pits, probes, and borings; noting evidence of cavities in soil and rock; loss of air pressure or drilling fluid during drilling; and the condition of soil and bedrock from samples collected.

A discussion of the various site investigation methods follows:

Geologic maps: 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 fracture 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.

Aerial photography: Aerial photos are a simple, quick method of site reconnaissance. Inspection of vegetation 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 in stereo image. 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.

Site visit: An onsite reconnaissance is an inexpensive, important step in finding potential site constraints. Although many karst features are obvious to the eye, it is advantageous to conduct the site visit with an individual knowledgeable in karst geology. Prior to the site visit, field personnel should review geologic maps, topographic maps, and aerial photos to help anticipate where problems might be found. It is important to review drainage patterns, vegetation changes, depressions, and bedrock outcrops to look for 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 particularly simple and often overlooked part of the site visit is to interview 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 location of karst features should be noted on the site map for later reference. These can be compared to other information collected to assess the risk potential for karst-related problems.

Test pits: 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 (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: 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.

Test borings: Test borings often 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 and provide undisturbed samples that can be subjected to laboratory testing. 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. When drill holes are sealed, the volume of fluid cement grout placed in the drill hole can also yield a measure of the size of openings in the subsurface.

Geophysical methods: Geophysical methods can serve as a rapid reconnaissance tool to detect physical anomalies in the subsurface that may be caused by karst features. These methods are especially suited to surveying linear corridors and are non-disruptive to the land. Geophysical data are often useful for extrapolating between locations where other 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 hinder the depth of penetration and resolution of geophysical signals and 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.

Recommended Procedures When Karst Features Are Identified

The site investigations described above may reveal the location of suspected areas of ground subsidence. These findings should be compared to the proposed layout of site facilities. Wherever possible, facilities should be sited to avoid suspected areas of potential ground subsidence. Where relocation of facilities is not practical, remedial measures and design standards can be employed to minimize future ground failure. Remedial sealing of voids in the soil or bedrock and/or compaction of soil and rock voids maybe a viable in some areas.

The product of the preliminary site investigation is a determination of whether the development site has karst features and therefore warrants a more detailed site investigation. The product is usually a site map, which shows the location of any known or suspected karst features. It should be noted that while the presence of sinkholes or caves is diagnostic of karst, their absence does not necessarily mean that karst will not be a problem at the site (Hubbard 2004).

B.3.2 Detailed Site Investigations

Detailed site investigations are required in the design of all building, roads, stormwater conveyance, 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. Presence of any of these features could pose a danger to groundwater quality, a construction hazard, or an increased risk of sinkhole creation at a proposed centralized stormwater facility.

The design of the geotechnical investigation should reflect the size and complexity of the development project, and 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 soil borings or observations needed to adequately characterize subsurface conditions can be determined by the geotechnical consultant and the requirements of the local reviewing authority.

The investigation should determine the nature and thickness of subsurface materials including the depth to bedrock and the water table in the area(s) of the site where construction is planned. The investigation is an iterative process that may need to be expanded until the desired detailed knowledge of the site is obtained and fully understood. Pertinent site data to collect includes:

- Bedrock characteristics (e.g., type, geologic contacts, faults, geologic structure).
- 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
- Photo-geologic fracture trace map
- Bedrock outcrop areas
- Sinkholes, closed depressions, and solution-enlarged voids
- Cave openings
- Springs
- 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
- Site-scale watershed boundaries based on large scale site topography (i.e., one foot or less contour intervals)
- Layout of proposed buildings, roads, and stormwater structures (and estimated site impervious and turf cover)
- Existing stormwater flow pattern

Stormwater designers should retain the services of a qualified consultant experienced in working in karst landscapes. 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

Electric resistivity tomography has proven to be a particularly useful technique to identify subsurface anomalies at a scale that impacts stormwater design. 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.

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. Stormwater designers should retain the services of a qualified karst hydrologist or hydrogeologist to perform the trace. Also, designers are advised to coordinate with the Underground Injection Control (UIC) Program 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.

B.3.3 Soil Borings

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:

- Within each individual geologic unit present based on local, state, or federal geological mapping sources
- Adjacent to sinkholes or related karst features at the site
- Along photo-geologic fracture traces, including alignment of sinkholes
- Adjacent to bedrock outcrop areas
- Within the planned boundaries of any centralized stormwater facility
- 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:

- Description, logging, and sampling over the entire depth of the boring
- 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.
- When conducting a standard penetration test, record the estimates of soil engineering characteristics including "N" or estimated unconfined compressive strength.

B.3.4 Boring Requirements for Centralized Stormwater Facilities

The density of borings shall result in a representative sampling of the proposed facility. In general, a minimum of five borings shall 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 remainder within the proposed impoundment.

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 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.

B.3.5 Plan Submittals

At least one subsurface cross section should be submitted with the stormwater plan, showing confining layers, depth to bedrock, and water table, if encountered. It should extend through the centerline 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 practice should be included for reference to present subsurface data.

Consultants should identify and locate karst features 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. In these cases, an easement, buffer, or reserve area should be identified on the development plats for the project so that all future landowners are aware of the presence of sinkholes on their property.

B.4 Assess Future Groundwater Contamination Risk

B.4.1 Designation of Stormwater Hotspots

The other 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 1 presents a list of potential land uses or operations that may be designated as a stormwater hotspot. It should be noted that the actual hotspot generating area may only occupy a portion of the entire proposed use 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 future operations, in all or part of the site, should be designated as a stormwater hotspot.

Table B.1: Potential Stormwater Hotspot and Site Design Responses.

Potential Stormwater Hotspot Operation	SWPP Required?	Restricted Infiltration	No Infiltration
Facilities w/NPDES Industrial permits	Yes	■	■
Public works yard	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	●	

Note: *For a full list of potential stormwater hotspots, please consult Schueler et al (2007)*

Key: ■ depends on facility ● Yes

Shaded Area 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 water ordinance.

If a site is designated as a hotspot, a range of stormwater treatment and pollution prevention practices can be applied to prevent contamination of surface or groundwater, particularly when the hotspot discharges to a community drinking water supply or **wellhead protection area**. Depending on the severity of the hotspot, one or more of the following management strategies outlined in Section B.4.2 may be required by the local review authority.

B.4.2 Management Strategies for Stormwater Hotspots

If the future operations at a proposed development project are designated as a stormwater hotspot, then one or more of the following management actions are required (Table B.1).

1. **Stormwater Pollution Prevention Plan (SWPPP).** This plan is required as part of an industrial or municipal stormwater permit and 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 but can be designated as potential stormwater hotspots by the local review authority as part of their local stormwater ordinance (these are shown in the shaded areas of Table B.1).

It is recommended that these facilities include an addendum to their stormwater plan that details the pollution prevention practices and employee training measures that will be used to reduce contact of pollutants with rainfall or snowmelt.

2. **Restricted Infiltration**. A minimum of 50% of the total runoff reduction volume must be treated by a filtering or bioretention practice prior to any infiltration. Portions of the site that are not associated with the hotspot generating area should be diverted away and treated by an acceptable stormwater practice.
3. **Infiltration Prohibition.** If a site is classified as a potentially severe hotspot, the risk of groundwater contamination is so great that infiltration of stormwater is prohibited. In these cases, an alternative stormwater practice, such as closed bioretention, sand filters, or constructed wetlands must be used to filter the entire runoff reduction volume before it reaches surface or groundwater.

B.4.3 Underground Injection Control Permits

The Safe Drinking Water Act regulates the infiltration of stormwater in certain situations under the Underground Injection Control (UIC) Program, which is administered by either the EPA or a delegated state groundwater protection agency, Tennessee Department of Environment and Conservation. 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” wells.

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, 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.

Federal and State 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, name and address of legal contact, ownership of property, nature and type of injection well(s), and operating status of injection wells. Additional information on Class V well requirements can be accessed at:

http://www.tn.gov/environment/permits/injetwel.shtml

The regulatory authority then reviews this inventory data, and may determine the injection is authorized, require more information, issue a UIC permit with best management practice requirements, or order the well closed.

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.” 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. EPA defines man-made structures as including pipes, swales, ditches, excavations, drains, graded slopes, or any other device that is intended to channel fluids toward or into a sinkhole. In Tennessee, 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 a Class V UIC permit. This is even true if the improved sinkhole is downstream of stormwater treatment practices, either on site of off-site. Discharges to improved sinkholes on adjacent downstream properties are only allowed when appropriate legal agreements are made with the property owners of the improved sinkhole.

The second situation where a UIC permit or 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 in this Technical Bulletin have been created to avoid classification as Class V injection wells. These design modifications include minimum geometric dimensions, surface pretreatment, soil filtering, and design of “closed practices” that have filter fabric or under drains which daylight to the surface.

B.4.4 Stormwater Discharge 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 predevelopment flows to the existing sinkhole to maintain subsurface hydrology. In either case, the following rules pertain:

- The sinkhole or karst feature receiving post development stormwater runoff shall be considered a Class V Injection Well.
- The designer should conduct a survey for public or private drinking water wells with a ¼ mile of their improved sinkhole, and submit data on any wells found to the UIC permit authority.
- As such, the designer must notify the appropriate agency that regulates groundwater and administers the UIC permit. An underground injection permit will be extremely difficult to obtain if the proposed land use or operation at the site is designated as a severe stormwater hotspot.
- It is strongly advised that a dye trace be performed to understand how additional stormwater flows will move through groundwater, particularly if wells are located nearby.
- The design goals are to prevent increased runoff volumes from discharging to the sinkhole, but to maintain the discharge of the predevelopment runoff volumes so as to maintain groundwater recharge.
- Designers should maintain both the quality and quantity of runoff to predevelopment levels prior to discharge into an existing sinkhole. Operationally, this means that designers must treat the full water quality volume in an acceptable runoff reduction practice before discharging to a sinkhole (i.e., full runoff reduction volume for runoff produced by one inch of rainfall over contributing impervious surfaces.
- The operation and maintenance of stormwater practices shall be included as a condition of the required underground injection permit issued by the appropriate state or federal reviewing agency.

B.5 General Stormwater Design Principles in Karst

B.5.1 Site Design

- Designers should perform the preliminary and detailed site investigations prior to beginning site and stormwater design to fully understand 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 their presence.
- Minimize site disturbance and changes to soil profile, including cuts, fills, excavation, and drainage alteration near karst features.
- Sediment traps and basins should only be used as a last resort after all other erosion and sediment control options have been considered and rejected. 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.
- Require notification procedures on the design plans for both erosion and sediment control and stormwater management.
- Minimize the amount of impervious cover created at the site so as to reduce the volume and velocity of stormwater runoff generated.
- Take advantage of subsurface conditions when locating building pads, and place foundations on sound bedrock.
- The location of new or replacement septic systems near improved sinkholes may be regulated by the local public health authority. Many recommend that septic systems should be located at least 100 feet away of 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 possible to increase infiltration and accommodate flows from extreme storms.

B.5.2 Stormwater Design

- 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.
- Small-scale low impact design (LID) 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 are 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 IC, and/or has a surface ponding depth greater than three feet. Examples include wet ponds, dry 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 permit.
- Designers should refer to the list of preferred and acceptable stormwater practices as outlined in Table B.2.
- 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 handle or bypass the 2- and 10- year design storm, following the methods outlined in Section B.5.4.
- Designers should maintain both the quality and quantity of runoff to predevelopment levels and minimize rerouting of stormwater from existing drainage.

Table B.2: Stormwater Practice Selection in Karst Regions.

Stormwater Practice	Stability in Karst Regions	UIC Permit?	Design and Implementation Notes
Bioretention	Preferred	No	
Urban Bioretention[1]	Preferred	No	
Rain Tank/Cistern	Preferred	No	
Rooftop Disconnection	Preferred	No	15 feet foundation setback
Green Roofs	Preferred	No	
Dry Swale	Preferred	No	Lined with underdrains
Filtering Practices	Preferred	No	Water-tight
Filter Strips	Preferred	No	Flow to karst swales
Grass Channel	Adequate	No	Compost amendments
Soil Compost Amendment	Adequate	No	
Small Scale Infiltration[2]	Adequate	No	Not at stormwater hotspots
Micro-bioretention	Adequate	No	Closed systems
Permeable Pavers	Adequate	No	
Constructed Wetlands	Adequate	Maybe	Use Liner and Linear Cells
Wet Ponds	Discouraged	Maybe	Liner Required
Dry ED Ponds	Discouraged	Maybe	Liner Required
Wet Swale	Prohibited	No	Infeasible
Large Scale Infiltration[3]	Prohibited	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 B.4
3 Contributing drainage area of 20,000 sf of IC or more

- As a general rule, the stormwater system should avoid large contributing areas, deep excavation, or pools of standing water.
- The potential hotspot status of the proposed use of the development should be evaluated prior to design. If the site is defined 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 as outlined in WVDEP (2006), MDE (2000), or CCDP (2007). These techniques are related to the size of the sinkhole and are further described in Section B.7.

B.5.3 Stormwater Modeling

Many of the traditional NRCS hydrologic models over predict predevelopment runoff from karst terrain, as a result of the high initial abstraction of karst, as well as the fact that concentrated storm flows are often rapidly converted to subsurface flows (Laughland, 2007). In general, model over-predictions are greatest for the smaller storms and lower for larger storm events, such as the 100-year storm.

Consequently, designers must carefully modify their NRCS hydrologic and hydraulic computations to reflect the lower predevelopment peak discharge rates. Several options are provided by VA DCR (1999) and Laughland (2007), the most common of which are the multiplier factors used to adjust TR-55 and TR-20 pre-development rates, shown in Table B.3.

It should be noted, however, that the authors indicate more hydrologic monitoring and modeling research is needed to get predictions that are more reliable. Karst designers are advised to consult Fennessey and Miller (2001) who recommend that post development runoff rates should be computed based on site impervious cover alone. In any event, the adjustment factors shown in Table B.3 apply only to predevelopment runoff and should never be used for post-development runoff computations.

Table B.3: Multipliers for Adjusting Predevelopment Runoff Quantities for Karst Impact Adapted from Laughland (2007) and VADCR (1999).

% 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
80	0.38	0.51	0.62
60	0.55	0.66	0.74
40	0.73	0.80	0.85
20	0.91	0.92	0.93
0	1.00	1.00	1.00

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

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

B.5.4 Recommended Procedures for Conveying Runoff from Larger Storms

Karst areas often have no defined channels in or near small or moderate sized development sites. Instead, predevelopment runoff is conveyed in parabolic type swales across adjoining properties. When developing a karst site, the peak storm runoff rate to these swales shall be restricted to the existing karst-adjusted peak runoff rate or the pre-development forest rate, whichever is less.

This is calculated by reducing the allowable peak flow rate resulting from the 1.5-, 2-, and 10-year, 24-hour storms to a level that is less than or equal to the peak flow rate from the site assuming the site was in a good forested condition. This is typically computed by multiplying the forested peak flow rate by a reduction factor (i.e., the runoff volume from the site when the site was in a good forested condition divided by the runoff volume from the site in its proposed condition).

The total post development runoff volume may not exceed the pre development volume for the 2-year storm or more frequent storms. Storms in excess of the 2-year storm may discharge a larger volume.

B.6 Design Adaptations for Specific Stormwater Treatment Practices

B.6.1 Preferred Practices

Impervious Area Disconnection: Impervious area disconnection is strongly recommended for most residential lots 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. The discharge point from the disconnection should extend at least 15 feet from any building foundations.

Rainwater Harvesting Tanks: Rainwater harvesting tanks are a preferred practice in karst terrain of the Tennessee, as long as the rooftop surface is not designated as a stormwater hotspot.

- 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: Since bioretention areas require shallow ponding and treat runoff through a prepared soil media, they are generally appropriate for karst regions with the following design modifications to reduce the risk of sinkhole formation or groundwater contamination:

- If bedrock is within three feet of the bottom invert of a proposed bioretention area, the bioretention should be equipped with an under drain to convey treated runoff to an appropriate discharge point. If groundwater contamination is a strong concern, the bottom of the facility should be lined by an impermeable filter fabric.
- The scale of bioretention application is extremely important in karst terrain. Larger bioretention designs that rely on exfiltration of treated runoff into underlying soils are not recommended.
- It is recommended that the contributing area to individual bioretention areas be kept to less than 20,000 square feet of IC. Micro-bioretention and small-scale bioretention practices are preferred over larger bioretention basins.
- The minimum depth of the filter bed can be relaxed to 18 inches if the geotechnical investigation indicates that further excavation may increase karst vulnerability.
- Other tips to reduce the vertical footprint are to limit surface ponding to 6 to 9 inches, and save additional depth by shifting to a turf cover rather than mulch.
- It is important to maintain at least a 0.5% slope in the underdrain to ensure drainage and tie it into the ditch or conveyance system.
- 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 down-gradient setbacks from buildings, structures, and roadways should be as described in Table B.4.

Table 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 sf	2500 to 20,000 sf	20,000 to 200,000 sf
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 CDA	Runoff Reduction Volume
Observation Well/Cleanout Pipes	No	No	No
Type of Pretreatment	External (leaf screens, etc.)	Filter strip or grass channel	Pretreatment Cell
Recommended Max Filter Depth	Max 3 Foot Depth	Max 5 Foot Depth	Max 6 Foot Depth
Media Source	Mixed on site	Obtained from Approved Vendor	
Head Required	Nominal 1 to 3 foot	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 up-gradient

Dry Swale (closed): Shallow dry swales work well in karst terrain when they utilize impermeable filter fabric liners and under drains.

- The invert of the dry swale shall be located at least two feet above bedrock layers or pinnacles.
- If a dry swale facility is located in an area of sinkhole formation, standard setbacks to buildings should be increased.
- The minimum depth of the filter bed can be relaxed to 18 inches, if head or water table conditions are problematic.
- A minimum underdrain slope of 0.5% slope must be maintained to ensure positive drainage and be tied into an adequate discharge point.

Urban Bioretention: Three forms of bioretention for highly urban areas can work acceptably within karst terrain since they are enclosed in a concrete shell and do not interact with groundwater - stormwater curb extensions, expanded tree planters and foundation planters. 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.

Filtering Practices: Stormwater filters 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.
- Construction inspection should certify that the filters are indeed water tight
- The bottom invert of the sand filter should be at least two feet above bedrock
- The minimum depth of the sand filter bed can be reduced to 24 inches.

Green Roofs: Green roofs are a preferred treatment option in karst terrain for commercial institutional and industrial sites, but they may somewhat limited application given the forms and intensity of development in the Ridge and Valley Province. The overflow from the green roof should extend at least 15 feet away from the building foundation.

Filter Strips: The use of conservation filter strips is highly recommended, particularly when storm flow discharges to the outer boundary of a karst swale protection area. Grass 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.

B.6.2 Adequate Practices

Grass Channel: Grass channels are an acceptable practice in karst terrain, as long as they do not treat hotspot runoff. The following design adaptations apply to grass channels in karst terrain.

- Soil compost amendments can be incorporated into the bottom of grass channels to improve their runoff reduction capability.
- Check dams are generally discouraged for grass swales in karst terrain since they pond too much water (although 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 can 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 tied into an adequate discharge point.

Soil Restoration: No special adaptations are needed 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 (for definitions and design requirements, See Table B.4). Designers may choose to infiltrate less than full water quality volume in a single practice (and use another runoff reduction practice to pre-treat or filter runoff prior to the infiltration facility.

Some other design modifications for small scale infiltration in karst terrain include:

- Designers should maximize the surface area of the infiltration practice, and keep the depth of infiltration to less than 24 inches.
- Soil borings must indicate at least three feet of vertical separation exist between their bottom invert and the bedrock layer.
- Where soils are marginal, under drains may be used.
- In many cases, bioretention is a preferred stormwater alternative to infiltration in karst areas.

Infiltration is prohibited if the contributing drainage area is classified as a severe stormwater hotspot.

Permeable Pavers: Permeable pavers are an acceptable option in karst terrain if geotechnical investigations have eliminated concerns about sinkhole formation and groundwater contamination.

- Full infiltration from permeable pavement is not recommended for large scale pavement applications and is prohibited if the site is designated as a severe stormwater hotspot, or discharges to areas known to recharge to aquifers used as a water supply.
- Permeable pavement is acceptable when they are designed to with an impermeable bottom liner and underdrain. A minimum 0.5% underdrain slope must be maintained to ensure proper drainage.
- The rock used in the reservoir layer should be carbonate in nature to provide extra buffering capacity.

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 to assess this risk in the planning stage. If they are employed, designers should:

- Use an impermeable liner and maintain at least three feet of vertical separation from underlying bedrock.
- Shallow, linear and multiple cell wetland configurations are preferred.
- Deeper basin configurations, such as the pond/wetland system and the ED wetland have limited application in karst terrain.

B.6.3 Discouraged Practices

Dry Extended Detention (ED) Ponds and Wet Ponds: The use of either dry ED or wet ponds in karst terrain is highly discouraged, because of frequent recurring failures due to sinkhole formation. At a minimum, designers must demonstrate that:

- A minimum of six feet of unconsolidated soil material exists between the bottom of the basin and the top of the bedrock layer.
- Maximum temporary or permanent water elevations with basins do not exceed six feet. Annual maintenance inspections are conducted to detect sinkhole formation. Sinkholes that develop should be reported

immediately to local and state officials (see Section B.7.1) 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 B.7).

- A liner is installed that meets the requirements outlined in Table B.5.

Table B.5: Required Groundwater Protection Liners for Ponds in Karst Terrain (WVDEP, 2006 and VADCR, 1999).

Pond Excavated at least 3 Feet Above Bedrock	24 inches of soil with maximum hydraulic conductivity of 1 x 10^{-5} cm/sec
Pond Excavated within 3 Feet of Bedrock	24 inches of clay[1] with maximum hydraulic conductivity of 1 x 10^{-6} cm/sec
Pond Excavated Near Bedrock within wellhead protection area, in recharge area for domnestic well or spring, or in area with high fracture density or significant geophysical anomalies	Synthetic liner with a minimnum thickness of 60 ml.

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)

B.6.4 Prohibited Practices

Wet Swale: These practices are not generally feasible in karst terrain since the water table rarely reaches the land surface.

Large Scale Infiltration: Large scale infiltration is defined as individual practices that infiltrate runoff from a contributing drainage area between 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- and small scale infiltration or bioretention are preferred stormwater alternatives in karst terrain.

B.7 Sinkhole Remediation in Stormwater Practices

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

B.7.1 Sinkhole Notification

The existence of a new sinkhole within a temporary erosion control practice, road right of way or stormwater management practice shall be reported to the local stormwater review authority within 24 hours or the next business day. A plan for investigation and stabilization shall be coordinated with the local review authority, and repairs shall commence immediately after receiving design approval. Until repairs are completed, a temporary berm shall be constructed to divert surface flow away from the sinkhole. Documentation of sinkhole repairs shall be submitted to the UIC program.

B.7.2 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 may 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 (less than ten 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 (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.

Soil Borings may be taken using augers, core, 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 (bridge abutments, major roads, load bearing structures). This investigation involves a closely spaced boring program 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.

B.7.3 Sinkhole Stabilization

Stabilization of reverse-grade backfilling, grouting or subsurface engineering structures, as follows:

a) **Reverse-graded backfilling** 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 shall 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 installed 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.

b) **Grouting** is generally discouraged, unless it is combined with the graded filter (a) 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 well.

c) **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.

B.7.4 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, although this is not always possible if the sinkhole forms within the stormwater conveyance system or centralized pond.

REFERENCES

Carroll County Department of Planning. (CCDP). 2007. Water Resource Management Manual for Carroll County, MD. Bureau of Resource Management. Westminster, MD.

CSN Technical Bulletin No1: Stormwater Design Guidelines for Karst Terrain in the Chesapeake Bay Watershed. Version 2.0. Chesapeake Stormwater Network. http://chesapeakestormwater.net/2012/03/technical-bulletin-no-1-stormwater-design-guidelines-for-karst-terrain/

Fennessey, L. and A. Miller, 2001. "Hydrologic Processes During Non-Extreme Events in Humid Regions." Proceedings of the 2001 Pennsylvania Stormwater Management Symposium. October 17-18, 2001. Villanova University. Philadelphia, PA.

Fennessey, L. 2003. "Defining Natural Land Areas Critical to Stormwater Control in Karst Regions." Proceedings of the 2003 Pennsylvania Stormwater Management Symposium. October, 2003. Villanova University. Philadelphia, PA.

Hubbard, D. 2004. "Use of Regional Sinkhole Mapping for Sinkhole Susceptibility Maps." Proceedings: Ninth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst. Geotechnical Publication No. 122. American Society of Civil Engineers.

Laughland, J. 2007. "Adjusting Hydrology Models and Using Karstic Features." Stormwater Management Design in Karst Terrrain. Facility Design Group. County Engineer, Jefferson County, WV.

Maryland Department of Environment (MDE). 2000. Maryland Stormwater Design Manual."Appendix D-2: Geotechnical Methods for Karst Feasibility Testing. http://www.mde.state.md.us/Programs/WaterPrograms/SedimentandStormwater/stormwater_design/index.asp

Minnesota Stormwater Steering Committee (MSSC). 2005. The Minnesota Stormwater Manual. Chapter 13. Additional guidance for karst, shallow bedrock, groundwater, soils with low infiltration capacity, potential stormwater hotspots, and sediment disposal areas, St Paul, MN.

Pennsylvania Department of Environmental Protection (PA DEP). 2006. Pennsylvania Stormwater Management Manual. Harrisburg, PA.

Schueler, T., Hirschman, D., Novotney, M., Zielinski, J. 2007. Manual 3: Urban Stormwater Retrofit Practices Manual: Urban Subwatershed Restoration Manual Series. Center for Watershed Protection, Ellicott City, MD.

Sweetland Engineering Associates (SEA). 2000. Spring Creek Watershed Plan. Chapter 4 Water Quality Considerations. Prepared for Centre County Commissioners. Pennsylvania.

Virginia Department of Conservation and Recreation (VADCR). 1999. Virginia Stormwater Management Handbook. Technical Bulletin No. 2. Hydrological Modeling and Design in Karst.Division of Soil and Water Conservation. Richmond, VA.

West Virginia Department of Environmental Protection. (WVDEP). 2006. Stormwater management structure guidance document. Groundwater/UIC program. Morgantown, WV.