CSN TECHNICAL BULLETIN No. 1

STORMWATER DESIGN GUIDELINES FOR KARST TERRAIN IN THE CHESAPEAKE BAY WATERSHED VERSION 2.0

Developed by Karst Working Group
Released June 2009

<u>Table of Contents</u> **2**

Purpose of this Supplement

This stormwater design supplement has been prepared for engineers, plan reviewers, and public works officials to guide better stormwater decisions when land is developed in karst regions of the Chesapeake Bay watershed. Until now, available local and state guidance on this topic has been uneven, sometimes conflicting and certainly not comprehensive. An informal working group has spent the last year developing this guide.

It is intended that the Technical Bulletin can be incorporated directly or by reference into local and state land development codes, ordinances, regulations, permits and engineering manuals in the Bay watershed that govern how stormwater is managed in karst terrain. The supplement 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 edition. First, the effect of land development on karst terrain is complex and hard to predict, and requires professional analysis to reduce the risk of geological hazards, damage to infrastructure and groundwater contamination. Second, the bulletin has been produced to respond to the recent growth pressures in many small communities in the Great Valley, Eastern Panhandle and South Central Pennsylvania. The working group acknowledges that past approaches to stormwater and land development in karst terrain have been inadequate to safeguard the public and the environment.

In addition, the working group notes that 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 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).

Section 1: Why Karst Terrain is Different

Three of the major tributaries to the Chesapeake Bay flow through karst country, they are the Susquehanna, the Potomac, and the James River. This band of karst terrain runs through the Bay watershed, and encompasses portions of Maryland, Pennsylvania, Virginia and West Virginia (Figure 1). Karst in the Bay watershed 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).

The karst terrain in the Bay watershed 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 collapse of surface sediments caused by the intrusion of stormwater from the surface into deep, underlying voids.

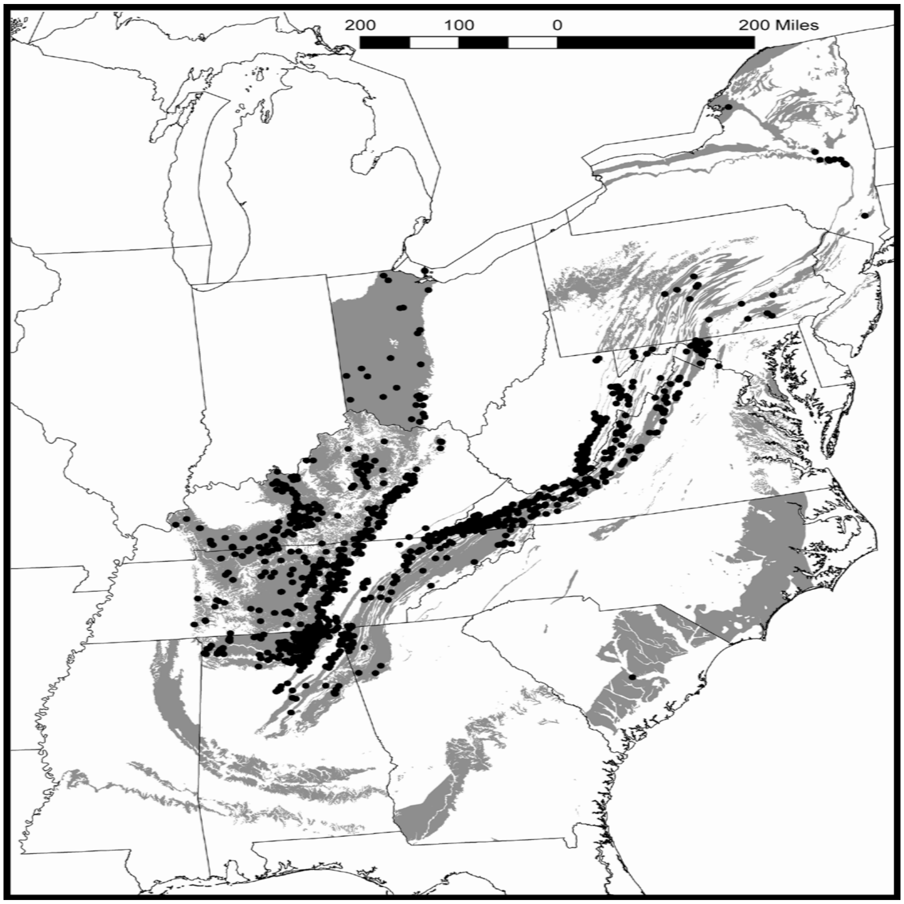

Figure 1 Karst Distribution in Bay States: grey = karst, black = caves
(Source: Weary, 2005)

The presence of karst terrain within the Ridge and Valley Province (and select portions of the Piedmont Province) of the Bay watershed 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 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 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 faces 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 (see Section 8 for a glossary of karst terms). 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. 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.

Rural Development Patterns and Growth Pressures*:* The karst region of the Bay watershed has experienced 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 with many small lots or subdivisions constructed outside of water and sewer service areas. Consequently, many communities in karst terrain mainly rely on public or private wells to provide drinking water and septic systems to dispose of wastewater. Rural land development increases demand on groundwater resources, and in times of drought, lowers the water table and causes wells to dry up. These problems are exacerbated when poor stormwater management on the same development also reduces groundwater recharge.

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 that merit special protection, 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.

Section 2: A Unified Approach for Stormwater Design in Karst Terrain

This Technical Bulletin 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 Bulletin they can find more information about it.

The flow chart 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 solely intended as a guide for stormwater design and is not meant to be used as a prescriptive process for local stormwater plan review.

Figure 2 Flow Chart for Stormwater Design in Karst Terrain

Section 3: Preliminary and Detailed Site Karst Investigations

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. Some important additional elements of preliminary site investigation are described in Technical Bulletin 2 of the VA DCR Stormwater Management Handbook (1999).

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 the 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).

3.2 Detailed Site Investigation

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 area 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**, **grikes** 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 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.

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, and 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.

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 reminder 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 feet 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

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 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 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.

Section 4: Assess Future Groundwater Contamination Risk

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.

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 4.2 may be required by the local review authority.

Table 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 (2004)			
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			

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 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 water ordinance (these are shown in the shaded areas of Table 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 water quality volume (WQv) 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 wetland must be used to filter the entire WQv before it reaches surface or groundwater.

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, as shown in Table 2. 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 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.epa.gov/safewater/uic/class5/comply_minrequirements.html. 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 most Bay states, this definition would also include directing increased stormwater runoff volumes into an existing sinkhole from new upland development. The manner and scope by which Class V wells are regulated differs among the five Bay states where karst is found, and designers should consult with the lead regulatory agency in their state to ensure their project is in compliance.

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 defacto 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, except where noted in Table 3. 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.

Table 2: Underground Injection Control Permit and/or Authorization Agency in Each Bay States with Karst

BAY STATE	REGULATORY AUTHORITY
MARYLAND	MDE
NEW YORK	EPA REGION 2 *
PENNSYLVANIA	EPA REGION 3 *
VIRGINIA	EPA REGION 3 *
WEST VIRGINIA	WV DEP

* in states where EPA administers the UIC program, Class 5 wells are "rule- authorized", meaning that they do not require a permit, but the operator must contact the agency to inventory their well. Consult Appendix A and B for more specific state contact information

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.

Section 5: General Stormwater Design Principles in Karst

The following general principles should be considered in site layout and the design of stormwater systems:

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 to increase infiltration and accommodate flows from extreme storms

5.2 Stormwater Design Principles for Karst

- Treat runoff as sheetflow 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 3.

- 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 5.4.

- Designers should maintain both the quality and quantity of runoff to predevelopment levels and minimize rerouting of stormwater from existing drainage.

Table 3. Stormwater Practice Selection in Karst Regions				
Stormwater Practice	**Suitability in Karst Regions**	**Bay-wide Design Spec #** [4]	**UIC Permit?**	**Design and Implementation Notes**
Bioretention	Preferred	**9**	No	
Urban Bioretention [1]	Preferred	**9a**	No	
Rain Tank/Cistern	Preferred	**6**	No	
Rooftop Disconnection	Preferred	**1**	No	15 feet foundation setback
Green Roofs	Preferred	**5**	No	
Dry Swale	Preferred	**10**	No	Lined w/ underdrains
Filtering Practices	Preferred	**12**	No	Water-tight
Filter Strips	Preferred	**2**	No	Flow to karst swales
Grass Channel	Adequate	**3**	No	Compost amendments
Soil Compost mendment	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
Wet Ponds	Discouraged	**14**	Maybe	Liner Required
Dry ED Ponds	Discouraged	**15**	Maybe	Liner Required
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 5
[3] Contributing drainage area of 20,000 sf of IC or more
[4] The most current version of the Bay-wide Stormwater Specifications can be downloaded from www.chesapeakestormwater.net

.

- 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 shall 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 (2004), MDE (2000) or CCDP (2007). These techniques are related to the size of the sinkhole, and are further described in Section 7.

5.3 Stormwater Modeling in Karst Areas

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 4.

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 4 apply only to predevelopment runoff, and should never be used for post-development runoff computations.

TABLE 4: Multipliers for Adjusting Predevelopment Runoff Quantities for Karst Impact Adapted from Laughland (2007) and VA DCR (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

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.

5.5 Karst Swale Protection (KSP) for Stormwater Management.

SEA(2000) proposed a water quality volume credit for protection of natural drainage ways present at 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 (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 by reducing site IC to the karst swale in the water quality or runoff reduction equation by twice the KSP 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:

- 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 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.

- The KSP area must be located on the development site, and the maximum total KSP credit is 50% of the site impervious area.

- It is good practice to combine a KSP with an adjacent filter strip to accept off-site stormwater runoff.

Section 6: Design Criteria for Specific Stormwater Treatment Practices

This section describes recommended design adaptations for stormwater practices installed in karst terrain. The base design specification for each practice can be found at the Chesapeake Stormwater Network website, www.chesapeakestormwater.net.

Section 6.1 Preferred Practices

Rooftop Disconnection: Rooftop disconnection is strongly recommended for most residential lots less than 6000 square feet, particularly if it can be combined with a secondary micro-practice to increase runoff reduction and prevent seepage problems. (See Bay-wide 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.

Rain Tanks: Rain tanks are a preferred practice in karst terrain of the Bay watershed, 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, it should be equipped with an under drain to collect 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 in karst regions.
- It is recommended that the contributing area to individual bioretention areas be kept to less than 20,000 square feet of IC. These 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 six to nine 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 4.

Table 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	Remaining WQv up to Full Cpv
Observation Well/ Cleanout Pipes	No	No	Yes
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 feet	Moderate 1 to 5 feet	Moderate 2 to 6 feet
Building Setbacks	15 ft down-gradient 25 ft up-gradient	15 down-gradient 50 ft up-gradient	25 ft down-gradient 100 ft upgradient

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. 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 Bay-wide Stormwater Design Specification No. 2.

Section 6.2 Adequate Practices

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

- o Soil compost amendments can be incorporated into the bottom of grass channels to improve their runoff reduction capability.
- o 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).
- o The minimum depth to the bedrock layer can be 18 inches.
- o A minimum slope of 0.5% must be maintained to ensure positive drainage.
- o 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 5). 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.

Table 5: The Three Design Scales for Infiltration Practices

Design Factor	Micro Infiltration	Small-Scale Infiltration	Large Scale Infiltration
Impervious Area Treated	250 to 2500 sf	2500 to 20,000 sf	20,000 to 100,000 sf
Typical Practices	Dry Well, French Drain, Paver Blocks	Infiltration Trench Permeable Paving	Infiltration Trench Infiltration Basin
Runoff Reduction Sizing	Minimum 0.1 inches over CDA	Minimum 0.3 inches over CDA	Remaining WQv up to Full Cpv
Minimum Soil Infiltration Rate	0.5 inches/hour	1.0 inches/hour	1.0 inches per hour
Design Infil. Rate	50% of measured rate		
Observation Well	No	Yes	Yes
Type of Pretreatment	External (leaf screens, etc)	Filter strip or grass channel	Pretreatment 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 sf of infiltration area
Building Setbacks	15 ft down-gradient 25 feet up-gradient	15 ft down-gradient 50 feet up-gradient	25 ft down-gradient 100 feet up-gradient

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 areas 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 (i.e., VA DCR Level 2 Design) 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.

Section 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 restricted, 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 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 7).
- A liner is installed that meets the requirements outlined in Table 6.

Table 6. Required Groundwater Protection Liners for Ponds in Karst Terrain (WVDEP, 2006 and VA DCR, 1999)	
Pond Excavated at least Three Feet Above Bedrock	24 inches of soil with maximum hydraulic conductivity of 1 x 10^{-5} cm/sec
Pond Excavated within Three 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 domestic well or spring, or in area with high fracture density or significant geophysical anomalies.	Synthetic liner with a minimum 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)	

Section 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.

Section 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.

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 certified by a registered professional engineer and submitted to the local review authority

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.

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.

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.

Section 8: Glossary of Terms and List of Acronyms

8.1 Karst Terms

Carbonate Bedrock - A rock that consists of one or more carbonate minerals. Carbonate rock successions (or sequences) are those in which carbonate rock is dominant, but which also contain rocks of other lithology. Typical carbonate rocks are limestone, dolomite and marble.

Cave - A natural opening formed in the rocks below the surface of the ground large enough for a man to enter. It may consist of a single connected opening or a series of small or large chambers connected by galleries.

Conduit - Relatively large dissolutional voids, including enlarged fissures and tubular tunnels; in some usage the term is restricted to voids that are water-filled. Conduits may include all voids greater than 10mm in diameter, but another classification scheme places them between arbitrary limits of 100mm to 10m. Whichever value is accepted in aparticular context, smaller voids are commonly termed sub-conduits

Epikarst - A relatively thick (the thickness may vary significantly, but 15 to 30 meters thick is a good generalization) portion of bedrock that extends from the base of the soil zone and is characterized by extreme fracturing and enhanced solution. It is separated from the phreatic zone by an inactive, relatively waterless interval of bedrock that is locally breached by vadose percolation. Significant water storage and transport are known to occur in this zone.

Estravelle - An intermittent resurgence or exsurgence, active only in wet seasons. May act alternatively as a swallow hole and as a spring according to ground-water conditions.

Grike - A solutionally enlarged vertical or steeply inclined joint in the surface of a karstland, extending for up to a few meters into the limestone.

Karst - A terrane, generally underlain by limestone or dolomite, in which the topography is chiefly formed by the dissolving of rock, and which may be characterized by sinkholes, sinking streams, closed depressions, subterranean drainage, and caves

Karst area – A region with topography dominated by features of solutional origin. Geomorphically, the dominant features usually but not always obviously present, are sinkholes and caves.

Karst swale –NEED DEFINITION OR DELETE

Improved sinkhole – Any sinkhole which has remediated or fitted with engineering improvements to ensure groundwater quality and recharge rate. Also, any sinkhole which has been designated as a stormwater outlet at internally-drained sites, and as such falls under UIC permitting requirements.

Insurgence - A term proposed to describe a point of inflow for surface water into subsurface conduits.

Losing Stream - A stream or reach of a stream in which water flows from the stream bed into the ground. In karst terranes, losing streams may slowly sink into fractures or completely disappear down am open sinkhole.

Resurgence - Re-emergence of karst ground water a part or all of whose waters are derived from surface inflow into a sinkhole at higher levels. Point at which an underground stream reaches the surface and becomes a surface stream.

Rock Pinnacles - These are a particularly mature form of karren, and form sharp edges and peaks that can reach several meters in height. Generally, pinnacles need a long period time to form. Regionally they are nearly always covered by surface soil, and form the uppermost portion of the epikarst.

Sinkhole - General term for closed depressions. They may be basin, funnel, or cylindrical shaped, and are formed by both soil raveling (cover collapse) and cavern roof failure (vault collapse).

Swallet - A place where water disappears underground in a limestone region. A swallow hole generally implies water loss in a closed depression or blind valley, whereas a swallet may refer to water loss into alluvium at a streambed, even though there is no depression.

Throat – An opening into the subsurface at the base of a sinkhole through which soil and water is conducted underground. Sinkhole throats can be soil or rock bounded, but most often form a conduit in the bedrock.

Turloughs - A karst depression that may be dry or flooded according to season or prevailing weather conditions; derived from the Irish term for 'dry lake'. Oscillations in the general ground-water level, including variations in response to local or more distant tidal effects are the probable mechanism for water level changes in the true turloughs.

Wellhead Protection Area -

8.2 Stormwater Terms

Stormwater hotspots - any operation or activity that produces higher pollutant concentrations in runoff or melt-water, or has a higher risk for spills, leaks or illicit dischargers
.
closed
karst swale
open
runoff reduction
water quality volume

MORE TO BE ADDED

8.3 List of Acronyms

ADT	average daily traffic volume
CDA	contributing drainage area
CPv	channel protection volume
ED	extended detention
ESC	erosion and sediment control
IC	impervious cover
LID	low impact development
KSP	karst swale protection area
NPDES	National pollutant discharge elimination system
NRCS	Natural Resources Conservation Service
SWPPP	Stormwater pollution prevention plan
UIC	Underground injection control
WQv	Water quality volume

Section 9: Sources and References Cited

An informal working group of karst experts, stormwater practitioners and state and federal regulators reviewed and contributed to this technical bulletin. Special thanks are extended to Chris Anderson (Page County, VA), Twila Carr (West Virginia DEP), Bob Denton (Potomac Environmental Services) Tom Devilbiss (Carroll County, MD), Mike Eller (EPA Region 3), Jim Lawrence (VA Tech), Wil Orndorff (Virginia DCR). Michael Schwartz (Freshwater Institute), Wayne Webb (Winchester, VA), Sherry Wilkins (West Virginia DEP).

In addition, the following references and resources were consulted for this technical supplement.

American Rivers. 2007. Using green infrastructure in karst regions. Washington, DC. www.americanrivers.org

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

CWP. 2007. *National Pollutant Removal Performance Database Version 3.0*. Center for Watershed Protection, Ellicott City, MD.

Denton, R. 2008. Stormwater management in karst: a regional perspective. Potomac Environmental Services. Presented at Panhandle Stormwater Workshop. Martinsburg, WV.

Field, M. 2002. A Lexicon of Cave and Karst Terminology with Special Reference to Environmental Karst Hydrology. U.S. Environmental Protection Agency EPA/600/R-02/003

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

Hirschman, D., K. Collins and T. Schueler. 2008. Appendix G. Technical Memorandum: The Runoff Reduction Method. Virginia Department of Conservation and Recreation. National Fish and Wildlife Foundation. Center for Watershed Protection. Elicott City, MD.

Hubbard, D. 2004. Use of regional sinkhole mapping for sinkhole susceptibility maps. Proceedings of the Ninth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst. Geotechnical Publication No. 122. American Society of Civil Engineers.

Hyland, S. 2005. Analysis of sinkhole susceptibility and karst distribution in the Northern Shenandoah Valley (Virginia); impacts for LID site suitability models. M.S. Thesis. Virginia Polytechnic Institute and State University. Blacksburg, VA.

Laughland, J. 2007. Adjusting hydrology models and using karstic features. Stormwater Management Design in Karst Terrane. Facility Design Goup. 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 et al 2007. *Urban Stormwater Retrofit Practices*. Manual 3 in the Urban Subwatershed Restoration Manual Series. Center for Watershed Protection. Ellicott City, MD.

Schueler, T. 2008. Technical Support for the Baywide Runoff Reduction Method. Chesapeake Stormwater Network. Baltimore, MD www.chesapeakestormwater.net

Schueler, T. 2000. Microbes and Urban Watersheds- Ways to Kill Em. *Watershed Protection Techniques.* 3(1):566-574

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

U.S EPA. 2008. June 13 2008 Memo. L. Boornaizian and S. Heare. Clarification on which stormwater infiltration practices/technologies have the potential to be regulated as “Class V” wells by the Underground Injection Control Program. Water Permits Division and Drinking Water Protection Division. Washington, D.C.

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

Weary, D. 2005. An Appalachian region karst map and progress toward a new national karst map. Proceedings USGS Karst Interest Group. USGS Scientific Investigations Report 2005-5160

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

Appendix A

Karst-Related Digital Geospatial Data Sources

Maryland

Maryland Geologic Quadrangles. Maryland Geological Survey. Scale varies.
http://www.mgs.md.gov/esic/publications/pubcatdigiquad.html
http://www.mgs.md.gov/esic/publications/pubcatdigicnty.html

USGS Geologic Quadrangles. Scale 1:24,000. Enter state name in "Search text in title:" and choose "Geologic Quadrangle" in "Select USGS publication series:".
http://pubs.er.usgs.gov/usgspubs/index.jsp

Pennsylvania

Bedrock Geology of Pennsylvania. 2001. Pennsylvania Bureau of Topographic and Geologic Survey, Department of Conservation and Natural Resources. Scale 1:250,000.
http://www.pasda.psu.edu/uci/MetadataDisplay.aspx?entry=PASDA&file=dcnr_bedrockgeology2001.xml&dataset=480

Sinkhole Inventory and Online Database. Pennsylvania Bureau of Topographic and Geologic Survey, Department of Conservation and Natural Resources.
http://www.dcnr.state.pa.us/topogeo/hazards/sinkhole/default.asp

PDF versions of 1:24,000 surficial geology. Pennsylvania Bureau of Topographic and Geologic Survey, Department of Conservation and Natural Resources.
http://www.dcnr.state.pa.us/topogeo/pub/openfile.aspx

Density of Mapped Karst Features in South-Central and Southeastern Pennsylvania. Pennsylvania Bureau of Topographic and Geologic Survey, Department of Conservation and Natural Resources.
http://www.dcnr.state.pa.us/topogeo/map68/index.aspx

USGS Geologic Quadrangles. Scale 1:24,000. Enter state name in "Search text in title:" and choose "Geologic Quadrangle" in "Select USGS publication series:".
http://pubs.er.usgs.gov/usgspubs/index.jsp

Virginia

USGS Geologic Quadrangles. Scale 1:24,000. Enter state name in "Search text in title:" and choose "Geologic Quadrangle" in "Select USGS publication series:".
http://pubs.er.usgs.gov/usgspubs/index.jsp

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

Virginia Division of Mineral Resources
- https://www.dmme.virginia.gov/commerce/
- Geologic quad maps and digital data
- Karst Feature Maps
- Publications 44, 83, and 167.
- Local Karst Maps
- Publications 102 (Clarke County) and 070 (Giles County)

West Virginia

Geologic Map of West Virginia. 1968. WVGES. Scale 1:250,000.
http://www.wvgis.wvu.edu/data/dataset.php?action=search&ID=43

Karst regions derived from 1968 geological map of West Virginia. Scale 1:250,000
http://www.wvgis.wvu.edu/data/dataset.php?action=search&ID=133

Fracture Trace Map and Single-Well Aquifer Test Results in a Carbonate Aquifer in Berkeley County, West Virginia. 2005. Kurt J. McCoy, Melvin H. Podwysocki, E. Allen Crider, and David J. Weary. Scale varies by dataset.
http://pubs.usgs.gov/of/2005/1040/

Fracture Trace Map and Single-Well Aquifer Test Results in a Carbonate Aquifer in Jefferson County, West Virginia. 2005. K.J. McCoy, M.H. Podwysocki, E.A. Crider, and D.J. Weary. Scale varies by dataset.
http://pubs.usgs.gov/of/2005/1407/

USGS Geologic Quadrangles. Scale 1:24,000. Enter state name in "Search text in title:" and choose "Geologic Quadrangle" in "Select USGS publication series:".
http://pubs.er.usgs.gov/usgspubs/index.jsp

Regional/National

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 Karst: 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/

Appendix B

Chesapeake Bay Karst Contacts and Resource/Websites

Maryland

Tom Devilbiss, Hydrogeologist and Deputy Director
Carroll County Government
225 N. Center Street,
Westminster, Maryland 21157
410-386-2639
tdevilbiss@ccg.carr.org

Pennsylvania

William E. Kochanov, P.G.
Department of Conservation and Natural Resources
Bureau of Topographic & Geologic Survey
3240 Schoolhouse Road
Middletown, PA 17057-3534

Phone: 717-702-2033
717-702-2017 (main office)
717-702-2065 (fax)

West Virginia

Twila Stowers Carr, ERS III, RS
WV Department of Environmental Protection
Groundwater Program
3810 Greensburg Road
Martinsburg, WV 25404
304-267-0173

George Dasher, Geologist III
WV Department of Environmental Protection
Groundwater Program
601 57th Street SE
Charleston, WV 25304
304-926-0495

Mark D. Kozar, Hydrologist
U.S. Geological Survey
West Virginia Water Science Center
11 Dunbar Street,
Charleston, WV 25301

304-347-5130 ext. 228
mdkozar@usgs.gov

WVU Geology Department
Dorothy Vesper, 4337
Joe Donovan, 4308
Henry Rauch
304-293-5603

Virginia

Wil Orndorff, Karst Protection Coordinator
Virginia DCR Natural Heritage Program
8 Radford Street, Suite 201
Christiansburg, VA 24073

(540) 394-2552
(540) 394-2504

Joseph Fagan, Karst Protection Specialist
Virginia DCR Karst Program
8 Radford Street,Suite 201
Christiansburg, VA 24073
540-394-2552
joseph.fagan@dcr.virginia.gov

Carol Zokaites
Karst Education Coordinator
540-394-2553
carol.zokaites@dcr.virginia.gov

Virginia Cave Board
Virginia Division of Natural Heritage
Department of Conservation and Recreation
217 Governor Street, 3rd Floor
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 DEQ
Ground Water Characterization Program
http://www.deq.virginia.gov/gwcharacterization/
Joel P. Maynard (Valley and Ridge contact)
4411 Early Rd

P.O. Box 3000
Harrisonburg, VA 22801
Phone: (540) 574-7864
jpmaynard@deq.virginia.gov

New York

Arthur N. Palmer
State Univ. of New York at Oneonta (retired)
607-432-6024

Castendyk, Devin
State Univ. of New York at Oneonta
CASTENDN@oneonta.edu

Other Karst Resources

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

Karst Information Portal: www.karstportal.org.

National Cave and Karst Research Institute: 1400 Commerce Dr. Box 4. Carlsbad , NM 88220. USA. Email: gveni@nckri.org. Phone: (575) 887-5517