4-5 HYDROLOGIC MODELING in KARST

Karst is a landscape in which underlying geologic strata are commonly riddles with caves, crevices, and cavities that alter "typical" surface runoff infiltration rates common in other non-karst areas. In Virginia, most karst lands are underlain by soluble limestone and dolomite, collectively referred to as "carbonate rock.

The limestone and dolomite valleys west of the Blue Ridge mountains are separated by narrow ridges largely composed of sandstone and shale. Lower ridges are often composed of sandy dolomites and limestones. Both of these terrains can exhibit extreme karst topography, with first and second order streams that abruptly, or gradually lose drainage to the cavernous subsurface, temporal streams with large subsurface drainage areas, "blind valleys" (i.e., large linear sinkholes that are often mistaken for adequate drainage ways), and *estavelles* or hydrologically-active sinkholes that normally receive drainage from surrounding areas, but also discharge water in time of flood (Jennings, 1985).

Obviously, karst areas present problems to those attempting to work with conventional hydrologic models. Typically, modeling of a karst site or watershed via SCS or other traditional methods provides poor representation of runoff rates, with regard to both flooding and over-design of conduits and stormwater management facilities. This is largely because standard hydrologic modeling methods lack allowances for losses into sinkholes, fractures, crevices or caves that may exist in the carbonate units. Neither do models typically account for the stormwater that joins surface runoff as "interflow" when the collective capacity of interconnected conduits and cavities in the subsurface is exceeded.

Pre-development runoff rates for karst areas versus non-karst areas can differ by a large percentage even when two sites exhibit similar soil and topographic characteristics. In addition, karst hydrology can be unpredictable from surface observations, in that the consistency of bedrock permeability, porosity, and stability and vary widely over a short distance. In the karst areas of western Virginia, the formation of conduits and caverns in the bedrock are directly related to the solubility of the carbonate rock, and the structural trends (bedding planes, faults, prominent fracture patterns, etc) imposed on the rock during geologic time. In the short term, karst collapses and basin fractures can occur along these trends during climactic extremes which result in flooding and subsequent rise in the water table elevation.

The identification of karst terrain in a project area should be based on local geology and soils maps, and on field verification of karst features. In some parts of the state, standard 1:24000 topographic maps show less than 50% of the karst features that can be detected with inexpensive field observation. Aerial photographs reviewed in stereo almost always provide useful information about the karst hydrology by enabling the identification of structural trends along which groundwater and surface drainage tend to flow. The presence of sinkholes, swales, sinking steams or dry stream beds, caves, and limestone/dolomite outcrops should be mapped in the earliest stages of planning a development. Initial reconnaissance should not be limited to the site, but should extend well beyond site boundaries in order to correctly identify large-scale karst features. Since the modes in which surface and ground waters interact can fluctuate dramatically in response to climatic change, karst features identified through photo-interpretation and field work should be observed under a wide range of weather conditions, especially during periods of runoff, flooding, or snowmelt, to accurately represent pre-development conditions.

The following reference is an excellent source of information for local governments and citizens living in areas underlain by karst topography: Living On Karst, A Reference Guide for Virginia Communities, 1996, Virginia Department of Conservation and Recreation, Division of Natural Heritage. Terri Brown, Project Coordinator, Route 4, Box 99-J, Staunton, VA 24401 (540) 332-9239

4-5.1 Karst loss

Karst loss is a term given to surface runoff loss into bedrock strata in areas underlain by limestone formation. Unlike other calculation factors, such as curve numbers (which deal with characteristics of the land surface), a karst loss factor is intended to depict projected losses into bedrock. The determination of karst potential in any given area may be simplified by the observation of noticeable indicators such as caves, crevices, limestone outcrops, sink holes, ponds that appear to lack sufficient contributing area, and disappearing streams. In other cases, karst infiltration areas may be difficult to identify since definitive karst features are not always obvious. Generally, a lack of natural drainage way erosion or inadequately sized drainage ways (for the size of the contributing area) may be clues to karst loss. Other observations may include undersized drainage conduits that never run full.

Accounting for karst loss in the hydrologic modeling is intended to more accurately simulate actual conditions in deriving runoff rates. Mapping of a geographic area (when limited in size) may be productive in defining a karst loss zone (an area underlain by karst bedrock). However, it should be noted that the delineation of such zones should be viewed as a method for estimating karst loss, not an accurate representation of the actual site-specific karst loss rate. Accurate karst loss modeling requires **extensive** field investigation at each site under consideration to obtain comprehensive information about sub-surface strata. In many cases the expenditure necessary to fully model a site is prohibitive. Therefore, as an alternative, karst loss projections may be comparatively simple and be fairly accurate. John C. Laughland P.E., County Engineer; Jefferson County, West Virginia, has investigated karst loss modeling and the following discussion is adapted from his research. Please note that this is one method of many and more detailed investigative guidance may be presented in the future to help identify the extent of karst loss.

Projecting karst loss in hydrologic modeling of limestone requires some specific examination (field inspection) of the subject area, along with a geologic examination of the underlying strata in order to predict the extent of the karst loss zone. It should be noted that many urban development sites, being relatively limited in size, will fall exclusively in or out of a karst loss zone. In these cases, the watershed need not be split into karst and non-karst areas.

The following procedure is recommended for estimating karst loss:

1. Delineate the contributing drainage area or watershed to be studied.

2. Define any sinkhole areas within the contributing drainage area where surface drainage has no means of escaping offsite, other than downward through the karst strata (i.e. cracks, sinks, etc.). These areas can be assumed to contribute no surface discharge and can be subtracted from the contributing drainage area from Step 1.

3. Determine the amount of the contributing drainage area (from Step 2) underlain by karst strata (in percent).

4. Calculate the peak rate of runoff from the contributing drainage area using standard hydrologic methods, and reduce the calculated value by multiplying by the *Karst Loss Modification Value* (**Table 4-10**) based on the percent karst (% Karst) calculated in Step 3.

Table 4-10 (developed using the *PSU-IV Program* by G. Aron et al) provides modifiers based on the percentage of the contributing area that is underlain by karst strata. The modifiers are used to adjust the peak rate of runoff calculated using standard modeling techniques. For example, the calculated 2-year peak discharge of 12 cubic feet per second (cfs) from a drainage area that has been determined to be underlain by 80% karst zone (with no observed sinkhole areas) would be reduced as follows:

$$12 \text{ cfs} \times 0.38 = 4.5 \text{ cfs}$$

This represents a peak rate reduction of 62%. Note that as the storm frequency decreases (i.e. 2-year frequency to 10-year frequency storm) the multiplier decreases and has less affect on the result. This is due to the fact that karst exerts less of an influence as the rainfall rate increases and underground voids fill with water.

There are other potential methods that can be utilized to model Karst, such as the use of a *TYPE I* rainfall distribution within a *TYPE II* karst area or the manipulation of the Runoff Curve Number (RCN) or *Initial Abstraction* (Ia) values (when using SCS methodology). Each method of manipulation, however, has both advantages and disadvantages in accurately representing the impacts of karst topography on runoff rates.

Adjustment for karst loss is recommended only when analyzing pre-development site conditions . The premise behind karst adjustment is to better approximate actual site conditions, which produce lower peak rates of runoff than that approximated without an adjustment factor. Once development occurs, karst features may become more obliterated from extensive site grading activity. Also, the addition of impervious cover, along with construction of a surface drainage system may offset karst losses that may be present. Therefore karst adjustment for post-developed conditions is not recommended.

TABLE 4 - 10
Karst Loss Modification Values

% Karst	Storm Return Frequency		
	(2)	(10)	(100)
100	.33	.43	.50
90	.35	.46	.56
80	.38	.51	.62
70	.47	.58	.68
60	.55	.66	.74
50	.64	.73	.80
40	.73	.80	.85
30	.82	.86	.89
20	.91	.92	.93
10	1.00	.98	.97
0	1.00	1.00	1.00

4-5.2 Karst Surcharge

A topic not frequently noted in karst modeling is sinkhole surcharge . In this phenomenon, the opposite condition than that expected from karst loss occurs. Rather than dampening the runoff peak, there can be depressed surface areas, or sinkholes, that experience surcharge (flooding) during rainfall events. This is due to the connectivity of the underground conveyance network. These natural run off detention areas may or may not be significant in the overall hydrology of a watershed, but they may exert substantial impact on small sites, subjecting development in the area to inundation. A shift of detention catchment to other offsite karst areas is also possible when onsite development activity fills a sinkhole. Karst is unpredictable and changes at the surface may bring about sub-surface hydrologic modification. Due to the complexity of karst , sinkholes or surface depressions should never be filled unless a comprehensive evaluation of the feature is completed first.

4-6 INVESTIGATION, DESIGN AND REMEDIAL MEASURES FOR AREAS UNDERLAIN BY CAVERNOUS LIMESTONE

This section is adapted from the New Jersey Soil Erosion and Sediment Control Design Manual published by the New Jersey Department of Agriculture. This guidance was developed to assist conservation district personnel, land owners, and consultants in the proper procedures for addressing areas where karst topography may pose a threat to development. While the guidance is not intended as a panacea of prevention and treatment techniques, it does provide information for an initial survey of an area suspected or known to be underlain by karst topography.

4-6.1 Introduction

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

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

4-6.2 Site testing for detection of potential karst-related problems

The most effective and economical approach to designing and installing a successful soil erosion and sediment control system in karst areas is to evaluate the potential for ground failure by first collecting easily obtainable information on surface and subsurface conditions prior to construction activities. To obtain geologic maps applicants may contact the Virginia Department of Mines, Minerals and Energy, Division of Mineral Resources.

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 fractures sets may be more prone to solution than others. The relationship between topography and the distribution of geologic units may reveal clues about the solubility of the specific rock units. Geologic maps are often available at various scales, the most common being 1:24,000. Digital geologic data may be available as well.

Aerial photography: Aerial photos are a simple, quick method of site reconnaissance. Inspection of photos can quickly reveal vegetation and moisture patterns that provide indirect evidence of the presence of cavernous bedrock. Piles of rock or small groups of brush or trees in otherwise open fields can indicate active sinkholes or rock pinnacles protruding above the ground surface. Circular and linear depressions associated with sinkholes and linear solution features and bedrock exposures are often visible when viewed 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 on-site reconnaissance is an inexpensive, important step in finding potential site constraints. Although many karst features are obvious to the eye, it is an advantage to conduct the site visit with an individual knowledgeable in karst geology. Prior to the site visit field personnel should review geologic maps, topographic maps, and air 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 hinders 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.

4-6.3 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 may be a viable in some areas.

Site Design and Construction

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

Minimize site disturbance, including cuts and fills and drainage alteration.

Minimize impervious surface so as to minimize the volume of surface runoff generated.

Employ storm-water management measures that minimize flow velocities and ponding to avoid erosion of over-saturated of soils.

Waterproof pipefittings and pipe-to-basin fittings to minimize underground leaks. Leaks weaken and erode soils around underground conduits.

Place foundations on sound bedrock.

Erosion and Sediment Control Facilities

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

The site should be designed to take maximum advantage of topography. Modifications of site topography should be minimized.

Changes to the existing soil profile, including cuts, fills, and excavations, should be minimized.

Where practical, drainage facilities should consist of embankments at or above grade. Excavation into the existing soil profile to construct swales and basins should be minimized to the degree possible.

Temporary and final grading of the site should provide for drainage of storm-water runoff away from structures.

All SWM facilities, including grassed waterways, diversions and lined waterways, should be designed to disperse the flows across the broadest channel area possible. This reduces the level of soil saturation and reduces the potential for soil movement. Shallow trapezoidal channel cross sections are preferred over parabolic or v-shaped channels.

Sediment basins and traps should be used as a last resort for sediment control in karst areas, and should be used only after other designs have been considered and rejected. The ESC plan should attempt to minimize drainage area sizes and therefore the need for basins or large traps.

Vegetative cover should be established as rapidly as possible over exposed areas. Construction scheduling should strive to minimize the time that soil excavations are open and non-vegetated. This reduces the time that the site is exposed to periods of concentrated flows as well as preventing excessive drying of soils.

Utility trenches should be back filled with in-situ soils or low permeability fill material to discourage sub-surface water flow along the trench. Clay dams may be used at intervals along the trench excavation to impede subsurface flow along the trench. Trench backfill should be compacted to prevent future settlement and ponding. Backfill densities for open areas should exceed 90% of ASTM D-1557 maxima. Densities for areas supporting structures such as roadways should equal or exceed 95% ASTM D-1557 maxima. All underground piping should have water -tight fittings. The piping should be designed to withstand some limited displacement due to the probable ground settling and/or downward migration of trench bedding material into solution features.

Stormwater Conveyance

Stormwater conveyance structures to be used in karst areas should be designed in such a way as to dissipate overland flow over the largest area possible. Every attempt should be made to avoid concentration of flows and ponding. Grassed waterways can be effective storm-water-diversion structures in karst areas. Particularly effective are waterway designs that are shallow and broad, providing maximum bottom width and wetted perimeter to disperse flow over the greatest area.

SWM Facilities

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

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

When they function properly, SWM basins can be effective in removing contaminants commonly found in storm water, including heavy metals, nutrients, herbicides, pesticides, solids, and bacteria. Most of these contaminants are attenuated by sedimentation and soil filtration in the basin bottom. Sinkholes undermine the beneficial effects of basins on water quality by allowing introduction of untreated surface runoff directly to ground water. They "short-circuit" the hydraulic benefits of basins by allowing bypassing of outlet structures.

One strategy is to provide a pre-treatment which does not utilize the detention of stormwater to settle out or filter pollutants. Refer to **Minimum Standard 3.15** for manufactured water quality BMPs which can serve as pre-treatment devices or even spill containment BMPs for commercial/industrial development in karst areas. These structures will not eliminate the potential for karst collapse, however they do provide water quality benefits in order to minimize the potential for the contamination of groundwater.

SWM basin sites can be evaluated and facilities designed and retrofitted to guard against sinkhole formation and improve performance from a water-quality perspective. Testing procedures and design elements recommended to minimize detention basin failure include:

Minimize the coverage of the site by impervious surfaces, so that basin size will be minimized.

Evaluate soil texture. The basin should be constructed to minimize excessive seepage. Highly cohesive soils such as silt and clay loams may require minimum preparation of basin bottoms. Soils with low cohesive strength, such as sandy loams may require compaction and/or replacement or modification by the addition clay binders or the installation of clay or synthetic liners. Refer to **Minimum Standard 3.06**, Table 3.06-3 for clay liner specifications.

Investigate soils and bedrock below the basin for presence of voids. Repair existing voids and/or perform preventative grouting of basin substrate.

The following guidelines should be incorporated into the design and maintenance specifications of SWM basins constructed in karst topography:

- Basin profiles should be broad and flat to allow maximum dispersion of detained flow.
- Basin bottoms should be smooth to avoid ponding.
- Inlet and outlet structures should be designed to provide diffuse discharge of water; avoid concentration of flows. Under drains are preferred to provide gradual discharge of water and to avoid prolonged ponding of water.

- Repair sinkholes that occur in basin after construction.

<u>Response and Remediation of Sinkholes Occurring During Construction</u>

It is possible for sinkholes to form during construction of a project. Sinkholes that occur during construction should be repaired immediately to prevent their enlargement and associated adverse impacts. When sinkholes occur during construction the site supervisor should take the following steps:

- Report the occurrence to the plan approving authority within twenty-four (24) hours of discovery;

- Halt construction activities in the immediate area of the sinkhole until it is stabilized. Secure the sinkhole area.

- Direct the surface water away from the sinkhole area, if possible, to a suitable storm drainage system.

- Communicate proposed remediation plan to the plan approving authority. Some jurisdictions may have local requirements for notification and review as well.

- Repair any damage to ESC measures and restore ground cover and landscaping;

- In those cases where the hazard cannot be repaired without adversely affecting the ESC design, the applicant should submit contact the plan approving authority for approval of changes to the plan.

The type of repair chosen for any sinkhole depends on its location, the extent and size of the void, the type of infrastructure planned for the sinkhole area. Sinkhole sealing methods can include the use of available on-site materials, dry or wet grout, filter material and geotextiles. General recommendations and references are available from the Department of Conservation and Recreation upon request.

All sinkhole remediation activities should be under the direct supervision of a geologist, or geotechnical engineer with experience in limestone investigations and remediation practices. A certified professional should perform all borings.

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(USDA manuals and handbooks can be obtained through the National Technical Information Service Research Department, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA, 22161, 703-487-4780, 703-321-8541 (fax))