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ORIGINAL ARTICLE

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Drainage and flooding in karst terranes

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Abstract Flooding in karst terranes is a commonly occurring geo-hazard. It causes damage to property, businesses, and roadways. It can lead to the formation of cover-collapse sinkholes and groundwater contamination. Generally, three types of flooding or their combinations are related to karst: recharge-related sinkhole flooding, flow-related flooding, and discharge-related flooding. Understanding of the type of flooding is essential for solving the flooding problem. Areas prone to karst flooding should be recognized, and restrictions and laws on land use should be implemented. Runoff and erosion control plans should address the unique characteristics of karst features. Digging out clogged sinkholes, creating retention basins, or installing Class V Injection Wells are possible solutions to improve drainage of storm water. Solutions to flooding problems in karst areas should also be coordinated with the water quality control to prevent groundwater contamination.

Keywords Flooding · Sinkhole · Karst · Recharge · Discharge · Groundwater flow

Introduction

Karst terrain is a unique landscape produced by the dissolution of carbonate bedrock. Sinkholes, one of karst topography's main features, are causes of concern when building a home, business, or road. Many sinkholes function as nature's storm drains. When they cease to adequately transfer water to the subsurface, water will back up into the sinkhole and cause flooding. Unlike man-made storm drain systems, subterranean karst is a dynamic system with many different factors capable of affecting the rate of water flow (Ogden and Scott 1997). Flooding in karst terranes causes damage to property, businesses, and roadways (Fig. 1). It can lead to the formation of cover-collapse sinkholes and groundwater contamination. Three types of flooding are related to karst. In most cases, flooding incidents are related to a combination of these three basic types.

1. *Recharge-related sinkhole flooding*. This type of flooding occurs when a sinkhole's drainage capacity is not adequate to transfer the storm water runoff to the subsurface. The sinkhole in-take or throat may be plugged by trash disposal, soil, and debris eroded from the drainage basin. Human construction may increase the runoff rate to a sinkhole so that the rate of recharge exceeds the acceptance capacity of the sinkhole drain.
2. *Flow-related flooding*. Karst development is often controlled by the geologic formations and structures. In karst aquifers, water can move quickly to an area with smaller flow-through cross-section or where water is coming in from other tributaries in the same drainage basin. Flooding will occur when the in-coming flow rate exceeds the flow capacity of the conduits in the aquifer. Excessive sedimentation, rock fall, or human activities including sinkhole remediation during construction can reduce the flow capacity of the conduit.

3. *Discharge-related flooding*. This type of flooding occurs when groundwater discharge is reduced due to an increase in water levels at discharge points. The groundwater flow can even be reversed from its normal flow direction. Construction of dams in surface water to which the groundwater discharges can reduce the discharge rate from the karst aquifer.

Understanding of the type of flooding is essential to the solution of the flooding problem. Areas prone to karst flooding should be recognized, and restrictions and laws on land use should be implemented. Runoff and erosion control plans should address the unique characteristics of karst features. Digging out clogged sinkholes, creating retention basins, or installing Class V Injection Wells are possible solutions to improve drainage of storm water (Barner 1997; Dinger and Rebmann 1986; Kochanov 1995). Solutions to flooding problems in karst areas should also be coordinated with the water quality control to prevent groundwater contamination.

With the increase of urban expansion, sinkholes are being filled in and leveled to make way for new subdivisions and parking lots. With the increase of buildings and pavement, the area of infiltration becomes smaller and smaller causing too much stress on the remaining drainage area, which can cause severe flooding in cities. Each sinkhole that is filled in or paved over means that the water it used to take must go somewhere else, such as into another sinkhole, which can cause problems due to their limited storage and infiltration capacity.

Cities and states with karst terrains have begun to implement new restrictions and laws on land being developed (Reese et al. 1997; Doughty 1989; Fischer and Lechner 1989; Richardson 2003). Some methods include digging out clogged sinkholes, creating surface drainage systems such as retention basins, or installing Class V Injection Wells for quicker drainage of storm water (Crawford 1986). Class V Injection Wells are regulated by the Environmental Protection Agency's Underground Injection Control program and authorized by the Safe Water Drinking Act. Sinkhole improvement for drainage can be as simple as digging out a sinkhole to expose a conduit or as elaborate as installing a well with a sophisticated pumping system. Unfortunately, injection wells do not usually help flooding in wide, shallow solution sinkholes (Crawford 1984). Data logs from previous flooding events can help developers to determine the present-day capacity of the underground drainage system. Unfortunately, compiling information, designing proper drainage techniques, and maintaining the area are costly to the developers. Any shortcuts on materials and drainage constructions can cause additional sinkhole collapses or subsidence.

Fig. 1 Flooding in a karst area in Tennessee, USA

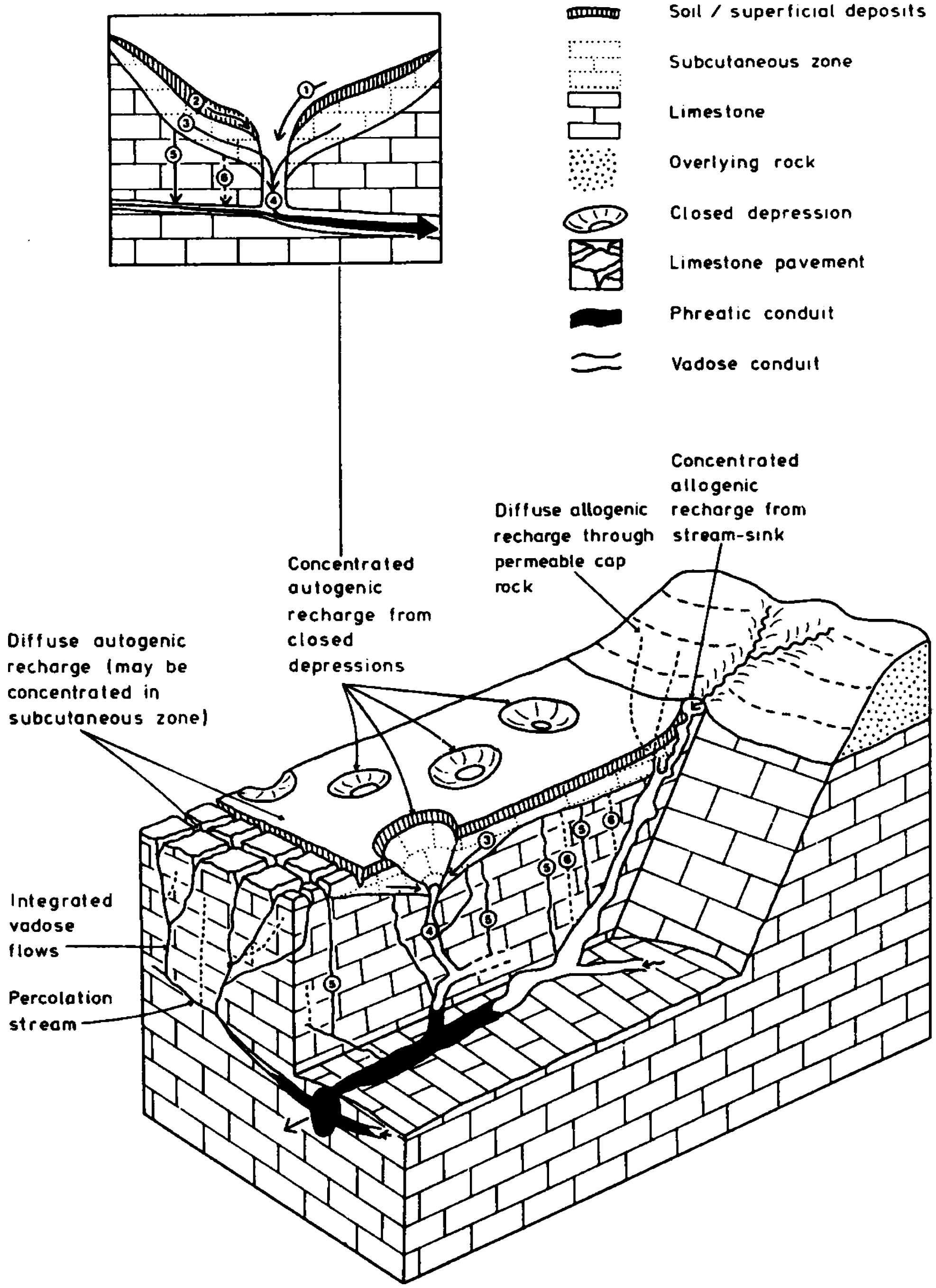
It may not be feasible to prohibit any development in areas that encompass or affect sinkholes or other karst features. However, if the potential impacts on storm water management and groundwater quality are identified, assessed, and addressed through professional studies at the earliest stages of the development approval process, many adverse impacts can be prevented.

Recharge-related flooding

Recharge types

A karst hydrogeological system is bounded by the groundwater divides and the associated surface topography divides (Fig. 2). It is generally recognized that recharge conditions in karst terranes are more favorable than non-karst ones. Considering different recharge sources, Ford and Williams (1989) classified the recharge into autogenic and allogenic recharges. Autogenic recharge is derived solely from precipitation falling directly onto the karst outcrops. Allogenic recharge is derived from neighboring or overlying non-karst rocks, which often occurs as concentrated point inputs of sinking (losing) streams. Both water chemistry and recharge volume per unit area tend to be different in these two styles of recharge, with considerable consequences for the scale and distribution of the development of secondary permeability (Palmer 1991). The capacity of the input passage is the ultimate regulator of the volume of recharge. Thus, if infiltration rate is too great, then ponding occurs, giving rise to overflow via surface channels or to surface flooding in blind valleys and poljes. Lloyd et al. (1991) demonstrated that the recharge conditions are related to the overlying soil. If the soil is less permeable than the rock beneath, then it provides a recharge regulator, limiting recharge to the infiltration capacity of the soil. Permeable rock formations overlying the karst, referred to as epikarst zone, also act as percolation "governors"

Fig. 2 A conceptual model for drainage in a karst area (From Gunn 1986). (*1* overland flow, *2* through flow, *3* subcutaneous flow, *4* shaft flow, *5* vadose flow, and *6* vadose seepage)



in much the same way, their vertical saturated hydraulic conductivity being the principal control.

The presence of an epikarst is a unique phenomenon for karst areas. As shown in Fig. 3, the epikarst consists of the uppermost portion of the unsaturated rock where significant fracturing, solutional enlargement, and storage may occur. It is often separated from the water table by a relatively less permeable rock that is sporadically breached by subcutaneous drains and vadose shafts (Quinlan 1989). When the volume of water entering the epikarst begins to exceed the drainage capacity of the zone, a hydraulic gradient may develop with a subcutaneous drain acting as the lowest point of hydraulic head, similar to a pumping well (Williams 1985). Lateral flow and transport to subcutaneous drains may exceed several hundred meters and allow for rapid flow rates. Water ponding or flooding occurs when the lateral flow rate exceeds the flow capacity of these subcutaneous drains.

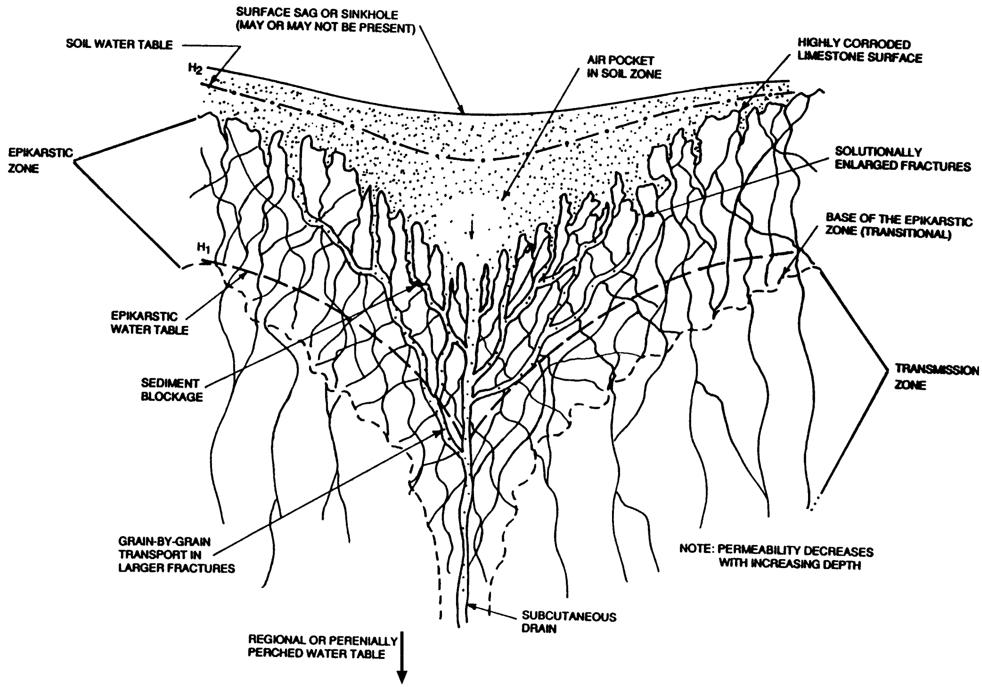


Fig. 3 Recharge processes through epikarst (modified from Williams 1985)

A well-developed karst surface is often lack of surface streams. Overland flow during storms is diverted into many closed depressions, which are often referred to as solution sinkholes. Solution sinkholes result from dissolution of carbonate rock along fractures over geologic time and often develop internal drainages. Troester et al. (1984) observed that at the highest stage of maturity, sinkholes develop a "star" pattern in aerial view as the sinkhole pirates more well-defined channels. Sinkhole catchment basins similarly progress in maturity from linear to pentagon shaped, which can be further modified by topographical slope. Rainfall or runoff entering into the closed depressions and flows directly into the aquifer through the sinkhole drains. The insertion in Fig. 2 shows the flow components within such sinkholes.

Collapse sinkholes result from raveling of overburden materials of groundwater flow, which can be enhanced by human beings' activities. Because collapse sinkholes do not have openings created by surface solution, they may have very different recharge behavior. A collapse sinkhole may not necessarily develop an internal drainage basin on surface. Flooding within such sinkholes is more related to groundwater conditions in the subsurface, where the sinkholes act as "sources" of water rather than "sinks." When a collapse sinkhole occurs within an existing solution sinkhole, the collapse sinkhole tends to function as a drain for the solution sinkhole.

Paleo-collapse columns are paleo-sinkholes that develop through bedrocks overlying karstified limestone. These sinkholes are often filled with rock fragments of the overlying strata. The fills can be unbounded and unconsolidated. Although formation mechanism of the paleo-sinkholes is still not well understood, the fact that they can act as passageways for water flow is not debatable. Flooding induced by such sinkholes, especially flooding in mines, can be catastrophic and unpredictable (Li and Zhou 1988; Zhou 1997).

Table 1 summarizes the relationship between a hydrogeological classification of sinkholes, the associated recharge sources, and possible flooding types. Surface flooding affects houses and roadways, while subsurface flooding impact underground utilities and mining operations.

Drain capacity of sinkholes

Determination of the drainage capacity of each sinkhole is complex. It relates to the sinkhole types (Table 1) and the aquifer system to which the drained water discharges. When sinkholes connect springs through conduits, open fractures, or shafts, the drain capacity depends on the size of the conduit and the difference between the water level in the sinkholes and the pressure at the springs. When discharge at the springs is free (not under pressure), the drain capacity of the sinkholes is then related to the water level in the sinkhole (Bonacci 1987). For mature solution sinkholes with internal drainage basins, the bowl sizes of the sinkholes are partially indicative of their drain capacity. For collapse sinkholes, their drain capacity is more related to the openness of the sinkhole throats. In general, the drain

Table 1 Recharges related to flooding in karst aquifers

Recharge passageways through sinkholes	Recharge sources		Type of flooding	
	Autogenic	Allogenic	Surface	Underground
Swallets, drain shafts for sinking streams		X	X	X
Solution sinkholes, surface depressions, vertical shafts	X		X	X
Collapse sinkholes	X		X	X
Paleo-collapse columns	X	X		X

capacity of sinkholes and the affecting factors need to be evaluated on a sinkhole-by-sinkhole basis. During karst studies, detailed descriptions of sinkholes in field are crucial in evaluating their hydrologic functions.

In-situ monitoring or controlled water-injection tests at sinkhole sites are also useful tools to estimate the drain capacity of the sinkholes. It is very important to understand that the drain capacity is related to the whole aquifer system. The sinkhole that is under study may be just one of many recharge points to the aquifer. Figure 4 shows some of the flow data collected at a sinkhole site and the associated spring, as illustrated in Fig. 5. Every recharge event at the sinkhole caused a response at the spring; however, some of the spring responses were not clearly related to the recharge at the sinkhole. Dye tracer tests proved that the sinkhole connects to the spring (Stephenson et al. 1999), and the spring drains an area far beyond the sinkhole site (Ogden 1994). Over the monitoring period, the sinkhole could drain at least 0.425 m^3/s (15 cfs) of storm water runoff.

Flow-related flooding

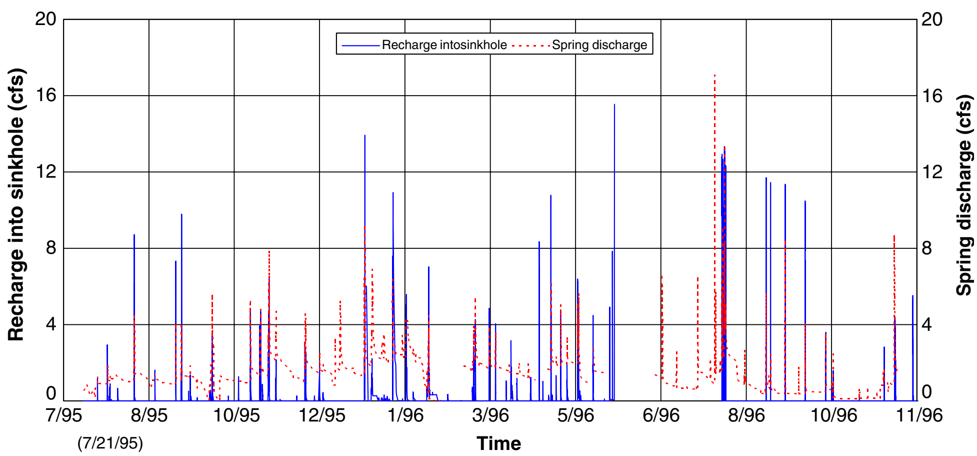
Void types

Groundwater flow in karst aquifers includes diffuse flow, conduit flow, and intermediate member of mixing flow with one type of flow dominating over the other. One characteristic feature of a mature karst aquifer is the presence of master drains for the groundwater system. The master drains are usually the active primary conduits that receive infeeders from the sinkhole drains (White 1993). Flow occurs in fissures, enlarged fissures, and conduits (Table 2). Because water flow follows the least-resistance principle, groundwater in small fissures or porous matrix tends to flow toward the enlarged fissures and conduits. Between enlarged fissures and conduits, the conduits have higher conductivity and thus groundwater in enlarged fissures tends to flow towards the conduits. As a result, groundwater is collected by and flows through the main conduits, a phenomenon referred to as confluent flow (Zhou 2000).

Irregularity of groundwater level

The multiple porosities of a karst aquifer often lead to a dynamic water level fluctuation zone (Fig. 5), which is also referred to as transitional zone. The transitional zone in karst aquifers is generally much greater than that in porous-medium aquifers. The peak groundwater level may be tens of meters higher than the lowest water level at the same location. In addition, the magnitude of the water level fluctuation is not uniform throughout the aquifer, depending on the void types intercepted by

Fig. 4 Recharge into a sinkhole and discharge at a connected spring



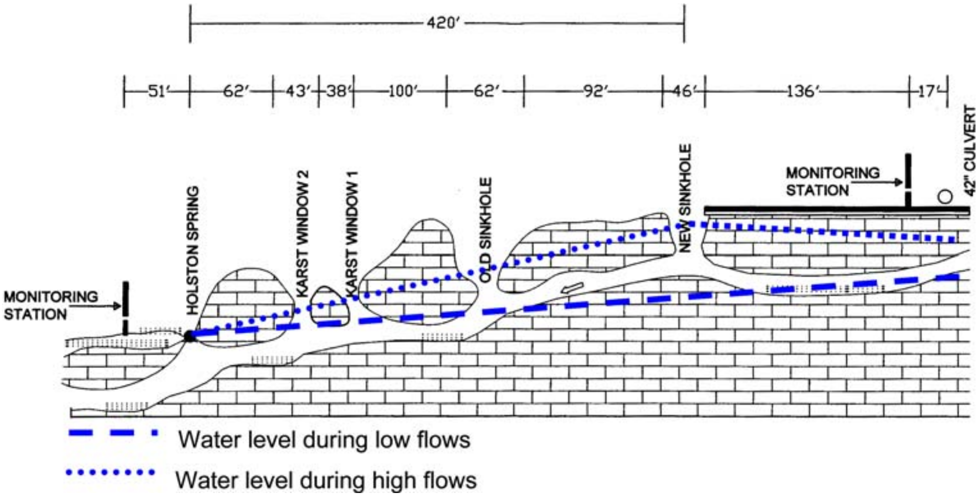


Fig. 5 Water levels during high-flow (*dotted line*) and low-flow (*dashed line*) conditions

Table 2 Void types in karst aquifers

Flow system	Void type	Void size (cm)	*Hydraulic characteristics*
Conduits	Cavern/solution-enlarged fractures	> 1	*Can be either laminar flow or turbulent flow, depending on the flow velocity and water depth*
Fissures	Fracture/crack	0.001–1	*Predominantly laminar flow and can be turbulent flow under high hydraulic gradient*
Voids	*Matrix void*	*< 0.001*	*Laminar flow*

monitoring wells. The magnitude of the groundwater level fluctuation in karst aquifers and its irregularity are often underestimated in practice, which contributes to some of the flooding problems.

Figure 6 shows a model consisting of two monitoring wells. Monitoring Well 2 (MW2) connects to a conduit, while Monitoring Well 1 (MW1) intercepts a fracture. A horizontal fracture connects these two wells. Flow

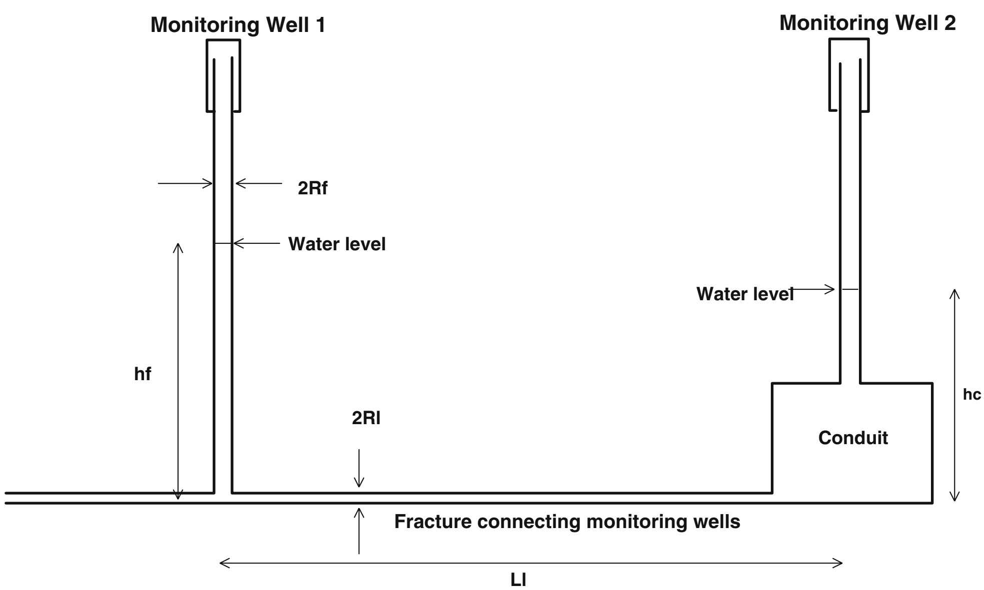


Fig. 6 Monitoring wells intercepting conduit and fracture

through the fracture link is governed by the Darcy-Weisbach equation (Smart 1999):

$$Q = 2\pi g^{0.5} R_l^{2.5} (i/f)^{0.5}$$

where g is the gravity acceleration, i is the hydraulic gradient, $i = (h_f - h_c)/L_l$, L_l is the distance between the monitoring wells, h_f is the water level in MW1, h_c is the water level in MW2, R_l is the radius of the fracture link, and f is the Darcy-Weisbach friction factor. Because the model results are relatively insensitive to f and L_l, they are held constant at 0.05 and 10 m, respectively (Smart 1999).

Similar to the approach used by Smart (1999), a time-series approach is taken for the investigation of the response of the conceptual karst system to recharge events. Because water preferentially flows through the conduit, the hydrologic response occurs first in the conduit. The recharge is thus modeled as an independent time sequence of hydraulic head in MW2, representing a typical hydrograph in a karst conduit. The head change in MW1 is then computed from the volumetric water balance of free-surface storage reservoirs:

$$\Delta h = \left(\sum Q_{in} - \sum Q_{out}\right)\Delta t/(\pi R_f^2)$$

where Δt is the time step, Δh is then applied to the current head to obtain the subsequent head in MW1. Figure 7 shows the response of MW1 to the hydrologic input from MW2.

Due to confluent flow in karst aquifers, the water level in MW1 lags behind that in MW2, and has a magnitude lower than that in MW2. The departure of the MW1 signal from the MW2 signal can be defined by differences in the peak water levels (amplitude difference), the maximum difference in water levels, and the time lag (phase difference).

The modeling exercises indicate that water level in a karst aquifer responds differently to a recharge event, depending on where the monitoring well is located. Water level may increase significantly and rapidly at one part of the aquifer, while the water level may show minor change at some other parts of the same aquifer. The differences in both phase and magnitude are much related to the size of the link fracture. Greater differences result from smaller link fractures. Therefore, blockage of flow passageways, either naturally or artificially, in a karst aquifer may lead to abnormally irregular changes in the water level configuration.

Clearly, prevention of flooding in karst areas requires prediction of the peak water level. However, accurate prediction of the peak level in a karst aquifer is challenging. The difficulties arise from two sources—the highly dynamic response of the conduit system to recharge events and the low permeability of the matrix block in the absence of solution openings. In response to recharge events, conduits permit exceptionally rapid transfer of water, while the storage reservoirs (fractures/matrix voids), which may contain the majority of the water in the karst aquifer, slowly adjust to autogenic recharge from sinkholes and backflooding from the primary conduits. During recession periods, the head loss in conduits is much lower than that in surrounding

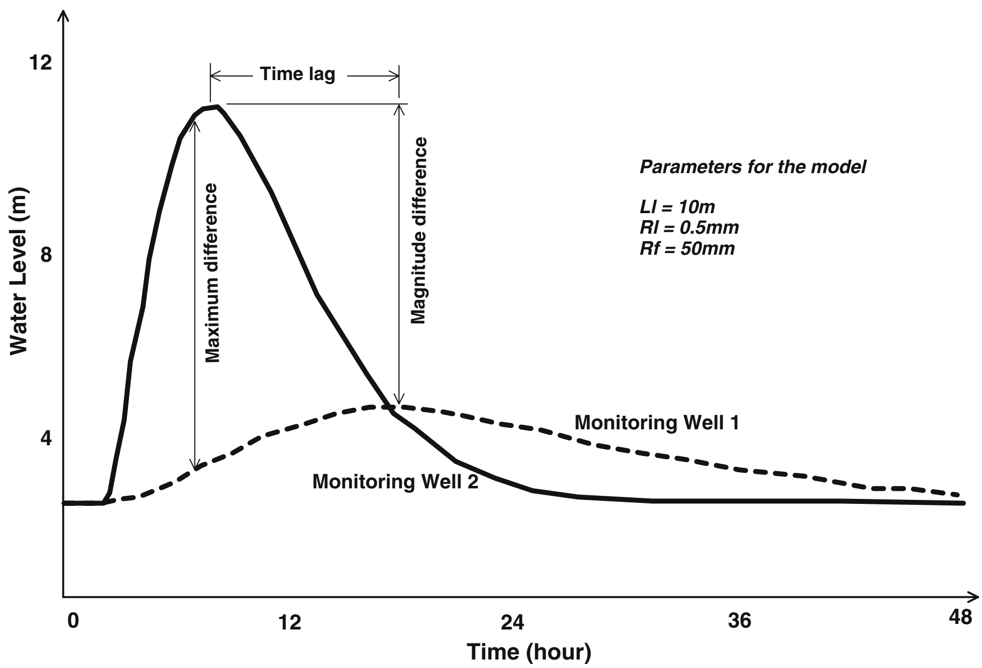


Fig. 7 Simulated water levels in two monitoring wells (modified from Smart 1999). Monitoring Well 1 intercepts a fracture, while Monitoring Well 2 intercepts a conduit

fractures or matrix blocks and the water stored in the matrix gradually drains into the conduits to sustain the spring flow. If times permit equilibrium between the water flow in the conduit and that in the matrix, a unified water level can be obtainable. When a karst aquifer is receiving water from rain events, the peak water levels in small fractures and conduits are different. The impact of precipitation on the water level in conduits may be instantaneous, the impact on the water level in fractures/matrix voids, however, is cumulative. The water level in fractures is affected not just by the most recent precipitation, but precipitations in the last several months or years.

In-situ monitoring at springs that occur at different elevations can provide useful information of the water level in conduits. Monitoring of water level at sinkholes can also provide useful information. Long-term and high-frequency measurements in monitoring wells, when they intersect a conduit or a fracture, are essential to understand the flow conditions in karst aquifers. Statistical analyses that correlate water level measurements in monitoring wells to precipitation at nearby weather stations can be used to estimate the peak water levels.

In a groundwater monitoring program that involves two karst springs, one surface stream, and two monitoring wells, Jie et al. (2003) designed a floating system to monitor flows at an upper spring for water levels in conduit. Their statistical analysis of over 2-years' monitoring data at the monitoring wells indicates that the water levels are impacted by 15-month preceding rainfalls. Well logs and tracer test in one of the wells indicate that the monitoring wells intercept a fracture system.

Discharge-related flooding

The hydraulic connection of surface water to groundwater in karst aquifers is shown not only at recharges but also at discharges. Springs are often the natural discharge points for karst water, which may feed a surface stream. If the surface channel is not adequate to accommodate the amount of discharge from the karst springs during a storm, flooding may occur as the water spill over the river banks. This kind of flooding is similar to surface water flooding. The most common flooding that is related to discharge in karst areas is caused by water impoundments at the discharge points or at the surface rivers such as construction of reservoirs or dams. The following consequences are expected when a reservoir is impounded in a karst area where conduit flow dominates:

- Increase in the drainage base level of the groundwater
- Back flow into the aquifer along the karst conduits
- Decrease in hydraulic gradient of the karst aquifer
- Transfer dried or intermittent springs at higher elevations to perennial ones
- Create springs at locations where water used to sink into the subsurface
- Decreases of flow velocity in the aquifer
- Decrease of flow rate from the aquifer to the surface stream.

As a result, karst valleys or depressions that drain into the karst aquifer are more prone to flooding or the severity of flooding becomes greater. The disastrous flooding events that occurred in 1993 and 1994 in the Nabapian karst valley of Guangxi Province, China are excellent examples of this type of flooding (Xiang et al. 1997).

The Nabapian karst valley is located 14-km upstream of the outlet of an underground river—Banwen Underground River (Fig. 8). The elevation of the valley ranges from 284 to 310 m above mean sea level (amsl), and the elevation of the outlet of the underground river is 177 m amsl. The underground river is the only drainage from the area and flows into the Yantan Hydroelectric Reservoir. After water was impounded in the reservoir in 1993, the water level was kept at 223 m amsl, which is 46 m higher than the original outlet of the underground river. When precipitation of 1,184 mm occurred between June and August, 1993, and 1,555 mm between May and August, 1994, record floods occurred in the karst valley, submerging the valley 3–6-m deep with some areas reaching 15-m deep. The floodwater remained for 88 and 124 days, respectively. The impoundment of the Yantan Reservoir increases the probability of flooding in the Nabapian valley because of the following three facts.

- The impoundment of the reservoir decreased the drainage capacity of the underground river. The impoundment decreases the flow-through area and the hydraulic gradient.
- The impoundment of the reservoir reduced the storage capacity of the underground river system. The storage volume helps regulate the flood levels.
- The impoundment of the reservoir enhances the deposition of particles, thus reducing the self-cleaning capacity of the underground river.

Solutions to karst flooding

Solution of karst flooding requires knowledge of the unique characteristics of karst systems and regulatory control of human being's activities in sinkhole areas. A flood-prone sinkhole is not an isolated geologic feature, rather a source or sink that connects to the whole karst system. An intimate relation between surface water and groundwater is characteristic of karst aquifers.

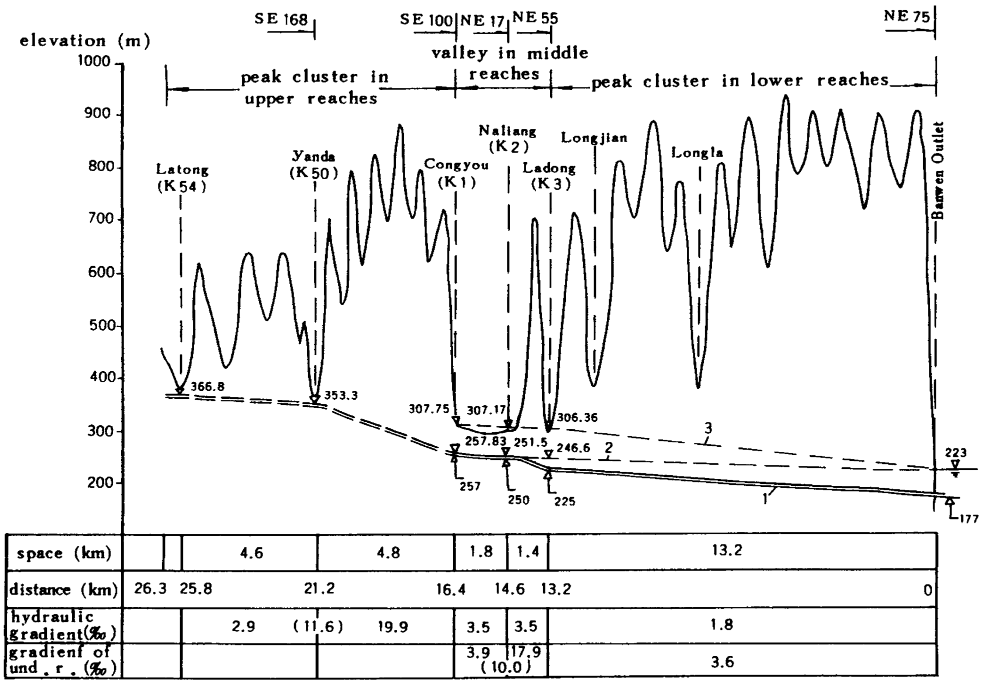


Fig. 8 Profile of flooded Nabapian valley (Jiang et al. 1997)

Sinkholes can function as sinks that funnel surface water into the subsurface; they can also act as sources through which groundwater discharges. Flooding in karst is a result of water imbalance between recharge and discharge. Water balance analysis, however, requires identification of the groundwater basin. Unlike a surface drainage basin that can be delineated by the topographic highs, a karst drainage basin may not have firmed divides by the topographic highs. Delineation of the karst basin may require a comprehensive investigation using specialized techniques, such as tracer tests, geo- or hydrogeo-physics, and long-term groundwater monitoring.

Best management practices (BMPs) are still the most effective way to control flooding. Any BMPs used to prevent flooding should also maintain the stability of the site and be able to improve the water quantity. The most effective practice to prevent flooding usually entails the control of runoff before it reaches a sinkhole. The three major functions of water quantity BMPs are to: (1) increase the storage of the sinkhole (depression storage, epikarstic storage, and unsaturated storage); (2) reduce the recharge rate (interception, reduction in infiltration, increase in the travel time of runoff to the sinkhole, and evaporation) or increase the recharge capacity (drainage wells); and (3) enhance the discharge capacity. The design criteria for flood control are typically based on the reduction of runoff peaks for rare rainfall events. A detention pond is often effective in attenuating the peak flow resulting from such a design storm. If the treatment of the runoff is not a concern, a dry detention pond may be the most efficient technique to prevent flooding prior to flowing into a sinkhole. Dry ponds are not very effective in removing pollutants due to their short detection time, but they can intercept debris that might plug the sinkhole throat. Detention ponds are most effective if installed on the upstream side of the sinkhole. It should be noted, however, that space limitations may rule out the possibility of constructing a detention pond. In addition, ponding runoff on a pervious surface may trigger the development of a new sinkhole collapse. Practices that could reduce stormwater runoff volumes from the watershed include increasing vegetation density, terracing slopes, using runoff spreaders, and using porous pavement. Filtration systems designed specifically at sinkhole sites may serve dual purposes—flood control and water treatment (Zhou et al. 2005).

Regulation is another important aspect of flood control in karst. The following particular issues should be properly addressed to reduce the flooding risk in karst areas:

- Plugging of the throat (drainage shaft) of the sinkhole by debris and/or sediment;
- Limitation of the carrying capacity through karst conduits by collapses, plugging, and intrusion of inflows from other sinkholes or sinking streams;
- Limitation of conduit capacity by elevated water levels in receiving water;
- Exceeding the sinkhole storage capacity and carrying capacity of conduits due to increased runoff volume and peak flows caused by an increase of the impervious area within a watershed;

- Filling, grouting, or building in sinkholes; and
- Sedimentation/siltation in conduits and at spring orifices.

Conclusions

Flooding in karst results from water imbalance between recharge and discharge. It can be related to recharge, flow, or discharge, depending on the site-specific conditions. Although flooding is a characteristic of karst terranes, human being's activities further increase the probability and severity of flooding in some areas. The classification of karst flooding into recharge-, flow-, and discharge-related is a first step toward the solution of a flood problem. When dealing with karst aquifers, one should take the whole system into the scope of work. Understanding of the unique characteristics of karst aquifers and regulatory constrains on human being's activities are required to deal with flooding problems.

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