January 2008

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Martin Sauter

Lee J. Florea
Western Kentucky University, lflorea@bsu.edu

others

Recommended Repository Citation

Sauter, Martin; Florea, Lee J.; and others. (2008). Focus group on karst hydrology - conceptual models, aquifer characterization, and numerical modeling. *Frontiers of Karst Research*, 77-81.
Available at: http://digitalcommons.wku.edu/geog_fac_pub/8

Focus Group on Karst Hydrology – Conceptual Models, Aquifer Characterization, and Numerical Modeling

Group Participants: Martin Sauter, Leader. Matt Covington, Lee Florea, Franci Gabrovsek, Yongli Gao, Ronald Green, Jason Gulley, Russell Harmon, Ellen Herman, Pierre-Yves Jeannin, William K. Jones, Todd Kincaid, P.J. Moore, John Mylroie, Ira D. Sasowsky, Elizabeth Screaton, and Carol M. Wicks

INTRODUCTION

Flow of water in a karst catchment is mainly determined by the hydraulic gradient to a point of discharge (spring, river or coastline), the geometry of the karst features (fissures, fractures, conduits, and other zones of dissolution-enhanced high hydraulic conductivity), the sources (sinking streams, sinkholes, and the epikarst), and temporal variation of the recharge input. While the bulk hydraulic gradient can be determined in the field, the geometry of the karst features, their hydraulic parameters and their spatial distribution require considerable effort to quantify. Although some caves appear very spectacular and voluminous (if accessible), the fraction of rock occupied by caves in a karst system frequently is less than a few percent. This implies that these features are difficult to detect by drilling and even more difficult to parameterise hydraulically. Due to their important role in conducting water flow, both vertically in the vadose zone and horizontally in the phreatic zone, they cannot be neglected either (Klimchouk *et al.*, 2000).

In order to be able to predict flow through karst aquifers, it is critical to first design plausible conceptual models. Conceptual models provide a framework to support more quantitative mathematical models. Conceptual models are followed by a first principles understanding of ground water flow including quantized inputs and outputs. The final step is the quantitative mathematical or computer model. Such models allow, for example, the assessment of water resources, vulnerability of karst ground water to contaminants, potential flooding risks, and infiltration rates into caves.

In this report, different conceptualizations of karst systems are provided in order to convey an understanding of the different recommendations formulated for future research initiatives. The recommendation categories are assembled into different groups: processes, quantification of recharge and infiltration, characterization, models, and cross-disciplinary research needs.

CONCEPTUAL MODELS OF WATER FLOW IN KARST SYSTEMS

In recent decades, it has been realized that karst processes must be considered in a broader context than the traditional dissolution in circulating meteoric water. Karst, both surface landforms and caves, formed by water circulating downward (and also laterally) from a meteoric source on the land surface is referred to as *epigenetic* karst. Karst, mostly caves, formed by water migrating upward from depth is referred to as *hypogenetic* karst. Hypogenetic karst is often the product of dissolutional processes beyond the carbonic acid chemistry that is the primary driver for epigenetic karst, especially sulfur and sulfuric acid chemistry. Water often flows in epigenic karst aquifers in a turbulent regime. Flow in hypogenic systems is mostly laminar with caves embedded in a diffuse flow system that is completely decoupled from the surface hydrology. Models for karst aquifers developed in diagenetically mature, well-compacted carbonate rocks usually need to take account only of the conduit permeability and the fracture permeability. Matrix permeability is often very low although it is sometimes substantial. Such aquifers are referred to as *telogenetic* karst. Other aquifers develop is young carbonates where diagenetic processes may be incomplete. In *eogenetic* karst aquifers, matrix permeability is usually a dominant part of the flow system. Fractures may be a relatively minor feature.

Conceptual Models for Telogenetic Karst Aquifers

Most conceptual models of water flow in telogenetic karst distinguish three main zones (compartments) in the vertical direction. These are: the soil zone and epikarst, the unsaturated or vadose zone, and the phreatic zone. Although most conceptual models include similar structural features, the flow and storage processes assigned to them display large variations. Figure 1 presents a conceptual model of such a karst system.

The epikarst, a zone of increased weathering near the land surface, determines the distribution of recharge to a karst aquifer

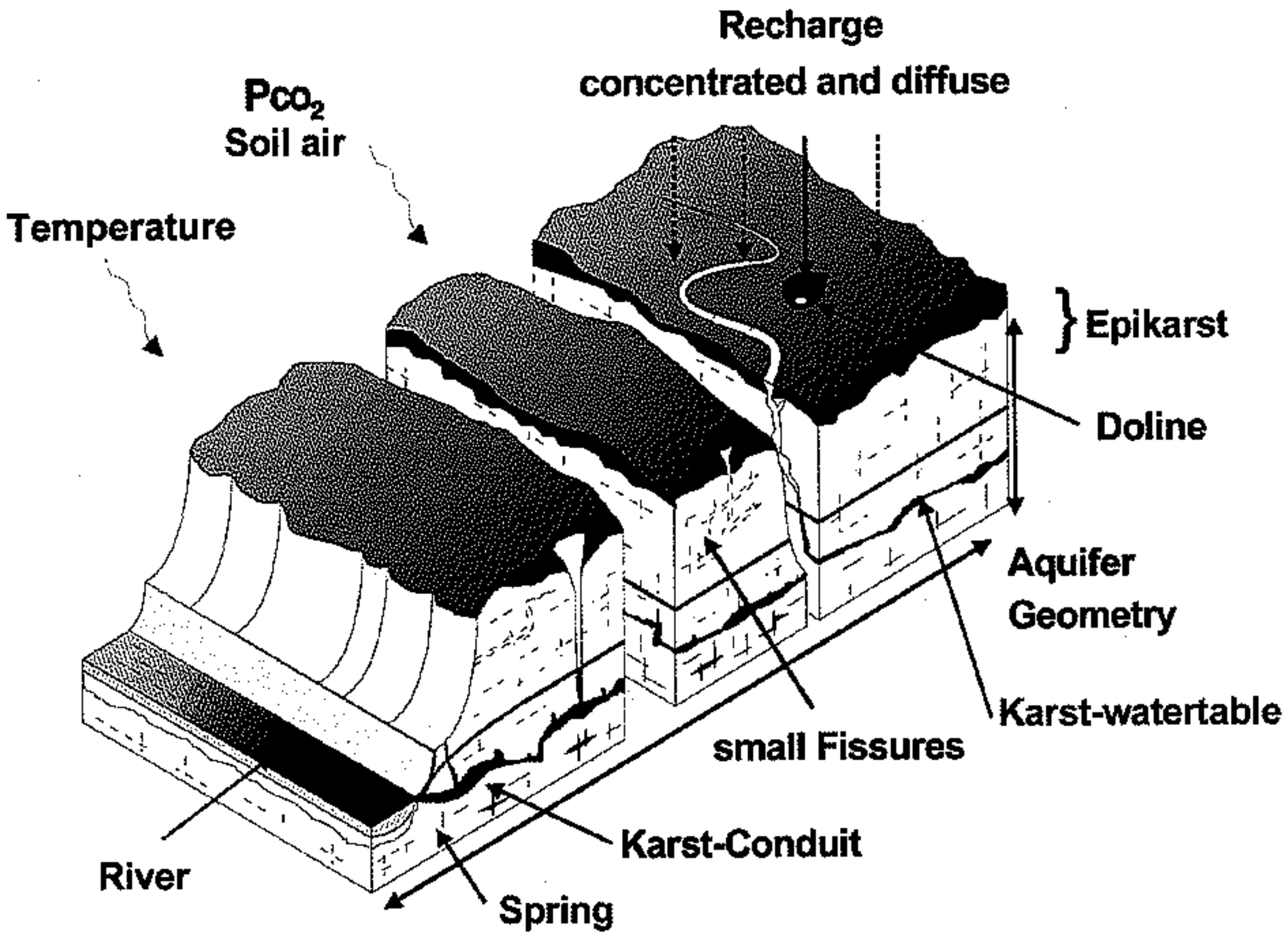

Figure 1. Conceptual model of a telogenic karst system in dense well-lithified carbonate rock (After Liedl and Sauter, 2003).

in both space and time. It can be visualised as a perched aquifer system channelling diffuse input towards shafts and sinkholes. The presence of the epikarst is believed to explain the highly heterogeneous water input to the system, both in space and time. Furthermore, it links climatic and near-surface geological conditions with the karstification of a limestone aquifer, defining both the hydraulic and the chemical boundary conditions for the development of the karst system. An understanding of the functioning of the epikarst is therefore a prerequisite for the quantification of infiltration (Jones *et al.*, 2003; Geyer *et al.*, 2008).

Due to the complex and heterogeneous nature of karst systems, quantification of recharge input is a major challenge. In order to be able to predict short term responses of karst systems to recharge events with numerical models, knowledge of the quantity of recharge, it's temporal and spatial variability and of the infiltration mechanism is a prerequisite.

Karst aquifers are characterized by highly varied hydraulic properties which are a result of the complex interactions between karst conduits, discrete fractures and the rock matrix. Conduits are characterized by low storage and high flow velocities, while the discrete fissured system and the rock matrix display much higher storage and low flow velocities. Due to this dual-porosity, dual-permeability structure of the carbonate medium the resulting hydraulic parameters are difficult to interpret from standard investigation techniques such as hydraulic tests, and cannot be easily regionalized at the catchment scale.

Conceptual Models for Eogenetic Karst Aquifers

Eogenetic aquifers, almost by definition, have high matrix permeabilities. The high matrix permeability creates a large accessible storage that is a significant contribution to the flow system. Flow in the matrix can be modelled as classical Darcian flow. However, it is the difficult to account for extensive conduit development in such aquifers, but the conduits are definitely present. Quantitative models must then address the interchange of conduit flow and matrix flow. Aquifers in the Paleozoic rocks of eastern United States are telogenetic karst as are many of the aquifers of Europe and the Mediterranean. Examples of Eogenetic karst are the Floridan Aquifer and the carbonate islands of the Caribbean.

In coastal regions, where carbonate rocks extend below sea level a circulating pattern of sea water and fresh water develops which enhances karst development in both dense and diagenetically immature limestones. The resulting cavities, known as halocline or flank margin caves are thought to contribute to reservoir porosity later in their geologic history (Sasowsky *et* *al.*, 2008). Flank margin caves have an entirely different role in aquifer hydrology than do the integrated conduit systems of telogenic karst.

Modeling efforts on flank margin caves has been undertaken but much remains to be done (Fig. 2)

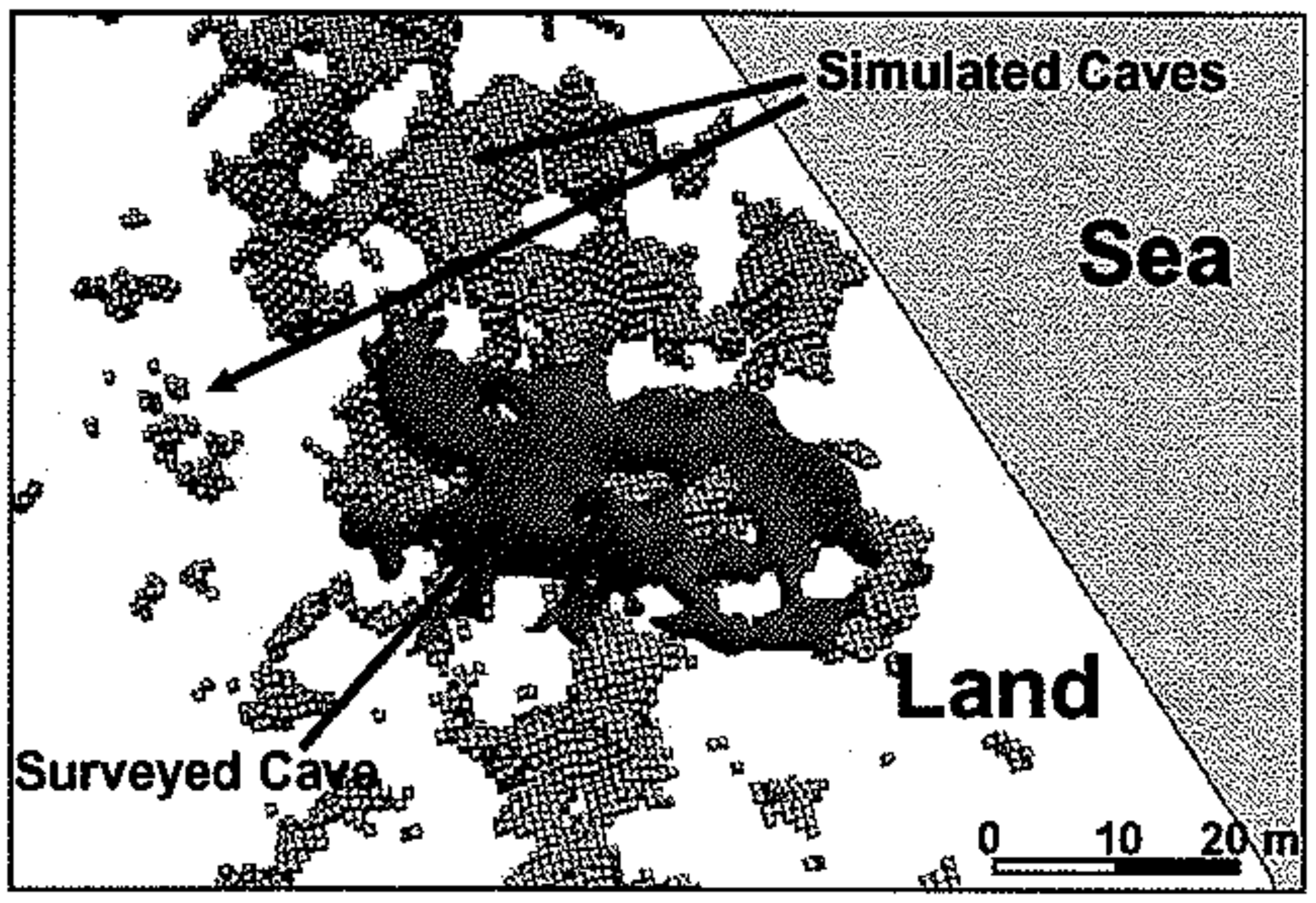

Figure 2. Computer generated model of a flank margin cave (box pattern) compared with a cave survey (smooth pattern). From Labourdette *et al.* (2007).

Conceptual Models for Hypogenetic Karst Systems

Karstification by rising deep-seated solutions has been recognized so recently that the development of conceptual models remains an open problem (Klimchouk, 2007). Unlike both telogenetic and eogenetic varieties of epigenetic karst where the chemical processes are moderately well understood, even the chemistry of hypogenetic karst poses many open questions. Some of the deep-seated solutions are derived from petroleum reservoirs, some are associated with volcanic activity, and some are deep-seated brines. For the most part, hypogenic karst flow systems are recognized only by caves that are later exposed. Active systems can be intercepted by drill holes, but both chemistry and flow hydraulics of the processes taking place at depth are poorly understood.

PROCESSES

A number of relevant flow, transport, to some extent reaction processes, have been implemented into the various types of models (discrete, hybrid, continuum models).

In a karst system, a number of different processes are superimposed so that the influence of individual processes is difficult to quantify, especially if their spatial and temporal variability is relevant. For example: The increase of discharge at springs can be attributed to: a) the specifics of storm intensity, spatial distribution and temporal variability, b) the characteristics of evapotranspiration at the soil – vegetation – atmosphere boundary, c) the heterogeneous infiltration process with rapid infiltration via fractures and sinkholes and slow infiltration through the vadose zone rock matrix, and d) the dualistic flow and storage processes in the phreatic zone (see also Smart and Hobbs, 1986) (Fig. 3). The analysis of spring discharge data therefore requires an appropriate conceptual model, the identification of the individual flow processes in the different compartments, as well as characterization of the geometry and hydraulic properties of the flow paths. Continuous measurement of the input functions such as precipitation and evapotranspiration is important.

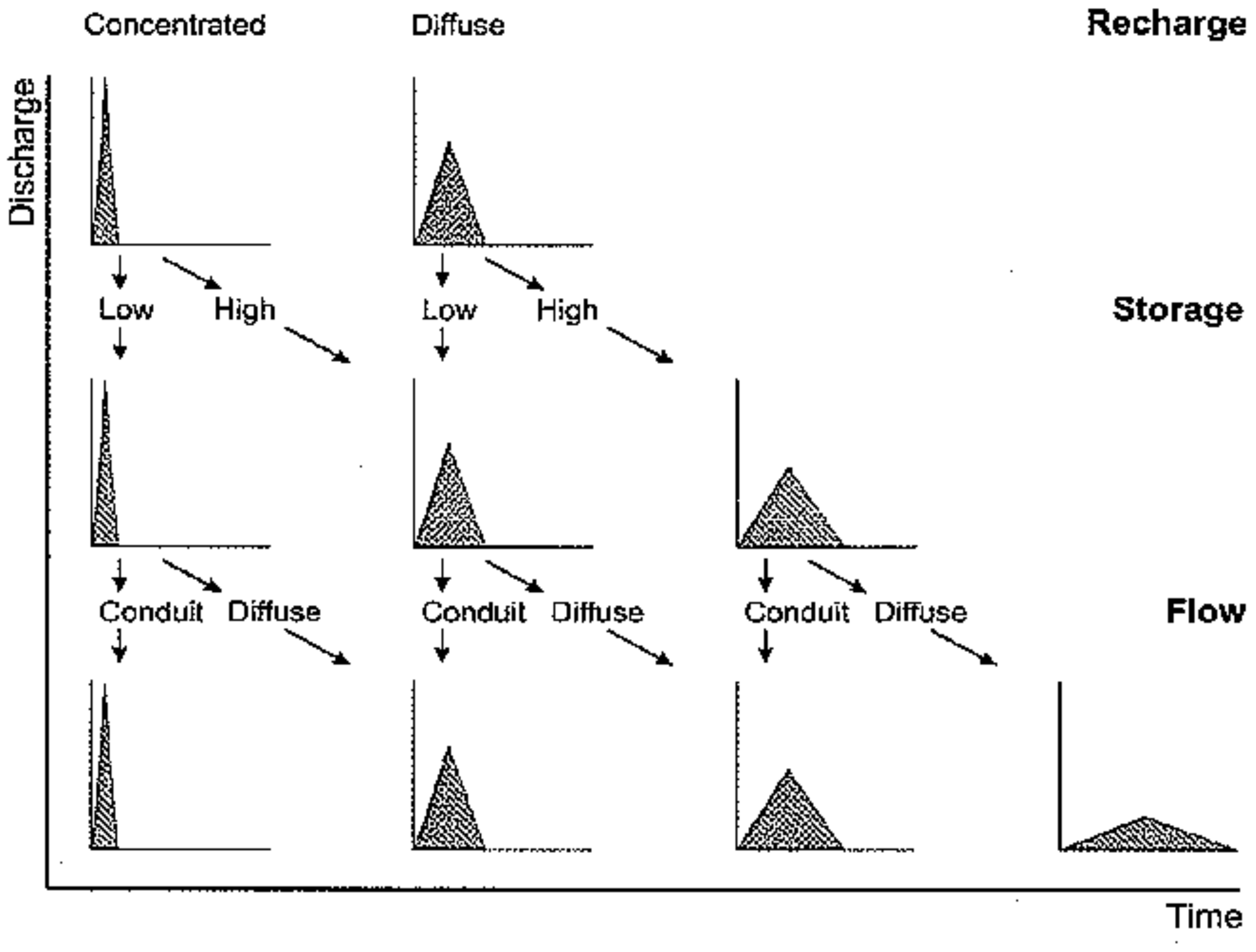

Figure 3. Schematic diagram to demonstrate the superposition of different processes and the influence of the different compartments on spring discharge (after Smart and Hobbs, 1986)

Further process understanding is required for the quantification of:

a) **Unsaturated flow**: Are film flow processes relevant?

b) **Open channel flow**: Is this process relevant at various flow conditions? Can certain observed thresholds, observed in the discharge pattern be explained by open channel flow conditions?

c) **Turbulent flow**: Although difficult to parameterize, turbulent flow processes can explain many observations in karst flow and transport (e.g. dispersion, tailings in tracer breakthrough curves). A quantitative and efficient approach in the identification and model implementation of turbulent flow processes is required. (Computational fluid dynamics models can simulate theses processes at laboratory scale, but the calculations are much more difficult at the catchment scale).

d) **Sediment transport**: What determines sediment transport; are there thresholds?

e) **Variable density flow**: Flow in island and coastal karst settings is determined, apart from the general characteristics of the carbonate limestone materials, by the variability in salt concentrations. Although in many circumstances, advective flow dominates flow behaviour there might be still-water environments, where convective processes might be important (e.g. for carbonate dissolution processes etc.).

f) **Multiphase flow**: Although important in the context of e.g. contaminant transport, multiphase flow processes will be difficult to identify and parameterise in this complex and highly heterogeneous environment. However, the development of models that incorporate multiphase flow processes (also air / water) might assist in understanding certain observations.

g) **Conduit-matrix exchange**, and the geochemical reactions that occur across this boundary, particularly in eogenetic karst.

Apart from the identification of processes and the characterisation of process parameters, it is also important to initiate investigations into an efficient implementation of these processes into the respective (discrete, hybrid, continuum) numerical models. To improve applicability of models to a larger segment of problems and the overall quality of model input, we need to improve our understanding of measurable parameters in karst systems and develop basic empirical relationships based on those parameters.

Badly needed are investigations into the system responses and thresholds. Extreme storm events are useful probes if aquifers are adequately instrumented so that complete response records can be obtained.

QUANTIFICATION OF RECHARGE INPUT AND INFILTRATION

Independent assessment of recharge is of prime importance for any model construction. Since recharge in karst aquifers occurs both spatially distributed (diffuse) as well as locally concentrated via sinking streams, shafts and dolines (discrete), substantial effort needs to be invested in its characterization. This includes:

a) **The quantification of total recharge at the soil base level**: Soils in karst regions are often very thin and frequently very patchy (often alternating between bare rock and soil pockets). Therefore, traditional classic soil moisture balance techniques do not necessary apply. Methods need to be developed, including hydrological, remote sensing and geophysical techniques, which take into account the specifics of karst soils.

b) **Characterization of flow and transport in the vadose zone**: The vadose zone, extending between the base of the epikarst and the ground water table frequently measures more than 50 metres, sometimes several hundreds of metres. The presence of this zone transforms the already complex recharge input signal into an even more complex one, composed of a rapid and a slow input with variable fractions and a variable temporal response. An integrated approach, using hydrogeological and geophysical characterization techniques is expected to provide at least some indications of the respective input functions.

These types of investigations are expected to be most successful if performed on a catchment scale. Quantitative measurement of input (precipitation) and output (spring discharge) can then be measured and an overall water balance established.

CHARACTERIZATION

The prime characteristic of telogenetic karst aquifers is, apart from their genetic history, the heterogeneity and the extreme contrast in the hydraulic parameters of highly conductive, but low storage, conduits and the low conductive but high storage fractured matrix. Although the conduit network dominates the flow pattern, it is extremely difficult to detect with drilling or traditional geophysical techniques because of its low volume fraction in the bulk aquifer. Therefore, active conduits cannot be properly characterized hydraulically or structurally, unless they are accessible for divers or located within the vadose portion of the cave system. Indeed, a fundamental limitation of all modelling efforts to date is that the conduit system must be put into the model "by hand". If the location and characteristics of the conduit system are completely unknown, any models and the corresponding model output will be of limited value.

Techniques need to be developed that provide the basis to locate individual conduits via novel geophysical or telemetric techniques and detailed mapping of hydraulic potential. Furthermore, cave mapping can be expected to provide analogues for submerged cave networks and the understanding of the genetic history of karst networks (geomorphological, paleokarst investigations) as well as numerical karst genesis modelling can supply additional information for the outline of the geometry of conduit networks.

In the case of hypogenic caves, the mere existence of a cave is difficult to determine as discrete recharge and discharge points are not available for sampling and measurement. Such caves can be quite large, for example, Carlsbad Caverns, yet have no obvious indication on the surface. Geophysical methods would also be useful, particularly if they could detect cavities at great depths.

MODELS AND MODEL DEVELOPMENT

A variety of modelling strategies have been developed. All show some promise but none are really satisfactory. The recent employment of lattice Boltzmann techniques for process modelling in karst appears promising. The overall goal should be process-oriented models that emphasize efficient numerical computation of large, catchment scale models, while honouring small scale heterogeneities.

Furthermore, since the different models require different model parameters (e.g. spatially averaged, discrete geometric, double continuum etc.) model adapted characterisation strategies need to be developed. The differences in parameterization strategies need to be highlighted and the relationship between actually measurable parameter (via hydraulic tests, etc.) and model calibrated parameters needs to be clearly stated.

COMMUNICATION AND CROSS-DISCIPLINARY RESEARCH

In order to further research into the hydrology, biology, ecology and geochemistry of karst, appropriate platforms need to be set up:

a) Provide a common language and understanding.
b) Organize joint experiments.
c) Provide common data bases (cave surveys, tracer experiments, hydraulic tests).
d) Identify suitable benchmark sites (karst catchments) for common interdisciplinary experiments. These catchments will:

i. Have long-term data records,
ii. Be relatively "simple" geologically and hydraulically
iii. Provide the basis for multidisciplinary research topics, e.g. the influence of microbial and biogeochemical processes on carbonate dissolution
iv. Be suitable, so that jointly (hydro-bio-chem) organised experiments have a chance to alter system behaviour.

CONCLUDING REMARKS

Although an obvious statement, it is important to reiterate that model selection needs to be based on the formulation of the problem to be solved. This requires a concise statement of the problem, an initial plausible conceptual model, the identification of relevant processes and parameterisation strategies.

Since wrong conclusions are frequently being drawn from erroneous model selection and interpretation of model results, it is suggested that a tool box/guidelines be developed for of sound karst modelling protocols. This means that guidelines should be formulated that suggest investigations and modelling strategies, based on the karst conceptual models and the problem in question. Benchmark catchments and sample calculations can demonstrate their application to real case studies.

Quantitative assessment of flow and transport in karst, the identification of important processes as well as the determination of process parameters among ground water professionals is generally hampered by the lack of understanding of the particulars of karst systems. It is important to convey to the professional public via appropriate media techniques (karst portal, etc.) that "karst is different." It is also important to convey the expanded concepts with the distinction between epigenetic and hypogenetic karst and between telogenetic and eogenetic karst.