

Adaptation of Numerical Modeling Approaches for Karst Aquifer Characterization

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Dresden, 16. April 2012

Essentially, all models are wrong, but some are useful.

George E. P. Box

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ABSTRACT

Karst aquifers can be conceptualized as dual flow systems comprised of a low-conductive matrix with embedded high-conductive conduits / preferential flow zones. Discharge in conduits ranges from low-velocity laminar flow to high-velocity transitional and turbulent flow. Commonly employed continuum models do not account for the specific behavior of transitional and turbulent flow. In response to this limitation, enhancements have been made to MODFLOW, a commonly used groundwater flow model, by adding a discrete conduit network to the matrix continuum (hybrid model). The Conduit Flow Process (CFP) package is the latest realization of this model approach.

CFP Mode 1 (CFPM1) computes laminar and turbulent flow in discrete conduits that are coupled to the laminar continuum model. CFP Mode 2 (CFPM2) accounts for turbulent flow in preferential flow layers by adapting the continuum model. Therefore, laminar hydraulic conductivities are converted into turbulent hydraulic conductivities. CFPM2 was further modified to consider steady turbulent pipe flow. Karst models based on CFPM2 require potentially less input data and computational efforts than karst models based on CFPM1. Furthermore, CFPM2 integrates more easily into MODFLOW versions including e.g. transport models. Parameter studies for a synthetic catchment demonstrates that continuum models with turbulent flow representation and an additional flow barrier between conduits and matrix can represent karst systems similar to hybrid models.

For simulation of highly transient flow processes in karst conduit systems, i.e. during flood events, it is crucial to consider dynamics such as free-surface flow, wave propagation, and changes between pressurized and non-pressurized conduit flow. The coupled overland- and groundwater flow model MODBRANCH was therefore enhanced to consider unsteady and non-uniform flow processes in karst conduits. Flow in discrete conduits is simulated using the Saint-Venant-equations for free-surface flow. Contrary to overland flow, the cross sectional area of karst conduits is finite. Accordingly, both pressurized and non-pressurized flow may occur within conduits. To simulate pressurized flow, a hypothetical, narrow, open-top slot (Preissmann slot) is added to the conduit crown, which allows the use of the free-surface flow equations for fully filled conduits. Beyond this, the model features a variable time step to consider wave speed variations, for example due to the transition from free-surface to pressurized flow. Parameter studies for a synthetic catchment demonstrate the significance of free-surface flow representation for variably filled conduits.

KURZFASSUNG

Karstgrundwasserleiter können als duale Fließsysteme konzeptionalisiert werden, bestehend aus einer geringdurchlässigen Matrix mit eingebundenen hochdurchlässigen Bereichen, z. B. Karströhren. Der Abfluss in den hochdurchlässigen Bereichen reicht von langsamer laminarer Strömung bis zu schneller turbulenter Strömung. Herkömmliche numerische Grundwasserströmungsmodelle berücksichtigen nicht die spezifischen Eigenschaften von nicht-laminarer Strömung (Übergangsbereich laminar-turbulent bzw. turbulente Verhältnisse). Ein Ansatz um diese Einschränkung zu umgehen, ist die Erweiterung des laminaren Kontinuums um ein diskretes Röhrenmodell, das zustandsabhängig laminare und turbulente Strömung berücksichtigt (Hybridmodell). Eine aktuelle Umsetzung dieses Ansatzes ist Conduit Flow Process (CFP), ein Modul für das weitverbreitete Grundwasserströmungsmodell MODFLOW.

CFP Mode 1 (CFPM1) berechnet laminare und turbulente Strömung in diskreten, mit dem Kontinuummodell gekoppelten Röhren. CFP Mode 2 (CFPM2) berücksichtigt nicht-laminare Strömung in hochdurchlässigen Schichten mit einer angepassten hydraulischen Leitfähigkeit des Kontinuummodells. CFPM2 wurde weiter modifiziert, so dass auch turbulente Strömung in Karströhren berechnet werden kann. Dadurch kann möglicherweise der Parameterbedarf sowie der Rechenaufwand gegenüber Hybridmodellen reduziert werden. CFPM2 lässt sich einfach in vorhandene MODFLOW Modelle einbinden, z. B. zur Berechnung von Transportprozessen. Parameterstudien für ein idealisiertes Karsteinzugsgebiet zeigen, dass Kontinuummodelle bei Berücksichtigung der turbulenten Strömung sowie des zusätzlichen hydraulischen Widerstand zwischen Röhren und Matrix, Karstsysteme ähnlich wie Hybridmodelle darstellen.

Zur Simulation von instationären Prozessen in Karströhren, z. B. ausgeprägte Abflusssignale infolge pulsformiger Grundwasserneubildung, ist es notwendig, dynamische Prozesse infolge Freispiegelabfluss, Wellenausbreitung sowie Wechsel zwischen Abfluss in teil- und vollgefüllten Röhren zu berücksichtigen. Aus diesem Grund wurde das numerische Modell MODBRANCH, welches ein diskretes Oberflächenwassermodell mit einem Kontinuummodell koppelt, so angepasst, dass instationäre und nichtgleichförmige Abflussprozesse in Karströhren berücksichtigt werden können. Der Abfluss in diskreten Röhren wird dabei mit den Saint-Venant-Gleichungen für Freispiegelabfluss berechnet. Im Gegensatz zu Oberflächengewässern ist der für den Abfluss zur Verfügung stehende Querschnitt in Karströhren limitiert, so dass sowohl Freispiegel- als auch Druckabfluss innerhalb der Röhren auftreten kann. Druckabfluss wird mit Hilfe eines schmalen virtuellen Schlitzes an der Röhrenoberkante simuliert (Preissmann Schlitz), der auch im Fall vollgefüllter Röhren die Anwendung der Gleichungen für Freispiegelabfluss erlaubt. Durch die Verwendung eines variablen Zeitschrittes kann die geänderte Dynamik beim Übergang von Freispiegel- zu Druckabfluss berücksichtigt werden. Parameterstudien für idealisierte, synthetische Karsteinzugsgebiete demonstrieren die Bedeutung der Berücksichtigung von Freispiegelabfluss in teilgefüllten Röhren.

INTRODUCTION

Groundwater can be defined as water situated beneath the ground surface, e.g. *Bear* [1988], that moves according to existing head gradients. Groundwater is part of the global water cycle and a vital resource for drinking water supply because these stores are usually extensive, well protected, and naturally clean. Mainly, groundwater is fed by recharge processes due to precipitation or infiltration of surface water. Groundwater is stored in the void space of underground layers (like pores, fissures, or fractures) that, if a sufficient amount of water can be extracted, are denoted as aquifer. Contrary, underground formations without sufficient extractable water are denoted as aquitard (low permeable) respectively as aquiclude (impervious, containing water) or aquifuge (impervious, without containing water).

1.1 Overview About Karst Hydrologic Systems

Aquifers consist of permeable rock or unconsolidated material, like sand or gravel. In the latter one, e.g. alluvial or fluvial aquifers, water moves more or less continuously through the intergranular pore space. This continuous porosity is also denoted as primary porosity. In contrast, rock formations like granites or quartzites provide only limited primary porosity. Therefore, water moves in joints and fractures, which are denoted as secondary porosity. If the rock is water soluble, for example limestone, dolomite, or gypsum, initially small fractures can enlarge to highly permeable preferable flow paths. These solution enlarged features are also denoted as tertiary porosity.

Often, the existence of water soluble rock results in karst areas, which are characterized by solution enlarged highly permeable underground structures. Beside this,

karst is distinguished by further morphological features and, according to *Ford and Williams, 2007*, may be defined as:

“... comprising terrain with distinctive hydrology and landforms that arise from a combination of high rock solubility and well developed secondary (fracture) porosity ...”.

Approximately 13 % of the Earth's surface are underlain by soluble rocks and, hence, can form karst [*Williams and Fong, 2011*], see Figure 1-1. Roughly 20–25 % of the Earth's population depends on karst groundwater [*Ford and Williams, 2007*]. Figure 1-2 gives an obvious example for karst landscapes with fractured soluble rock and large solution enlarged matured conduits that are fallen dry due to water level sinking.

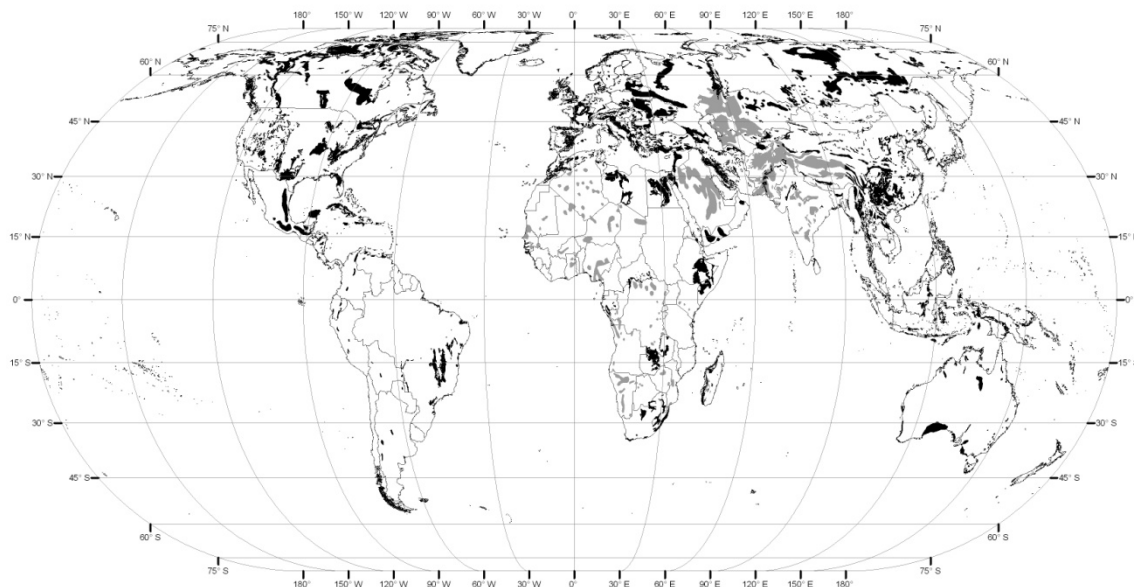


Figure 1-1: Global distribution of major outcrops of carbonate rocks, from *Williams and Fong* [2011]



Figure 1-2: Karst landscapes showing karst features, pictures from the Provence (France); left: *Vallis Clausa – Fontaine Vaucluse*; right: *Gorges de Verdon*

Sustainable aquifer management is a crucial step to provide groundwater with sufficient quantity and quality, whereas in management terms an aquifer might be considered as storage with inflows, e.g. recharge by precipitation or seepage from surface water, and outflow, e.g. well abstraction and baseflow in rivers and drains [Brunner and Kinzelbach, 2005]. Consequently, groundwater management can be accounted as redistribution of inflows [Brunner and Kinzelbach, 2005]. As every aquifer is unique, there is no uniform approach for groundwater management. Rather it is necessary to consider the specific features of every single aquifer system. Contrary to unconsolidated rock aquifers, which are widespread, typically considered as high productive, and, therefore, might be considered as standard situation, karst aquifers exhibit fundamental differences that need special consideration. Subsequently, some selected features are presented aiming to highlight the unique and exceptional status of karst aquifers:

- The permeability of the solution enlarged conduits is significantly enlarged compared to the surrounding fractured and / or porous rock matrix resulting in a very strong heterogeneity and anisotropy of hydraulic properties, and, therefore, to a dual flow character of karst; cf. *Kiraly* [1975], *Sauter* [1992], and *Király* [2002].
- Recharge processes in karst hydrologic systems are very heterogeneous with strong localized direct recharge into conduits through e.g. sinkholes and diffuse distributed recharge in the rock matrix; cf. *Gunn* [1986] and *Geyer et al.* [2008].
- Groundwater velocities can be extremely fast within a karst catchment ranging up to several meters per second. This may result in largely extended catchments and water protection areas; cf. *Gunn* [1986] and *Doerfliger et al.* [1999]. Further, solution enlarged flow features result in an increased contamination hazard as water moves rapidly whereas the natural attenuation potential is coevally quite low due to the very limited potential for effective filtration, sorption, or other natural cleansing processes; cf. *Lehr and Lehr* [2000].
- Groundwater outflow is locally concentrated at one or a few springs whereas the temporal spring discharge pattern is highly variable; cf. *Sauter* [1992], *White* [2002], *Birk et al.* [2004] and *Király* [2002].
- Due to anisotropy, the direction of groundwater flow within karst conduits can deviate from the overall flow direction within the catchment; cf. *Gunn* [1986] and *Huntoon* [1995].

- In several cases, the exact position as well as the specific characteristics of the highly permeable conduit system, like diameter, shape, or elevation, is unknown; cf. *Doerfliger et al.* [1999], *Bakalowicz*, [2005], and *Geyer* [2008].
- There is the potential danger of rapid contaminant movement into the aquifer through sinkholes and other karst features resulting in enhanced vulnerability of karst water to pollution cf. *Katz et al.* [2009].

Due to these exceptional specifics, the use of karst water is potentially associated with serious problems regarding quality and quantity, which is emphasized by several authors, for example *Groves* [2007] and *Pfeffer* [2009].

Since karst reservoirs are such a vital groundwater resource, sustainable groundwater management is necessary to meet the requirements of the society. To this end, challenging efforts are conducted regarding exploration, investigation, and characterization of karst aquifers, e.g. *Atkinson* [1977], *Sauter* [1992], *Birk* [2002], *Goldscheider and Drew* [2007], and *Geyer* [2008]. In this context, numerical flow models are suitable tools to manage groundwater resources as they are potentially able to predict the system behavior in case of varying system parameters, for example in- or outflow. Various model approaches are able to consider the karst-specific behavior [*Sauter et al.*, 2006] and several studies demonstrate the benefits of using numerical models for karst aquifer investigation, e.g. *Liedl and Sauter* [2000] and *Birk et al.* [2005]. However, existing numerical models simplify the system and, therefore, maybe neglect potentially important processes. Beyond this, existing numerical models for karst aquifers are technically demanding, which clearly reduces the practical applicability.

1.2 Previous Related Work

Hybrid models are a promising numerical approach to consider karst features. These models couple a continuum model, which represents the fractured porous rock matrix, with a discrete pipe model, which represents the karst conduits. Therefore, hybrid models are suitable to represent the dual flow characteristics of karst aquifers [*Teutsch and Sauter*, 1998; *Sauter et al.*, 2006]. These and other model approaches for karst aquifers are introduced in section 2 of the thesis.

The hybrid model Carbonate Aquifer Void Evolution (CAVE) is an extension of the U.S. Geological Survey (USGS) groundwater flow model MODFLOW [*McDonald and Harbaugh*, 1988] and was initially developed at the University of Tübingen, Germany [*Clemens*, 1997; *Hückinghaus*, 1998; *Liedl and Sauter*, 2000; *Liedl et al.*, 2003]. Orig-

nally, CAVE was applied to study long term processes like the development of carbonate aquifers. Subsequently, CAVE was continuously further developed. *Bauer* [2001] added routines to reflect the influence of the upper karst surface (Epikarst), to allow time-variable boundary conditions and re-wetting of conduits, and to consider calcite dissolution chemistry. *Birk* [2002] supplemented routines to compute transport processes for heat and substances and to consider gypsum dissolution chemistry. Consequently, CAVE was used to investigate short term processes too, for example the karst spring response on recharge events [*Liedl and Sauter*, 2000; *Birk et al.*, 2006] or tracer tests [*Birk et al.*, 2005]. Later on, the USGS implemented parts of CAVE into the Conduit Flow Process (CFP) for MODFLOW-2005 [*Shoemaker et al.*, 2008 b] and, therefore, made this hybrid model approach widely available.

Several techniques are available to investigate and characterize karst aquifers. *Geyer* [2008] developed and applied several methods for karst aquifer characterization like a time-continuous approach for inflow determination, multi-tracer tests for conduit system characterization, and isotopic measurements to investigate the unsaturated zone behavior. The author highlights the fact that karst characterization with a single method is burdened with a number of limitations like restrictions to a specific scale, restrictions to parts of the karst system (e.g. only the conduit system), or uncontrolled boundary conditions (e.g. recharge). One promising approach is the development and application of model approaches that combine the information achieved from different field experiments on a spatially and temporally comprehensive scale [*Geyer*, 2008]. However, these model approaches need to represent a large variety of processes on different scales and, therefore, are facing very demanding requirements. They need to consider for example: (A) the aforementioned dual flow characteristics of karst aquifers, (B) storage effects due to variably filled karst conduits, and (C) dynamic flow processes considering inertia and momentum forces that may be important on very short time scales.

1.3 Objectives, Methodology, and Structure of This Work

Available flow models for karst aquifers are restricted by the limited number of implemented processes as well as by high efforts when it comes to application, caused by, for example, demanding numerical schemes, high parameter demand, and the lack of experience. Some studies, for example *Scanlon et al.* [2003] and *Worthington* [2009] demonstrate benefits of applying relatively easy-to-use equivalent porous

media models for karst aquifers. However, these models neglect turbulent flow in highly permeable conduits and, therefore, are potentially limited. Contrary, conducted field studies demonstrate the evidence to consider additional processes, for example variably filled conduits as observed in the field by *Raeisi et al.* [2007] and *Prelovšek et al.* [2008].

Variably filled conduits are likely to occur, especially in matured karst systems with several solution enlarged conduits [*Quinlan and Ewers*, 1985]. However, almost all hybrid models are limited to fully filled conduits (see section 2). In consequence, they neglect free-surface flow effects like the specific velocity of signal transmission (i.e. wave propagation) and the reflection of the conduit storage capacity. Consideration of variably filled conduits will become increasingly important for the further examination of regional scale experiments like large scale pumping test [*Maréchal et al.*, 2008] as parts of the conduit system may dewater and, therefore, turn from pressurized flow to free-surface flow closely related with the release of stored water. The interaction of both matrix and conduits is important for such experiments because with ongoing withdrawal, the relative impact of water transfer from the matrix to the conduits will increase. The hybrid model approach is suspected to be a suitable tool to reflect these processes. Beside this, hybrid models accounting for dynamic flow in variably filled conduits are likely able to significantly broaden the understanding of signal transmission in karst conduits, e.g. flood wave routing in matured karst systems with consideration of matrix interaction as observed in the field by *Raeisi et al.* [2007].

Consequently, these thesis aims to contribute to the ongoing model evolution by providing numerical codes that overcome some of the aforementioned limitations in order to result in reasonable tools for investigation, characterization, and management of karst aquifers. Future models should broaden the range of considerable processes and should aim to cover a wide variety of temporally and spatially scales.

The thesis is organized in a cumulative way and, therefore, comprises several manuscripts published in scientific journals. At the beginning, **section 2** aims to provide the conceptual framework for karst aquifer modeling. Concepts are briefly discussed and available numerical karst models are introduced. Based on this state of the art, model tools are developed to overcome existing limitations. A MODFLOW based single-continuum approach that incorporates turbulent flow is introduced in **section 3**. This simple but powerful approach is able to compute the dual karst hydraulics on an enhanced spatial scale. Because this approach is based on the commonly and wide-

spread used MODFLOW code, users can access the whole range of existing MODFLOW related tools and packages, for example transport codes and graphical user interfaces. Next, the model is used to investigate the significance of turbulent flow representation in continuum models. To this end, a parameter study is conducted for an idealized karst catchment.

To simulate dynamic flow processes in variably filled conduits, an unsteady and non-uniform hybrid model is adapted that is able to reflect processes on short time-scales, coevally considers conduit storage, as well as the interaction with the matrix. The model adaptation is documented in **section 4**. Subsequently, the hybrid model is used to investigate the significance of dynamic flow processes in variably filled conduits. To this end, the model is applied to an idealized karst catchment in order to investigate the influence of several parameters on karst spring responses. The thesis is closed with a comprehensive discussion and outlook in **section 5**.

CONCEPTUAL FRAMEWORK FOR KARST MODELING

A model stands for the realization of a schematic and symbolic representation of the real system, e.g. *Anderson and Woessner* [2002] and *Király et al.* [1998]. In order to depict karst water resources by model approaches, it is necessary to identify what parts and processes of the system are relevant and need to be considered while modeling. First of all, the (unknown) hydrologic reality is abstracted to a schematic system representation, i.e. a conceptual model. The conceptual model gathers information of the entire system in a physical visualization, which can be subsequently interpreted and translated in mathematical models by using the appropriate equations and parameters, for example *Bear* [1988] and *Anderson and Woessner* [2002]. Due to the fundamental impact of conceptualization on the modeling process, this step needs special consideration, e.g. *Oreskes and Belitz* [2001] and *Bredehoeft* [2003].

Subsequently, a generalized conceptual model for karst hydrologic systems is presented to explain the fundamental functioning of karst. Following, flow processes in karst aquifers are briefly reviewed. It is challenging to characterize karst water reservoirs due to the exceptional characteristics of karst like strong heterogeneity and anisotropy [*Bakalowicz*, 2005]. A condensed review about investigation methods provides an overview on how to obtain parameters to describe karst aquifers. One promising way to investigate the functioning of karst is the application of numerical models. Based on the wide-ranging conceptual view, a general idea about model approaches for karst is introduced that is able to deal with the dual characteristics of karst.

2.1 A Generalized Conceptual Model for Karst Systems

Morphologically, karst areas and landscapes are distinguished by the presence of water soluble rock and, therefore, feature some typical and unique structures both on the surface and beneath, for example dolines (sink holes), poljes (large flat plains) and solution enlarged underground structures like caves and conduits. Surface drainage is rare or absent within a karst area with surface water entering the underground concentrated via sink holes or diffuse via the water unsaturated vadose zone where underground flow processes result in solution enlarged features in the host rock, see also Figure 1-2 in section 1. A comprehensive overview about karstification and karst geomorphology is given for example by *Ford and Williams* [2007] and *Palmer* [2007].

Near the surface, the rock matrix may be weathered and, hence, constitute a locally perched aquifer. *Mangin* (1975) introduced the term epikarst for this part of the karst system. The epikarst is characterized by an enhanced, more homogenous hydraulic conductivity and porosity. The epikarst layer is not necessarily continuous with a thickness of about 10 m [*Doerfliger et al.*, 1999]. Functionally, epikarst plays an important role in recharge generation [*Klimchouk*, 2004]. Below the epikarst, water percolates gravitational driven through the water unsaturated vadose zone towards the water saturated aquifer.

In a more groundwater related view, the process of karstification can be measured respectively characterized in terms of permeability and specific porosity [*White*, 2003]. In this context, *White* [2002] stated:

"...The characterizing features of karst aquifers are the open conduits which provide low resistance pathways for ground water flow and which often short circuit the granular or fracture permeability of the aquifer. Conduit flow often has more in common with surface water than with ground water. Karst hydrology requires a mix of surface water concepts and ground water concepts..."

The rock matrix itself offers only very limited intergranular pore space resulting in low primary porosity and matrix permeability depending on the rock type [*White*, 2003]. The rock matrix is intermitted by small fractures and fissures that increase porosity, i.e. secondary porosity. Fracture permeability is characterized by fracture aperture and fracture spacing, both parameters are statistically distributed [*White*, 2003]. Consequently, fracture permeability is averaged over a certain volume in order to result in a representative elementary volume (REV). Fracture permeability adapts due to solution

and range up to fracture apertures of about 10 millimeters [White, 2003]. Solution processes caused by water flow further enlarge fissures and fractures resulting in conduit structures denoted as tertiary porosity with conduit diameters ranging from 10 millimeters up to several meters [White, 2003] and, therefore, a strongly enlarged permeability. In consequence, the spatial parameter distribution in karst systems is very heterogeneous and anisotropic, for example Kiraly [1975, 2002], Sauter [1992], Huntoon [1995], and others. The conduits, which can form an interconnected network, interact with the matrix in terms of drainage (base flow) or recharge (flood flow).

Some early conceptual models classified karst aquifers by relating their flow patterns to the geological setting, i.e. only based on the type of permeability, [White, 1969; Shuster and White, 1971; White, 1977]. According to this, flow systems range from diffuse flow along small interconnected openings to conduit flow through large solution passages. These concepts are further enhanced by Quinlan and Ewers [1985], who presented a systematic approach to characterize karst aquifers in terms of the flow system formation. Accordingly, diffuse-flow karst systems are characterized by a continuous net of cracks, fissures, and fractures without a well developed conduit system. Groundwater flow can be assumed to be laminar and the aquifer lacks a distinctive heterotrophy and anisotropy. If solution processes enlarge fissures and fractures to distinctive conduits, groundwater flow will be almost completely occurring in the conduits, resulting in a conduit-flow karst system. The diffuse-flow and the conduit-flow karst systems are both end members with several intermediate stages denoted as mixed-flow karst systems [Quinlan and Ewers, 1985], see Figure 2-1 for details.

Gunn [1986] proposed an enhanced conceptual model for conduit flow dominated karst aquifers that are characterized according to three main system components controlling the karst reservoirs behavior: (1) the nature of inputs, i.e. recharge, in order to quantitatively assess recharge as well as areas vulnerable to pollution; (2) the location and capacity of storages; and (3) the way in which transfer mechanisms transmit these inputs through the system to the outlet of the catchment, i.e. the spring.

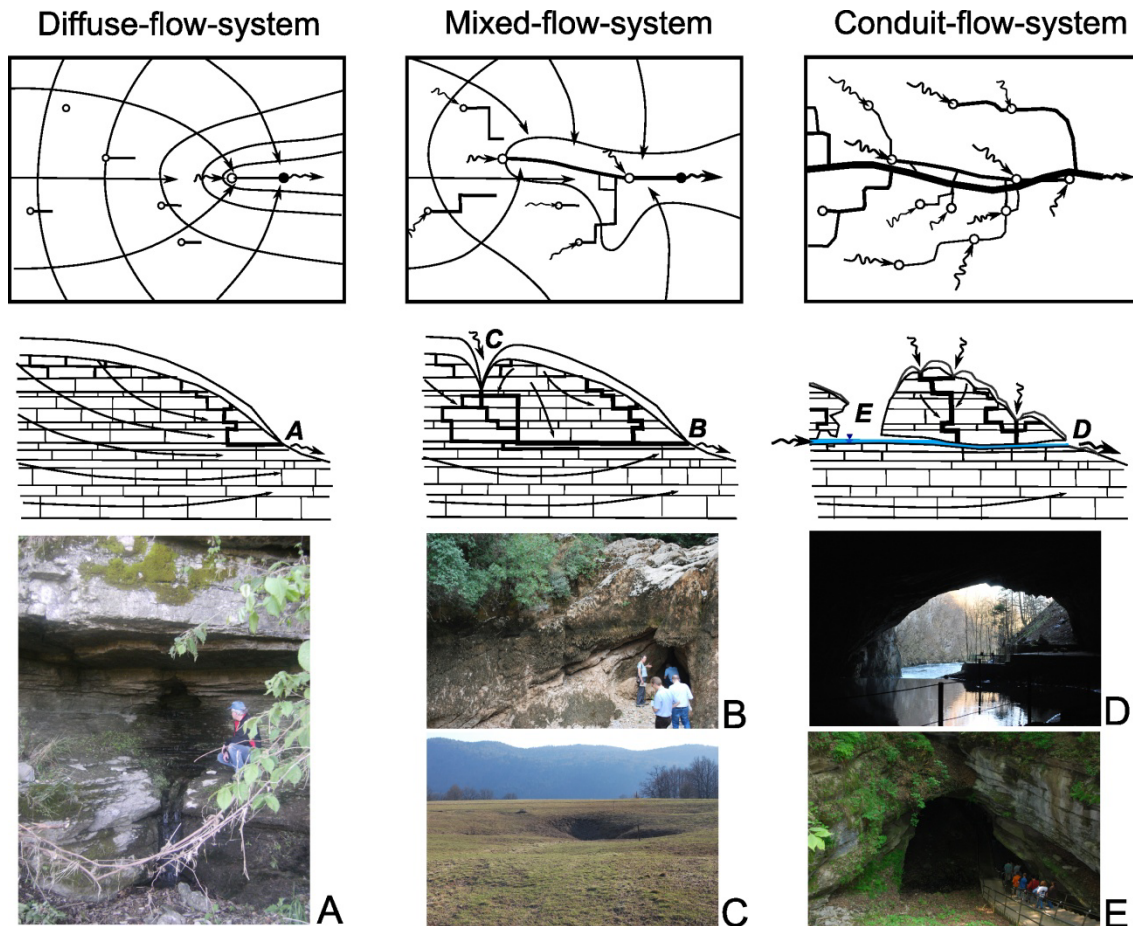


Figure 2-1: Conceptual consideration of different flow systems; modified after *Shuster and White* [1971] and *Quinlan* [1985]; characters A-E within the sketches are linked to the photos representing some typical features: **A)** diffuse karst spring, North-West Arkansas (USA); **B)** karst spring, near Montpellier (France); **C)** sinking hole, Planinsko polje (Slovenia); **D)** outlet of an underground river, Planina cave (Slovenia); **E)** entrance to the cave system via a collapsed structure, Mammoth cave, Kentucky (USA).

Inputs

Discharge at karst springs is practically maintained by recharge on the associated catchment (autogenic) or from adjacent non-karstic areas (allogenic). Beyond this, recharge is differentiated in a diffuse and direct part [Gunn, 1986]. Direct recharge enters the conduit system immediately by infiltration through sink holes or shafts resulting in fast flow in the highly permeable structures. Contrary, diffuse recharge mainly percolates through the unsaturated zone resulting in continuously slow inflow [Atkinson, 1977 and Geyer, 2008]. The epikarst can take an exceptional role while input generation to karst systems with re-distribution and concentration of flow [Klimchouk, 2004].

and *Williams*, 1983]. Comprehensively, at least four sources for recharge can be distinguished [*White*, 2003]: (1) Allogenic recharge: surface water entering directly the karst system (e.g. swallets of sinking streams), (2) Autogenic direct recharge: overland flow entering directly the karst system (e.g. through sinkholes), (3) Autogenic diffuse infiltration: precipitation on the surface that enters the karst system via the soil zone, the epikarst, and through fractures and the matrix of the vadose zone, and (4) Perched catchments: depending of the geological settings, an environment may provide some locally perched groundwater systems. These perched systems act as storage and provide water to the main aquifer via flow through the remaining vadose zone.

Storages

Gunn [1986] considers mainly four types of storages within a karst catchment: (1) soil and (2) epikarst, both situated in the unsaturated zone, and (3) matrix plus (4) conduits in the saturated zone. The relative importance of the unsaturated zone storage in the soil and epikarst layer depends on the system geometry, i.e. the thickness. Unsaturated zone storage can be important providing up to 100 % of the total storage [*Gunn* 1978 in *Gunn*, 1986]. In the saturated zone, water is stored diffusively in the rock matrix and only minor parts of approximately 5 % of the total storage represent conduit storage [*Gunn*, 1986]. For example, 3.5 % of the Mendip karst's (UK) overall storage is situated in conduits [*Atkinson*, 1977]. Another example is provided by *Sauter* [1992], who estimated the storage coefficients for the Gallusquelle karst catchment (Germany) as about 0.011 for the unsaturated zone (35 % of overall storage), about 0.02 for the fissured matrix (64 % of overall storage), and about 0.0003 for the conduits (1 % of overall storage).

Transfer

Transfer processes occur in both the unsaturated zone and the saturated zone and can be subdivided into several sub-processes like (1) overland flow, (2) infiltration, (3) throughflow, (4) percolation, (5) subcutaneous flow, (6) shaft flow, (7) vadose flow, (8) vadose seepage, (9) diffuse flow, and (10) conduit flow [*Gunn*, 1986]. Water in the saturated zone transfers signals (e.g. pulse recharge) through the rock matrix, small fractures and fissures, as well as through solution enlarged conduits. Conduits can be further divided in fully filled pipes resulting in pressurized flow, open channels resulting in free-surface flow, and reservoirs whereas each type result in a specific signal transmission behavior as demonstrated by *Covington et al.* [2009].

White [2003] further generalized this conceptual view of karst hydrologic systems by an approach containing all components that are present in all karst aquifer flow systems. To this end, a list of parameters like matrix hydraulic conductivity, conduit hydraulic conductivity, conduit system response time, and conduit - fracture coupling coefficients are suggested in order to describe all components and processes and, therefore, to characterize the karst hydrologic system. Finally, the here introduced conceptual model splits complex karst systems into several parts that can be further investigated and characterized with numerous methods like field experiments or computer modeling. In the end, this results in a better understanding of the complex nature of karst hydrologic systems. In summary, the basic features of karst systems are depicted in Figure 2-2.

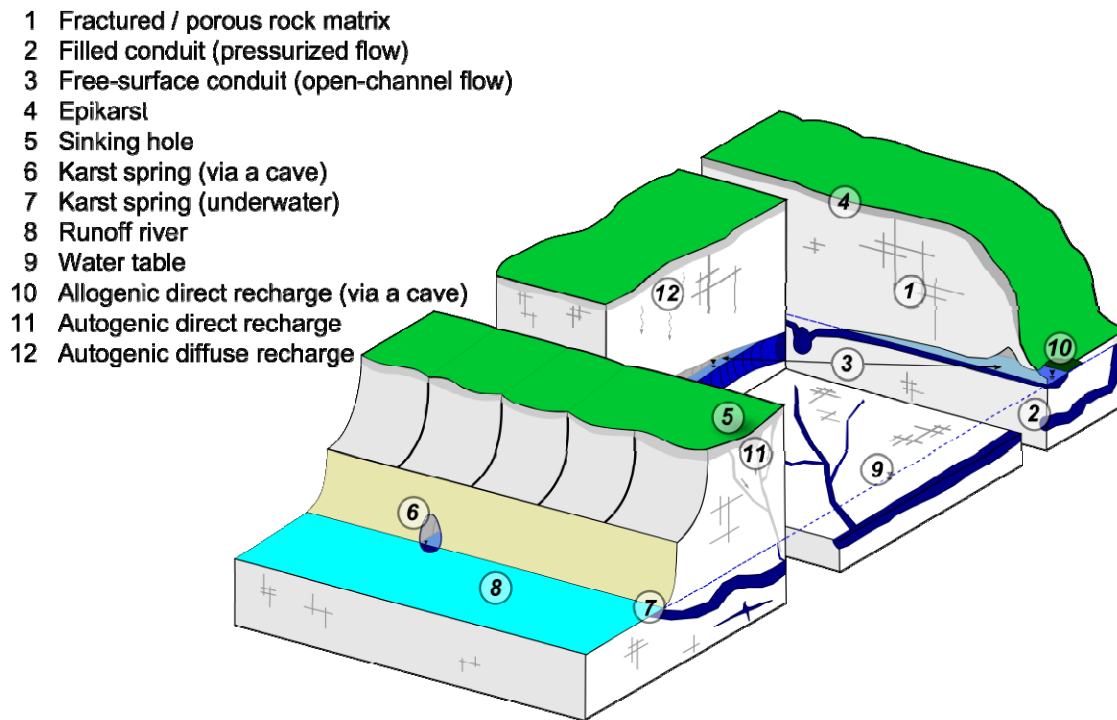


Figure 2-2: Conceptual view of a karst water reservoir, modified from Bauer [2001], Birk [2002], and Geyer [2008].

Scale dependency

The existence of fissures, fractures, and solution enlarged structures within the rock matrix result in a distinctive heterogeneity of hydraulic parameters. Consequently, Kiraly [1975 and 2002] proposed the scale dependency of hydraulic conductivity. Figure 2-3 illustrates this behavior. Accordingly, the hydraulic conductivity on small sample scale is determined by the hydraulic conductivity of the rock matrix, respectively the primary porosity and, therefore, is very low. By increasing the sample scale, conductiv-

ity enhancing features like fractures and fissures, respectively secondary porosity, are included resulting in an increase of the overall hydraulic conductivity. If a sufficiently large spatial scale is considered, the primary and secondary porosity features become statistically isotropic and the aquifer volume may be described as representative elementary volume – REV [Bear, 1988]. The inclusion of solution enlarged conduits further increases the sample hydraulic conductivity and creates a very distinctive anisotropy and heterogeneity that contradicts the REV concept.

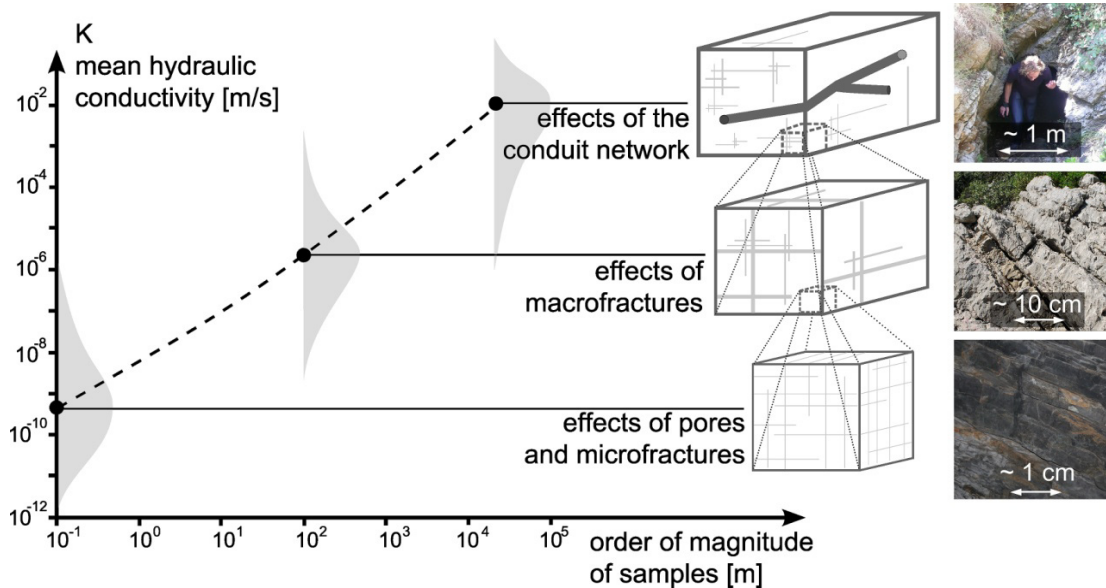


Figure 2-3: Scale dependency of hydraulic conductivity; modified from *Sauter* [1992] and *Király* [2002].

The specific and unique nature of karst hydrologic systems regarding heterogeneity, anisotropy, and scale dependency results in a characteristic hydrologic behavior. Heterogeneity occurs practically in all three main systems of karst: inputs (localized direct recharge and diffuse recharge), transfers (hydraulic conductivity), and storage (rock matrix and solution enlarged conduits). As a consequence, spring discharge reflects the characteristics of the karst system with a specific response time depending mainly on (1) the recharge distribution, (2) the conduit system, and (3) the area of the groundwater basin [White, 2002]. Comparably fast reacting springs exhibit temporally highly variable discharge coupled with a distinctive variation of physicochemical parameters like temperature and conductivity, for example *Király* [2002], *Birk et al.* [2004], *Luhmann et al.* [2011]. Figure 2-4 depicts this behavior for the Cent Fonts Spring in South France. Other studies highlight the influence of specific conduit features on spring hydrographs, for example *Raeisi et al.* [2007] and *Prelovšek et al.* [2008] indicating the influence of the filling grade on the observed signals.

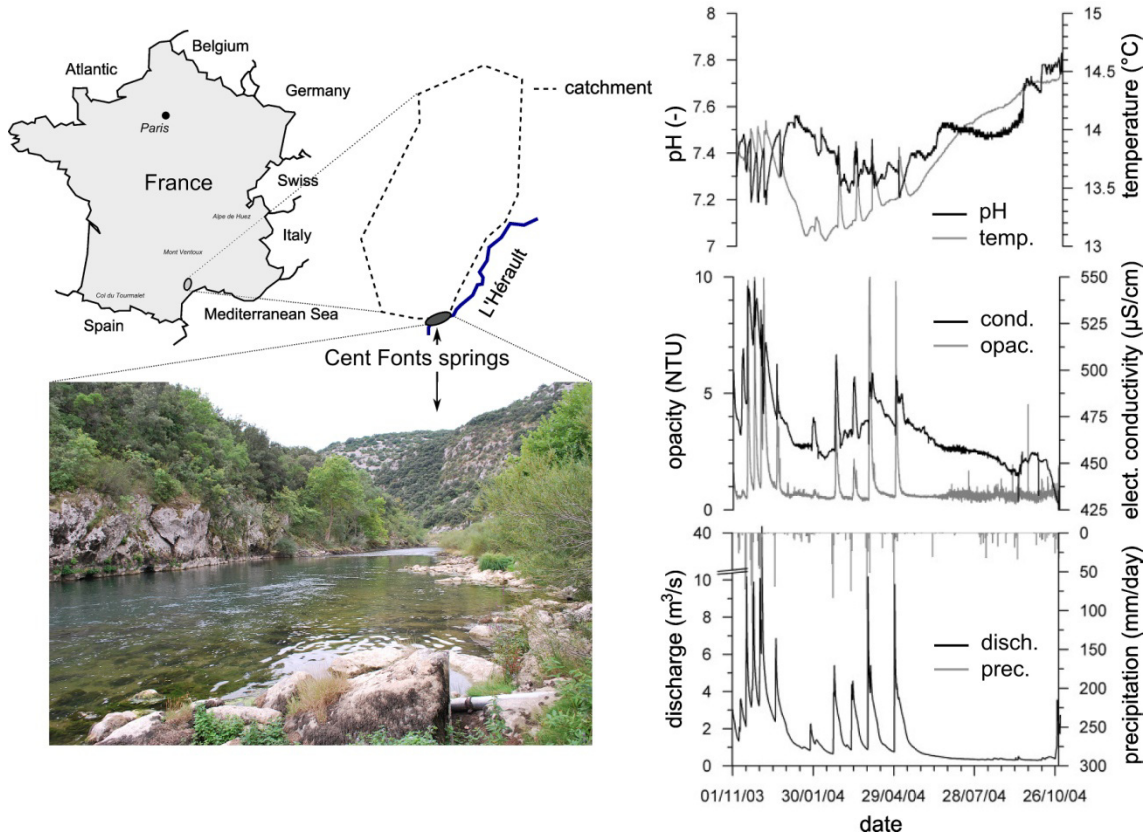


Figure 2-4: Temporal variation of discharge and physicochemical parameters at the Cent Fonts Spring, France, data from *Birk and Geyer* [2006].

2.2 Flow Processes in Karst Aquifers – An Overview

As previously discussed, karst aquifers are triple porosity systems consisting of a fractured porous rock matrix (primary and secondary porosity) and solution enlarged features (tertiary porosity). Groundwater occupies all these porosities. However, the characteristic hydraulic behavior of groundwater in the various compartments differs strongly. This section aims to provide a very brief overview about the wide range of flow processes in karst aquifers and additionally introduces concepts and equations to describe these flow processes. Beginning with a concise general overview about flow resistance, concepts to describe ground water motion in the various compartments of karst aquifers are introduced. A detailed discussion of selected flow processes is included in the subsequent chapters 3 and 4.

Flow conditions can be distinguished in laminar or turbulent state. In case of laminar flow, viscous forces dominate over inertia forces. Laminar conditions are characterized by an orderly flow with water moving in more or less straight and parallel stream lines. The fundamental characteristic of turbulence is the chaotic flow behavior with

random fluctuation and stochastic property changes, resulting in rapid variation of pressure and velocity in both space and time; cf. *Young et al.* [2004]. In case of turbulent flow, inertia forces dominate over viscous forces. The flow state is characterized by the dimensionless Reynolds number, which is the ratio of inertia to viscous forces

$$Re = \frac{vd}{\nu} \quad [2-1]$$

where d [L] is some representative length dimension [L], for example the diameter of a flow channel [Bear, 1988] or the pipe diameter [Young et al., 2004] and ν [L²T⁻¹] is the kinematic viscosity.

Flow resistance

Several forces affect fluid flow, for example pressure, gravity, shear and viscous forces. The resulting specific flow behavior can be described by a number of phenomenological flow equations in the manner

$$\Delta h = \xi lv^2 \quad [2-2]$$

where Δh is head loss [L], ξ is a coefficient representing geometrical measures and the flow resistance behavior [T²L⁻²], l is the length of flow [L], and v is the velocity [LT⁻¹]. With adequate values for ξ , equation 2-2 results for example in the Darcy-Weisbach equation used for pipe flow [Jain, 2001] or the Chézy equation used for open-channel flow [Jain, 2001].

For slow and, therefore, laminar flow, the coefficient ξ used in equation 2-2 can be determined according to Stokes' law (e.g. *Young et al.* [2004]). Therefore, hydraulic resistance is inter alia dependent on flow velocity. Consequently, ξ is a function of velocity and finally, equation 2-2 can be slightly varied for laminar flow as

$$\Delta h = \zeta lv \quad [2-3]$$

where ζ is a coefficient representing geometrical measures and flow resistance for laminar flow. For example, equation 2-3 represents Darcy's law for groundwater flow in porous media with hydraulic conductivity $K = 1/\zeta$. Laminar pipe flow is described in a similar manner by the Hagen-Poiseuille equation, which can be derived from the Darcy-Weisbach equation respectively from equation 2-2 [Young et al., 2004]. Note that the surface roughness of the solid boundary is embedded within the laminar flow layer and

does not affect flow resistance. In conclusion, laminar flow is characterized by a linear relationship between the forcing gradient and the resulting flow velocity (equation 2-3).

With increasing velocity, flow will become turbulent. The roughness of the solid boundary is an important parameter affecting turbulence. Starting at some irregularities at the conduit wall, longitudinal water flow is disturbed forming eddies, fluctuations, and enhanced transversal dispersivity [Young *et al.*, 2004]. The velocity distribution within the conduit is not uniform with the highest values in the center descending to the conduit wall. With increasing velocity, turbulence occurs in the middle of the conduit remaining the wall irregularities still inside a laminar boundary layer. Further increase of velocity result in a growing influence of wall irregularities on the turbulence behavior whereas the flow conditions change from transitional to fully turbulent [Young *et al.*, 2004]. Consequently, turbulent flow resistance is determined by some measure that accounts for surface roughness. Further, with an increasing Reynolds number, the flow resistance coefficient will become more and more independent from velocity. One common way to describe non-laminar pipe flow based on equation 2-2, respectively the Darcy-Weisbach equation, is the Colebrook-White equation, which considers transitional as well as turbulent flow, cf. for example Young *et al.* [2004]. Flow in open channels is predominantly turbulent and frequently described by the Manning equation, which can be derived from equation 2-2, respectively the Chézy equation, by using an empirical relation to describe roughness [Jain, 2001]. Finally, turbulent flow is characterized by a nonlinear relationship between the forcing gradient and the resulting flow velocity, which is represented by a power function; cf. equation 2-2.

Equation of Motion for Karst Groundwater

Fluid flow needs to comply with mass conservation and momentum conservation, provided that the fluid is considered as homogeneous, velocity changes are small compared to the speed of sound, no exchange of thermal energy occurs and changes in stored thermal energy are negligible [Jain, 2001]. Mass conservation is achieved by equaling the fluid mass increase of a control volume to the difference of mass inflow and outflow. Momentum conservation is achieved by equaling the sum of all external forces of a control volume (gravity, pressure, and shear forces) to the product of mass and acceleration [Jain, 2001].

For laminar groundwater flow in a fractured and or porous rock matrix, local inertial forces can be assumed to be negligible with respect to resisting forces meaning that

local acceleration becomes zero [Bear, 1988]. Mass conservation is considered by the continuity equation; e.g. Bear [1988]. Therefore, three-dimensional transient ground-water movement in porous media can be described with flow resistance based on the well known Darcy law, which is similar to 2-3, and under consideration of the continuity principle resulting in the three dimensional groundwater flow equation (for example Bear [1988] or any textbook on groundwater hydraulics)

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h_M}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h_M}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h_M}{\partial z} \right) - \psi = S_S \frac{\partial h_M}{\partial t} \quad [2-4]$$

where K_{xx} , K_{yy} , and K_{zz} are the hydraulic conductivities along orthogonal principal axes of anisotropy, designated x , y , and z [LT^{-1}], h_M is the head within the matrix [L], ψ is the external volumetric flux per unit volume and represents sources and/or sinks of water [T^{-1}], and S_S is the specific storage [T^{-1}]. Note that this equation includes non-steady flow controlled by time dependent boundary conditions.

Karst water flow in highly permeable discrete structures needs further consideration as the hydraulic conductivity and, therefore, the amount of moving water is comparatively large. In principle, karst hydraulics in solution enlarged conduits is familiar to the concepts used for urban drainage. Yen [2004] provides a comprehensive overview about sewer hydraulics. Subsequently, flow in discrete structures is classified in (A) pressurized flow in fully filled conduits, also denoted as pipe flow, and (B) free-surface flow in partly filled conduits, also denoted as open-channel flow. Investigation of pressurized flow is comparatively easy as the conveyance area of flow and, therefore, the geometrical parameters remain constant while driving gradients vary. Typically, turbulent pressurized flow is described with the Colebrook-White equation based on equation 2-2, for example Young *et al.* [2004]. On the contrary, geometrical measures for free-surface flow are dependent from driving gradients. Due to momentum and inertia forces dynamic flow processes are likely to become more important meaning that acceleration cannot longer be neglected. Further, flow processes can be classified by the spatial and temporal behavior of pressure head and discharge as listed below:

- Regarding their time dependency as steady or unsteady flow: Flow is steady if the unknown flow quantities head and velocity do not change with time. Contrary, unsteady flow reflects the temporal variation of flow and therefore processes like release or storage of water.
- Regarding their space dependency as uniform and non-uniform flow: Flow is uniform if the unknown flow quantities head and velocity do not change with the lon-

itudinal distance, i.e. along the direction of water flow. On the contrary, nonuniform flow accounts for spatial variations, for example waves.

Figure 2-5 illustrates the characteristics respectively the appearance of steady / unsteady and uniform / nonuniform flow.



a) Steady and uniform flow: Channel in South-West Florida (assuming lateral in- and outflow is negligible)



b) Steady and non-uniform flow: Surfing on the steady wave at the Eisbach river in Munich / Germany (Picture taken by Bernd Reuschenberg)



c) Unsteady and non-uniform flow: Allogenic recharge to the Lurbach karst system near Graz / Austria. Snow melt and variable river geometry result in temporally and spatially variable flow. (Picture taken by Cyril Mayaud)

Figure 2-5: Photographs giving examples for the occurrence of flow types (note that unsteady and uniform flow is rare and not included here).

The dynamic behavior of open-channel flow is described with the continuity equation (mass conservation)

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \quad [2-5]$$

where Q is discharge [L^3T^{-1}] and t is time [T], and the equation of motion (momentum conservation)

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q^2}{A} \right) + gA \frac{\partial h}{\partial x} + gA(s_f - s_0) = 0 \quad [2-6]$$

with s_f the friction slope and s_0 the bottom slope. These set of equations is also known as Saint Venant equations and they describe fully dynamic flow, cf. *Jain* [2001]. The equation of motion may be simplified as diffuse wave (neglecting acceleration) or kinematic wave (neglecting acceleration as well as spatially variable head), cf. *Jain* [2001]. For steady uniform flow, equation 2-6 is redundant, equation 2-5 reduces to $\partial Q / \partial x = 0$, and discharge Q can be described based on equation 2-2 (considering continuity with $Q = vA$); *Jeannin* [2001].

Water Transfer Between Conduits and Rock Matrix

Water in the conduits interacts with water in the rock matrix. Due to the distinctive heterogeneity of karst aquifers, strong head differences between conduits and rock matrix are likely to occur. Commonly, water exchange between discrete structures and a continuum is described with a linear, head dependent transfer term [Barenblatt *et al.*, 1960; Liedl *et al.*, 2003; Bauer *et al.*, 2003]

$$Q_{ex} = \alpha_{ex} \Delta h_{C-M} \quad [2-7]$$

where Q_{ex} is the water exchange between conduits and matrix [L^3T^{-1}], α_{ex} is the water transfer coefficient [L^2T^{-1}], and Δh_{C-M} [L] is the head difference between conduit and matrix.

2.3 Field Investigation Methods to Characterize Karst Aquifers

The subsequent section aims to give a brief introduction about field scale investigation methods for karst aquifers as they provide fundamental data – inter alia – to develop a plausible conceptual representation of karst systems (cf. section 2.1) and to describe karst hydraulics based on adequate equations (cf. section 2.2). Typically, an aquifer is characterized by standard investigation techniques like geological mapping and field methods, for example borehole tests (cf. chapter 8 in *Freeze and Cherry* [1979]). Resulting point data are extrapolated respectively interpolated to achieve a spatially comprehensive view of the aquifer. As discussed previously, the existence of highly permeable conduits within a rock matrix will result in a distinctive heterogeneity and anisotropy. Hydraulic parameters like conductivity are depending on the scale of the investigation method [Király, 1975], cf. Figure 2-3. For that reason the use of standard investigation methods is not sufficient for karst aquifers. Consequently, methods to investigate and characterize karst water resources differ from those commonly used for typical unconsolidated aquifers like sands and gravel. Several authors give a deep and broad insight into karst aquifer characterization, e.g. *Ford and Williams* [2007] and *Geyer* [2008].

According to *Geyer* [2008], characterization methods on the field scale can be classified in (A) artificial experiments and (B) global approaches. Artificial experiments can be further subdivided in borehole tests and artificial tracer tests. Typically, borehole test methods originate from standard aquifer characterization techniques and encompass for instance pumping tests [Eagon, 1972; Sauter, 1992; Gringarten, 2008],

slug tests [Sauter, 1992], recharge respectively injection tests [Sauter, 1992], or logging techniques like geophysical measurements or video analysis. Results represent typically the rock matrix around the borehole and, therefore, characterize the karst aquifer on local scale in the vicinity of the borehole. Another group of artificial experiments are tracer techniques, for example single tracer tests [Atkinson *et al.*, 1973; Sauter, 1992; Birk *et al.*, 2004] or multi-tracer tests [Geyer *et al.*, 2007]. These tests provide information about conduit related characteristics on regional scale, for example the conduit geometry in means of the total volume [Birk *et al.*, 2005; Geyer *et al.*, 2007] but they cannot provide information about the spatial location and the network pattern and, therefore, fail to characterize conduit related anisotropy.

Contrary to artificial tests, global approaches are based on analyzing the system behavior in a natural context, which is commonly done by spring hydrograph analysis; see for example Jeannin and Sauter [1998]. The spring hydrograph reflects the system reaction on input signals and, therefore, gives insight in the functioning of the karst catchment on a larger scale (compare Figure 2-4). Spring hydrograph analysis is a major characterizing technique for karst aquifers that is in widespread use [Droque, 1972; Mangin, 1984; Padilla and Pulido-Bosch, 1995; Bailly-Comte *et al.*, 2008]. Global approaches can be further subdivided based on the investigated system in concentrated and diffuse flow and transport analysis. The first one (concentrated) corresponds to event analysis, e.g. induced by strong recharge incidents, and provides information on the highly permeable karst features. For example, Ashton [1966] claims that the time lag between the reactions of spring discharge and physicochemical parameters to a recharge event is a measure for the conduit volume. Contrary, diffuse flow and transport analysis corresponds to baseflow recession [Maillet, 1905] and provides information on the rock matrix, which is drained by the conduits [e.g. Kovács *et al.*, 2005]. However, commonly applied global methods lack detailed knowledge about the input signal, i.e. distribution of diffuse and direct recharge as well as recharge rate and, therefore, might be seen as uncontrolled experiments. Figure 2-6 gives a systematic overview about the various characterization methods.

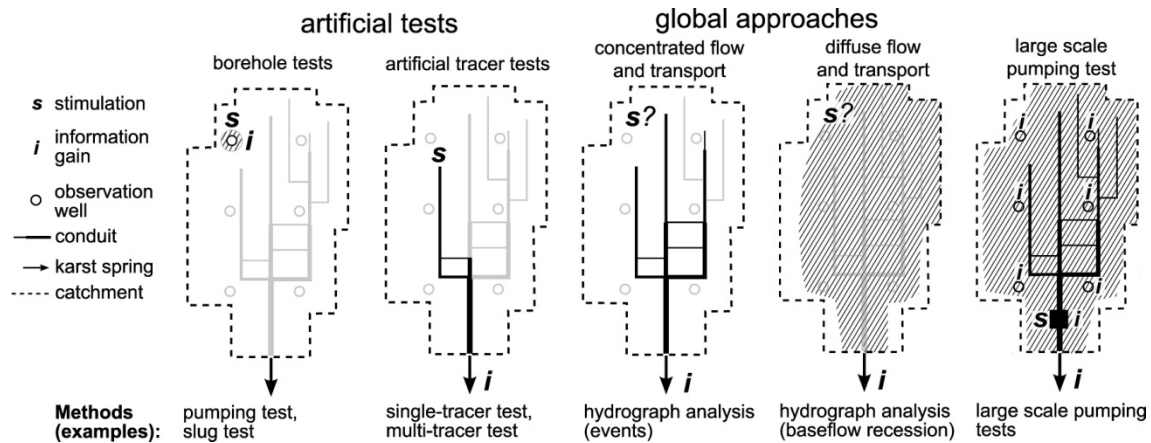


Figure 2-6: Systematic overview about field scale investigation methods according to Geyer [2008].

Large scale pumping tests may overcome some limitations of global methods as they use a defined pumping rate and therewith stating a controlled experiment [Maréchal *et al.*, 2008; Geyer, 2008]. In such experiments, water is directly extracted from the conduit system with a comparatively high pumping rate resulting in a unique and scale comprehensive system response. Ladouche *et al.* [2007] and Maréchal *et al.* [2008] describe a large scale pumping test within the Cent Fonts catchment in South France (see also Figure 2-4). During this controlled global experiment, the pumping rate was kept constant at 400 liters per second for approximately 2 months. Conduit and matrix heads were measured during the experiment representing the reaction of the solution enlarged conduit system as well as of the rock matrix. Figure 2-7 gives an insight in the test site. Due to the long term pumping, these experiments are capable to characterize the conduit system (early times), the interaction between matrix and conduits (intermediate times), and the matrix (late times). For that reasons, this kind of extensive field experiments overcome existing scale limitations of traditional methods for karst characterization [Geyer, 2008]. Beside such large controlled experiments, existing facilities that abstract water from the conduit system for water supply reasons can possibly be considered as global controlled experiment too, and therefore overcome the high investment demand.

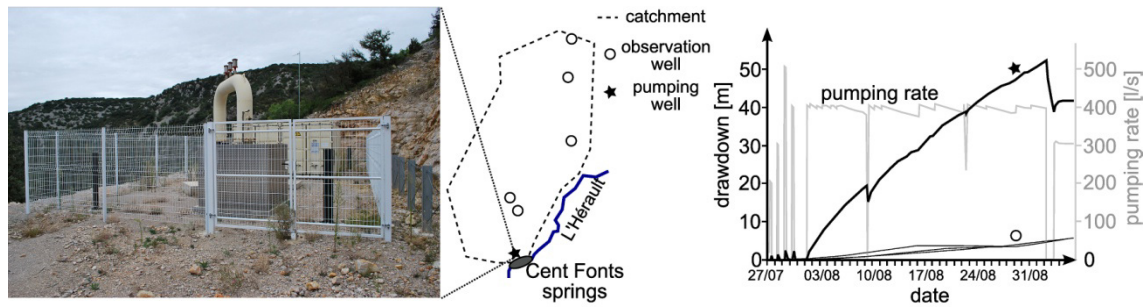


Figure 2-7: Large scale pumping test – *left side*: photo and map of the pumping well (see also Figure 2-4); *right side*: observed pumping rate and draw-down in the conduit and the matrix wells, data from *Maréchal et al.* [2008].

2.4 Modeling of Karst Hydrologic Systems

Model application is one necessary step that enhances the principal understanding of karst hydrologic systems [Király *et al.*, 1998]. Based on a proper conceptual model (section 2.1), karst hydraulics can be described by adequate equations (section 2.2), whereas necessary data and parameters can be obtained by suitable field investigation methods (section 2.3). For more complex situations, the aforementioned karst system representation can be done more sufficiently by use of numerical methods. The nature of karst systems with triple porosity, heterogeneity, and anisotropy result in special needs regarding flow modeling. For example both laminar and turbulent flow may occur within the rock matrix and the solution enlarged conduits. Hence, necessary methods and tools for flow modeling differ from those commonly applied, e.g. for typical unconsolidated aquifers like sands or gravel. The following section aims to introduce model concepts for karst systems and give a brief overview about existing numerical tools.

2.4.1. Model Concepts for Karst Systems

Overall, mathematical model approaches for karst hydrologic systems are classified regarding their consideration of spatially distributed heterogeneities into (1) lumped parameter models and (2) distributed parameter models [Sauter *et al.*, 2006].

Lumped Parameter Models - Global methods

Lumped parameter models examine the hydraulic response of the overall karst system considered in its entity. The analysis investigates the systematic coherence between input signals (recharge) and system response (spring discharge) i.e. as trans-

fer function approach, for example *Kiraly* [2002], *Geyer et al.* [2008], or *Maréchal et al.* [2008]. These models are not physically based and, therefore, often called Black-Box- or Input-Output-Models. Due to the easy application and the moderate parameter demand, lumped parameter models are in widespread use. A typical application for lumped parameter models is the analysis of spring hydrographs, cf. also section 2.3.

Distributed Parameter Models

Distributed parameter models describe the karst hydrologic system quantitatively based on spatial properties, for example hydraulic conductivity. To this end, the karst hydrologic system needs to be discretized spatially in order to describe groundwater flow for each element with the adequate flow equation (compare section 2.2). Contrary to lumped parameter models, distributed models need to be parameterized with adequately spatially allocated input data, which are more or less rare [*Sauter et al.*, 2006]. Further, solution enlarged karst features result in strong heterogeneity and anisotropy contradicting the concept of an REV. Hence, distributed model approaches need the capability to consider heterogeneity and anisotropy. *Teutsch and Sauter* [1991] proposed an early classification scheme for distributed model approaches potentially applicable to karst hydrologic systems. The numerical model approaches are classified based on investigation effort, practical applicability, and their capability to simulate heterogeneities, see Figure 2-8.

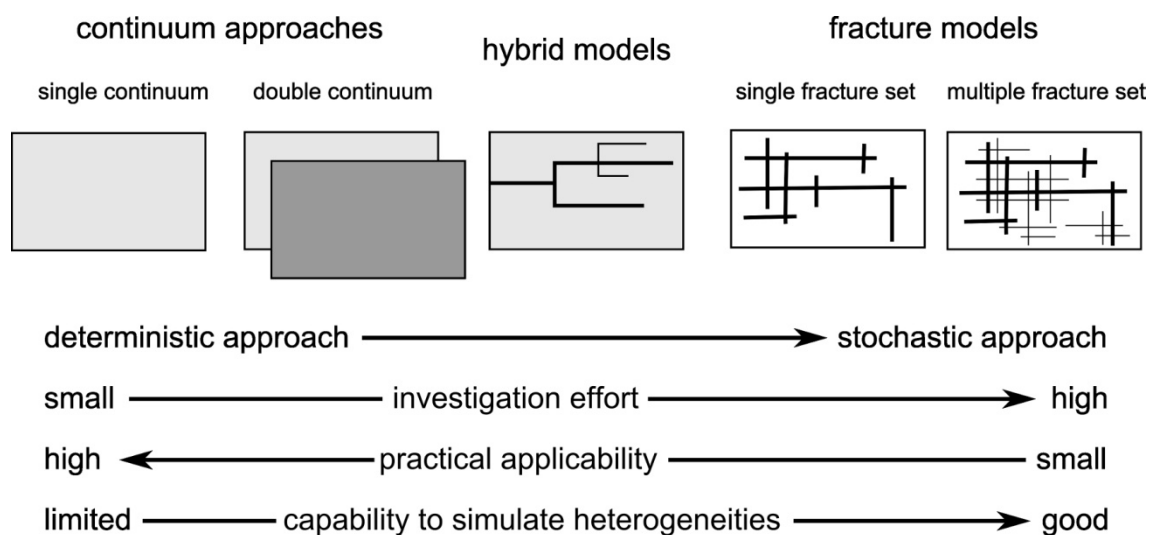


Figure 2-8: Schematic representation of numerical model approaches, according to *Teutsch and Sauter* [1991].

2.4.2. Distributed Parameter Models for Karst Aquifers

Continuum models for porous media aquifers are commonly based on the Darcy equation, state of the art tools, and, therefore, in widespread use [Anderson and Woessner, 2002]. Continuum models are the most basic approach to compute karst aquifer hydraulics. They represent the aquifer in terms of the REV with originally heterogeneous hydraulic properties lumped over a certain distance. Consequently, the investigation demand respectively the data amount is small and the practical applicability is high. Well known groundwater models are for example the 3D finite element code FEFLOW [DHI-WASY GmbH, 2011], a commercial code for professional application, and the USGS 3D finite difference groundwater model MODFLOW [McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; Harbaugh et al., 2000; Harbaugh, 2005]. The MODFLOW architecture is modular with freely available source code that is continuously maintained and further developed. Consequently, several additional hydrologic processes are added to the MODFLOW main core making the software a suitable research tool by own code modification. The MODFLOW computation core is embedded in several graphical user interfaces, for instance Processing MODFLOW [Chiang, 2005], VISUAL MODFLOW [Schlumberger Water Services, 2011], GMS [Aquaveo, 2011], GROUNDWATER VISTAS [ESI, 2011], or MODEL MUSE [Winston, 2009], which allow easy usage of the numerical model.

The simplest technique for distributed modeling of karst aquifers is the single-continuum approach. However, standard groundwater models lack turbulent flow. Though, this approach still appears to be frequently used for practical applications. In doing so, single continuum models lump both flow components together whereas conduits are represented by highly conductive cells, sometimes denoted as smeared conduit approach [Painter et al., 2006]. Worthington [2009] applied MODFLOW to model the Mammoth Cave aquifer. Highly conductive cells were used to consider the karst conduits explicitly. With this, model results are more accurate than those computed by comparable single continuum models without highly conductive cells. Though, an enlarged conductivity was applied to bulky cells with 200 m width and full height of the single layer (100 m in places), hydraulic conductivity and therewith flow velocities were underestimated in the model compared to real conduits with diameters in the range of centimeters to some meters [Worthington, 2009]. Consequently, flow tends to be slower than in real conduits and, therefore, turbulence is not as important in such coarsely discretized models. On the other side, results of such models are not

adequate for local scale applications like computation of transport processes. Some numerical approaches are capable to account for turbulent flow by correction of the hydraulic conductivity [Halford, 2000; Shoemaker *et al.*, 2008 b; Kuniansky *et al.*, 2008]. Consequently, simple single-continuum models may be capable to account for karst specific features. Chapter 3 of this thesis gives an insight in using single-continuum models to account for turbulent flow.

Double-continuum approaches are able to consider two flow systems representing the rock matrix and the solution enlarged conduits, and are for that reason more capable to consider the dualistic flow system of karst aquifers. To this end, two continua representing the slow-flow matrix system respectively the fast-flow conduit system are coupled by use of a linear exchange factor in a manner, which is comparable to well known double-porosity approaches [e.g. Barenblatt *et al.*, 1960]. Double-continuum models are applied to karst aquifers for example by Teutsch [1988], Sauter [1992], Lang [1995], and Mohrlok [1996]. One potential drawback of these models is, however, that the spatial connection between matrix heads and the conduit system is neglected because spatial information of the high-conductive system is not considered.

Contrary to continuum approaches, fracture models represent solution enlarged conduits and large fractures explicitly as discrete preferential flow paths. Therefore, this widely available type of models [Jing, 2003] may be used to investigate karst features. Fractures can be considered either by individual parameterization or by some adequate statistical parameters. As shown in Figure 2-8, fracture models can be further distinguished in single fracture set models and multiple fracture set models that combine several fracture sets. However, the practical application of fracture models for karst systems is restricted due to the high investigation effort. The identification of specific fractures and conduits is predominantly not possible due to the lack of investigation methods respectively the enormous investigation effort. Fracture description with statistical parameters is only sufficient for limited portions of the aquifer. For that reason, application of fracture models may be restricted to small scales with well known fracture features, for example Cacas *et al.* [1990] and Kolditz [2001]. By use of multiple fracture sets, explicitly known preferential flow paths can be combined with statistically assigned parameters. To sum up, fracture network models require exceptional investigation effort and, therefore, are limited with respect to their practical applicability.

Hybrid models combine a continuum model with a discrete structure model, e.g. *Kiraly* [1998]. For karst related applications, the continuum model represents slow and laminar flow processes in the rock matrix and the discrete flow models represent fast and optional turbulent flow in solution enlarged conduits. Water flow in the continuum is commonly covered by the linear Darcy law and water flow in the discrete structures is computed by linear and nonlinear equations, typically based on the Darcy-Weisbach approach for pipe flow (cf. equation 2-2). Both compartments are coupled via a head-dependent linear transfer coefficient; compare also section 2.2. Consequently, hybrid models are able to consider the spatial characteristics of solution enlarged karst conduits, the specific behavior of turbulent flow, as well as scaling issues. To this end, hybrid models seem to be adequate tools for karst characterization as they recognize the influence of the conduit networks spatial pattern [*Geyer*, 2008], as well as the co-existence of laminar and turbulent flow conditions. Therefore, hybrid models are suitable to reflect the dual characteristics of karst aquifers even on local scale and may provide useful insights to the functioning of karst systems as.

Several authors documented hybrid model approaches respectively their application for karst aquifer modeling, for example *Kiraly* [1979, 1984, 1998], *Clemens* [1997], *Hückinghaus* [1998], *MacQuarrie and Sudicky* [1996], *Kaufmann and Braun* [2000], *Bauer* [2001], *Birk* [2002], *Liedl et al.* [2003], *Shoemaker et al.*, [2008 b], and *DeRooij* [2008]. One potential drawback for hybrid model application to karst system is the high parameter demand that results in enhanced investigation effort. Some parameters are ambiguous like those describing the interaction between matrix and conduits. Further, the absence of graphical user interfaces still limits the widespread use of existing karst hybrid models. Originally, hybrid models are intended for research related applications like the investigation of karst aquifer genesis (speleogenesis), for instance *Liedl et al.* [2003], *Dreybrodt et al.* [2005], *Rehrl et al.* [2008], *Kaufmann* [2009], and *Hiller et al.* [2011].

The numerical model Carbonate Aquifer Void Evolution (CAVE) was developed to examine speleogenesis [*Clemens*, 1997; *Hückinghaus*, 1998; *Liedl et al.* 2000, 2003; *Bauer*, 2001; *Birk*, 2002]. CAVE couples a discrete pipe network that computes flow based on the Darcy-Weisbach approach to a MODFLOW continuum. Further, CAVE comprises simple routines to consider carbonate respectively gypsum dissolution as well as heat and substance transport. Beside speleogenesis, hybrid models are applied for other karst scenarios. For instance, *Birk et al.* [2005, 2006] demonstrated the ability

of hybrid models for karst aquifer characterization. *Hill* [2008] and *Hill et al.* [2010] used hybrid models for site-related modeling of the Weeki Wachee karst terrain, West Central Florida, USA, whereas the relative importance of the linear transfer term that considers the interaction between matrix and conduits was highlighted.

An important step forward for karst modeling is the wide distribution of adequate numerical approaches. In this context, the USGS adapted and further developed CAVE flow routines into the MODFLOW-2005 Conduit Flow Process (CFP) [*Shoemaker et al.*, 2008 b] denoted as CFP Mode 1 (CFPM1).

→ The functionality of MODFLOW-2005 CFP was introduced to a broad readership by **Reimann and Hill [2009]** respectively **Reimann [2009]**. Both papers are embedded additionally into this thesis and can be found in Appendix A1.

2.4.3. Perspectives for Model Development (Outlook to Chapters 3 & 4)

As already mentioned, solution enlarged permeability is the outstanding characteristic of karst aquifers resulting in the aforementioned distinctive heterogeneity and rapid, potentially turbulent flow. Due to scaling of hydraulic properties, solution enlarged conduits interact with the surrounding rock matrix in a specific way. Existing distributed model approaches to consider these characteristics are typically developed and applied in a research related context. Use of these models is demanding, for example expert knowledge is necessary to prevent numerical issues. Graphical user interfaces are rare or missing, making it hard and time consuming to use the models. However, maybe it is possible to represent karst hydraulics within specific catchments conceptually simplified by neglecting some processes like dynamic flow in variably filled conduits. In this context, it can be possible to capture the relevant characteristics of a karst catchment by using a simplified numerical model approach.

Continuum models representing turbulent flow might be useful to overcome some limitations. According to *Teutsch and Sauter* [1991], see also Figure 2-8, they offer high practical applicability. *Halford* [2000] considered turbulent flow in the vicinity of wells with a modified MODFLOW continuum model. *Shoemaker et al.* [2008 b] adapted this approach as Mode 2 to the MODFLOW-2005 Conduit Flow Process (CFPM2). CFPM2 is well evaluated with laboratory experiments [*Kuniansky et al.*, 2008], and seems to be very useful for groundwater flow modeling [*Shoemaker et al.*, 2008 a]. However, CFPM2 is intended to represent turbulent flow in highly conductive karstic layers but not in discrete conduits [*Shoemaker et al.*, 2008 a; *Shoemaker et al.*

2008 b; *Kuniansky et al.*, 2008]. CFPM2 can be integrated easily in frequently used MODFLOW environments (for example graphical user interfaces) because it adapts the hydraulic conductivity of the continuum depending on the Reynolds number. Therefore, CFPM2 can be a way to overcome some limitations of existing karst models like the lack of graphical user interfaces, missing additional processes like transport, and the high numerical demands of hybrid models.

Birk and Rehrl [2009] as well as *Rehrl and Birk* [2010] compared CFPM2 with existing hybrid models respecting the ability to represent pipe flow hydraulics. However, results indicate that CFPM2 differs from commonly used hybrid models. Beside this, existing hybrid models like CAVE and CFPM1 realize the matrix-conduit coupling with a head dependent water transfer coefficient that is quite sensitive for hydraulics [*Bauer et al.*, 2003]; see also equation 2-7. Hence, it is reasonable to analyze if and in what way continuum models potentially can represent karst aquifers similar to hybrid models. Consequently, investigations are addressed in the following directions:

- Further modification of CFPM2 to consider turbulent conduit type flow in continuum cells. Consequently, the turbulent flow representation of the existing CFPM2 was adapted to account for conduit type flow too. The work is subsequently documented in section 3.1: **Reimann T., Birk, S., Rehrl, C., and Shoemaker, W. B. (2011)**, Modifications to the Conduit Flow Process Mode 2 for MODFLOW-2005: Ground Water, doi: 10.1111/j.1745-6584.2011.00805.x.
- The significance of turbulent flow representation in continuum models was investigated by using the adapted CFPM2. The work is subsequently documented in section 3.2: **Reimann, T., C. Rehrl, W. B. Shoemaker, T. Geyer, and S. Birk (2011)**, The significance of turbulent flow representation in single-continuum models, Water Resources Research, 47, W09503, doi:10.1029/2010WR010133.

Further it is necessary to broaden the range of processes that can be considered with numerical approaches to cover the existing conceptual model of karst hydrologic systems (section 2.2). The diameter of solution enlarged karst conduits can range up to several meters, which is typically for matured karst (compare Figure 2-1). It is likely that free surface flow occurs in such large karst conduits, for example if the overall ambient water table is descending. Free surface flow is highly dynamic as water table fluctuations are coupled with storage changes. Strong recharge events like storms result in increased recharge coupled with increased conduit discharge. Subsequently, it is reasonable that free surface flow conditions changeover to pressurized pipe flow.

Some authors reported the occurrence of variably filled conduits in field experiments [Raeisi *et al.*, 2007; Prelovšek *et al.*, 2008]. Figure 2-9 illustrates this behavior and shows that the changeover from free-surface flow to pressurized flow occurs with a sudden change of conduit heads and the hydraulics of conduit flow. Likewise, dynamic processes can be important for extensively controlled experiments like the already mentioned large scale pumping test, compare section 2-3. For example, the very first system reaction on a sudden action, e.g. the start of pumping, can be assumed to be highly dynamic.

Temporally and spatially dependent information conducted through such scale integrative experiments can be evaluated with distributed models giving further insights to the systems functioning. However, most existing hybrid models do not represent fully dynamic flow in variably filled conduits on field scale. Therewith, free-surface flow processes and storage behavior of karst groundwater in solution enlarged conduits is not correctly considered. *De Rooij* [2008] presented a numerical approach that couples turbulent flow in variably filled discrete conduits with a matrix continuum. So far, application of this finite element code is restricted to a limited regional scale and spatial discretization.

Free surface flow in karst conduits may be regarded as 'surface stream with a top boundary', whereas flow processes can be potentially analyzed with methods for surface water [Gunn, 1986]. For that reason, overland flow models coupled to groundwater continuum models are an initial point for further model development. *Swain and Wexler* [1996] coupled a discrete dynamic overland flow model to the MODFLOW continuum. The resulting model is successfully applied on regional scale, for example *Evans* [2000]. *Zhang and Lerner* [2000, 2002] adapted the coupled model to investigate groundwater flow in fully saturated mining shafts.

- The existing model was further adapted in order to represent fully dynamic flow in variably filled karst conduits coupled to a groundwater continuum. This hybrid model was used to investigate the influence of variably filled conduits on signal transmission in karst aquifers. Further details can be found in section 4 of this thesis: **Reimann, T., T. Geyer, W. B. Shoemaker, R. Liedl, and M. Sauter (2011), Effects of dynamically variable saturation and matrix-conduit coupling of flow in karst aquifers, Water Resources Research, 47, W11503, doi:10.1029/2011WR010446.**

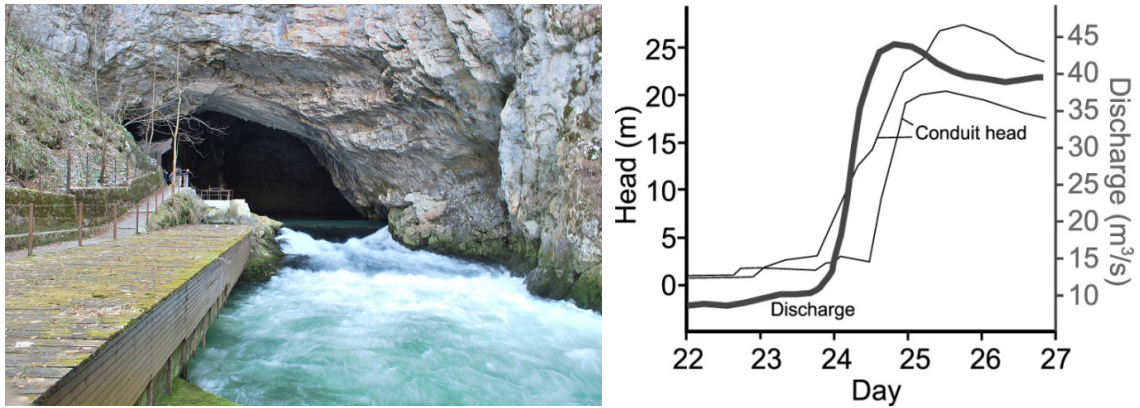


Figure 2-9: *Left:* Entrance to the Planina cave, Slovenia, with the river Unica flowing out; *right:* Measured conduit heads in two caves in downstream direction of the Planina cave. The conduit heads clearly indicate the change-over from free-surface flow to pressurized flow during a pulse recharge event (data from *Prelovšek et al. [2008]*).

3

TURBULENT FLOW REPRESENTATION IN CONTINUUM MODELS

3.1 Modification to the Conduit Flow Process Mode 2 for MODFLOW-2005

Due to the cumulative character of this thesis, the section is published as:

Reimann T., Birk, S., Rehrl, C., and Shoemaker, W. B. (2011), Modifications to the Conduit Flow Process Mode 2 for MODFLOW-2005: Ground Water, doi: 10.1111/j.1745-6584.2011.00805.x.

3.2 The Significance of Turbulent Flow Representation in Single-Continuum Models

Due to the cumulative character of this thesis, the section is published as:

Reimann, T., C. Rehrl, W. B. Shoemaker, T. Geyer, and S. Birk (2011), The significance of turbulent flow representation in single-continuum models, Water Resour. Res., 47, W09503, doi:10.1029/2010WR010133.

EFFECTS OF DYNAMICALLY VARIABLE SATURATION AND MATRIX-CONDUIT COUPLING OF FLOW IN KARST AQUIFERS

Due to the cumulative character of this thesis, the section is published as:

Reimann, T., T. Geyer, W. B. Shoemaker, R. Liedl, and M. Sauter (2011), Effects of dynamically variable saturation and matrix-conduit coupling of flow in karst aquifers, *Water Resour. Res.*, 47, W11503, doi:10.1029/2011WR010446.

GENERAL CONCLUSIONS

The functioning of karst hydrologic systems is a complex interaction of several elements and processes that results in the unique behavior of each single karst catchment. Section 2 provides an overview about the diversified appearance of karst from diffuse-flow to conduit-flow systems. According to the wide ranging conceptual representation of karst systems, numerical models can potentially be applied for karst settings. However, often these models are not intended for karst and, therefore, comprise limitations like neglecting potentially significant processes. To overcome some of these limitations, existing numerical models, which are intended for catchment scale application, are adapted to represent karst specific features. Subsequently, the modified numerical codes are used to investigate the significance of specific process representation on model results (Sections 3 and 4). Existing and adapted models are able to cover a whole range of situations occurring in karst aquifers. Consequently, numerical methods provide additional insights respecting the functioning of karst systems comprising processes on different temporal and spatial scales. To this end, investigations like borehole tests (local scale), tracer tests (catchment scale), spring hydrograph observation for natural events (short time scale) and baseflow recession (long time scale), as well as scale integrated experiments like large pumping tests, for example *Maréchal et al.* [2008], can be evaluated with distributed model approaches.

5.1 Summary of Model Adaptation and Perspectives for Application

Section 3 of this thesis deals with turbulent flow representation in continuum models. To this end, CFPM2 was modified to represent turbulent flow in a user-

defined way [Section 3.1]. With this, CFPM2 is able to compute laminar and turbulent conduit flow similar to hybrid models. Simple evaluation tests [Section 3.1] and model application on idealized catchments [Section 3.2] demonstrate the appropriateness of the modified CFPM2. A parameter study exemplified that single continuum models can reflect the dual characteristics of karst provided that (A) turbulent flow is adequately considered, and (B) the hydraulic interaction between conduits and matrix is adequately considered [Section 3.2].

Beyond this, the application of CFPM2 is linked with some potential limitations. CFPM2 computes flow under assumptions valid for slow groundwater movement whereas the equation of motion neglects dynamic processes like acceleration (compare equation 2-4). CFPM2 is not able to represent transient flow dynamics correctly as they can become important in variably filled conduits, for example wave propagation. For that reason, CFPM2 might be restricted to fully filled conduits respectively to processes on extended time scales. Actually, the CFPM2 modifications are implemented technically in a straightforward way whereas every turbulent computation is based on a preceding laminar computation [Section 3.1], which can result in numerical issues (e.g. for distinctive turbulent conditions where a laminar calculation fails). Further research is necessary to apply CFPM2 for real catchments, for example to investigate adequate ways for discretization and parameterization.

So far, the modified CFPM2 was employed on field scale to simulate the discharge of the Wakulla-Leon Sinks submerged cave system of the Woodville Karst Plain, Florida (USA) [Kuniansky *et al.*, 2011] in comparison to other model approaches. Employed model approaches comprised namely (1) single continuum laminar flow as MODFLOW-2005, (2) single continuum laminar and turbulent flow as the modified CFPM2, and (3) a coupled continuum/pipe flow hybrid model as CFPM1. Results indicate that the modified CFPM2 simulate the observed peak discharge well. Spring hydrographs of the turbulent continuum model (2) were comparable with the hybrid model (3) indicating the potential use of CFPM2 to simulate real catchments.

Section 4 of this thesis deals with turbulent flow in variably filled conduits. Flow characteristics for free-surface flow in karst conduits are similar to overland flow. Consequently, available couplings of overland flow models to groundwater continuum models – namely MODBRANCH [Swain and Wexler, 1996] – are already adapted for groundwater flow in mining shafts [Zhang and Lerner, 2000; 2002]. These existing numerical codes were further adapted to represent fully dynamic flow in variably filled

karst conduits coupled to a matrix continuum [Section 4]. The functionality of the resulting dynamic hybrid model was demonstrated by some basic performance tests. Model studies on an idealized karst catchment indicate the significance of free-surface flow representation in karst conduits, whereas signal transmission in both karst conduits and matrix rely on the conduit filling grade [Section 4]. Consequently, the dynamic hybrid model complements existing model approaches to consider dynamic processes in variably filled karst conduits that can be important on short time scales or in situations when fully filled conduits dewater.

However, usage of the dynamic hybrid model is technically and numerically very demanding. The parameter demand is high and exceeds those for commonly used hybrid models such as CFPM1. Additional parameters like conduit bottom elevation respectively bottom slope, shape and geometry of conduits are sensitive but availability for real catchments is limited. Hence, the model usage for predictive forward simulations can be restricted. So far, the model was applied to comparably easy and idealized situations. Future work should expand the implementation of the dynamic hybrid model to more complex real catchments. An initial step was the usage of the dynamic hybrid model to investigate the transition of event based recharge signals for the Lurbach karst catchment, Austria [Lompe, 2010]. The Lurbach catchment is characterized by distinctive allogenic recharge, which is routed through the karst aquifer and appears after an underground passage of approximately 3 km air-line distance at two springs. A specific time lag between in- and outflow in the range of some hours (depending on the specific event) indicate at least the partial existence of free-surface flow processes. By using a simple and straightforward numerical model based on the dynamic hybrid model approach, Lompe [2010] was able to qualitatively reproduce the behavior of the real karst catchment. However, due to the specific field situation and the model parameterization, the computation comprised free-surface conduit flow only.

Future application of dynamic hybrid models to karst systems can be accomplished in several ways. Some suggestions are listed below:

- Evaluation of the fast response to pumping in early stages of large scale experiments, for example during step wise pumping tests; e.g. *Maréchal et al.* [2008].
- Simulation of recession periods including dynamic processes due to water release from conduit storage during the transition from pressurized to free surface flow.

- Investigate the influence of the conduit filling grade on speleogenesis, i.e. evolution of conduits under the condition of free-surface flow.
- Investigation of hydrographs in well-defined subsections of mature conduit systems, under consideration of a variable conduit filling grade. Subsequently, two examples for such field sites are briefly introduced, which offer well defined conditions and fit within the conceptual framework of the dynamic hybrid model:
 - *Raeisi et al.* [2007] measured hydrochemographs of Logsdon River within the Mammoth Cave System in Kentucky (USA). The conduit at the investigation site is about 3 m high and 7 m wide, with an estimated water stage for baseflow conditions of around 1 m [*Raeisi et al.*, 2007], see also Figure 5-1 a. Observed field data include events with transition from free-surface to full pipe flow, which result in a distinctive behavior respecting specific conductivity, compare Figure 5-1 (right).
 - A similar well defined system is presented by *Prelovšek et al.* [2008], who measured discharge and head inside of cave systems around Planinsko polje, Slovenia, with field data clearly indicating the transition between free-surface and full pipe flow; compare also Figure 2-9.

Scenarios without strong external hydraulic stress and with negligible dynamic flow processes can be investigated using easier approaches like turbulent continuum models or existing hybrid models. Beyond this, these methods can produce adequate initial data for dynamic hybrid models, which are quite important in order to result in stable model runs.

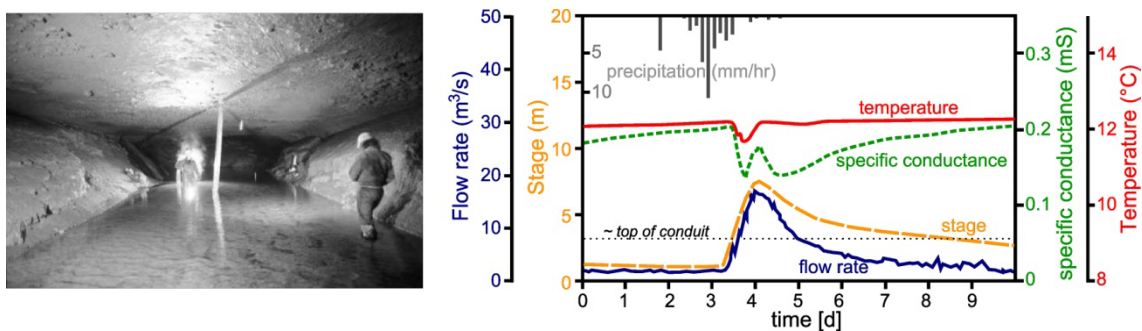


Figure 5-1: Left: Picture from the Logsdon River test site, taken from *Groves and Meiman* [2001]; right: Hydrochemograph from the Logsdon River for an event with transition from free-surface flow to full pipe flow; data from *Raeisi et al.* [2007].

Up to now, the presented adapted numerical models (Sections 3 and 4) were mainly applied to simple idealized catchments in order to investigate the significance

of single processes without potential interferences caused by more complex situations. Results show that processes like turbulent flow and dynamic flow in variably filled conduits can be important and should be conceptually considered, especially on transient situations and short time scales. Future application should comprise more complex idealized catchments as well as real catchments in order to proof and advance model development.

5.2 Perspectives for Model Development

The implementation of transport processes for heat and substances in distributed parameter models for karst systems is a promising step for future model application. With this, models can be used on catchment scale for an extended event analysis as well as to investigate the behavior of artificial and natural tracers, for example *Liedl et al.* [2000], *Birk et al.* [2005, 2006], and *Birk and Geyer* [2006]. The main transport processes for substances in karst conduits comprise advection and dispersion, commonly described by a 1D advection-dispersion transport equation, e.g. *Birk et al.* [2005]. However, field measurements of tracer breakthrough curves often show a distinctive tailing, which cannot be described adequately by the advection-dispersion equation [*Geyer et al.*, 2007]. It seems possible to consider tailing effects by additionally incorporating retarded matrix diffusion [*Birk and Geyer*, 2006].

Development of karst transport models can build up on existing modules, predominantly intended for the CAVE hybrid model. In particular, existing transport modules for karst conduits comprise:

- 1D advective transport in conduits [*Birk*, 2002],
- 1D advective transport in conduits coupled to a continuum transport model [*Spiessl*, 2004],
- 1D advective-dispersive transport in conduits [*Birk et al.*, 2005],
- 1D advective-dispersive transport with matrix diffusion respectively retarded matrix diffusion [*Birk*, 2002; *Birk et al.*, 2006; *Birk and Geyer*, 2006].

As a first step, the above listed routines can be updated and implemented into the latest MODFLOW based hybrid models (i.e. CFPM1 and the dynamic hybrid model).

Heat transport can be easily described with methods for substance transport due to the similarity between heat and substance movement: heat convection in conduits is comparable to advection, heat dispersion in conduit is similar to substance dispersion, and heat conduction in the rock matrix can be considered by diffusion [*Birk*,

2002]. Additionally, it seems important to consider radiation in partly filled conduits. *Covington et al.* [2011] demonstrate the use of heat transport processes for karst characterization whereas the relative importance of convection, conduction, and radiation is a function of time. The conduit's filling grade is important since radiation in partly filled conduits can be significant [*Covington et al.*, 2011], which emphasizes the significance of free-surface flow representation in hybrid models.

Alternative to hybrid approaches, CFPM2 can potentially be used for transport computation by using existing transport models available for the standard MODFLOW continuum, for example MT3DMS (*Zheng and Wang*, 1999). In this case, the interaction between karst conduits and rock matrix needs special consideration in order to account for the scale dependency between conduits and matrix (compare also section 2-1). A first attempt to simulate transport processes by this methodology is presented by *Shoemaker and Zhu* [2010].

Beyond the consideration of transport, further implementation of additional processes can potentially improve the applicability of the models. Some examples and suggestions are listed below:

- It can be useful to consider cave interior deposits like sediments as they can become important in some situations. *Ford and Williams* [2007] provide an overview about cave interior deposits, which can result for example from fluvial transport and erosion. Cave interior deposits can potentially act as additional flow and storage domain that is likely to influence transport processes (i.e. result in retardation).
- Another promising step for future model development can be the inclusion of buoyancy processes by considering density dependent flow. Some very productive karst aquifers are situated in the vicinity of sea water, for example the Floridan aquifer (USA) or coastal aquifers along the Mediterranean Sea. Hence, in these coastal settings the interaction between fresh- and saltwater can affect karst water hydraulics. One way to consider variable-density flow can be the use of SEAWAT [*Langevin et al.*, 2007], a MODFLOW/MT3DMS based code to simulate variable density groundwater flow. SEAWAT may be used together with CFPM2 or, alternatively, the approach can be adapted for hybrid models.
- Adaptation of the numerical models on specific field situations, for example by adding karst specific boundary conditions to consider the discharge-stage functional behavior for variably filled conduits.

Beyond putting effort into the development of the numerical algorithms, it is important to provide adequate post- and preprocessing interfaces too, in order to allow potential users the application of the models. Existing hybrid models like CFPM1 or MODBRANCH, which are provided freely through the USGS, need specific input files that are hard to compile and potentially bear the risk of being misleading or erroneous. Initial steps to overcome this limitation are already done. For example, the commercial graphical user interface Groundwater Vistas [ESI, 2011] is able to compile CFPM1 input files. However, much more efforts are necessary to provide adequate data sets for dynamic hybrid models because these tools are very sensitive to:

- initial conditions (heads in both conduits and matrix) because of the highly dynamic nature of hydraulics that can potentially result in instabilities, e.g. if inadequate initial conditions induce some artificial gradients;
- conduit bottom elevation, which represents one of the driving forces for discharge;
- boundary conditions, e.g. if flow at the boundary is computed as a function of stage.

Therefore, it seems promising to handle a conceptual situation case sensitive with different numerical models that are combined under a common user interface. For example, hybrid models like CFPM1 can compute the steady state situation and, therefore, can provide initial conditions for dynamic hybrid models like MODBRANCH adapted for conduits (ModBraC). Next, dynamic hybrid models can evaluate short term events with consideration of dynamic flow processes in variably filled conduits. Subsequently, steady hybrid models can evaluate the long term spring flow behavior. For this reason, the development of a Karst Model Input Generation Tool (KarstING) is initiated as add-in for Microsoft Excel. Figure 5-2 schematically depicts the intended workflow of KarstING.

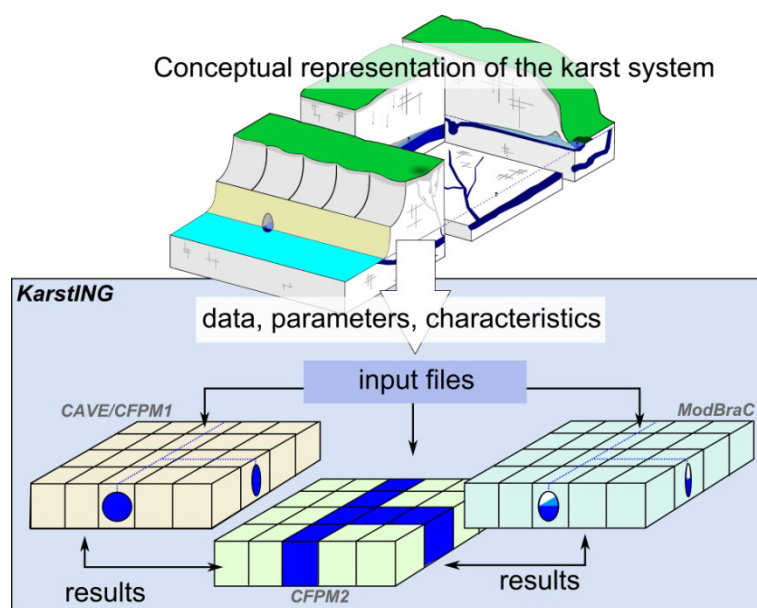


Figure 5-2: Schematic representation of the intended workflow of a graphical user interface for numerical karst models (KarstING)

KarstING is able to compile the input files for the hybrid models CAVE/CFPM1 and ModBraC and, therefore, can provide model input files for several numerical codes that are based on one conceptual model. KarstING gathers all data that represent conceptually the karst aquifer, e.g. geometrical and hydraulic properties of the conduit network as well as of the rock matrix. Subsequently, KarstING compiles the necessary input data to transfer this information to the numerical models CAVE/CFPM1 and ModBraC. In doing so, this approach results in an efficient way to investigate one specific karst aquifer with different numerical approaches. Future development aims to share additional results between different karst models like CAVE/CFPM1, ModBraC and CFPM2 to allow case specific use of adequate model approaches. Therefore, such user interfaces are important interfaces between model development and model application, which, in reverse, can positively stimulate model development. Finally, in terms of karst aquifer characterization and management, it is desirable that numerical karst models are established as an additional method that provides further insights and understanding with respect to one of the globally most important groundwater resources – karst aquifers.

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APPENDIX-01

PUBLISHED PAPERS INTRODUCING MODFLOW-2005 CONDUIT FLOW PROCESS (CFP)

Due to the cumulative character of this thesis, the papers in this appendix are published as:

Reimann and Hill (2009), MODFLOW-CFP: A new Conduit Flow Process for MODFLOW-2005, Ground Water 47(3), 321-325, doi: 10.1111/j.1745-6584.2009.00561.x.

Reimann (2009), MODFLOW-2005 CFP – Ein Hybridmodell für Karstgrundwasserleiter, Grundwasser 14(2), 139-145, doi: 10.1007/s00767-009-0102-4.

APPENDIX-02

MODEL RELATED FILES

A data medium is available that contains the source code respectively the executable files of the adapted numerical models

- MODFLOW-2005 Conduit Flow Process (with modified Mode 2) as used for chapter 3
- MODBRANCH adapted for conduits – ModBraC as used for chapter 4

Further, the data medium contains model input files and results as presented in chapters 3 & 4. The data medium is provided on request to thomas.reimann@tu-dresden.de (alternatively mail@reimann-thomas.de).

The numerical models as well as the model studies are carefully tested. Despite the authors' best efforts, errors may still exist. Distribution of the numerical models respectively the model files does not constitute any warranty by the author. Furthermore, no responsibility is assumed by the author for use or misuse of the computer programs.