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HYDROGEOLOGICAL CHARACTERISATION AND MODELLING OF SPRING CATCHMENTS IN A CHANGING ENVIRONMENT

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ABSTRACT

Sustainable management and protection of spring waters must be based on reliable predictions of flow and transport phenomena. Process-based models are frequently applied to accomplish this task. The provision of adequate model parameters is a prerequisite for predictive modelling. Frequently, this involves the use of inverse modelling, i.e. model parameters are adjusted until model results match field observations. Thus, process-based models are employed not only for prediction (predictive models) but also to support the aquifer characterisation (interpretative models). This work provides an overview of modelling techniques that can be applied to spring catchments for the aquifer characterisation or predictive purposes. The selection of an appropriate model must account for the type of aquifer: Continuum models describing flow through porous media are based on effective macroscopic properties of a representative elementary volume. Yet spring catchments are often composed of fractured or karstified hard rocks. The length scale of the discontinuities in these rocks may be so large that continuum approaches are found to be inadequate. Therefore, other distributed parameter models, such as discrete fracture networks or hybrid models that combine continuum and discrete approaches have been developed. All these models have in common that they require spatial parameter distributions. From a practical point of view, the application of distributed parameter models poses great challenges to the hydrogeological characterisation of spring catchments, in particular, in alpine terrain. These practical issues suggest the use of parsimonious global modelling approaches (lumped parameter models), in which the spring catchment is represented by only few global parameters rather than by spatial parameter distributions. Some of these approaches are empirical, i.e. they do not account for the physics of flow. Others are based on solving the flow equations for certain scenarios. Recently, process-based global approaches have emerged that incorporate the spatial heterogeneity of the spring catchment in the model equation. It is suggested that this type of approach is more appropriate than empirical models if predictions are required in a changing environment.

Die nachhaltige Bewirtschaftung und der Schutz von Quellwässern müssen auf zuverlässigen Prognosen von Strömungs- und Transportvorgängen beruhen. Zur Bewältigung dieser Aufgaben werden oft prozess-basierte Modelle angewendet. Modellierungen für Prognosezwecke setzen die Bereitstellung geeigneter Modellparameter voraus. Dies ist oft verbunden mit inverser Modellierung, d.h. die Modellparameter werden angepasst, sodass die Modellergebnisse den Feldbeobachtungen entsprechen. Prozess-basierte Modelle werden also nicht nur zur Prognose (Prognosemodelle) eingesetzt, sondern auch zur Aquifercharakterisierung (interpretative Modelle). Diese Arbeit gibt einen Überblick der Modelltechniken, die zur Aquifercharakterisierung und für Prognosezwecke in Quelleinzugsgebieten eingesetzt werden können. Bei der Auswahl des geeigneten Modells muss die Art des Grundwasserleiters berücksichtigt werden: Kontinuum-Modelle, die die Strömung durch poröse Medien beschreiben, basieren auf effektiven makroskopischen Eigenschaften eines repräsentativen Elementarvolumens. Quelleinzugsgebiete sind jedoch oft aus geklüfteten oder verkarsteten Festgesteinen aufgebaut. Die Längenskala der Diskontinuitäten in diesen Gesteinen kann so groß sein, dass sich Kontinuum-Ansätze als ungeeignet erweisen. Aus diesem Grund sind andere distributive Modelle, wie etwa diskrete Kluftnetzwerk- oder Hybrid-Modelle, die Kontinuum-Ansätze und diskrete Ansätze kombinieren, entwickelt worden. All diese Modelle haben gemeinsam, dass sie räumliche Parameterverteilungen erfordern. Aus praktischer Sicht stellt die Anwendung distributiver Modelle große Herausforderungen bezüglich der hydrogeologischen Charakterisierung der Quelleinzugsgebiete, insbesondere in alpinem Gelände. Diese praktischen Gesichtspunkte legen die Anwendung parametersparsamer globaler Modelle (Lumped-Parameter-Modelle) nahe, in denen das Quelleinzugsgebiet durch wenige globale Parameter anstelle von räumlichen Parameterverteilungen repräsentiert wird. Einige dieser Ansätze sind empirisch, d.h. sie berücksichtigen nicht die Physik der Strömungsprozesse. Andere basieren auf der Lösung der Strömungsgleichungen für bestimmte Szenarien. In jüngerer Zeit sind prozess-basierte globale Ansätze aufgekommen, die die räumliche Heterogenität des Quelleinzugsgebietes in der Modellgleichung berücksichtigen. Modellansätze dieser Art scheinen geeigneter als empirische Modelle, wenn Prognosen in einer sich ändernden Umwelt gefordert sind.

1. INTRODUCTION

In many regions of the world, spring waters are used for drinking water supply. While only 8% of the drinking water consumed in Germany is derived from these water resources (BGW, 2010), spring waters contribute more significantly to the water supply in alpine regions. In Switzerland and Austria, for instance, spring waters provide 40% (SVGW, 2008) and 49%

(Lebensministerium, 2004), respectively, of the drinking water. Large parts of these areas are underlain by karst aquifers, which tend to focus flow via solutions conduits toward prominent points of outflow, the karst springs.

Sustainable management and protection of water resources in a changing environment must be based on reliable predictions of flow and transport phenomena. Process-based (physical) models are frequently applied to accomplish this task. Prediction by process-based modelling essentially relies on an adequate aquifer characterisation providing the necessary model parameters. Frequently applied aquifer characterisation techniques, such as hydraulic borehole testing and tracer testing, involve the use of inverse modelling, i.e. model parameters are adjusted until model results match field observations, thus yielding estimates of aquifer parameters. Thus, process-based models are employed not only for prediction (predictive models) but also to support the aquifer characterisation (interpretative models). Interpretative groundwater models may be used to test or refine different conceptual models or to quantify hydraulic aquifer parameters, while predictive models employed for water resources management, for instance, aim to predict the aquifer response to pumping, construction activities, or climate change. Both interpretative and predictive models of spring catchments have to meet the challenge of linking small-scale processes (e.g., laminar or turbulent flow, transport, and reactive processes) and knowledge about the spatial heterogeneity (fault zones, solution conduits, recharge distribution) in order to provide an adequate understanding of the flow and transport behaviour at catchment scale (Fig. 1). The purpose of this paper is to provide an overview of appropriate modelling techniques that can be applied for this purpose.

2. UNCONSOLIDATED MATERIALS VS. HARD ROCKS

2.1 UNCONSOLIDATED MATERIALS

Groundwater in unconsolidated materials, such as sand and gravel, flows through pore spaces. As typical porous structures are very irregular, the detailed structure and geometry of the pore spaces must remain unknown. Even if it were known, flow and transport modelling of pore-scale processes would not be computationally and economically feasible, because the length scale of the pores is generally many orders of magnitudes smaller than that of the area of investigation. Thus, effective macroscopic properties of the porous medium must be defined as average of the microscopic properties over a “representative elementary volume” (REV) (Bear, 1972). This REV, on the one hand, must be of sufficient size such that there is no longer any statistical variation in the values of the properties with the size of the volume. On the other hand, the REV must be small with respect to the scale at which significant variations of macroscopic properties such as porosity or permeability may be expected. Models that are based on this macroscopic approach are referred to as continuum models (e.g., Sahimi, 1995).

Various textbooks on the application of continuum approaches for groundwater flow modelling have been published during the last decades (e.g., Kinzelbach, 1986; Anderson and Woessner, 1992; Wang and Anderson, 1995). Flow modelling nowadays can be considered as a standard technique regularly applied to solve groundwater-engineering tasks. The commonly employed groundwater flow models are distributive models, i.e. they explicitly account for the spatial heterogeneity of the aquifer. In general, data required for steady-state flow modelling include aquifer geometry and the spatial distributions of hydraulic conductivities and recharge; transient simulations, in addition, require data on aquifer storage and time-series of recharge.

Typically, there is some uncertainty in these parameters or part of the required data is missing. Therefore, hydraulic head data is commonly used to calibrate flow models, i.e. model parameters, such as hydraulic conductivity, are adjusted within the given range of uncertainty until the simulated match the measured heads. A common problem encountered, however, is the ambiguity of the model calibration. For instance, the outcome of a steady-state model calibration is non-unique if both hydraulic conductivities and recharge are simultaneously adjusted. Thus, adequate characterisation techniques must be employed to provide sufficient data.

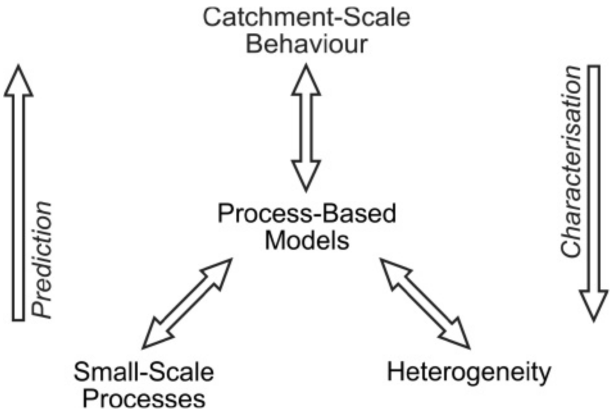

FIGURE 1: Linkage of small-scale processes, spatial heterogeneity, and catchment-scale flow and transport behaviour using process-based models for characterisation or prediction.

In the last decade, high-resolution characterisation methods based on direct-push technology have become a viable alternative to conventional drilling-based approaches for the investigation of unconsolidated formations. Direct-push technology uses hydraulic rams supplemented with vehicle weight and/or high-frequency percussion hammers to rapidly advance small-diameter pipes into the subsurface. Several efforts have been made to estimate hydraulic conductivity with direct-push technology through various modifications of conventional hydraulic tests (cf., Butler et al., 2002; McCall et al., 2002; Sellwood et al., 2005). Thus, although the characterisation of unconsolidated aquifers remains a formidable task, promising methods are under way.

2.2 Hard Rocks

Spring catchments are frequently dominated by hard rocks comprising intact rock bodies separated by discontinuities termed fractures. Depending on the type of rock, the porosity of intact rock bodies ranges from nearly zero to values much higher than the porosity created by fractures. The permeability of intact rock bodies is often relatively low though. Thus, discontinuities provide the major flow paths in fractured rocks. Dissolution of soluble rocks, such as limestone and dolomite, causes widening of fractures, thus creating karst aquifers with a third type of porosity, the highly permeable solution conduits. Since the karst conduit system is often regionally well connected, karst springs may drain large catchment areas and thus frequently provide a high discharge. This makes them an obvious choice for water supply purposes (e.g., water supply of Vienna).

Karst aquifers can be considered as dual or triple porosity systems. On the one hand, the vast majority of storage is provided by not substantially widened fractures (fissured system) and/or by the porous rock matrix. On the other hand, the karst conduit system occupies only a small void ratio but is much more permeable than both the fissured system and the porous matrix (e.g., White, 1988; Worthington et al., 2000).

In general, it can be expected that the REV of a fracture system is larger than that of a porous medium, and the REV of a conduit system is larger than that of a fracture system. Thus, when attempting to represent fractured rocks or karst aquifers by continuum models, it should be envisioned that REVs can exist at several scales (e.g., Domenico and Schwartz, 1990). The data employed in a continuum model should come from a testing program at the relevant scale. Yet for large-scale features the REV may not exist at all (i.e. the properties of the rock mass continue to change along with an increase of the testing volume) or may be so large that it is inappropriate. As a consequence, continuum models may be considered to be inadequate in some instances, making other modelling approaches warranted, which allow a more appropriate representation, in particular, of regionally extensive discontinuities such as faults or solution conduits. As a consequence, besides continuum models, other types of distributed modelling approaches emerged during the last decades, all of which have in common that they require spatial parameter distributions as model input.

From a practical point of view, however, the application of distributive modelling approaches poses great challenges to the hydrogeological characterisation of spring catchments, in particular, in alpine terrain, which hosts the most important springs in Austria. Alpine spring catchments are commonly hard to access; their altitude is high and may vary strongly over short distances; their geology may be very complex and the aquifers may be highly anisotropic and heterogeneous. These practical issues suggest the use of global modelling approaches (lumped parameter models), in which the spring catchment is represented by one or more global parameter(s) rather than by spatial parameter distributions.

The following section provides an overview of both global and distributive approaches that can be applied for interpretative or predictive modelling in spring catchments.

3. MODELLING APPROACHES

3.1 GLOBAL MODELS

The behaviour of springs exhibited, e.g., by variations of discharge (hydrograph) or physicochemical parameters (chemograph), such as electrical conductivity, water temperature, and chemical or isotopical composition, reflects the global response of the catchment to the input of water. Global models use a single parameter or a group of parameters to reproduce from a given input function the observed system responses (Sauter et al., 2006). The input function can be a time series of precipitation, point or non-point tracer input and the output function spring discharge or the temporal variation of the tracer concentration at the spring. Global models are often found to agree well with measured spring discharge data (e.g., Barrett and Charbeneau, 1997; Scanlon et al., 2003; Jukić and Denić-Jukić, 2009). Since they include only few adjustable parameters, their calibration is likely to be less ambiguous than that of more complex distributive models. Thus, they are frequently employed for the characterisation of spring catchments, e.g., by analysing spring responses to recharge and the subsequent recession behaviour. In general, inferences from spring hydrographs are based either on the analysis of single events or on that of time series of hydraulic or physicochemical parameters (Jeannin and Sauter, 1998).

Frequently, single event analytical techniques are based on the analysis of the hydrograph recession. A number of equations have been developed to describe the recession behaviour of springs (for an overview see, e.g., Tallaksen, 1995; Dewandel et al., 2003). Some of them are entirely based on mathematical fits to data, i.e. empirical approaches not accounting for the physics of flow (e.g., Padilla et al., 1994). Others are based on solving the flow equations for certain scenarios. In general, only the latter provide quantitative information about the structure of the aquifer and on its hydrodynamic parameters such as storage properties and permeability (e.g., Troch et al., 1993; Szilagyi and Parlange, 1998).

The overall shapes of the recession curves are generally similar (reduction of flow rate with time) from one aquifer to another. The curve shape is determined by the hydrodynamic properties of the aquifer, such as hydraulic conductivity, storage coefficient, hydraulic gradient and the geomorphologic characteristics of the catchment area (e.g., Eisenlohr, 1997a). Other factors are also believed to play an important role, for instance, climate and season, the saturation stage of the soil as well as its thickness and spatial distribution (Lacey and Grayson, 1997; Lorup et al., 1998), and for karst aquifers the epikarstic and vadose zone (Kaufmann, 2003; Trček, 2007).

The two most common methods employed for recession analysis are based on fitting the recession curve with exponential and quadratic formulas, respectively (Dewandel et al., 2003).

Multiple exponential reservoir models describe the entire recession process by fitting a series of exponential curves to different hydrograph segments (Sauter, 1992; Baedke and Krothe, 2001). The hyperbolic function model attempts to describe the entire recession process by one mathematical formula (Drogue, 1972), whereas the approach by Mangin (1975) assumes an exponential baseflow recession and determines the fast recession by an additional function. Other hydrograph analytical methods are based on physical principles (process-based models). For instance, it was suggested that hydrographs following sharp perturbations on the hydraulic head can be described as one-dimensional diffusive fluxes based on Darcy's law (Criss and Winston, 2003; Winston and Criss, 2004). Some process-based approaches are based on the analysis of slow hydrograph recession segments only (Rorabaugh, 1964; Kovács et al., 2005). In the approach by Rorabaugh (1964), which was applied, e.g., by Sauter (1992) and Baedke and Krothe (2001), the spring catchment is represented by a homogeneous equivalent porous medium with one-dimensional flow toward the spring. The long-term approximation of the corresponding flow equation yields an exponential function, in which the recession coefficient is dependent on the size of the catchment area and the hydraulic aquifer properties. The early recession, however, is found to be dependent on the initial conditions, i.e. on the characteristics of the recharge event and the pre-event hydraulic-head distribution, and generally deviates from the exponential recession (Birk and Hergarten, 2010).

More recently, it has been suggested to incorporate the spatial heterogeneity of the spring catchment in global approaches (Kirchner, 2006). One such attempt addressing the hydrograph recession is provided by Kovács et al. (2005): The spring catchment is represented by fissured matrix blocks of identical size and shape, which are drained by a highly permeable conduit system toward the spring; similar to the approach by Rorabaugh (1964) an exponential long-term recession is derived and the recession coefficient is found to be dependent on the size of the blocks and their hydraulic properties. Kovács and Perrochet (2008) extended this approach to the entire flood hydrograph. Hergarten and Birk (2007) further developed this concept by assuming that the blocks are of different size, following a fractal distribution. As opposed to the long-term exponential recession, the fast recession is found to exhibit a power-law behaviour, which is dependent on the fractal dimension of the size distribution.

Time series analysis provides a mathematical analysis of the global hydraulic response of the flow system to a succession of recharge events. Originally, time series techniques have been developed for analysing any type of time series and later were applied in hydrology (e.g., Chow, 1978; Padilla and Pulido-Bosch, 1995; Lee and Lee, 2000). An overview of different methods and their application to karst catchments is provided by Jeannin and Sauter (1998). Interpretations of the conventional time series analysis of hydrographs are based on both univariate (auto-correlation, spectral analysis) and bivariate (cross-correlation, cross-spectral analysis) methods. Univariate methods characterise the individual structure of a single time series, while bivariate methods consider the analysis of transfer functions between input (infiltration) and output (spring hydrograph). The auto-correlation method identifies some overall characteristics of the system, mainly cyclic variations of time series (Box and Jenkins, 1976; Eisenlohr et al., 1997b), which are hardly revealed by recession analysis. The spectral analysis method is similar but reveals periodicities more powerful within the time series (e.g., Box and Jenkins, 1976; Labat et al., 2000a; Rahnemaei et al., 2005). Cross-correlation and multifractal analysis methods examine quantitatively the relation between precipitation signal and spring hydrograph and their time displacement (Box and Jenkins, 1976; Padilla and Pulido-Bosch, 1995; Labat et al., 2002). For linear and stationary systems linear transfer functions can be defined converting an input precipitation signal into an output hydrograph through the convolution of kernel functions (e.g., Neuman and DeMarsily, 1976; Dreiss, 1989b; Labat et al., 1999; Long and Dericson, 1999; Denić-Jukić and Jukić, 2003). Wavelet analysis (Grosman and Morlet, 1984) represents an alternative to spectral and correlation analysis. A detailed explanation of the application of wavelet analysis in hydrogeology is provided by Labat et al. (2000b). In general, the aforementioned methods for the analysis of time series are not based on physical processes and do not explicitly account for the spatial heterogeneity of spring catchments. Thus, they do not provide an explicit linkage between small-scale processes and spatial heterogeneity of the catchment as proposed by Fig. 1.

3.2 DISTRIBUTED PARAMETER MODELS

Distributed parameter models are frequently used for spatial simulation of groundwater flow and transport, but the reliability of results is strongly dependent on whether the model parameters are properly identified. The real geological structure of spring catchments is generally complex, heterogeneous and mostly unknown. A large amount of data and thus high investigation effort is required for identifying the spatial heterogeneity within the catchment. Although distributive groundwater modelling has been studied for decades, identifying the spatial distribution of a heterogeneous aquifer remains a formidable task because of the limitation in both quantity and quality of data. Yet it may be desired to apply distributed parameter models, as they allow the representation of more realistic distributions of system properties. Distributed parameter modelling techniques may consider both spatial and temporal variations of hydraulic parameters and boundary conditions. Thus, they require detailed information on aquifer geometry, hydraulic parameter fields, and recharge conditions. Distributed parameter modelling requires the subdivision of a model domain into homogeneous sub-units, for which physically based equations can be applied to describe groundwater flow or transport. Deterministic groundwater models generally require the solution of flow (and transport) equations. This can be done analytically if the parameters and boundaries are highly idealised. More frequently, numerical methods are applied, yielding approximate solutions to the governing equations through discretisation of space and time (e.g., Konikow and Reilly, 1998).

Teutsch and Sauter (1998) and Sauter et al. (2006) provide a summary and classification of possible model representations of fractured rocks and karst aquifers. Five model representations of different complexity are distinguished. The model selection depends on the required investigation effort, the capability to simulate specific flow characteristics, and the practical applicability. Equivalent porous media models include single and double continuum approaches. The simplest approach is the single-continuum porous equivalent, which does not explicitly account for properties of the individual fractures or conduits but uses effective macroscopic aquifer properties as described in section 2.1. These models generally have proved adequate for simulating regional groundwater flow (e.g., Angelini and Dragoni, 1997; Scanlon et al., 2003). However, it has been suggested (Teutsch, 1993) that the single continuum approach is inadequate to simulate groundwater flow in highly karstified aquifers. Nevertheless, this approach still appears to be most frequently used in practical applications of distributed parameter models.

Different porosity components (matrix, fracture, conduit) can be distinguished by coupling two (or more) continuum models yielding a double-continuum (or multiple-continuum) porous equivalent model (e.g., Teutsch and Sauter, 1998). Teutsch (1993) used a dual continuum approach to model moderately to highly karstified aquifers. Regional groundwater flow has been adequately simulated by, e.g., Sauter (1992). Teutsch and Sauter (1998) suggest that the continuum approach is most desirable for practical applications, as it appears to be least demanding with respect to the investigation efforts. Yet according to these authors continuum models have only limited potential for representing heterogeneities such as prominent fractures or conduits. Thus, the authors discuss the suitability of the various model approaches for different types of application. It is suggested, for instance, that single continuum models may be appropriate when dealing with water budget issues but are not suited for simulating hydraulic responses of karst aquifers to recharge events.

Discrete models explicitly represent the different geometries and hydraulic properties of fractures or conduits within a rock mass. Discrete fracture models have been frequently applied for simulating flow and transport in hard rock formations (e.g., Long et al., 1985; Andersson and Dverstorp, 1987; Cacas et al., 1990; Dverstorp et al., 1992; Jeannin, 2001). These models require information on the location, hydraulic properties, and geometry of fractures or conduits. Since the knowledge of properties of the individual fractures or conduits is rather limited this can only be done by use of stochastic models that incorporate probabilistic approaches (National Research Council, 1996). Thus, field application of discrete models requires the measurement of fracture properties (geometry, hydraulic conductivity) and associated spatial statistics, which causes high investigation efforts. These large efforts generally permit the use of such models for simulating regional flow, e.g., in spring catchments.

Hybrid models, coupling discrete models with continuum models, represent an intermediate approach. The discrete model can be used for an explicit representation of large-scale features, such as prominent faults or conduits, while the continuum model represents the other components (e.g., porous matrix and/or dense network of narrow fissures) (e.g., Kovács and Sauter, 2007). Thus, Teutsch and Sauter (1998) suggest that the investigation efforts needed to apply this type of model are between those of continuum models and discrete models. One example of a hybrid model is provided by the coupled continuum-pipe flow and reactive transport code CAVE (Carbonate Aquifer Void Evolution; Liedl et al., 2003; Rehrl et al., 2008). Recently, the conduit flow module implemented in CAVE has been further developed and released as Conduit Flow Process (CFP) for the well-known USGS flow model MODFLOW-2005 (Shoemaker et al., 2008). Hybrid models similar to CAVE were developed by, e.g., Annable and Sudicky (1998) and Kaufmann and Braun (2000).

4. CHARACTERISATION OF SPRING CATCHMENTS

The provision of reliable data on aquifer properties and hydrological stresses is a prerequisite for the predictive application of process-based models in spring catchments. If data are scarce the model calibration will be non-unique, in particular, if distributed parameter models are employed. The existence of large-scale features, such as prominent faults or solution conduits, poses specific challenges to the characterisation of spring catchments situated in hard rocks (e.g., Winkler et al., 2007). The following sections address aquifer characterisation techniques that may be used for constraining model parameters, particularly in karstified hard rocks.

4.1 BOREHOLE TESTS

Hydraulic borehole tests such as packer tests, slug tests, and pumping tests, provide parameter estimates at scales ranging from few metres to hundreds of metres. Fundamentals of these methods are provided, e.g., by Kresic (2007). Hydraulic borehole tests appear to be appropriate to obtain parameter estimates for continuum models representing the porous matrix or densely fractured hard rocks.

Using borehole methods for data acquisition, however, is considerably more expensive and time-consuming in hard rocks than in unconsolidated materials, as the great mechanical strength of hard rocks makes it impossible to apply high-resolution methods based on direct-push technology (see section 2.1). In addition, the unsaturated zone is often very thick, in particular, in highly permeable rocks (e.g., karst rocks), i.e. deep boreholes are required. Thus, investigation efforts are comparatively high even if continuum approaches are used. To make things worse, discrete or hybrid models require information about geometric and hydraulic properties of discontinuities, which is generally not directly obtained by conventional slug-test or pumping-test analysis. Thus, standard hydraulic borehole tests are hardly able to provide reliable spatial parameter distributions in a time- and cost-effective manner at the level of detail needed for distributive models of spring catchments, e.g., in alpine terrain.

4.2 Tracer testing

As boreholes are usually not directly connected to karst conduits, it is difficult to obtain quantitative information about the conduit system by borehole-based methods. In contrast, surface karst features, such as sinkholes and karst springs, are likely to be connected to the conduit system. Thus, tracer testing between sinkhole and karst spring, i.e. injection of artificial tracers into a sinkhole and tracer sampling at a karst spring, provides one promising method for the quantitative characterisation of conduit properties.

Käss (1998) and Benischke et al. (2007) provide overviews of groundwater tracing techniques. In investigations aimed at identifying point-to-point connections, e.g., for the delineation of spring catchments qualitative tracer detection can be sufficient. Yet, more detailed information can be obtained from quantitative groundwater tracing (e.g., Field and Pinsky, 2000; Birk et al., 2005; Geyer et al., 2007).

Similar to tracer tests, contaminant concentrations in spring waters that originate from well-defined point sources may be used for characterising the transport properties of spring catchments. For instance, the behaviour of conservative and reactive micro-pollutants and bacteria provides additional insight into the transport mechanism operating within the spring catchment (Heinz et al., 2006, 2009).

Although tracer testing is found to be well suited for the characterisation of karst spring catchments, the selection of an appropriate model for data interpretation is a challenging task. While simple models might not be able to adequately match the measured breakthrough curve and thus yield biased parameter estimates, more complex models may suffer from the ambiguity of the model calibration resulting from the large number of unknown parameters. The latter is particularly true for the application of distributed parameter models. Numerical hybrid models, for instance, require that properties of both the conduit system and the fissured system be defined. Thus, other methods that provide additional information about the karst aquifer should be combined with tracer testing.

4.3 Analysis of spring responses

Despite their extreme heterogeneity karst catchments offer one advantage over unconsolidated materials regarding the aquifer characterisation. In karst aquifers, groundwater resurfaces at a single spring or a limited group of springs. Thus, water discharging from a karst spring carries an imprint of the entire spring catchment (White, 2002). This makes it possible to infer aquifer properties from observations at the spring.

The spring hydrograph is an important characteristic of the catchment, reflecting the response of the aquifer to recharge. Fundamentals of spring hydrograph analysis are described, for instance, by White (1988) and Ford and Williams (2007). One useful characteristic of spring hydrographs is the ratio of peak discharge to baseflow. Flashy spring responses, i.e. high ratios of peak discharge to baseflow, are commonly observed in karst catchments with point recharge into well-developed conduit systems, whereas more dampened responses are typical of less karstified systems with diffuse recharge and poorly developed conduits (White 1988). Another characteristic of spring hydrographs commonly used to infer information about hydraulic properties of the aquifer is the form and rate of the recession curve (see section 3.1).

The analysis of spring hydrographs may be complemented by analysing time series of physicochemical parameters, such as electrical conductivity and temperature of the spring water, representing natural tracers that provide integral information about the karst catchment. Ford and Williams (2007) provide an overview of the interpretation of physicochemical spring responses. Due to the almost instantaneous transmission of pressure pulses, the spring discharge responds more quickly than physicochemical parameters, such as solute concentration or electrical conductivity. The water volume discharged during the time lag between hydraulic and physicochemical responses may be used as estimate of the conduit volume of the spring catchment (Ashton, 1966; Atkinson, 1977). The magnitude of the conductivity drop (or corresponding changes in solute concentration) can be used to separate by simple mass balance calculations the “new-water” component, i.e. the water rapidly infiltrating into karst conduits, from “old”, pre-event water (e.g., Dreiss, 1989a; Birk et al., 2004) or to obtain information about geometric properties of karst conduits using the recovery of solute concentrations back to the pre-event level (Grasso and Jeannin, 2002; Grasso et al., 2003).

It should be noted, however, that the aforementioned methods are founded on fairly simplistic conceptual aquifer models. Thus, the underlying assumptions require careful evaluation. One approach to provide a more reliable basis for the analysis of spring responses is process-based modelling of flow and transport processes, e.g., using a hybrid model such as the aforementioned CAVE. Two fundamentally different approaches can be distinguished (Fig. 2). On the one hand, forward modelling uses hypothetical but realistic model parameters in order to examine how spring responses depend on aquifer properties, such as conduit geometry. Thus, forward modelling enables the identification of controlling processes and parameters. In addition, information about properties of specific catchments can be obtained if characteristic patterns of simulated spring responses are recognised in the measured data (pattern matching). On the other hand, inverse modelling attempts to match measured spring responses by adjusting model parameters (model calibration). The resulting parameter values provide quantitative estimates of the corresponding aquifer properties. However, if there is little a priori information and thus the number of unknown parameters high, several plausible models that match the field data may exist, i.e. the solution is non-unique.

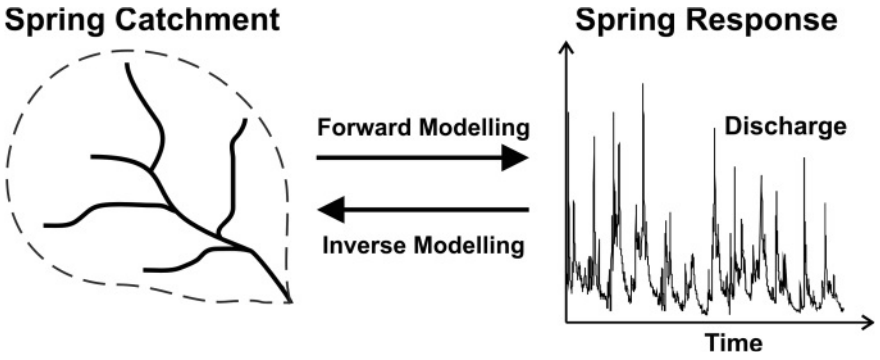

Figure 2: Application of process-based models to examine the influence of the catchment characteristics on spring responses (forward modelling) or to infer aquifer properties from spring responses (inverse modelling).

4.3.1 Forward modelling

Springs that are supplied by well-developed conduit systems show rapid responses to recharge events of both spring discharge and physicochemical parameters of the discharged water. A detailed theoretical understanding of how geometric properties of the conduit system determine these spring responses has not yet been developed though. Process-based forward modelling of spring responses, thus, aims at improving this understanding.

One example is provided by Covington et al. (2009) who examined the hydraulic propagation of storm pulses through karst systems. To identify characteristic response times of single elements of karst aquifers, transient flow in full pipes, open channels, and reservoirs combined with constrictions was simulated. The authors thus demonstrated that each element has a characteristic time scale that allows the separation of a recharge-dominated and a geometry-dominated regime. Aquifer properties can only be inferred from hydraulic spring responses if this characteristic time scale is sufficiently large compared with the length of the recharge period. Full pipes or open channels are found to be typically within the recharge-dominated regime suggesting that aquifer characterisation techniques that are based on the evaluation of spring hydrographs (e.g., recession analysis) are of limited use for characterising the properties of karst conduit systems.

Characterisation techniques based on the evaluation of physicochemical spring responses thus represent a sensible complementation of spring hydrograph analysis. Birk et al. (2006) applied the hybrid model CAVE to simulate physicochemical responses of a spring draining a hypothetical karst catchment in order to evaluate the aforementioned approach by Ashton (1966), who suggested that the water volume discharged between the rise in spring discharge and the change of physicochemical properties equals the total conduit volume of the spring catchment. Simulated spring responses were used to calculate estimates of the conduit volume, which were then compared to the actual conduit volume used in the simulation. The volume estimates were generally found to be higher than the actual conduit volume, as water from the fissured porous rock contributed to the water volume discharged at the spring. The accuracy of the volume estimates depends on the intensity and duration of the recharge event. In addition, the relation between estimated conduit volumes and recharge conditions was found to be dependent on the conduit geometry. Thus, the sensitivity of volume estimates to recharge conditions can potentially be used in a characterisation approach based on inverse modelling of hydraulic and physicochemical spring responses.

4.3.2 Inverse Modelling

Inverse modelling represents one approach to inferring quantitative parameter estimates from measured spring responses. The basic idea is to establish a mathematical aquifer model based on the available knowledge of the field site and to adjust unknown or uncertain model parameters such that the measured spring responses are matched, i.e. to calibrate the model. A fundamental difficulty often encountered is the non-uniqueness of the solution, i.e. several parameter sets may yield reasonable fits to the data.

In principle, the ambiguity of the model calibration can be reduced by improving the knowledge about the model parameters by thorough field investigation, e.g., using hydraulic borehole testing or tracer testing, thus reducing the number of unknown parameters or/and the uncertainty in the model parameters. Some appropriate methods were discussed in sections 4.1 and 4.2. However, the application of these methods to large spring catchments involves considerable time and cost efforts, which often cannot be afforded.

The non-uniqueness of the model calibration may also be reduced if several types of data are used as calibration targets. For instance, Birk et al. (2006) suggest that concentration and temperature responses provide complementary information about karst conduit systems. Thus, the characterisation of spring catchments may be improved by concurrently analysing several types of data. An example is provided by Birk et al. (2004) who combined the analysis of hydraulic and physicochemical responses of a karst spring (Urenbrunnen, SW-Germany). Using the data acquired at the Urenbrunnen site, Birk (2002) attempted to quantify conduit properties by inverse modelling using the hybrid model CAVE. Different model scenarios with conduit systems of different structure were calibrated using the long-term spring flow recession, the hydraulic spring response induced by water injection into a sink as well as the associated response of the electrical conductivity, and the shape and the peak of a tracer breakthrough curve. It was attempted to validate or falsify the various models using concentration and temperature responses measured after a recharge event. This proved helpful in testing assumptions on conduit structure and recharge mechanisms in the spring catchment and in separating the diffuse and conduit flow components. The model calibration, however, was still found to be highly non-unique.

A more efficient way to obtain unique results from inverse modelling might be the use of parsimonious global modelling approaches with only few adjustable parameters. For instance, Geyer et al. (2008) demonstrated that the temporal distribution of the direct, concentrated recharge into the karst conduit system can be identified using an inverse approach based on a two-reservoir model. The low permeability reservoir represents the fissured matrix blocks of the aquifer and the highly permeable reservoir the karst conduits. Another example is given by Butscher and Huggenberger (2008). These authors applied a global approach to assess the intrinsic vulnerability of karst springs and to identify flow processes that potentially affect the vulnerability of the system.

Similarly, recession models with few adjustable parameters may yield unique estimates of aquifer properties such as transmissivity or storage coefficient. Yet it should be noted that the resulting parameter estimates might be affected by the simplifying assumptions inherent in the modelling approach. For instance, global models representing the spring catchment by a homogeneous equivalent porous medium (e.g., Rorabough, 1964) yield higher transmissivities than those obtained with hydraulic borehole testing (e.g., Sauter, 1992). In addition, these approaches may not be capable of representing the recession behaviour under different hydrologic conditions. Evidently, this does not comply with the underlying concept, in which the recession coefficient is believed to be a property of the aquifer. As a consequence, recent global approaches (Kovács et al., 2005; Hergarten and Birk, 2007; Birk and Hergarten, 2010) try to provide more adequate representations of the flow processes and, in particular, to account for the heterogeneity of the spring catchment just as proposed by Fig. 1.

5. Predictive capabilities and uncertainties

Teutsch and Sauter (1998) provide a detailed discussion of the predictive capabilities of the various distributed parameter modelling approaches outlined in section 3.2. Typical model applications addressing spring catchments are classified in four problem classes, on the one hand, distinguishing between point source input and integral input, on the other hand between point observation and integral observation. According to these authors, the application of distributed parameter models is associated with high prediction uncertainty if point observations are addressed, i.e. it is considered to be problematic if not impossible (if point sources are involved, that is) to predict, e.g., hydraulic heads or solute concentrations in boreholes. Predictions addressing integral observations, such as spring responses to rainfall or contaminant input are associated with lower prediction uncertainty, in particular, if the input is integral (e.g., rainfall in small spring catchments). Teutsch and Sauter (1998) suggest the use of single- or double continuum models for applications addressing this problem class. Nevertheless, relatively few predictive applications of distributed parameter models are reported in fractured or karstified spring catchments as compared to unconsolidated alluvial aquifers. In addition to the high investigation efforts involved in the quantification of aquifer properties and boundary conditions, there is often (e.g., in alpine catchments) a lack of hydraulic head data needed for model calibration. As a consequence, model calibration may be highly non-unique and prediction uncertainty high. Thus, even if distributed parameter models in principle can be applied for predictive modelling, they may found to be inadequate for practical reasons.

If both input and observation are integral, global models suggest themselves as an obvious alternative to distributed parameter models. Global and distributed parameter models were compared in a case study addressing the Barton Springs, Edwards aquifer, USA (Scanlon et al., 2003). The well-known MODFLOW code was used for distributed parameter modelling and calibrated to measured hydraulic heads. In addition, a global model representing five stream catchments was applied in the same area. Both types of models were found to simulate the temporal variability in spring discharge fairly accurately.

Kovács and Sauter (2007), however, suggest that the predictive capability of global models is limited if they do not account for the laws of physics and the spatial structure of the catchment, which applies to empirical ‘black-box models’. As a consequence, model parameters can only be obtained from calibration and cannot directly be inferred from field data. Because of their non-physical nature, these methods can only be applied to describe flow and transport within observed ranges of input and output functions. Thus, their application in a changing environment involves high prediction uncertainty. Yet, as discussed in section 3.1, some global approaches are derived from laws of physics, such as groundwater flow equations, and more recently it has also been attempted to incorporate the spatial characteristics of the catchment into the equations (e.g., Hergarten and Birk, 2007). Such physically based “grey-box” models (Kovács and Sauter, 2007) have been successfully applied for single event analysis and thus can potentially be applied for predicting global responses of spring catchments (e.g., spring response to rainfall) under changing environmental conditions. Time series analytical models, however, are not directly related to physical parameters and fail to account for the temporal and spatial distributions of rainfall, which may affect the statistical parameters (Kovács and Sauter, 2007).

6. Conclusions

Distributed parameter models are frequently applied for predictive purposes in hydrogeological applications addressing unconsolidated alluvial aquifers. However, their application to spring catchments composed of hard rocks involves high investigation efforts that can rarely be afforded, in particular, in alpine settings; without proper aquifer characterisation, these models cannot be uniquely calibrated and thus fail to provide reliable predictions. If data is scarce, the more parsimonious global models may provide a viable alternative to distributed parameter models. The frequently employed empirical models, however, involve high prediction uncertainty in a changing environment as conditions may change beyond those considered in the model calibration. Process-based global approaches (grey-box) models that are based on the laws of physics thus appear to be more appropriate. These models need to be further developed, e.g., regarding the incorporation of the spatial structure of the catchment, and to be evaluated with respect to their practical applicability for predictive purposes.

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