Water exchange and pressure transfer between conduits and matrix and their influence on hydrodynamics of two karst aquifers with sinking streams

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S U M M A R Y

Karst aquifers are heterogeneous media where conduits usually drain water from lower permeability volumes (matrix and fractures). For more than a century, various approaches have used flood recession curves, which integrate all hydrodynamic processes in a karst aquifer, to infer physical properties of the movement and storage of groundwater. These investigations typically only consider flow to the conduits and thus have lacked quantitative observations of how pressure transfer and water exchange between matrix and conduit during flooding could influence recession curves.

We present analyses of simultaneous discharge and water level time series of two distinctly different karst systems, one with low porosity and permeability matrix rocks in southern France, and one with high porosity and permeability matrix rocks in north-central Florida (USA). We apply simple mathematical models of flood recession using time series representations of recharge, storage, and discharge processes in the karst aquifer. We show that karst spring hydrographs can be interpreted according to pressure transfer between two distinct components of the aquifer, conduit and matrix porosity, which induce two distinct responses at the spring. Water exchange between conduits and matrix porosity successively control the flow regime at the spring. This exchange is governed by hydraulic head differences between conduits and matrix, head gradients within conduits, and the contrast of permeability between conduits and matrix. These observations have consequences for physical interpretations of recession curves and modeling of karst spring flows, particularly for the relative magnitudes of base flow and quick flow from karst springs. Finally, these results suggest that similar analyses of recession curves can be applied to karst aquifers with distinct physical characteristics utilizing well and spring hydrograph data, but information must be known about the hydrodynamics and physical properties of the aquifer before the results can be correctly interpreted.

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Introduction

Classical hydrogeological surveys, such as well tests for estimating hydraulic parameters, tracer experiments, and speleological and geophysical observations provide only limited information on karst groundwater behavior because of the heterogeneous distribution of flow and storage within karst aquifers. Many methods using hydrodynamic or hydrochemical analyses of karst springs have been developed to understand both mass and pressure transfers within the aquifer. Primary among these methods is analysis of hydrograph recession curves, which assumes that spring behavior integrates all processes that occur in the aquifer. Such recession analyses can be based on many characteristics of the spring discharge such as flow, water temperature, chemical or isotopic composition as a “global response” of the karst aquifer to input events (Kiraly, 2003). For example, the aim of spring hydrograph separation, which is addressed in this paper, is to infer relative contributions from different components of a karst aquifer (Atkinson, 1977; Bonacci, 1993; Padilla et al., 1994). Although critical to wise use of water resource and remediation of introduced contaminants, water provenances (e.g., infiltration, pre-storm water stored in vadose or phreatic zones, etc.) requires measurements of tracers, typically natural or introduced chemicals, and is not included here.

Spring hydrographs have been used to infer geometric and hydrodynamic properties of the aquifer volumes that control underground flows, for example, between flow in large channels or large fissures and flow in thin fissures (Renault, 1959; Schoeller, 1965; Forkasiewicz and Paloc, 1967; Drogue, 1969), or conduit...
flow and diffuse (or matrix) flow (Atkinson, 1977; Baedke and Krothe, 2001; Martin and Dean, 2001; Martin and Sceatton, 2001). Following the model proposed by Maillet (1905), one or more exponential functions have been used to describe hydrograph recessions. For instance, Schoeller (1965) assumes that successive exponential decreasing limbs on spring hydrographs are due to changes of flow regimes (from turbulent to laminar). Alternatively, Forskiewicz and Paloc (1967) believe that the decline is due to depletion of various components of the aquifer which have successively lower hydraulic conductivity. These interpretations suggest that karst systems consist of several parallel reservoirs, all contributing independently to the discharge of the spring. Spring hydrographs are thus described by a model of multiple reservoirs, each of which empties with a characteristic exponential flow rate. As pointed out by Ford and Williams (2007), however, it seems unrealistic to consider different reservoirs to be hydraulically isolated from each other. Changes in hydrographs have also been explained to result from changes in catchment area, discharge of temporary springs (overflows) in temporary flooding of poljes or caves (Bonacci, 1993). Mangin (1975) considers that flood flow occurs when the spring hydrograph is still influenced by underground runoff and/or infiltration through the unsaturated zone, while a unique exponential decrease according to the Maillet (1905) law characterizes the base flow after infiltration stops. Consequently, an inflection point on the recession curve represents the end of the infiltration and is used to separate flood flow (also called quick flow), which demonstrates a non exponential decrease, from base flow, which demonstrates an exponential decrease (Mangin, 1975). In this conceptual model, groundwater movement and storage in fractures or intergranular porosity of the matrix is neglected, assuming that the strong contrast of several orders of magnitude in permeability between matrix and conduits limits exchange and makes the storage in the matrix negligible (Bakalowicz, 2005). Following this concept, base flow only originates from water that was previously stored in large karst voids called Annex to Drains System (ADS, also called “karst annexes” (Mangin, 1975; BRGM-CNRS, 1992; Mangin, 1994; Palmer, 2003; Bakalowicz, 2005)). These voids are supposed to be poorly connected with the main karst conduits, resulting in high hydraulic head loss and the observed exponential decrease of discharge with time (Mangin, 1975).

Numerical simulations have been used to test the interpretation of karst spring hydrographs. These simulations suggest that transient attenuation of high hydraulic head by a high hydraulic network of several orders of magnitude in permeability between matrix and conduits is sufficient to yield the observed exponential decrease that occurs between the flood flow and base flow phases (Kiraly and Morel, 1976; Kiraly, 2003; Kovacs et al., 2005; Kovacs and Perrochet, 2008). Eisenlohr et al. (1997) have shown that recession limbs of spring hydrographs cannot be interpreted solely in terms of infiltration process and discharge from components of the aquifer that are characterized by distinct hydraulic conductivities. The shape of the recession limbs also depends on the geometry and density of the high permeability channel network as well as on the form of the recharge function (Geyer et al., 2008).

The various conceptualizations of karst spring hydrographs lead to interpretations that can differ from each other or even be contradictory, largely because they depend strongly on characteristics of each study location, such as climate, dynamics of recharge, geology, regional hydraulic gradient, degree of karstification, and respective volumes of unsaturated and saturated materials. These studies often differentiate a flood flow component related to fast infiltration and groundwater flows within aquifer volumes of high hydraulic conductivity (conduits), from a slow component often called base flow, related to the slow depletion of the low hydraulic conductivity volumes or low permeability volumes (LPV, (Jeannin, 1996)), which represents the more or less porous matrix of the karst aquifer (intergranular porosity, joints and/or fractures).

Physical interpretation of recession curves, specifically the separation between flood and base flow, can be complicated for any single aquifer, or between aquifers, because the spatial and temporal distribution of recharge is generally unknown. Furthermore, karst aquifers often differ in the relative importance of matrix porosity within the aquifer, which depends on burial depths and resulting alteration of the carbonate. Karst aquifers found in largely unaltered carbonate rocks has been labeled as eogenetic karst systems, while highly altered, dense, and low porosity karst aquifers have been labeled as telogenetic karst systems (Vacher and Vacher, 2006). Most hydrodynamic studies of karst aquifers use telogenetic karst systems as examples and consequently may neglect the influence of intergranular matrix porosity on spring discharge (White, 2002). However, exchange of water between conduits and matrix occurs during floods (Martin and Dean, 2001), when hydraulic gradients between the conduit and matrix are reversed (Atkinson, 1977; Drouge, 1980; Jeannin, 1996; Bailly-Comte et al., 2009). These conditions result in base flow that is zero (or negative) (Kiraly, 2003). Indeed, the widely accepted assumption that base flow contributes to spring flow at the beginning of the flood event (see for example Atkinson (1977) or Bonacci (1993)) can only be true if the initial water level in the LPV is high enough to exceed that within the conduits throughout the flood.

Some karst aquifers provide the opportunity to simultaneously monitor inflows to conduits from allogenic inputs (i.e. sinking stream) and outflows from conduits at springs. When conduits are full of water, pressure is transmitted from the sinking stream to the spring, allowing direct measurement of allogenic recharge. This recharge differs from autogenic recharge where both diffuse and local infiltration through soils and epikarst (Mangin, 1975) distributes groundwater flow in the vadose zone into two distinct flow paths. One flow path contributes to flood flow and occurs in high permeability zones and the other is slow flow through the matrix porosity and contributes to base flow (Kiraly, 2003; Perrin et al., 2003).

In this study, only flow from the LPV to conduits will be referred to as base flow, which means that a negative flow will be considered as a recharge to the LPV from conduits, and consequently as a period without base flow. With these definitions, spring hydrograph separation should thus allow better understanding of standing karst aquifer flow, in particular the relative influence of high and low permeability volumes on karst spring flows, the consequences of flow inversions between these volumes, and the origin and evolution of base flow during and following floods, regardless of the porosity or permeability of the LPV. This paper is divided into two parts, the first of which briefly reviews previous work dealing with hydrodynamic analysis of karst spring hydrographs and describes mathematical models for drainage of the conduits and matrix. The second part focuses on two karst systems, one eogenetic and one telogenetic, in which conduit flows (presence of large cave systems), recharge and water level representative of conduits and LPV are well characterized. The two systems differ greatly in their head gradients and amounts of matrix porosity and permeability. These case studies allow application and evaluations of mathematical flow models to discuss the origin, the evolution and the relative importance of flood flow and base flow during and following recharge in two different karst contexts, and development of conceptual models to show the influence of exchange between matrix and conduits on flood hydrographs of karst springs.
Methods

Simple mathematical models for karst spring recession

Drainage of low permeability volumes (porous matrix) – Matrix Restrained Flow Regime (MRFR)

Boussinesq (1904) and Maillet (1905) were among the first authors to propose simple mathematical models for spring recessions. Others have expanded these initial models in attempts to improve mathematical fits to field measurements (Drogue, 1969, 1972; Mangin, 1975). Dewandel et al. (2003) and Ford and Williams (2007) review these different recession models.

In this study, the slow depletion of the LPV is assumed to control the flow regime at the spring during the base flow period on the spring hydrograph similar to groundwater flow in porous media. An approximate solution of the groundwater flow equation (without recharge) in one (Boussinesq, 1904) or two (Kovacs et al., 2005) dimensions for a porous, homogeneous, isotropic and unconfined aquifer gives a single exponential decrease. Kovacs et al. (2005) term this flow regime the Matrix Restrained Flow Regime (MRFR):

\[ Q_{\text{MRFR}}(t) = Q_0 \times e^{-st} \]  

(1)

where \( Q_{\text{MRFR}}(t) \) [L^3 T^{-1}] is the discharge at time \( t \), \( Q_0 \) [L^3 T^{-1}] is the spring discharge when the MRFR period starts and \( s \) is the recession coefficient [T^{-1}] usually expressed in days. This solution is referred to as model MRFR; Eq. (1) supposes that no delayed recharge occurs.

Boussinesq (1904) and Kovacs et al. (2005) expressed \( s \) according to physical parameters using an analytical approach. They show that the recession coefficient \( s \) is proportional to the ratio \( L^2 / C_0 \), where \( L \) is the length of the aquifer domain [L], \( T \) is the hydraulic transmissivity [L^2 T^{-1}] and \( S \) is the storativity [-] of the equivalent porous, homogeneous, isotropic and unconfined media.

Drainage of high permeability volumes (conduits) – Conduit Flow Regime (CFR)

The first part of a recession curve can be strongly influenced by recharge through the vadose zone modulated by its transfer through the phreatic zone (Mangin, 1975), which explains why flood flow is not easily described by mathematical functions. Therefore, we initially assume that springs respond only to an impulse in hydraulic head elevation in conduits, there is no diffuse recharge through the vadose zone, and there is no exchange between conduits and matrix. These strong assumptions and their applicability to real karst systems will be discussed subsequently.

Under these conditions, the whole conduit network is considered as a single reservoir (\( R \)) with infinite hydraulic conductivity, and the Bernoulli incompressible flow equation of fluid dynamics gives (Eq. (2a)):

\[ V_x(t) = \sqrt{2g h(t)} \]  

(2a)

where \( V_x \) is the flow velocity at the exit of \( R \) [L T^{-1}], \( g \) is the gravitational constant [L T^{-2}], and \( h \) is the hydraulic head in \( R \) [L]. Considering that the horizontal area of \( R \) is constant, the mass conservation in \( R \) during \( dt \) gives (Eq. (2b)):

\[ A_R \cdot dh = - a_R \cdot V_x \cdot dt \]  

(2b)

where \( A_R \) is the area of \( R \) [L^2] and \( a_R \) is the flow section at the exit of \( R \) [L^2].

Combining and rearranging Eqs. (2a) and (2b) gives Eq. (2c):

\[ dQ_{\text{CFR}} = -2g \frac{Q_o}{A_R} \cdot dt \]  

(2c)

where \( Q_{\text{CFR}}(t) \) [L^3 T^{-1}] is the discharge at time \( t \) at the exit of \( R \). The integration of Eq. (2c) between the flood peak time \( t_{\text{max}} \) and \( t \) indicates there is a linear decrease of the discharge according to time:

\[ \begin{cases} \beta = 2g \frac{Q_o}{A_R} \\ Q_{\text{CFR}}(t) = Q_{\text{max}} - \beta \times t \end{cases} \]  

(3)

where \( Q_{\text{max}} \) [L^3 T^{-1}] is the maximum discharge and \( \beta \) [L^3 T^{-2}] is the slope of the linear decrease of the spring discharge according to time expressed in \( \text{m}^3 \text{ s}^{-1} \text{ d}^{-1} \).

We refer to this simple model (Eq. (3)) as Conduit Flow Regime (CFR). It has been shown that \( \beta \) will take high values for a large flow section at the exit of \( R \), which can be related to a high degree of karstification (or a high conduit frequency) (Bailly-Comte, 2008). Inversely, \( \beta \) will be low for a high horizontal section in \( R \), meaning that a small amount of water is stored in the conduit system. It can also be demonstrated that quadratic head loss in \( R \), which conceptually represents conduit constrictions, does not modify the linear relationship in Eq. (3). In this case, \( \beta \) is found to be inversely proportional to the quadratic head loss coefficient (Bailly-Comte, 2008).

Base flow evolution

The difference between inflow at the swallet and outflow (\( \Delta Q \)) at the spring of a sink/rise karst system yields the groundwater discharge draining from (or injected to) the LPV to (or from) the conduit (Eq. (4)):

\[ \Delta Q = Q_A - Q_A \]  

(4)

where \( Q_A \) is the spring discharge and \( Q_A \) is the allogenic recharge.

This method allows computing base flow as the positive value of \( \Delta Q \) during and following floods and the amount of loss from negative values of \( \Delta Q \).

A comparison of case studies

Study areas

The Vène Spring in the Aumelas-Thau karst system

Near Montpellier, Southern France, the Vène Spring (Fig. 1A), Station Number 10162X00033) is a temporary spring partly fed by the sinking of the ephemeral Coulazou River (Bonnet and Paloc, 1969). The Coulazou River crosses the Aumelas Causse where the karst aquifer is formed in Jurassic limestones that are exposed at the surface (Fig. 1A).

This karst system, known as the Aumelas-Thau karst system, is an example of a telogenetic karst system, and feeds the ephemeral Vène Spring in high water conditions. A gauging station is used to estimate discharge a few meters downstream from the Vène Spring (Fig. 1A). In low flow, karst groundwater discharges farther to the southwest by other permanent karst springs below a Tertiary basin capped by imperious siliciclastic rocks. A monitoring network has been constructed in the region to assess the karst/river hydrodynamic interactions (Jourde et al., 2007; Bailly-Comte et al., 2008a,b). As part of this network, allogenic recharge is monitored using a gauging station upstream from the karst aquifer (Fig. 1A). Water level is recorded in a cave called Puits de l'aven (Fig. 1A) and in a monitoring well PZ2 (Fig. 1). Well PZ2 is a 120 m deep, uncased well which has been drilled into the Jurassic limestone; no large karst voids were identified during the drilling, though fractures and small karst drains were encountered. Previous studies show that this well represents hydrodynamics of the LPV influenced by the Coulazou River (Bailly-Comte et al., 2008b, 2009). Puits de l'aven is a cave that is at least 1300 m long with
The Santa Fe River sink/rise system within the upper Floridan aquifer.

In north-central Florida, the River Rise Spring is the main outlet of a sink/rise system sourced by the Santa Fe River (Fig. 1B). Similar to the Aumelas-Thau system, a monitoring network has been constructed to assess the exchange of water between matrix and conduit (Martin and Dean, 2001; Martin and Screaton, 2001; Screaton et al., 2004; Martin et al., 2006).

River Sink stage is recorded each day by the staff of the O’Leno State Park and converted to runoff based on a rating curve developed by the Suwannee River Water Management District (QA, Fig. 1B, Rating No. 3 for Station Number 02321898, Santa Fe River at O’Leno State Park). Water levels are recorded at a 10 min interval at the River Rise and converted to discharge using the rating curve produced by Screaton et al. (2004) (Fig. 1B). Eight wells have been screened close to the depth of the main conduit and four additional wells have been drilled and screened across the water table within a few meters of four of the deep wells. The deep wells are designated by a single digit (1–8) and the shallow wells are designated by the letter A (4A, 5A, 6A, 7A). Most of these wells are instrumented so that water level, conductivity, and temperature are monitored within the LVP at a 10 min time interval. These monitoring data provide information about pressure (water level) and mass (temperature and electrical conductivity) transfer in the matrix during floods.

In high flow conditions, flood pulses from the Santa Fe River are transmitted to the River Rise through large karst conduits (Screaton et al., 2004). Increases in the hydraulic head of the conduits lead to flow from the conduits to the porous matrix (Martin and Dean, 2001; Martin and Screaton, 2001). At this site, the matrix permeability is greater than at the Aumelas-Thau site, but is still significantly lower than the conduit permeability. Thus, even though Santa Fe River is an eogenetic karst system, the matrix represents an LPV relative to the conduit. Moore et al. (2009) have shown that the water chemistry in the Well 4 is relatively constant, though this well is within a few hundred meters of the main karst conduits (Fig. 1B), which suggests little exchange of mass between the conduit and Well 4. Consequently, we consider water level fluctuation in Well 4 as representative of hydrodynamics of the LPV. The complementary shallow Well 4A is compared to Well 4 to assess vertical hydraulic gradient within LPV. Finally, conduit head is characterized by measurements of water level at the River Rise.

Comparisons

Table 1 summarizes the main characteristics of the groundwater/surface water interactions and conduits/matrix hydrodynamic properties for these two karst systems, focusing on their genesis, their hydrologic regime, their hydrodynamics and especially the boundary condition that applies in the conduit system during flood.

The fundamental characteristics of the karst aquifers as well as the recharge condition in their conduits (see boundary conditions in Table 1) differ greatly in these two areas (Table 1), providing ideal settings for comparative studies of fundamental processes. Indeed, differences in topography between the two regions create differences in water table gradients, resulting in differences in flow rates through the aquifers, as well as responses to extreme precipitation events. In addition to topographic dissimilarities, physical properties of the aquifers differ because of their geologic histories (telogenetic vs. eogenetic). As a result of the age and deformation, the French karst aquifers in Languedoc contain little primary porosity and most water is stored within fractures and conduits. The lack of deformation of the Florida karst is reflected in the high primary porosity of the matrix rocks, up to 20% (Table 1, [Martin et al., 2006]). This high primary porosity allows for extensive water
storage and influences flow paths through the Floridan aquifer. These fundamental differences allow assigning typical flow behavior to each component of the karst spring hydrograph by different approaches:

– In the Aumelas-Thau system, flood flow and base flow at Vène Spring can be described according to time-series measurements of water level in Puits de l’aven and Well PZ2 when concentrated recharge along the riverbed ceases.

– In the Santa Fe sink/rise system, variations of base flow during the entire recession period can be computed using the difference between outflow and inflow, assuming that autogenic recharge can be neglected compared to inflows from the sinking stream.

### Flood flow and base flow at the Vène Spring

**Spring hydrographs analysis according to water level evolution in matrix and conduits**

In Aumelas-Thau, 19 flood events have been recorded at Vène Spring since October 2002; 10 have been described using simultaneous water level measurements in Well PZ2 and Puits de l’aven since April 2004. Three distinct types of recession curves have been identified at Vène Spring according to the initial (pre-storm) water level in Well PZ2 (Fig. 2):

During low water table conditions, i.e. after the summer drought, floods recorded at Vène Spring are relatively short, lasting only a few days. At these times, spring hydrographs shows a linear decrease with time (Fig. 2A) as long as the water level in conduits (Puits de l’aven) is higher than the water level in the matrix (Well PZ2). Water level in Well PZ2 slightly decreases at the beginning of the recession, indicating a recharge probably due to a low pressure transfer from conduit to LPV and eventually the influence of local fast infiltration, but this water level always stays lower than the water level in conduits. Moreover, it quickly reaches a constant value, which means that the water level evolution in LPV cannot explain the discharge evolution at the spring. Discharge at the spring during the whole recession is thus primarily influenced by the water level change in conduits. As a result, flood hydrographs only show the flood flow component influenced by conduit flow; it is an ideal example of the CFR condition. Bailly-Comte et al. (2009) showed that the low water table condition is characterized by \( h_{\text{LPV}} < 3500 \text{ cm asl} \) prior to the flood.

During medium to high water table conditions, floods recorded at Vène Spring are longer than during low water conditions. Spring hydrographs (Fig. 2B) initially show a similar evolution consisting of a linear decrease through time, while the water level in Well PZ2 increases slightly. This increase cannot explain the flood recession; it shows that conduits simultaneously feed the spring and recharge the LPV. An inflection point appears in the hydrograph as soon as the water level in conduits equals the water level in matrix (Well PZ2). This inflection point is thus interpreted as a flow regime modification within the karst drainage network, which abruptly changes from the CFR condition to the MRFR condition.

Under very high water table conditions, the LPV is already drained by an upper karst drainage system (which occurs when \( h_{\text{LPV}} > 4700 \text{ cm asl} \), see Bailly-Comte, 2008 for details). The spring hydrograph in Fig. 2C perfectly represents the MRFR condition since only the hydrodynamic properties of the matrix control the flow at the spring, assuming that the discharge capacity of the karst conduit system is no exceeded (which occur on this site when \( Q_s > 5.5 \text{ m}^3/\text{s} \) (Bailly-Comte et al., 2009)).

As a result, these three types of recession curves show that water level comparisons between Puits de l’aven and Well PZ2 allow an understanding of the conditions in the conduits or matrix that control the flow at the spring. These results also show that water level measurements in a well representing the LPV (PZ2) prior to the flood allow forecasting of the spring behavior (see the initial water level in PZ2 shown in Fig. 2). The CFR and MRFR mathematical models (Eqs. [1] and [3]) should only be used to fit recession curves of spring discharge when delayed recharge is negligible. This assumption is reasonable when allogenic recharge from an ephemeral stream constitutes the primary recharge, producing the quick response at the spring. In the three types of recession curves exemplified by Fig. 2 allogenic recharge ceased quickly after the river flooded, and most surface flow was captured by numerous sinkholes in less than 1 h. Consequently, \( Q_s \) was negligible when the recession started at the spring (Fig. 2). The recession can thus be interpreted as the spring response to an impulse recharge in conduits. Moreover, as a first approximation, water exchange between conduit and matrix can be neglected during the conduit flow period since the contrast of permeability between conduits and matrix is high and water movements through

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### Table 1

Comparisons of the two case studies showing the main characteristics of the groundwater/surface water interactions and conduits/matrix hydrodynamic properties.

<table>
<thead>
<tr>
<th>Type of karst aquifer</th>
<th>Aumelas-Thau system</th>
<th>Santa Fe sink/rise system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Telogenetic</td>
<td>Eogenetic</td>
</tr>
<tr>
<td>Distance (straight line) between the monitored sinkhole and the spring</td>
<td>5.3 km between the cave Puits de l’aven and the Vène Spring</td>
<td>4.7 km from River Sink to River Rise</td>
</tr>
<tr>
<td>Hydrologic conditions before a flood</td>
<td>No surface flows in the River and no flows at the spring</td>
<td>Base flow at the spring due to sinking surface streams and release of groundwater storage</td>
</tr>
<tr>
<td>Flood propagation between ( Q_s ) and ( Q_r ) (Fig. 1)</td>
<td>Flood transfer through open channel and karst conduits in both vadose and phreatic zone</td>
<td>Flood transfer through karst conduits in the phreatic zone</td>
</tr>
<tr>
<td>Allogenic recharge</td>
<td>Discontinuous recharge (intermittent river)</td>
<td>Continuous recharge, large flood events from upstream confined terrains that source the aquifer over few days to months</td>
</tr>
<tr>
<td>Time scale</td>
<td>Sinkholes are filled by surface water in few hours during flash floods, coming from non-karst terrains</td>
<td>Only River Sink drains the sinking stream</td>
</tr>
<tr>
<td>Number of sinkholes between ( Q_s ) and ( Q_r )</td>
<td>More than 15</td>
<td>High (around 20X, Martin et al., 2006)</td>
</tr>
<tr>
<td>Hydrodynamic properties</td>
<td>Low (few %)</td>
<td>High (around 20X, Martin et al., 2006)</td>
</tr>
<tr>
<td>Matrix porosity</td>
<td>During flood: Riverbed elevation = head boundary condition in karst conduits; then, water level in sinkholes decreases with no or few influence of allogenic recharge</td>
<td>Sinking surface flows = flow boundary condition in karst conduits</td>
</tr>
<tr>
<td>Boundary conditions in conduits</td>
<td>During flood: Riverbed elevation = head boundary condition in karst conduits; then, water level in sinkholes decreases with no or few influence of allogenic recharge</td>
<td>During flood: Riverbed elevation = head boundary condition in karst conduits; then, water level in sinkholes decreases with no or few influence of allogenic recharge</td>
</tr>
</tbody>
</table>
conduits towards the spring is enhanced by a strong hydraulic gradient through the conduits. These two factors explain why the CFR model (Eq. (3)) agrees with measurements.

Influence of the type of recharge on the flood propagation

A direct estimate of flow between conduits and LPV using Eq. (4) only applies when autogenic recharge is negligible so that recharge dynamics of the Santa Fe sink/rise system are known. Fig. 3C shows how the discharge at the River Sink (Fig. 1B) and the River Rise (Fig. 1B) varies during three large floods, two in 2005 and one in 2006. At this site, recharge to the aquifer was estimated at a daily time step by Ritorto et al. (2009) who used a mass-balance method similar to Dripps and Bradbury (2007).

In 2005, the River Sink discharge \( Q_s \) is always less than the River Rise discharge \( Q_r \), reflecting additional flow at the spring and continuous drainage of autogenic water even during flood periods. Initial water level in Well 4 was relatively high (1050 cm asl), but this level remains much lower than water level at the spring during the flood peak (Fig. 3B). Thus, autogenic recharge through the LPV cannot explain a higher discharge in \( Q_r \) (Fig. 3C). The positives values of \( AQ \) also show great variations dur-
ing the flood peak (Fig. 3B, see t1). These fluctuations and the positives values of ΔQ reflect fast infiltration through the thin and high permeability unsaturated zone, sinkholes and vertical shafts (i.e. fast autogenic recharge) which amplifies the flood peak transfer from River Sink to River Rise.

In 2006, a high flow event occurred with a lower initial water level in Well 4 prior to the flood (995 cmasl). The estimated autogenic recharge is higher than for the summer rainfall event (Fig. 3A), but fast autogenic infiltration appears to be relatively low since ΔQ exhibits negative peaks during the transfer of the flood peak (Fig. 3B, see t2). During the flood recession, water level in Well 4 becomes higher than at the River Rise (Fig. 3B, see t3), indicating that conduits drain the LPV following its recharge by diffuse infiltration. Consequently, t3 characterizes a flood recession influenced by delayed infiltration which could result from discharge from wetlands and perched water table lakes. This delayed infiltration explains the positive and smoothed values of ΔQ (Fig. 3B, compare t3 to t1). From June 2006 to December 2006 (Fig. 3B, see t4), no recharge occurs (no flows in River Sink and no or little recharge from rainfall on Fig. 3A). Delayed recharge through a few meter thick vadose zone (River Rise, 2007) may thus be neglected. LPV and conduits reach pressure equilibrium during the t4 period during which time a single exponential decreasing limb perfectly describes the base flow recession curve, as proposed by the MRFR model (Eq. (1)) without recharge. However, quick flows between matrix and conduit cannot be described using ΔQ since autogenic recharge is found to influence the flood transfer.

Case of simple allogenic recharge

Fig. 4 shows a flood that occurred at the end of summer 2008 for which the rainfall recorded from 08/16/2008 to 09/02/2008 in the confined catchment area (236 mm), upstream of the karst aquifer, is much higher than the rainfall recorded on the karst aquifer (156 mm). No recharge estimates are available, but because flooding occurred in the summer, medium to high evapotranspiration (ET) would be expected, reducing the relative influence of the autogenic recharge as compared to the allogenic recharge.

Cumulative flows are the same in River Sink and River Rise (~120 10^3 m^3 from 08/15/08 to 12/05/08), which could be misinterpreted as low matrix/conduit exchange during the flood transfer. Indeed, hydrographs are greatly modified from River Sink to River Rise (Fig. 4), which can be explained using water level time series at River Rise, and Well 4 and Well 4A (Fig. 1B). Synchronous measurements of water level are used to describe vertical ground-water flows by computing vertical hydraulic gradients between Well 4 and Well 4A (Fig. 4, see the gray line), while evolution of hydraulic gradient between Well 4 and River Rise (Fig. 4, see the black line) characterizes flow from LPV to conduits. Positive values of hydraulic gradients indicate downstream flow from Well 4A to Well 4 and from matrix to conduit respectively.

The gradients between the conduit (measured at the River Rise) and Well 4 and between Well 4 and Well 4A become negative simultaneously with the ΔQ becoming negative at the start of the flood. This timing indicates that allogenic water flows to the LPV in all directions around the conduit and that recharge from the surface through the LPV is negligible at that time. Subsequently in the recession curve, ΔQ and the hydraulic gradient between Well 4 and River Rise become positive at the same moment. Thus, hydraulic gradients within the LPV both between Well 4 and Well 4A and between the LPV and conduits (W4 and River Rise) reflects ΔQ, suggesting that ΔQ can be considered as a measure of exchange between LPV and conduits. A positive value for ΔQ can be considered the onset of baseflow to the spring, even though there is no inflection point on the spring hydrograph at this time.

This flood event shows how allogenic water is initially stored in the LPV (ΔQ < 0) and subsequently is released and drained by conduits (ΔQ > 0). In other words, ΔQ shows how exchange of water between matrix and conduit modifies the quick flow transfer, although cumulative flow at the sink and rise over the time of the flood does not reflect this exchange of water. Based on the ΔQ evolution shown in Fig. 4 between 08/25/08 and 09/04/08, there was clear exchange during this flood of around 30% of allogenic recharge. This amount of water was stored in the porous matrix during the flood before being slowly drained by conduits to the spring during the recession. Although the flow inversion between matrix and conduits is clearly shown by the discharge volumes, it does not generate a clear change in the spring hydrograph.

Comparisons of Aumelas-Thau and Santa Fe River sink/rise systems

Fig. 2A and B shows that the hydrograph recession of Vène Spring perfectly fits Eq. (3) when water level is higher in the cave (conduit) than in the well (LPV), which characterizes the CFR condition. Flow events at Vène Spring thus reflects discharge from a conduit network previously recharged by a pulse of allogenic recharge. Linear decreases of flow events are usually not observed on hydrographs of karst springs, even in karst systems where matrix porosity is very low, because of the influence of fast and delayed infiltration through the epikarst and the vadose zone. Indeed, the dynamics of recharge has such a strong influence on the flood flow transfer that it often becomes impossible to physically interpret the flood flow period, i.e. to assign a flow behavior to each flow period. At the Vène Spring, short and focused allogenic recharge easily allows separating the CFR component of the spring hydrograph.

Using numerical methods based on two-dimensional analytical solutions describing the hydraulic response of a theoretical karst aquifer with simple geometries, Kovacs et al. (2005) have shown

\[ \Delta Q \]

\[ \text{Rainfall (mm/d)} \]

\[ \text{Hydraulic gradient} \]

\[ \text{Daily discharge (m}^3\text{/s)} \]

\[ \text{River Sink discharge (Qa)} \]

\[ \text{River Rise discharge (Qs)} \]

\[ \text{Rainfall (mm/d)} \]

\[ \text{Hydraulic gradient} \]

\[ \text{Daily discharge (m}^3\text{/s)} \]

\[ \text{River Sink discharge (Qa)} \]

\[ \text{River Rise discharge (Qs)} \]
that both flood and base flow recessions should be characterized with exponential decreases, but with two different recession coefficients. If the recession coefficient is low, however, an exponential decrease is close to a linear decrease, but the hydrograph is consequently nearly flat, which is not consistent with the field observations in Fig. 2B and C. Another explanation of the linear decrease of flood flows observed at the Vène Spring (Fig. 2A and B) could be found by considering both the contrast of permeability between conduits and matrix, and the hydraulic gradient in conduits: In the Aumelas-Thau system, this contrast is high and hydraulic gradients between sinkholes in the riverbed and Vène Spring can exceed 1%, suggesting that water exchange between conduits and matrix is low compared to flow in the conduits. Limited exchange means that the conduit/matrix boundary can be approximated by a no-flow boundary, as proposed by the CFR mathematical model (Eq. (3)). In case of higher matrix permeability (fractures or intergranular porosity) and lower hydraulic gradients in conduits, exchange of water between the conduit and matrix could explain an exponential evolution of spring discharge as proposed by theoretical models with simple geometry (Kovacs et al., 2005).

When water level in Well PZ2 is high prior to the flood, it remains higher than the water level in conduits during the flood (Fig. 2C). Thus, karst conduits only drain the matrix and never re-strain groundwater flow as long as the discharge capacity of karst conduits is not exceeded. This process explains why spring hydrographs perfectly follow a single exponential decrease related to the relatively slow depletion of the LPV volume (Eq. (1)), which characterizes the MRFR condition (Fig. 2B after 5/7/07, and Fig. 2C).

Influence of two aquifer volumes of different hydrodynamic properties is also identified at the Santa Fe sink/rise system, highlighting the concept of double porosity of karst aquifers. Both continuous recharge at the sink (Qs) and water exchange between a highly permeable matrix and conduits drive the flood flow transfer, which prevents the use of Eq. (3) to describe the hydrodynamic behavior of the River Rise. Exchange of water between matrix and conduit can be compared to stream/aquifer interactions (or bank storage) which control the surface flow routing in open channels (Cooper and Rorabaugh, 1963; Pinder and Sauer, 1971; Hunt, 1990; Moench and Barlow, 2000; Chen et al., 2006). However some non negligible differences since surface flow routing in open channels and water flow routing in a conduit system under pressure are governed by different processes, and thus represented by different equations. Moreover, pressure in conduit flow can enhance the loss of water from conduits to matrix porosity.

Miallet's law (1905) can also explain an exponential decrease of discharge from the spring as due to the emptying of large karst voids poorly connected to the main karst conduit (karst annexes (Mangin, 1975)). Such karst voids or cavities were not encountered when drilling Well PZ2 (Aumelas-Thau) or Well 4 (Santa Fe River sink/rise), suggesting that groundwater is actually released from matrix porosity (intergranular porosity and/or from dissolved fractures and joints) during base flow according to Eq. (1) for both the eogenetic and telogenetic studied karst systems.

Conceptual model and discussion

These observations can be used to develop a conceptual model of groundwater flow through conduits embedded in matrices with variable amounts of porosity and hydraulic conductivity in response to a sudden increase of hydraulic head in the conduit system due to focused recharge. The evolution of spring hydrographs is exemplified by the Aumelas-Thau system for systems with high hydraulic gradients within conduits and contrasting permeability between conduits and matrix (Fig. 2). In this case conduits and LPV behave as two parallel reservoirs with two different hydraulic heads during quick flow recession. This condition continues for as long as the hydraulic head in conduits is higher than the hydraulic head in the LPV (from t0 to t1 on Fig. 5). Once pressure equilibrium between the conduit and LPV is reached, conduit flow regime (CFR) ends and Matrix Restrained Flow Regime (MRFR) begins. This modification to the flow regime occurs when the recession curve changes from a linear decrease to an exponential decrease at the Vène Spring (t1, on Fig. 5 – Site A) in the case of medium to high initial water level in the LPV. After matrix restrain flow regime (MRFR) begins, karst conduits drain groundwater stored in the LPV and the spring behavior only depends on the matrix hydrodynamic properties (e.g. after t1, on Fig. 5 – Site A). This condition induces an exponential decrease of the spring discharge, as described by Eq. (1).

This conceptual model can also be used to understand hydrodynamics at the Santa Fe sink/rise system (Fig. 5 – Site B). During flood flows, water exchange between conduits and the LPV imply that conduits and matrix are two dependent subsystems. The links between these subsystems means that the CFR condition will be more complex than in the previous case of low matrix porosity, and that groundwater flow will slowly change from the CFR to the MRFR condition without a visible inflection point on the spring hydrograph (Fig. 5 – Site B). Moreover, a low contrast of permeability between conduits and matrix and a high effective porosity are not consistent with the low initial water level in the LPV shown in Fig. 5. Thus, no schematic spring hydrograph is given for Site B in the case of low antecedent condition in the matrix.

Both systems studied show MRFR conditions which can be characterized by a single exponential decrease on the spring hydrograph, but values of the recession coefficient are much lower in the Santa Fe sink/rise system (α < 0.01 d⁻¹, Fig. 5) than in the Aumelas-Thau system (α > 0.1, Fig. 2B and C). This difference can be interpreted by considering a lower Cᵣ ratio in the Santa Fe sink/rise system, i.e. a lower hydraulic diffusivity since both karst aquifer lengths (L) are of the same order of magnitude (Fig. 1). A lower hydraulic diffusivity in the Floridan aquifer is consistent with the strong inertial behavior of eogenetic karst aquifers (Florea and Vacher, 2006). This characteristic is mainly due to the high porosity of the limestone (thus a high storativity and a low hydraulic diffusivity), which explains why this aquifer is one of the most productive aquifers in the world. In contrast, the matrix porosity of Jurassic limestones of the Aumelas-Thau system is low (thus a low storativity and a high hydraulic diffusivity) because of the low fracture porosity.

Base flow at River Rise, as defined as the positive value of ΔQ, is relatively low and constant as long as the discharge simultaneously decreases at River Sink and River Rise. Consequently, discharge variations at River Rise (Qₚ) are strongly influenced by the recharge in River Sink (Qₛ). Similar to this behavior in karst aquifers, low flows in surface streams are also controlled by base flow due to bank storage effects, which are also characterized by an exponential decrease (Cooper and Rorabaugh, 1963). As a result, identifying an exponential decrease on karst spring hydrographs does not necessarily mean that groundwater is released from the LPV to conduits. In a general way, dynamics of recharge has to be well identified before analyzing recession curves.

Consequences for karst spring modeling

Although the examples shown are systems dominated by allo-genic recharge, we suggest that the conceptual model has applicability to many karst systems. Most karst aquifers are connected to surface streams, which can be perennial, intermittent or ephemeral. These streams are drained by sinkholes (Zhou, 2007) or by focused recharge at particular points (sinkhole, swallow hole, ponor)
of endorheic area as a consequence of flooding of karst depressions like dolina and polje (Salvayre, 1964; Mijatovic, 1988; Currens et al., 1993; Bruxelles and Caubel, 1996; Lopez-Chicano et al., 2002; Bradley and Hileman, 2006). Recharge through the epikarst (Marguin, 1975) also occurs as temporary storage and fast infiltration through vertical shafts or paleo-conduits. This fast infiltration also occurs as temporary storage and fast infiltration (Marguin, 1975) also occurs as temporary storage and fast infiltration through vertical shafts or paleo-conduits. This fast infiltration (Marguin, 1975) also occurs as temporary storage and fast infiltration through vertical shafts or paleo-conduits. This fast infiltration (Marguin, 1975) also occurs as temporary storage and fast infiltration through vertical shafts or paleo-conduits. This fast infiltration (Marguin, 1975) also occurs as temporary storage and fast infiltration through vertical shafts or paleo-conduits. This fast infiltration (Marguin, 1975) also occurs as temporary storage and fast infiltration through vertical shafts or paleo-conduits.

Fig. 5. Schematic representation of high (C = conduit) and low (M = matrix) permeability volumes during flood and its consequences on flood hydrographs of the studied karst springs in response to a sudden hydraulic head elevation in conduits. Low, medium to high and very high initial water levels are depicted by the initial water level in Fig. 5. Schematic representation of high (C = conduit) and low (M = matrix) permeability volumes during flood and its consequences on karst spring conceptual modeling. Indeed, simple conceptual models commonly state that karst spring behavior can be simulated using a model with two reservoirs connected in series (see for instance (Kiraly, 2003; Geyer et al., 2008)). Recharge is split into low permeability and a high permeability reservoirs; the low permeability reservoir is slowly drained by the high permeability reservoir connected to the spring (Fig. 6A).

The depletion of the reservoir representing the low permeability volume in Fig. 6A also gives the antecedent recession, which is added to the fast infiltration during quick flow and is used to show the volume of water that is stored and released within the aquifer (see for instance (Atkinson, 1977)). Following this assumption, Fig. 6A shows that: (i) the LPV and conduits always contribute to spring flows, (ii) quick flows at the spring are considered as the sum of conduit flows and matrix flows and (iii) pressure equilibrium between the LPV and conduits are not considered. This hydrodynamic behavior is not consistent with our observations at both the Aumelas-Thu and Santa Fe River Rise systems, two systems with distinctly different aquifer properties. Our observations have important consequences for interpretations of recession curves and modeling of karst spring flows, particularly for interpretations of relative importance of base flow and quick flow from karst spring.
hydrographs (e.g. (Bonacci, 1993; Padilla et al., 1994)). Our results indicate that karst spring hydrographs should be interpreted according to both aquifer subsystems which control the flow regime at the spring, and to water exchange caused by hydraulic head difference between the LPV and conduits (Fig. 6B). These observations reflect karst systems as ensembles of conduits of relatively low storage capacity embedded in a low-permeability matrix where groundwater is stored and slowly drained by conduits, but that the low-permeability matrix can buffer flood pulses to varying degrees depending on its physical characteristics, primarily its porosity and permeability.

**Conclusion**

We have shown that for karst aquifers with low matrix porosity, quick flows at the spring correspond to a flow regime influenced by the hydrodynamic properties of the conduit network. In contrast, for karst aquifer with high matrix porosity, quick flow depends ultimately on the magnitude of water exchange between matrix and conduits. When conduits are filled with water without delayed infiltration and conduit/matrix exchange is low, a linear decrease is observed in the spring discharge, which can be interpreted as the emptying of the conduit network. These hydrograph characteristics are specific to karst aquifer with both low matrix permeability and focused recharge, exemplified by a sinking stream, inducing an instantaneous recharge of the conduit system. In this case, a unique inflection point on the decreasing limb shows a change of flow regime from CFR to MRFR. In most other cases, no simple mathematical fit can be used to analyze quick flows at the spring since infiltration dynamics and/or matrix/conduits exchanges strongly influence conduits flow.

We also demonstrate that a single exponential decrease characterizes the base flow when recharge ceases or become negligible, which can be explained by the drainage of the LPV by conduits. The recession coefficient can thus be used to estimate some hydrodynamic properties of the matrix component itself. These observations allow consideration of a different conceptual model for karst spring hydrograph analysis where discharge evolution at the spring results from pressure equilibrium between two aquifer subsystems of different hydrodynamic properties. This model requires recharge and water level time series in different subsystems of a karst aquifer to interpret the spring hydrograph. Each of these variables is easily obtained through monitoring pressure head at wells, springs and conduits when a sinking stream constitutes the main recharge of the karst system.

As a consequence of the strong spatial heterogeneity of karst aquifers, water level time series in wells are often considered as useless or hard to interpret at the karst system scale, particularly when compared to karst springs hydrographs. However, our observations show that “well-chosen” water level time series allow understanding hydrodynamics of low (matrix with intergranular, joints and/or fracture porosity) and high (conduits) permeability volumes, which together with simultaneous discharge time series at the spring are essential to understand the whole karst aquifer behavior.

As a result, considering porosity of the LPV and hydraulic gradients within conduit systems should improve the environmental impact assessment of pollutants in surface waters drained by karst sinkholes. Indeed, when matrix/conduit exchange is low, drainage of pollutants towards the spring should be fast and limited to the quick flow response at the spring, but also with little dilution. Conversely, high matrix/conduit exchanges should induce a delayed but diluted discharge of the pollutants, with potential sorption/desorption phenomena within the porous carbonate rocks. Differences in contaminant behavior in these two systems will be critical for remediation strategies. This idea could be reinforced by the use of natural tracers of the infiltration. For example high resolution
time series of temperature (Martin and Dean, 1999; Scretton et al., 2004) or specific electrical conductivity and regular sampling of major ions and total organic carbon (e.g. Batjial et al., 2003). Chemical tracers require knowledge of the variations of the selected tracer in the surface water and the unsaturated zone, as well as the characterization of pre-event waters in conduits.

Finally, we show how two karst systems that have distinct characteristics and are observed with similar field methods can be described by the same conceptual model. The unifying aspect of these karst aquifers is their double porosity behavior, regardless of the origin, extent and dynamics of the karstification process.

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