Pumping tests in a mixed flow karst system

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Case study: Cent-Fonts Karst System

The Cent-Fonts karst aquifer is a mixed flow karst system located in Southern France. Cent-Fonts spring constitutes the main outlet of the system.
Long-duration (> one month) pumping tests have been carried out in 2005.

During the pumping tests, the water is pumped in well F3 from a large karst cavity connected to the solution conduit network.
Pumping tests results

Effect of pumping at the spring
The discharge rate at the spring is modified by the pumping rate.

When the pumping rate exceeds the spring recession discharge flow, the spring dries-up.

Drawdown in the karst system
The drawdown is high and not stabilized after one month in the conduit.

The drawdown is low in the matrix.
Natural conditions: 
The karst conduit gets water from losses and matrix drainage.

Pumping conditions: 
The pumped water is abstracted from the conduit network. The induced drawdown contributes to increase the matrix/conduit exchange flow.
Interpretation using Classical Analytical Solutions

Classical analytical solutions are not able to properly simulate the measured drawdown at the pumping well in the karst conduit:
- Theis solution underestimates drawdown for short times
- Barker solution overestimates drawdown for short times.

Moreover, the significance of estimated parameters (T, S) is questionable.
Why is it difficult to interpret pumping tests in Mixed Flow Karst Systems?

> **Duality of flows** in mixed flow karst systems (MFKS):
  - Localized turbulent flow in karst conduits
  - Darcyan or diffuse flow in fractures and porous rock (matrix)

> Pumping tests done in wells intercepting the solution conduits are difficult to interpret because the geometry of cave networks and connections to the matrix are very often unknown.

> To describe the hydraulic properties of the karst aquifer and interpret pumping tests, the rate of flow exchange between the matrix and the solution conduits must be identified.
The duality of flows is modeled using a double continuum model with:
- Reservoir 1 (conduit network): assumed highly permeable with a uniform water level $h_c$
- Reservoir 2 (matrix): assumed porous with Darcyian flows towards conduits and uniform water level $h_m$

$\beta$ is the exchange flow between matrix and conduits
Exchange Flow modelling

Matrix natural contribution

\[ \beta(t) = Q_\alpha(t) + Q_{IND}(t) = Q_0 e^{-\alpha t} + Q_{IND}(t) \]

Matrix sollicitation (induced by pumping)

### One-Dimensional Flow

\[
Q(t) = \frac{L}{\sqrt{\pi}} \sqrt{\frac{T}{t}} s_e (7)
\]

\[
Q_{IND}(t) = 2l \sqrt{\frac{ST}{\pi}} \left( \sum_{i=1}^{N+1} \frac{(s_i - s_{i-1})}{\sqrt{t_{i-1}}} H(t - t_{i-1}) \right)
\]

with \( s_0 = 0 \) and \( s_{N+1} = 0 \) (9)

### Radial Flow

\[
Q(t) = 2\pi T s_e G(a), \quad a = \frac{2T}{Sr_e} (8)
\]

\[
Q_{IND}(t) = 2\pi T \left\{ \sum_{i=1}^{N+1} (s_i - s_{i-1}) G(a_{i-1}) H(t - t_{i-1}) \right\}
\]

with \( s_0 = 0 \) and \( s_{N+1} = 0 \)

\[
G(a) = \frac{4a_j}{\pi} \int_0^\infty u e^{-au} \left\{ \frac{\pi}{2} + \arctan \left[ \frac{\text{Y}_0(u)}{\text{J}_0(u)} \right] \right\} du
\]

where \( a_j = \frac{T(t_j - \theta)}{S_0} \) for \( j = 0 \) to \( N \) (10)

- \( l \) length of the trench (karst conduit network)
- \( r_0 \) radius of the well (karst conduits)
- \( G(a) \) well production function
- \( a \) dimensionless time
- \( J_0 \) and \( Y_0 \) first- and second-kind, zero-order Bessel functions respectively
- \( u \) dummy variable

\( T \) transmissivity of the aquifer (matrix);
\( S \) storage coefficient of the aquifer (matrix);
\( s_e \) constant drawdown at the trench or well (conduits);
Modeling Results using One-dimensional flow in the matrix

The model simulates very well the drawdown in the karst conduit, including the first pump stop (PS1) and the recovery phase (PS3).

Into the matrix, the trend of drawdown is rather well represented.

Main parameters:
\[ L = 5000 \text{ m} \]
\[ S_c = 1900 \text{ m}^2 \]
\[ T_m = 1.6 \times 10^{-5} \text{ m}^2/\text{s} \]
\[ S_m = 0.007 \]
Sensitivity Analysis

The numerical model is very sensitive to the free surface area of dewatering conduit network $S_c$ (vertical shafts and variably saturated conduits) and to the transmissivity $T_m$ of the matrix.

Reference model:
$S_c = 1900 \text{ m}^2$
$T_m = 1.6 \times 10^{-5} \text{ m}^2/\text{s}$
Flow Components

After pump stops (example: PS3), the conduit dewatering flow becomes negative and the matrix solicitation dramatically decreases. This corresponds to momentaneous inversion of exchange flow between conduits and matrix.
Conclusion

> Both the matrix (several kilometers away from the pumping well) and the conduit network are affected by the long-duration pumping test.

> The double continuum model composed of two reservoirs (conduit network and matrix) well reproduces the transient response in the pumping well.

> Free of deterministic finite difference/elements modeling, it is simpler than hybrid models.

> This model constitutes an advance in double continuum modeling of karst systems notably by an improvement in the calculation of the exchange flow rate between matrix and conduits.