Reply to Anonymous reviewer #1 (www.hydrol-earth-syst-sci-discuss.net/10/C1433/2013/)

We thank the reviewer for the critical notes and helpful suggestions. Comments, explanations, and further analysis are placed within the provided review notes and marked by using a different font and gray color.

The paper presents a modified version of the CFPM1 add-on package to Modflow, and an adaptation for a new BC in the coupled model. The add-on is described and its effects are shown on a very simple test model. Then a strongly simplified site model of the Cent Fonts spring catchment is used and simulation results for this case are shown. Overall, the paper is badly written and of low scientific content. The authors aim is (as stated in the conclusions section) to be able to interpret the pumping test by Maréchal et al. (2008; reference as cited in manuscript) using MODFLOW with the karst addons CFPM1.

The implementation of conduit associated storage to a distributive groundwater flow model integrates different storage concepts associated with karst systems. It is of importance for understanding karst spring responses and evaluation of large scale hydraulic tests. Therefore, it is scientifically important. The simplicity of the modeling concept allows the implementation of Conduit Associated Drainable Storage (CADS) to widely distributed modeling approaches such as MODFLOW and makes it also interesting for application studies. The purpose of our manuscript is to present the modeling concept and to show how it affects karst hydraulics. This is done by the presented modeling scenarios and an application outlook. Further application studies will follow and will include the complexity of natural karst systems. However, this is beyond the scope of our manuscript, which deals primarily with model development. So, we want to clarify our aims in order to avoid any misunderstandings

[Abstract] "… The objective of this paper is to analyze the significance of CADS and flow-limited boundary conditions on the hydraulic behavior of karst aquifers in water abstraction scenarios."

[Introduction] „…The objective of this article is to provide a distributive process-based modeling approach that allows the simulation of hydraulic impacts (discharge events, large scale hydraulic tests) on karst systems…"

The special setting of this pumping test makes a new lower boundary condition for the conduit system necessary, as otherwise water would be pumped into the spring. Also, a new feature of CFPM1 is developed, which is supposed to account for a fast storage mechanism. However, the model advancements are explained badly and the model for the field test is so strongly idealized, that no meaningful results are obtained. Also, there is no significant scientific advancement compared to the paper of Marechal et al. (2008).

The approach presented by *Maréchal et al.* (2008) was able to simulate the drawdown observed in the pumping well. However, in contrast to our distributed modeling approach, *Maréchal et al.* (2008) employed a conceptual modeling approach consisting of two homogeneous reservoirs, representing the karst conduit system and the matrix subsystems. Therefore, this approach is only of limited suitability for simulation of borehole responses in strongly heterogeneous and anisotropic aquifers such as karst because there is no spatial distribution of hydrodynamic properties (permeability and storage) or computed values (flows and heads). It is also limited regarding the simulation of aquifer boundaries and, therefore, has limited prediction ability for long time simulations. Finally, the here introduced model approach results in an advance compared to the *Maréchal et al.* 2008 paper because the spatial distribution of conduits as well as matrix heads can be considered.

Mayor issues:

1) The conceptual model description for the new kind of storage is incomplete and not clear at all. Where is the water? In which of the porosities? Why do the authors account for it that way? Why is storage not fast, but instantaneous? How do I get estimates of the parameters, what do they mean physically?

The description of the concept behind Conduit Associated Drainable Storage (CADS) is revised. In general, storage in karst systems occurs in

(A) the porous matrix (primary porosity),

(B) fractures / fissures (secondary porosity), and

(C) solution enlarged pathways like conduits (tertiary porosity).

The hybrid model concept considers two compartments:

(1) a representative elementary volume of the fissured / fractured matrix (A) and (B) simulated as continuum with laminar flow and storage (for CFP = MODFLOW-2005) and

(2) discrete conduits (C) with laminar and turbulent flow without storage (quasi-steady flow according to Darcy-Weisbach / Kirchhoff = distributed pipe model).

The hybrid model approach allows the simulation of strongly anisotropic hydraulic parameter fields and was applied in a number of modeling studies presented in scientific literature (e.g. *Király*, 2002, *Liedl et al.* 2003). In these works conduit flow was simulated as quasi-steady without drainable storage.

The existing hybrid model CFPM1 provides drainable storage only by the matrix continuum, which acts slowly. However, dynamic processes like water abstraction demonstrate that additional fast-reacting storage is present; an example is the continuous conduit drawdown at the early stage of the large scale pumping test reported by *Maréchal et al.*, 2008. This fast reacting storage is assumed to be provided by solution enlarged fractures (B2), other cavities (B3), and solution enlarged pathways (C) that are directly associated (connected) to the conduit system but do not directly affect flow (i.e. they are not part of the active flow system). Figure R1 illustrates this concept. Conduit associated storage (B2 / B3 / C) is not existent in the currently available hybrid model CFPM1.

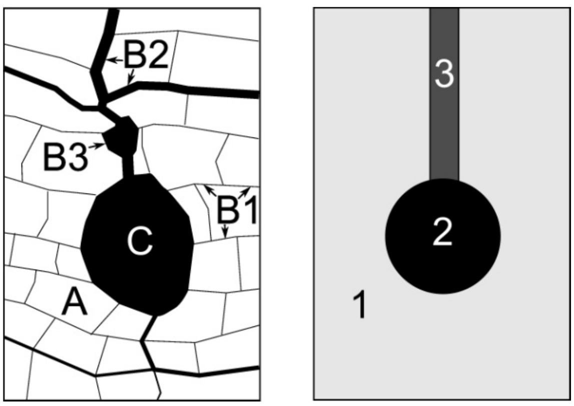


Figure R1: left: sketch of a karst aquifer with (A) fractured porous rock matrix, (B1) small fissures / fractures, (B2) large fractures, (B3) karst cavities, and (C) solution enlarged conduits. Right: Hybrid model concept with (1) = matrix and (2) = discrete conduits; (3) = Conduit Associated Drainable Storage (CADS).

Because of the direct linkage between highly conductive conduits and Conduit Associated Drainable Storage (CADS), the CADS response is instantaneous ($h_{conduit}$ = h_{CADS}, it is assumed there is no hydraulic resistance between CADS and conduits; CADS drainage can be regulated by conduit hydraulics).

The CADS volume (parameterized by the CADS width W_{CADS}) is a calibration parameter with a physical background and can be obtained, for example, from the reaction of conduit heads on hydraulic stress, e.g. start of pumping, stop of pumping, strong recharge signals directly routed in the conduits. For the given application outlook, conduit storage is provided as storage area (width x length = 1900 m^2) according to *Maréchal et al.* (2008); compare Figure 2 in *Reimann et al.*, 2013.

2) I see strong problems in 3D, as conduit storage associated with a conduit will overlap in case of multi- storey caves, thus yielding very large storage volumes by the CAD storage module, which will be unphysical to my understanding

This concern is less significant because CAD storage can be defined for the complete conduit flow system, whereas the CAD width (as input parameter) is derived by dividing the storage area by the length of the conduit system (i.e. if several conduits overlap and CADS is considered for each conduit, CADS width will be more narrow as compared to a single conduit). Further, CAD storage (i.e. W_{CADS}) can be defined for each node separately and can be deactivated (W_{CADS} = 0).

3) The intention of solving the problem this way is not explained. What special case is the model designed for? What are the assumptions used, and what are the limitations of the model?

The intention of solving the problem is previously provided, i.e. consideration of conduit associated storage (please refer to point 1). The assumptions are that this storage is hydraulically directly coupled to the conduit flow system. Actually, the model is limited as subsequently listed:

- Two storage fractions are considered: slow matrix storage and instantaneously acting conduit storage. Any hydraulic resistance between CADS and conduits is neglected.
- The conduit storage area (W_{CADS} x conduit length) is uniform with depth.
- CADS cannot consider horizontal flow (restricted on vertical drainage flow).

Beyond this, the intention of the developed conduit storage concept and the objective of our work are stated in the introduction of *Reimann et al.*, 2013.

4) Of the test cases, only the last one is of interest, the others show just preliminary steps and wrong/incomplete results and thus should be omitted. There is no verification shown for the implementation, just the effects are displayed (and not discussed and interpreted), which should be the intention of a test case. Basically, this is not a true test case, but an even more simplified application.

The development of modeling approaches requires the simulation of simplified test scenarios for better process understanding and code verification. The application on complex scenarios would not provide this information and is not the scope of this article. It should be done in further studies, e.g. to describe the effect of complex geometries on pumping test results. However, we can provide further verification and process studies if necessary.

<u>Verification test</u>

Subsequently, a simple verification test with a single conduit is described (essentially, this is only the conduit of the test setup described in section 3 / Figure 3 of the manuscript):

- Length x = 500 m, subdivided in 6 nodes, 5 tubes with radius r = 0.05 m.
- Laminar flow only with hydraulic conductivity K_c resulting from the Hagen-Poiseuille equation as 2340 m/s (for the equation refer e.g. to *Shoemaker et al.*, 2008, p. 8).
- CAD storage is considered for the upstream node only (node 1) with W_{CADS} = 0.1 m for the conduit length $L_{conduit}$ = 50 m.
- The conduit downstream boundary (node 6) is a 50 m fixed head.
- Initially 1 m^3/s upstream inflow in node 1 (= Q_0) results in an upstream head of 77.163 m respectively Δh = 27.163 m.
- Inflow stops immediately at t = 0.

Consequently, conduit heads will tend to 50 m (height of fixed head) and CADS is drained. The resulting (drainage) flow can be described by the recession function from *Maillet* (1905)

$$Q_t = Q_0 e^{-\alpha t} \qquad \text{eq. R1}$$

with

$$\alpha = \pi r^2 \frac{K_c}{W_{CADS} L_{CADS} x} \qquad \text{eq. R2}$$

Figure R2 shows the resulting recession behavior computed with Eq. R1 and CFPM1 / CADS. Both results are equal. CFP budget files account for 135.814 m^3 of water released from CADS, which is equal to W_{CADS} x L_{CADS} x Δh = *0.1 m x 50 m x 27.163 m*.

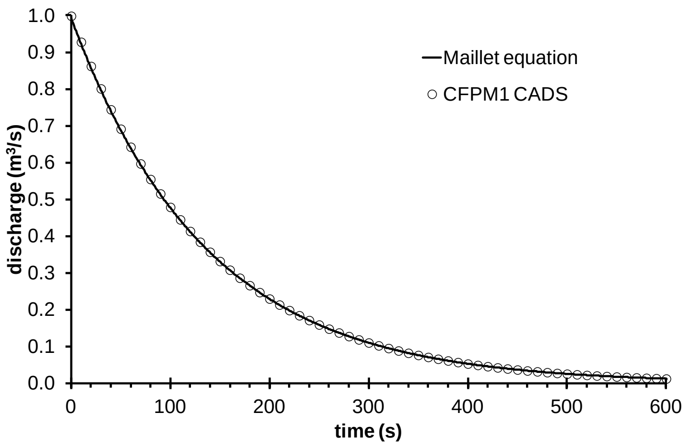


Figure R2: Verification for the CADS implementation within CFPM1.

<u>Test examples</u>

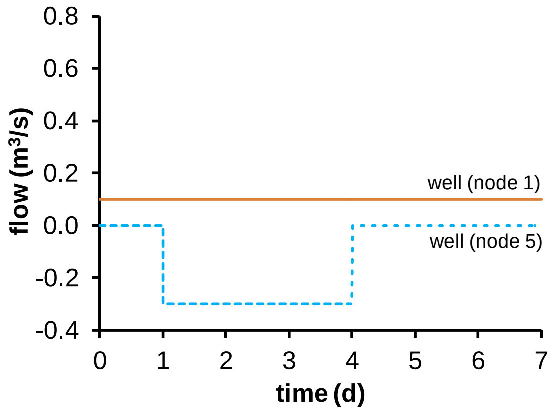
The intention of the test examples is to demonstrate the functioning of the model enhancements in a simplified (and therefore traceable) environment to allow a systematic process study. The description and discussion of the manuscript will be enhanced to strengthen our argumentation. As suggested, presentation of this part will focus on section 3.5 of the manuscript (CFPM1 with CADS and FHLQ). Results will be discussed and interpreted as subsequently listed:

- consideration of additional model results (conduit head, matrix head, flow terms),
- consideration of an additional model run without CADS for comparison.

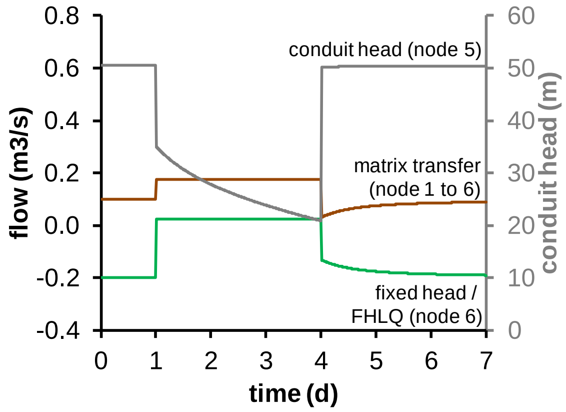
Following, a detailed interpretation / discussion of a basic model run (pumping rate 0.30 m^3s^{-1}, duration of water abstraction increased to 3 days, subsequently 3 days recovery; Figure R3):

- Pumping in node 5 results in water deficit (Figure R3 a).
- To avoid unhampered water inflow through the fixed head, the FHLQ boundary condition was applied; inflow was limited to 0.025 m^3s^{-1}; subsequently node 6 switches from fixed head to limited flow during the second day (Figure R3 b); while node 6 is a limited flow boundary, the head is no longer fixed and drawdown is possible (Figure R3 b/c).
- The existing water deficit is balanced by increased water transfer between matrix and conduit (Figure R3 b/c). The water transfer is induced by the increased hydraulic gradient between conduits and matrix continuum, resulting in conduit drawdown (equation 4 in *Reimann et al.*, 2013).
- Without CADS: the water deficit is balanced by matrix transfer only. Hence, conduit heads drop suddenly (Figure R3 b).
- With CADS: conduit drawdown results in increased water transfer and additional water release from CADS (Figure R3 c). Conduit heads change less abruptly than in the case without CADS. With ongoing pumping duration matrix transfer increases and CADS flow decreases. Finally, after a quasi steady state is reached, matrix transfer is similar to model runs without CADS (Figure R3 b/c).
- Water transfer between matrix and conduits affects matrix heads. The more water transfer is necessary (to balance an existing water deficit in the conduit) the more pronounced is the hydraulic gradient between matrix and conduit. Consequently, model runs without CADS result in a sudden drop of conduit heads that result in more distinctive matrix drawdown (Figure R3 d) because water transfer reaches the full quasi steady state amount right after water abstraction starts. Matrix drawdown for model runs with CADS consideration is delayed because the water deficit is additionally balanced by CADS flow. With ongoing time (and less CADS flow) the rate of matrix drawdown change over time is similar to models without CADS (Figure R3 e). However, the absolute difference in matrix drawdown between models with and without CADS remains constant because this is caused by the delayed water transfer in case of CADS.
- Subsequently after water abstraction is stopped (day 5, Figure R3 a, b) the model without CADS does not consider any water deficit. The FHLQ boundary at the outlet node 6 is replaced by a fixed head and conduit heads recover immediately to pre-pumping values. Conduit drawdown is no longer existent and spring flow (at node 6) is fed by matrix water transfer and water infiltration in node 1 (Figure R3 b). Because matrix heads are still lowered (Figure R3 d), water transfer from the matrix to the conduits needs some time to recover to the initial value (Figure R3 b).
- Subsequently after water abstraction is stopped (day 5, Figure R3 a, c) the model with CADS still considers a water deficit because CADS storage needs to be refilled. The water deficit is balanced by water inflow via the FHLQ boundary and matrix transfer (Figure R3 c). Conduit drawdown recovers with ongoing time in parallel with refilling the CADS. If CADS is refilled, the water deficit is no longer existent. Consequently, the FHLQ boundary switches to fixed head, flow inside the conduit is reversed and matrix transfer plus water infiltration in node 1 result in spring discharge.

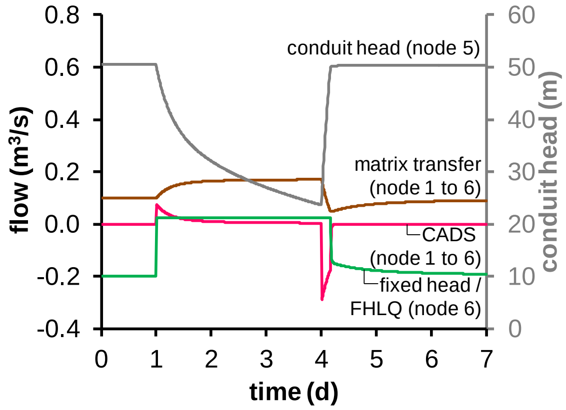
Sensitivity analyzes of CADS volume and pumping rate demonstrates the influence on conduit drawdown (see section 3.5 of the manuscript; model time discretization will be adapted in the manuscript, i.e. pumping / recovery for 3 days).



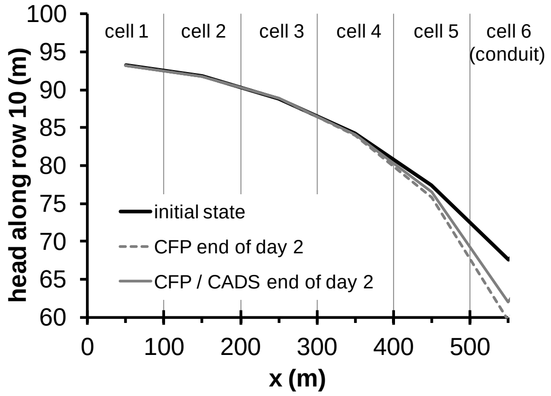
a) flow terms at node 1 (infiltration well) and node 5 (pumping well)



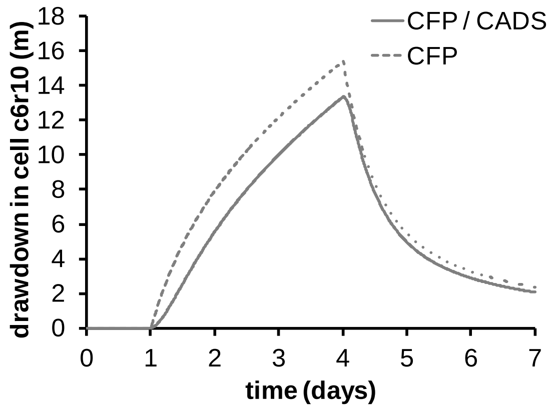
b) conduit head at node 5 (pumping well) and flow terms for CFP with FHLQ (without CADS)



c) conduit head at node 5 (pumping well) and flow terms for CFP with FHLQ and CADS



d) matrix heads along row 10 for both CFP with CADS and CFP without CADS



e) matrix drawdown over time in cell column 6 / row 10, where conduit pumping occurs

Figure R3: time series analysis of in- and outflow (a-c, negative flow indicate outflow from the conduit), matrix heads (d) for a simplified test case computed with CFP, and (e) matrix drawdown over time

This simplified model demonstrates the importance of the CADS concept:

- Without CADS, any water deficit (for abstraction scenarios) respectively water excess (for recharge events) that is not balanced by specific boundary conditions, e.g. a fixed head representing a spring, will result in an immediate change of water transfer between conduits and matrix that is directly associated with an immediate variation of conduit heads. Hence, conduit heads react instantaneously.

- Existing CADS immediately provides water (for a water deficit) respectively can store water (for water excess) and, therefore, can dampen the conduit and matrix head variation. Consequently, both conduit and matrix heads are sensitive on CADS.
- CADS results in delayed activation of matrix transfer and, therefore, delays the reaction of matrix heads. With ongoing time, when quasi steady state conditions are reached, the rate of matrix head change over time will be the same for models with and without CADS but the absolute difference in matrix heads will remain.

5) The application is over-simplified, and there is no attempt to show the measured data or all required model results (i.e. matrix heads, origin of exchange flows with time). As this field test is the actual aim of the manuscript, this is of mayor concern. The model setup is not explained completely, and the results are only shown exemplarily, not discussed. E.g. why is the exchange parameter so strongly sensitive? It seems this parameter is dominating the results completely.

Section 4 of our manuscript will be revised and enhanced. The case study (application outlook) is based on parameters that are in range of field observations. It shows that under these conditions CADS is of importance for karst hydraulics. It also provides a basis for more complex modeling set-ups and application studies, which require extended field site description and additional scenarios, e.g. different complex geometries. However, this was not the scope of our manuscript, which deals with model development and process understanding based on a simplified geometrical set-up. However, we have added an inversely calibrated model to the observed pumping test data (*Maréchal et al.*, 2008) to demonstrate the significance of the proposed CADS storage concept.

<u>Improvement of our current analysis</u>

We provide flow terms with time to discuss and interpret the sensitivity analysis more deeply, Figure R4 left. It is obvious that during the early stage of water abstraction CADS flow significantly contribute to balance the water deficit. As previously shown (Figure R3), this results in continuous conduit drawdown without an immediate head drop.

The <u>variation of CADS width</u> affects CADS flow, subsequently affects conduit-matrix transfer, and finally affects conduit and matrix heads. For example larger CADS results in increased CADS flow at the beginning of water abstraction. Consequently, the necessary amount of matrix transfer to balance the water deficit is decreased and transfer flow start with a delay, Figure R4 left. Therewith, conduit and matrix drawdown are delayed, too, respectively are decreased for the same point in time as compared to situations with fewer CADS, Figure R4 right. Analogously, reduced CADS volumes result in decreased CADS flow. Hence, the amount of matrix transfer is increased and occurs earlier to balance the water deficit. Figure R4 left. The increased amount of matrix transfer results in accelerated conduit and matrix drawdown, i.e. the drawdown at day 38 is increased as compared to the basic run, Figure R4 right.

The <u>variation of the transfer coefficient</u> affects matrix transfer and, subsequently, affects drawdown in both conduit and matrix (equation 4 in *Reimann et al.*, 2013). Contrary to CADS, the initial matrix head distribution is sensitive to the transfer coefficient because the transfer coefficient regulates transfer flow and head difference between matrix and conduits. Due to our conceptual model, the matrix is mainly drained by conduits and, therefore, the variation of the transfer coefficient is strongly affecting matrix heads.

For water abstraction scenarios, matrix drawdown is comparatively little sensitive to the transfer coefficient because the transfer coefficient determines mainly the necessary head difference between conduits and matrix. As shown in Figure 8 right of our manuscript (*Reimann et al.*, 2013), the necessary hydraulic gradient (respectively the variation due to different transfer coefficients) is mainly achieved by conduit drawdown.

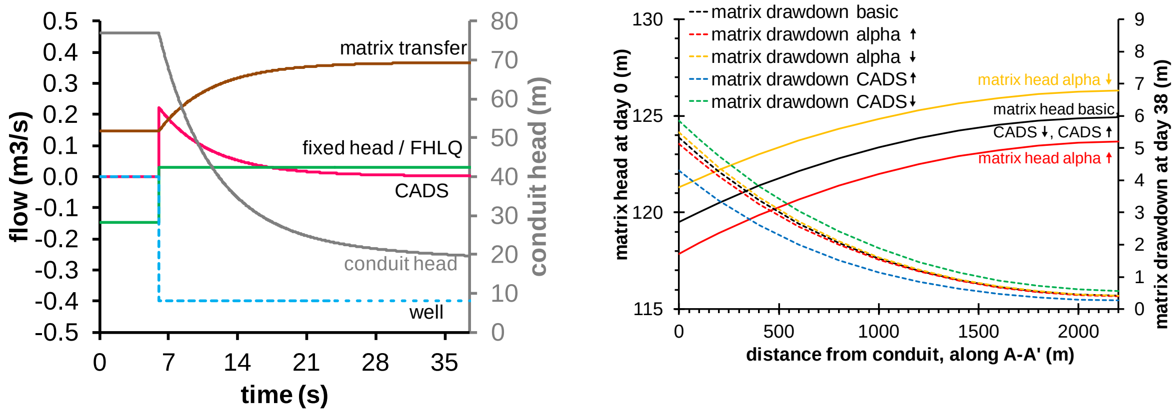


Figure R4: left: time series analysis of in- and outflow for the basic run and conduit head at the pumping well; right: matrix heads along cross section A-A' (see Figure 7 in *Reimann et al.* (2013), cross section ranges from the conduit through M1 / M2 / M3 to the catchment boundary)

<u>Comparison with measured data</u>

The current system understanding indicates that the initial situation (prior to pumping) regarding matrix heads depends on the spatial distribution of the conduit network and the acting transfer coefficient. CADS will affect matrix and conduit heads during pumping with continuous conduit drawdown. Because the pumping well is directly placed in the highly conductive conduit, the pumping rate will strongly affect hydraulics. Consequently, measured pumping rates are considered by the numerical model with a resolution of Δt = 3600 seconds. Further, during pumping the diffuse areal groundwater recharge of 200 mm per year is reduced to 10 % of the initial value because the field experiment was conducted during a dry period without recharge (*Maréchal et al.*, 2008). Here, the remaining 20 mm per year recharge is assumed as background value due to slow draining of the less conductive rock matrix.

Two model setups are automatically calibrated using PEST (*Doherty*, 2005) whereas K_m, (matrix hydraulic conductivity) S_m (matrix storage) and α (transfer coefficient) are considered as free parameters. Setup (1) uses W_{CADS} = 0.21 m and setup (2) uses W_{CADS} = 0.00. Calibration considered measured conduit drawdown at the pumping well plus matrix drawdown. Because the position of matrix drawdown relative to the conduit is unknown, only a rough estimation of Δh = 10 m with h_{ini} = 110 m (Maréchal et al. 2008) is assumed at position M2 (Figure 7).

The following parameters were obtained after calibration:

- setup (1), W_{CADS} = 0.21 m: α = 9.346E-05 m^2/s, $K_m = 3 \times 10^{-6}$ m/s, S_m = 0.0012,
- setup (2), W_{CADS} = 0.00 m: α = 3.577E-04 m^2/s, $K_m = 1 \times 10^{-6}$ m/s, S_m = 0.0008.

The resulting log-log plots of drawdown are shown in Figure R5. Considering that the aim of the simplified model is to evaluate different model concepts rather than finding a good fit, the deviation between measured and modeled heads is acceptable for setup (1). CFP with CADS is able to qualitatively describe the drawdown behavior with time for both conduit and matrix heads. A better fit of measurements could be obtained using a more realist geometry of model domain and karst conduits location.

Contrary, setup (2) is not able to represent the initial phase of the pumping test as well as the reaction of conduit heads on strong variations of the pumping rate because the model lacks CADS. This results in the already described instantaneous drop of conduit heads. The instantaneous conduit drawdown is also reflected by matrix heads at position M1, Figure R5 right. Further, setup (2) results in a larger transfer coefficient to compensate the lack of CADS by a more pronounced matrix coupling.

The resulting matrix heads prior to pumping as well as the drawdown after 38 days of pumping along the A-A' cross section are shown in Figure R6. Due to the increased transfer coefficient in setup (2), the initially existent hydraulic gradient within the matrix is more distinctive (i.e. steeper). Due to the lack of CADS, the matrix drawdown is increased, too (Figure R6).

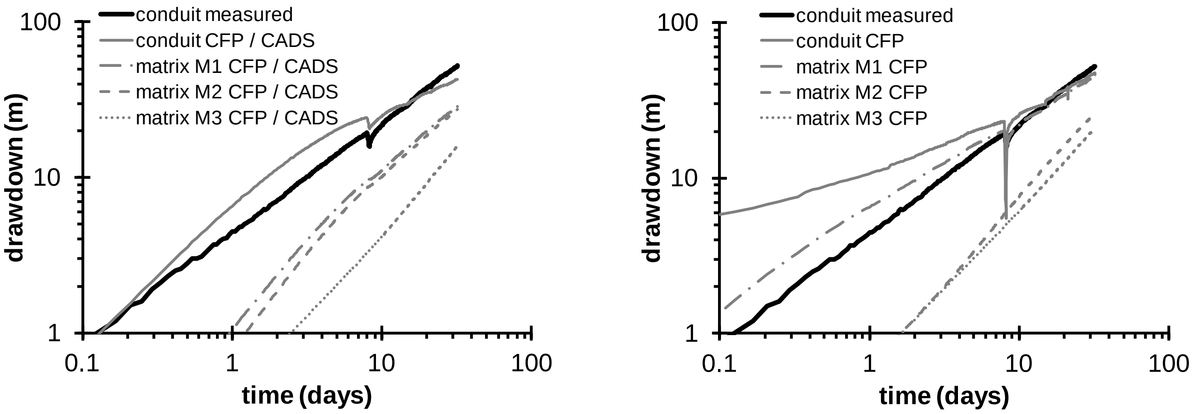


Figure R5: log-log plot of conduit and matrix drawdown; left: setup (1) with W_{CADS} = 0.21 m and right: setup (2) without CADS

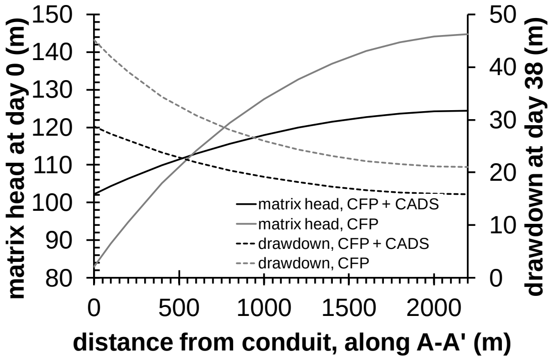


Figure R6: matrix heads along A-A' for the initial situation (prior to pumping) and matrix drawdown along A-A' at day 38.

The following conclusions can be drawn from this very simple application outlook:

- Matrix heads are sensitive to (a) the transfer coefficient, (b) the spatial distribution relative to the conduit as well as (c) the consideration of CADS (Figure R6). Consequently, hybrid models are suitable tools to characterize karst catchments with matrix and conduit head observations.
- CADS is necessary to account for the continuous drawdown of conduit heads with MODFLOW-2005 CFP. Subsequently, further methods can be used to investigate the conduit network geometry, e.g. drawdown derivative analysis and flow dimension analysis.
- Further model calibration should consider different spatial realizations of the conduit network geometry. Matrix and conduit head observations are necessary to evaluate different realizations.

There is many minor issues, which I do not list here, as they do not decide the basic issue. Thus I recommend to the authors to - make a true verification, and - conduct the field test modelling In the context of this, the model enhancements can be explained at put to use. A comparison of simulated data with measured data is required; I do not see any advancement on the Marechal paper in this work when staying just with hydraulics, so maybe including transport phenomena might bring new aspects.

Aim of the manuscript is not the evaluation of the large scale pumping test. Rather, the hybrid model CFPM1 is enhanced to consider CADS, which is important to model water abstraction scenarios like the large scale pumping test. Hence, the model can advance the analysis of the Maréchal et al. (2008) paper by considering the spatial distribution of the conduit and matrix heads. A detailed analysis of the large scale pumping test can be a forthcoming application of CFPM1/CADS.

Including transport phenomena can lead to further potential applications of CFPM1/CADS. Both heat and solute transport routines are currently implemented in CFPM1. However, the report and application of these routines is far beyond the scope of this manuscript.

As a last comment to the authors: Could it be that the same effect as with CAD could be obtained using a finer discretization of the matrix close to the conduit? This should actually yield comparable results. Following from this, a grid size sensitivity analysis of the field case is certainly required.

Our analysis demonstrates that this is not the case for our scenario, especially for the initial period of drawdown (Figure R5). However, the effect of CADS in the conduit can be achieved by CFP (without CADS) for specific parameter settings (e.g. large transfer coefficient, compare the previous section). However, such a model setup is not able to reproduce the behavior of matrix heads (Figure R4 right). For models with CADS the hydraulic gradients within the matrix are less steep, Figure R6. Hence, the spatial discretization of the matrix model is less influential.

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