Reply to Anonymous reviewer #2 (www.hydrol-earth-syst-sci-discuss.net/10/C2190/2013/)

We thank the reviewer for the critical notes and helpful suggestions on our manuscript *Reimann et al.* (2013a), subsequently noted *MANUSCRIPT*. Comments, explanations, and further analysis are placed within the provided review notes and marked by using a different font and gray color. Some points of this reply are very similar to the answers for anonymous reviewer #1 (*Reimann et al.*, 2013b, subsequently noted *REPLY#1*). For convenient reading, these answers are repeated here, too.

The submitted manuscript presents two newly developed features for the Modflow CFP karst hydrological model, namely the introduction of a storage volume associated with conduits and a type of discharge-limited boundary condition that was not previously implemented in the code. The new model features are specifically applied to test cases where water is abstracted from a karst conduit. The manuscript is for the most part clear and well-written and approaches questions of relevance to the field of karst modeling. However, the manuscript also suffers from a few shortcomings. Areas of significant concern are enumerated below, followed by some additional minor comments:

Significant concerns:

1. The conceptual model for, and physical meaning of, the "Conduit-associated drainable storage" (CADS) are unclear, particularly concerning how CADS relates to the common triple porosity conceptual model of karst. What are the volumes intended to physically represent?

REPLY#1 gives a revised description of the Conduit Associated Drainable Storage (CADS) concept, which is, for convenient reading, repeated here. 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 (REV) 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 =active pipe flow system).

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 that are directly associated (connected) to the conduit flow system but do not actively participate in pipe flow (for example formerly active flow systems that became inactive during speleogenesis). Figure R1 illustrates this concept. Conduit associated storage is not existent in the currently available hybrid model CFPM1.

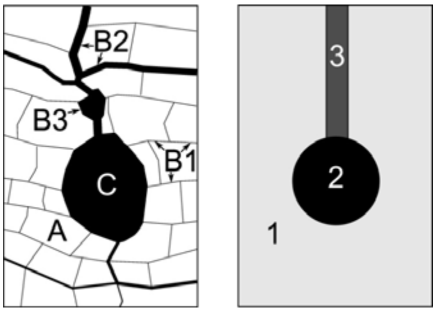

Figure R1: left: sketch of a karst aquifer (front view) with (A) porous rock matrix, (B1) small fissures / fractures, (B2) solution enlarged fractures, (B3) karst cavities, and (C) solution enlarged conduits. Right: Hybrid model concept with (1) = matrix and (2) = discrete conduits; (3) = Conduit Associated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

Because of the direct linkage between highly conductive conduits and 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 conduit head reaction on hydraulic stress, e.g. start of pumping, stop of pumping, or 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 the *MANUSCRIPT*.

In the conclusion section, it is claimed that the current model is congruent with the triple-porosity model of karst. Dual porosity models (such as CFPM1) typically consider conduits and the porous matrix. Therefore, they are missing the fracture porosity of the triple porosity model. However, in the first panel of Figure 2, it is shown that CADS represents extensions of the conduit system toward the surface. This would be part of the conduit system, and not the missing fracture porosity. As a result, the description of the model is confusing. If CADS is meant to represent fracture porosity, then it is not clear why this would only be associated with the conduit and not more broadly distributed within the matrix.

The application of dual porosity models allows the user to parameterize two continua. The definition of the two continua is done by the user. Our model simulates flow at catchment scale. At this scale, the hydraulic properties of the porous matrix and the small scale fracture network are usually merged within one continuum because an REV can be defined. Therefore, the fracture porosity is not missed in our approach. Hydraulic parameters of the REV (fissured/fractured matrix blocks) can be obtained from traditional hydraulic borehole tests (e.g. *Geyer et al.*, 2013). The discrete pipe model describes the properties of solution enlarged highly permeable conduits and directly associated storage (CADS).

CFPM1 considers conduits in terms of active flow systems (i.e. a porosity of 1 is accounted for flow velocities). However, due to the underlying computational framework with quasi-steady hydraulics, CFPM1 cannot consider storage associated with conduits. In reality, this storage can be provided, for example, by extensions of the conduit system, solution enlarged fractures or other cavities as previously discussed. Figure 2 of the *MANUSCRIPT* is a conceptual representation of the field setting from *Maréchal et al.* (2008), where the conduit extensions are not part of the active flow system and, therefore, can be considered by CADS. However, in order to clarify our manuscript, this part of Figure 2 will be replaced by Figure R1.

Along similar lines, the model is motivated by a need to damp the responses to pumping (or likely other forcing, such as recharge events). However, it's not clear to me that such damping observed in nature is not a result of fracture and matrix interactions. Perhaps this is discussed in Maréchal et al. (2008), but it would be useful to briefly discuss it here as well.

The large scale pumping test demonstrates that for early times water is provided by "karst conduit" storage. This can be analyzed by drawdown derivative analysis (*Bourdet*, 1989; *Maréchal et al.*, 2008; *Renard et al.*, 2009). The drawdown derivative is computed as

$$s' = \frac{\partial s}{\partial \ln t} \qquad \text{eq. R1}$$

with s' drawdown derivative, s drawdown, and t time (further details in *Bourdet*, 1989).

The resulting slope of drawdown and drawdown derivative on a log-log plot is equal to 1. This analysis will be added to the simple model study in section 3 of the MANUSCRIPT to demonstrate the different behavior of drawdown and drawdown derivative for situations with and without CADS, Figure R2.

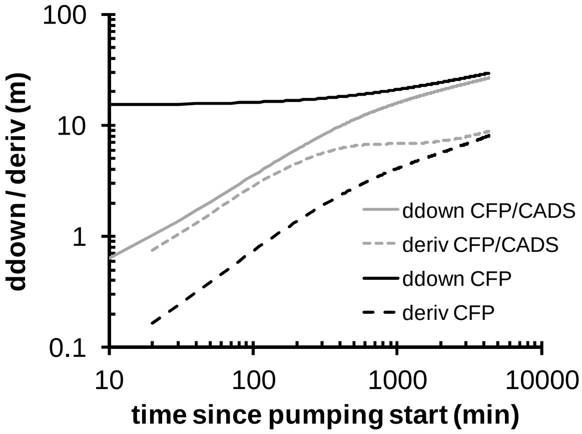

Figure R2: Drawdown and drawdown derivative for the simple model study for model representations with and without CADS.

This unit-slope drawdown / drawdown derivative is present during 1000 minutes of the large scale pumping test, i.e. for early times (Figure 6 in *Maréchal et al.* 2008). Hence, we assume that an instantaneous storage component ("karst conduit storage") is existent. Regarding its duration (1000 minutes), it cannot be the wellbore storage, but storage in karst conduits. This storage component is represented by CADS. Further evidence for the existence of such a fast storage is provided by rapid variations of hydraulic stresses, for example pumping stops that result in an almost instantaneous recovery of conduit heads (*Maréchal et al.*, 2008). For conduit flow, these variations of hydraulic stresses have been perfectly simulated using a double reservoir model including storage in the conduit network (Figure 10 in *Maréchal et al.* 2008). However, the model did less satisfactory simulate matrix drawdown due to the lumped model approach that neglects spatial properties of the matrix and piezometer locations relative to the conduit.

To what extent can similar damping be produced by conduit-matrix-fracture exchange? What features distinguish conduit-matrix interactions and this direct kind of storage?

Technically, it is possible to produce very similar damping of conduit heads with variation of conduit-matrix transfer and matrix parameters (porosity and hydraulic conductivity). However, if storage is provided by the fissured / fractured matrix only, the necessary model parameters result in a different matrix drawdown behavior that is not likely (enormous gradients within the matrix and massive drawdown). Analysis for the large scale pumping test from *Maréchal et al.* (2008) (section 4 of the *MANUSCRIPT*) is provided by *REPLY#1* and gives further explanation. For convenient reading of this text, some results are provided in Figures R3 and R4; conduit drawdown derivatives are additionally computed for early times.

Further, if only conduit-matrix-fracture exchange is existent, conduit heads react instantaneously on hydraulic stress, for example start or stop of pumping. The resulting slope of the drawdown and drawdown derivatives on a log-log plot is not congruent with a unit slope. In case of CADS slopes of both drawdown and drawdown derivative (log-log) are 1 (Figure R3). The reaction on pumping stops is also present in Figure R3 (around 11 500 minutes after pumping start) where the model without CADS computes an instantaneous drawdown recovery.

In conclusion, there are two substantial drawbacks in case conduit head damping is produced by conduit-matrix transfer only:

(1) The early drawdown behavior cannot reflect field measurement because “karst conduit” / well-bore storage is not existent. Rather, this storage is provided in the model by the matrix (via matrix–conduit water transfer). This matrix storage can be fast if adequate parameters are used. But matrix storage cannot be instantaneous because a hydraulic gradient between conduits and matrix is necessary to induce water transfer. Hence, conduit heads react with a more or less sudden reaction on hydraulic stress. The unit slope of drawdown and drawdown derivative is not present (Figure R3).

(2) Because fast storage is provided by the matrix, the model can hardly reproduce the matrix head reaction on hydraulic stresses (Figure R4).

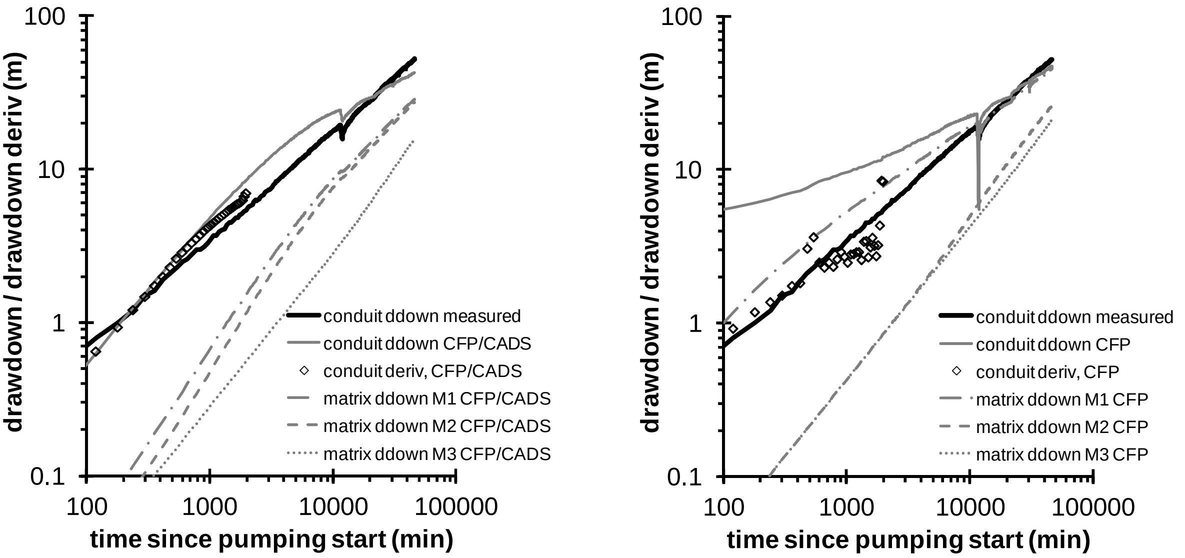

Figure R3: log-log plot of conduit / matrix drawdown and conduit drawdown derivatives since pumping start for the large scale pumping test scenario; left: setup (1) with W_{CADS} = 0.21 m and right: setup (2) without CADS;

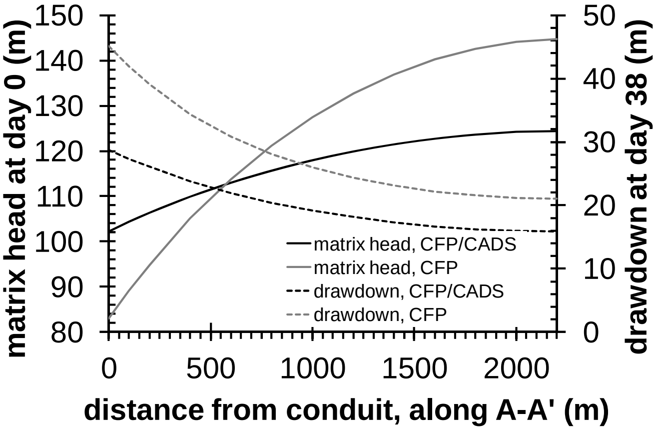

Figure R4: matrix heads along A-A' for the initial situation (prior to pumping) and matrix drawdown along A-A' at day 38 (see Figure 7 of the *MANUSCRIPT*; cross section A-A' ranges from the conduit through M1 / M2 / M3 to the catchment boundary; Figure 7 will be redrawn accordingly).

Another area of concern is that the mathematical nature of the model (whereby storage is immediately connected to the conduit) requires that the conduit be directly connected to a free surface (i.e. the water table). However, it's not clear how common or extensive this type of connection may be in phreatic systems. The mathematical model, at least as described, also allows extension of storage above the ground surface if conduit heads are sufficiently high. Since this occurs relatively frequently in karst systems, this limitation should at least be acknowledged.

We agree to this concern that results from the actual consideration of CADS without vertical differentiation (i.e. CADS is uniform along elevation). Actually, CADS is not limited by the ground surface. Future model development will consider this; CADS width will be variable along height so that a user can define W_{CADS} for each elevation, for example W_{CADS} is zero above the ground surface. For the moment we will add this limitation to our model description. (Note: model results presented in the *MANUSCRIPT* and the *REPLIES* are not affected by this limitation.)

2. The manuscript could be significantly strengthened by adding a discussion of how the CADS model relates to other previous models. For example, CADS is presented as an alternative to the more computationally intensive model for full pipes/open channels presented in Reimann et al. (2011). How successful is the new model at mimicking features of open channel drainage?

These models are not comparable. In case of free surface hydraulics, parameters like discharge area and wetted perimeter are variable. CFPM1 hydraulics represents only filled pipes. Water stored in the CADS is assumed to be immobile and, therefore, not accounting to lateral flow. Consequently, the flow resistance compared to an equivalent free surface channel is higher and more immobile water is stored in the CADS. A much more pronounced damping will result for CFPM1 with CADS.

Also, many previous workers have used linear and non-linear types of reservoir models that seem related to the storage model presented here (e.g. Mangin, 1905; Halihan and Wicks, 1998; Geyer et al., 2008; Covington et al. 2009). However, the similarities and differences between the dynamics of the CADS model and these conduit/reservoir models are not discussed. This relates back to my confusion about the conceptual model, as it is not completely clear what CADS is meant to represent physically.

CFPM1 with CADS represents a discrete pipe model coupled to a matrix continuum whereas pipe flow can be laminar or turbulent, depending on flow velocity. Often used lumped parameter modeling approaches do not consider a distributed hydraulic parameter field, e.g. *Maillet* (1905), *Geyer et al.* (2008), *Maréchal et al.* (2008) and others. *Halihan and Wicks* (1998) present a model approach of pipes that connect reservoirs to represent conduit-flow aquifers, i.e. matrix properties are not considered. Any reservoir flow results in instantaneous change in water level due to the missing water transfer with a matrix. Flow in the pipes is governed by smoothly turbulent flow equations. Hence, this model approach is similar to CFPM1 with CADS but lacks the distributed interaction with the matrix as well as the velocity dependent flow equations (laminar / turbulent flow). *Covington et al.* (2009) presented physically more enhanced representations of single karst network elements like full pipes, open channels and reservoirs. However, a primary limitation of this model is that it is only applied to single karst network elements without the consideration of matrix interaction. This analysis will be added to the introduction of our manuscript to provide insight into the demand of the model approach.

3. A new numerical feature of CFPM1 is introduced, and a few test cases are run, but no cases are run where results could be confirmed independently (i.e. by comparison to analytical solutions or other numerical models). Perhaps such tests were done, but it would be good if the results were at least briefly reported.

Please refer to the verification test presented in *REPLY#1*. There, CFPM1 with CADS is compared with the *Maillet* (1905) equation resulting in an excellent fit.

4. The extension of the model is relatively modest. While CADS is new, the new boundary condition has been implemented and/or discussed by other authors. The manuscript also presents relatively brief results from a few example cases. A more general discussion of the dynamics of the CADS model would be beneficial. One idea would be, instead of just presenting hydrographs, to plot some quantities representing hydrograph features (such as amount of damping) as a function of model parameters (such as storage volume width or matrix exchange coefficient).

A more general discussion of effects from CFPM1 with CADS on karst dynamics is given by *REPLY#1*. There, the variation of flow terms along time as shown in Figure R5 is discussed in detail. As suggested, we add this analysis to the case study of the *MANUSCRIPT* (section 4 “Case study”; further explanation of the model setup and the parameter variation is given there).

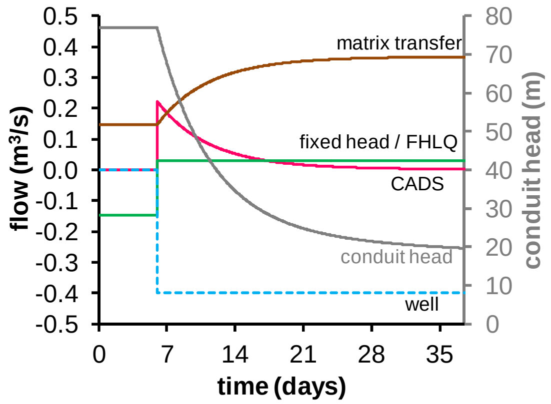

Figure R5: flow term variation with time for the initial model setup of the large scale pumping test scenario (see *MANUSCRIPT* and *REPLY#1;* pumping starts at day 6).

Variation of water transfer:

In comparison to CADS width, the variation of the transfer coefficient α is less influential to flow terms (matrix transfer and CADS), which only slightly vary, Figure R6 left. If α is increased, the following behavior results:

- smaller hydraulic gradient between matrix and conduit is necessary to result in similar water transfer. Consequently, conduit drawdown is reduced, Figure R6 left.
- Further, the increased α results in slightly more water transfer during pumping and, consequently, in slightly reduced CADS flow because the absolute flow to balance the water deficit (CADS + water transfer) remains constant.

If α is decreased, the behavior is reversed:

- increased hydraulic gradient between matrix and conduit with increased conduit drawdown.
- Slightly reduced matrix transfer and slightly increased CADS flow.

Variation of CADS width:

The variation of the CADS width W_{CADS} is influential to flow terms and conduit drawdown. If W_{CADS} is increased, the following behavior results:

- Outflow from CADS is longer available and, therefore, matrix water transfer increase is delayed because the absolute flow to balance the water deficit (CADS + matrix water) remains constant, Figure R6 right.
- The conduit drawdown with time develops more slowly because matrix water transfer is reduced. However, with ongoing time conduit drawdown tends to a value, which is not affected by CADS. Rather, the final conduit drawdown is depending from the water transfer coefficient, as previously discussed.

If CADS is reduced the behavior is reversed:

- CADS outflow declines faster with simultaneously increasing matrix water transfer. Consequently, conduit drawdown is accelerated.

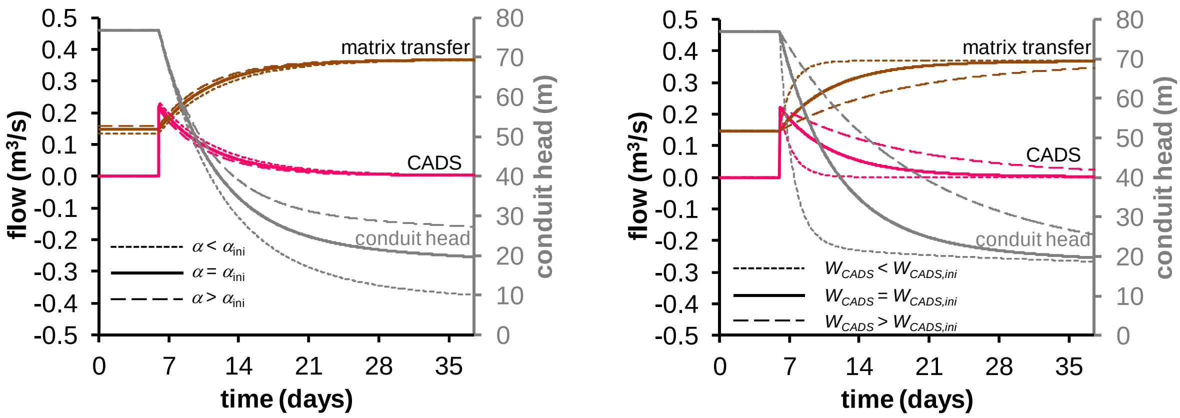

Figure R6: Flow terms variation with time; left) variable water transfer α; right) variable CADS width W_{CADS} (pumping starts at day 6)

Minor points:

1. Is the new code publicly available?

The executable together with an extensive documentation is available on our webpage:

http://www.tu-dresden.de/die_tu_dresden/fakultaeten/fakultaet_forst_geo_und_hydrowissenschaften/fachrichtung_wasserwesen/igw/forschung/downloads/cfpv2

2. Equation 3 is not what I have normally seen referred to as the Colebrook-White equation, but rather a combination of the Colebrook-White equation for the Darcy-Weisbach friction factor and the Darcy-Weisbach equation.

We will correctly refer to this equation as combination of the Darcy-Weisbach equation with the Colebrook-White equation.

All following minor points will be considered for a revised manuscript.

3. final sentence, section 2.1, “whereas” should be “where”

4. page 4474. What is “constantly increasing drawdown?” confusing wording

5. next sentence. “Respectively” is used incorrectly. “Or” might work.

6. pg. 4475. confusing wording. “only little water”

7. Table 1. Would be good to explain what the arrows mean.

8. Fig 3. “respectively” used incorrectly

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