TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Environmental Sciences Institute for Groundwater Management

Addition and Enhancement of Flow and Transport processes to the MODFLOW-2005 Conduit Flow Process

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Motivation

Intended model use

Karst characterization – artificial signals

Cent Fonts catchment, South France

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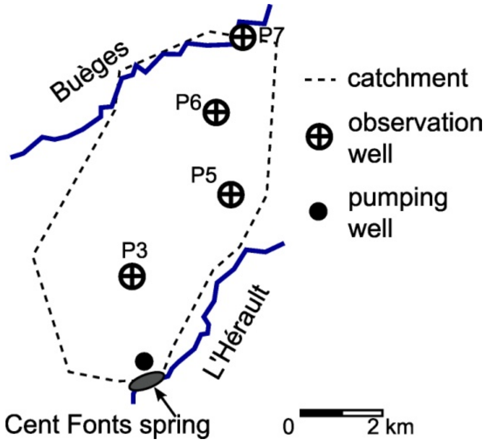

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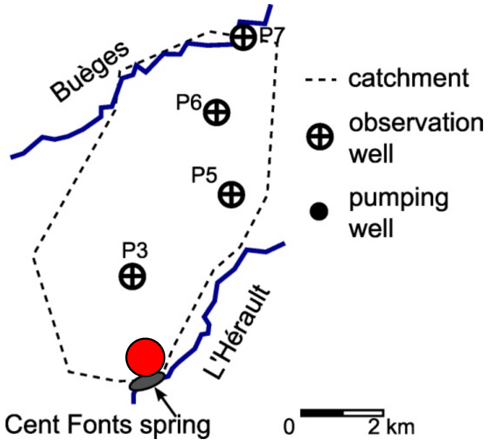

● pumping well

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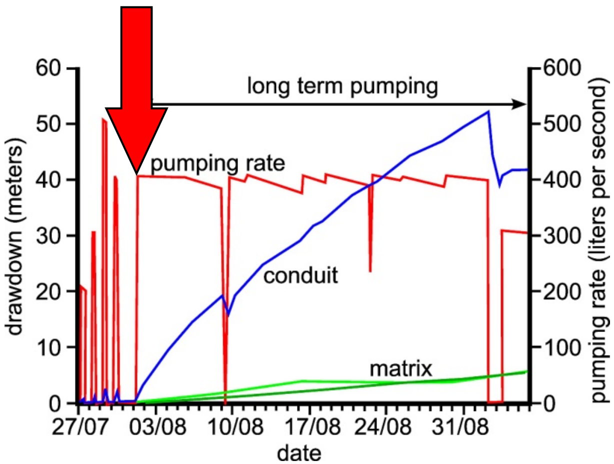

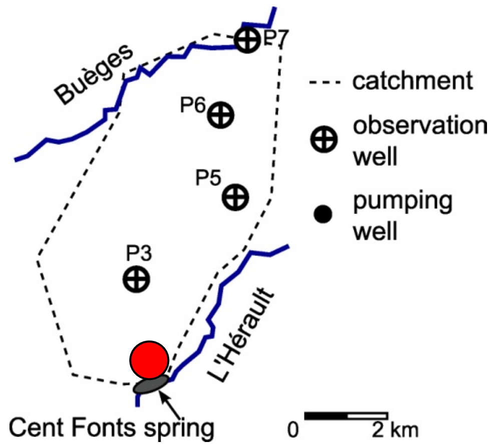

Data: Maréchal et al. 2008 a

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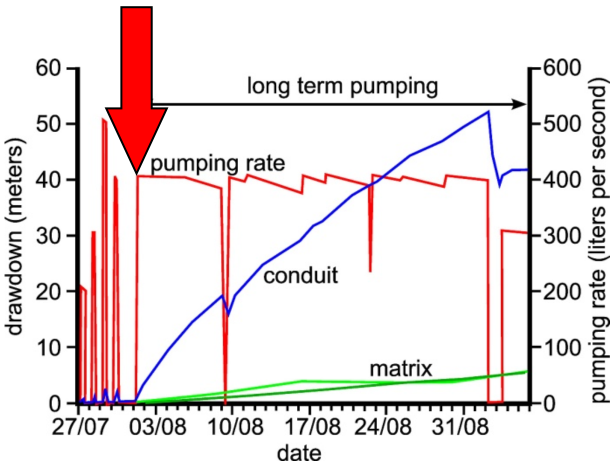

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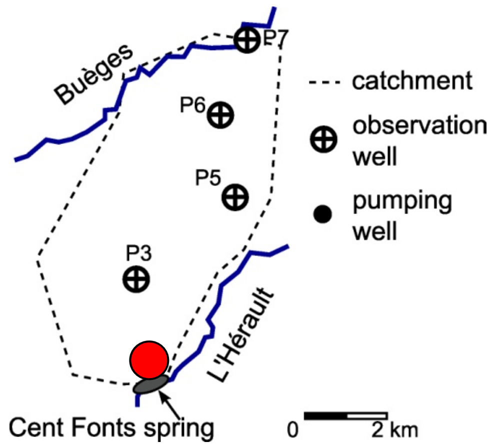

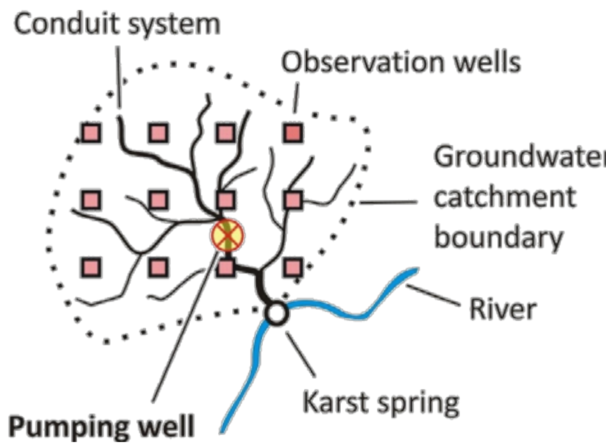

Geyer 2008

● pumping well

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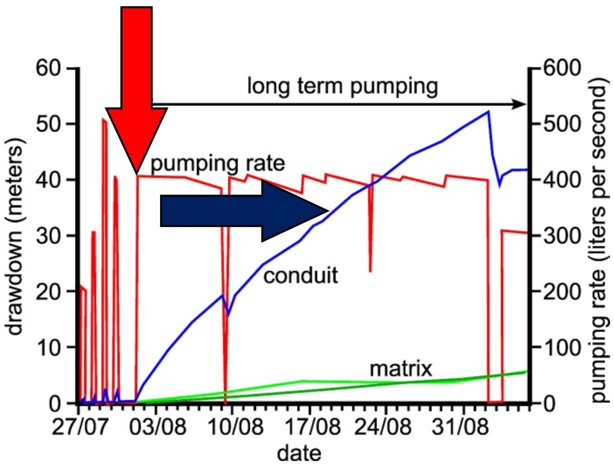
Intended model use

Karst characterization – artificial signals



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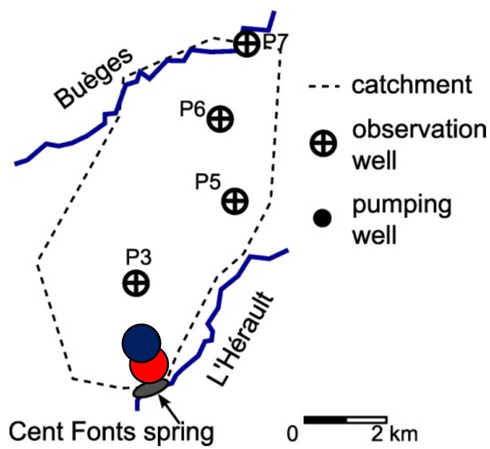
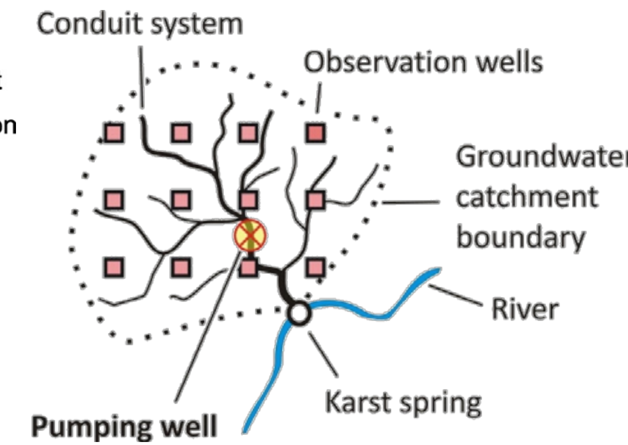




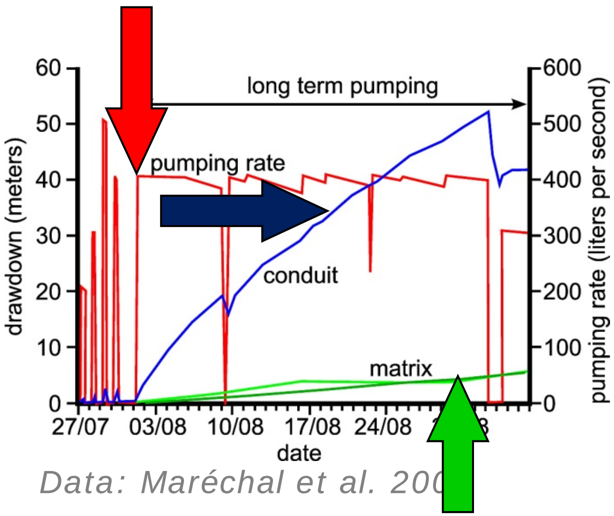
Geyer 2008

- pumping well
- conduit head observation

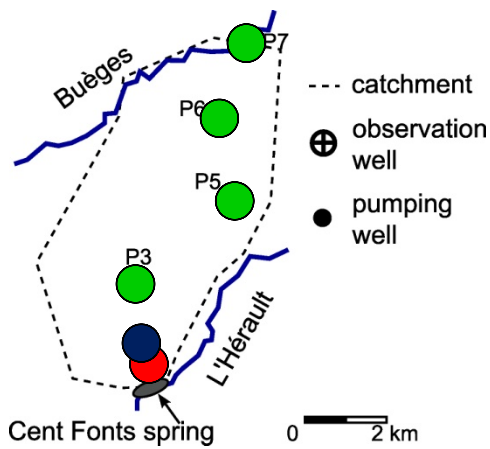
Motivation

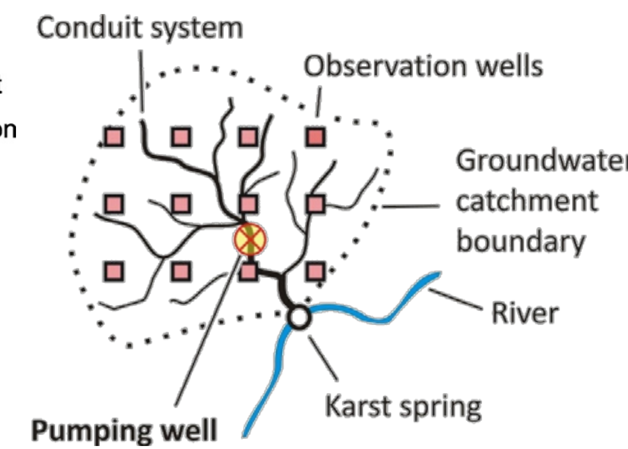
Intended model use

Karst characterization – artificial signals



Data: Maréchal et al. 200





Geyer 2008

- pumping well
- conduit head observation
- matrix head observation

Outline

1. Initial situation

2. Flow enhancements

    boundary conditions

    conduit storage

3. Transport enhancements

    solutes

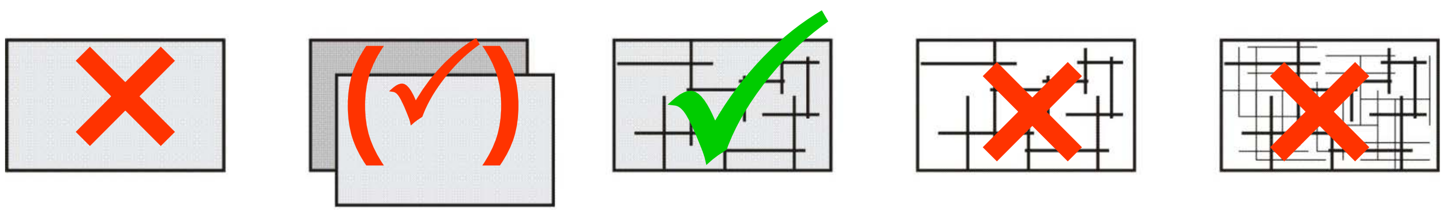
    heat

4. Conclusion

1. Initial Situation

Model approaches

SCPE	DCPE	HM	DSFS	DMFS
Single Continuum Porous Equivalent	Double Continuum Porous Equivalent	Hybrid Model	Discete Single Fracture Set	Discete Multiple Fracture Set



Deterministic Approach ⟶ Stochastic Approach

small ⟶ Investigation Effort ⟶ high

high ⟵ Practical Applicability ⟵ small

limited ⟶ Capability to Simulate Heterogeneities ⟶ good

(from Teutsch and Sauter 1991)

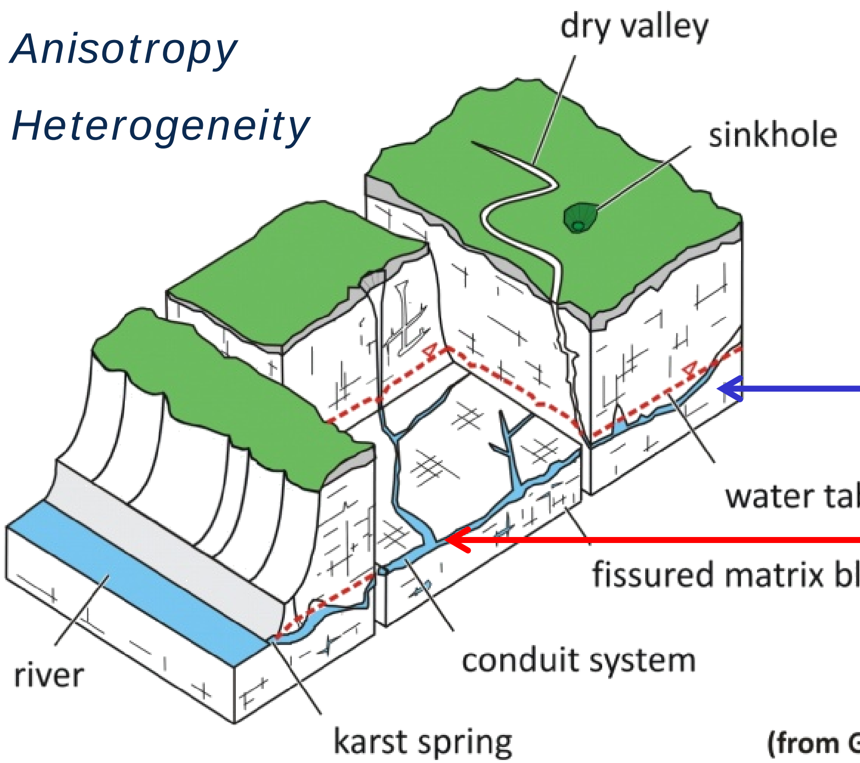
1. Initial Situation

Hybridmodels

Concept

Anisotropy

Heterogeneity



(from Geyer 2008)

Fractured porous rock matrix:

- low conductivity/large storage
- **linear flow (laminar)**

Karst conduits:

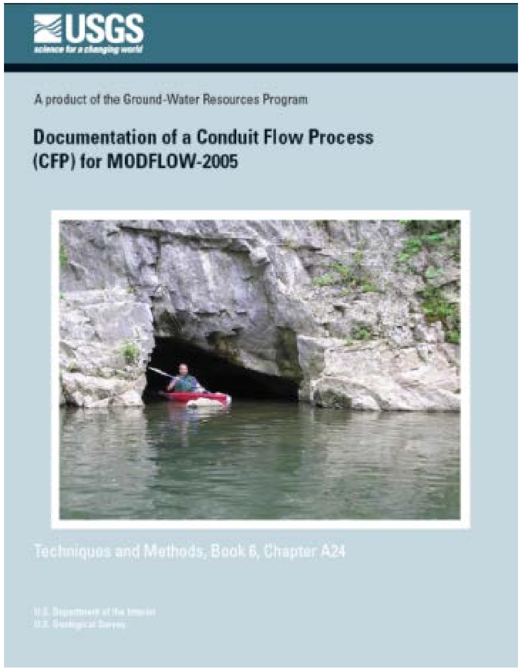
- large conductivity/low storage
- linear/**nonlinear flow (turbulent)**

1. Initial Situation

Hybridmodels

MODFLOW-2005 Conduit Flow Process (CFP)

- Freely available hybrid model CFP Mode 1 (CFPM1)
- CFPM1 considers discrete pipe networks
- coupling to MODFLOW-2005
- no transport processes
- Shoemaker et al. 2008: USGS TM 6 / A14

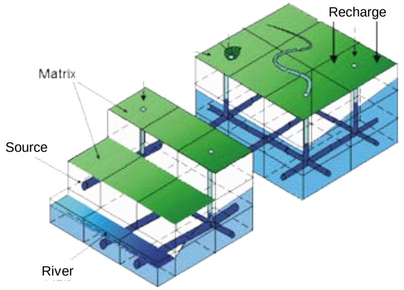


1. Initial Situation

Hybridmodels

CFPM1 hydraulics

→ laminar and turbulent flow in discrete pipes



Karst aquifer scheme (Bauer 2002)

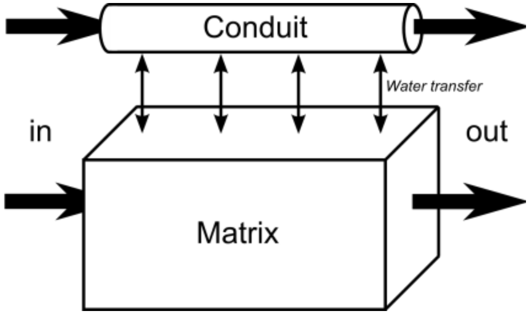
Matrix $$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)\pm W = S_S\frac{\partial h}{\partial t}$$

Conduit system

laminar $$v = -\frac{d^2}{32}\frac{g}{\nu}I$$ *Hagen Poiseuille*

turbulent $$v = 2log\left(\frac{k_c}{3.71d}+\frac{2.51\nu}{d\sqrt{2gdI}}\right)\sqrt{2gdI}$$ *Colebrook-White*

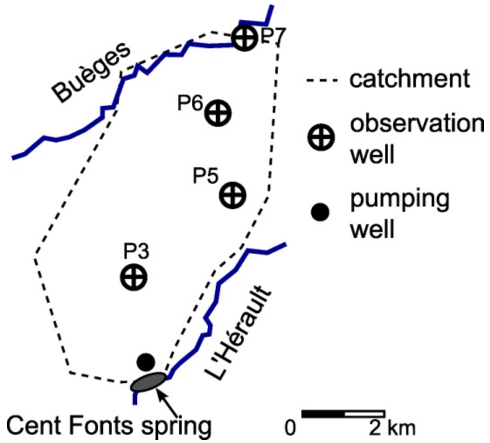
Transfer $$Q_{ex} = \alpha_{ex}(h_c - h_m)$$



1. Initial Situation

CFPM1 application

Large-scale pumping test (Maréchal et al., 2008)



some available data (e.g. Maréchal et al. 2008)

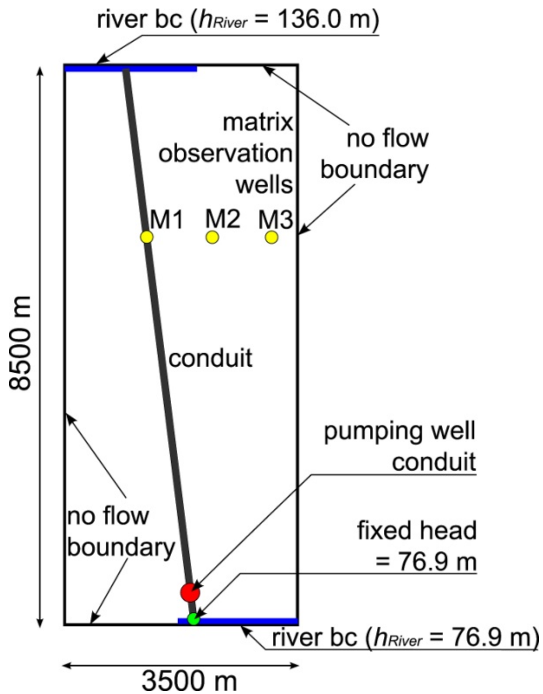
- conduit diameter ~ 3.5 m
- T_{matrix} 1.6E-5 m^2/s
- S_{matrix} 0.007
- Bueges loses ~ 0.015 m^3/s
- Herault inflow during pumping ~ 0.030 m^3/s
- and more ...

1. Initial Situation

CFPM1 application

Large-scale pumping test (Maréchal et al., 2008)

Conceptual model



some model characteristics

- fully filled pipes interacting with matrix
- uniform, straight conduit, diameter = 3.5 m
- 90 pipes / 91 nodes (conduit)
- spring represented by fixed head boundary
- K_{matrix} 9E-6 m^2/s; S_{matrix} 0.007
- 100 m x 100 m cells (matrix)
- pumping with 400 liters per second from the conduit
- transient MODFLOW computation

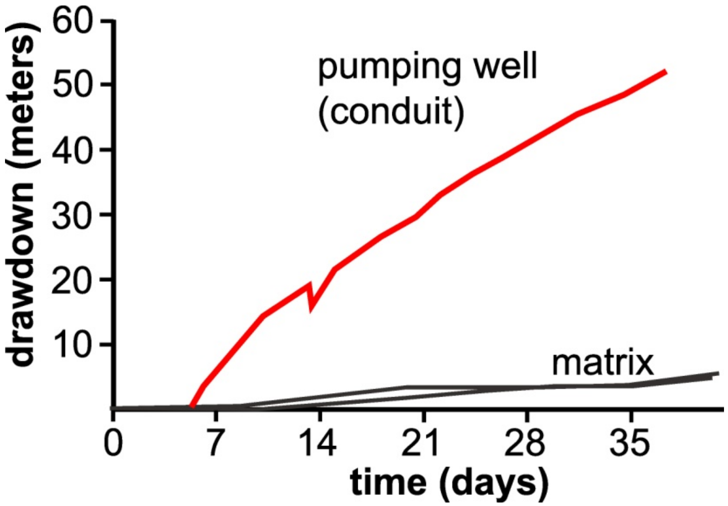
1. Initial Situation

CFPM1 application

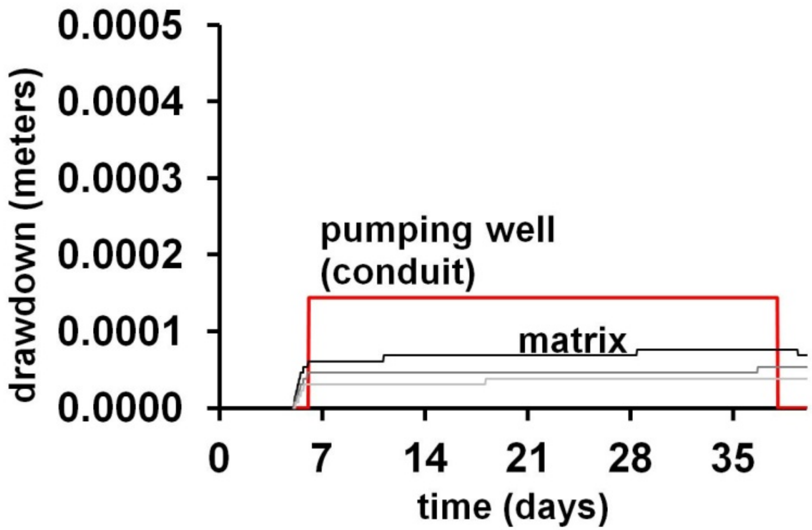
Large-scale pumping test (Maréchal et al., 2008)

Initial results

observed



computed



→ no significant drawdown; unhampered water inflow through fixed head

Outline

1. Initial situation
2. **Flow enhancements**
    - boundary conditions
    - conduit storage
3. Transport enhancements
    - solutes
    - heat
4. Conclusion

2. Flow enhancements

Boundary conditions

New Implemented

Fixed Head / Limited Flow (FHLQ)

- user defined flow threshold (e.g. limited inflow)

$$FHLQ = \begin{cases} h = H, & Q \leq Q_L \\ Q = Q_L, & \text{else} \end{cases}$$

H = fixed head value
Q_L = limiting flow threshold

Bauer et al. 2005

Cauchy

- head dependent flow (e.g. river)
- user defined flow threshold

$$Q_{cy} = c_{cy}(h - h_{cy})$$

c_{cy} = *Cauchy conductivity*
h_{cy} = *Cauchy head (e.g. river)*

Limited head

- temporarily fixed head (e.g. flooded sinkholes)

$$h_{LH} = \begin{cases} h\ computed\ (node\ is\ free\ flow), & h \leq H_{LH} \\ h = H_{LH}\ (fixed\ head\ boundary), & \text{else} \end{cases}$$

H_{LH} = limiting head

Fixed flow

- prescribed in- or outflow (e.g. well)

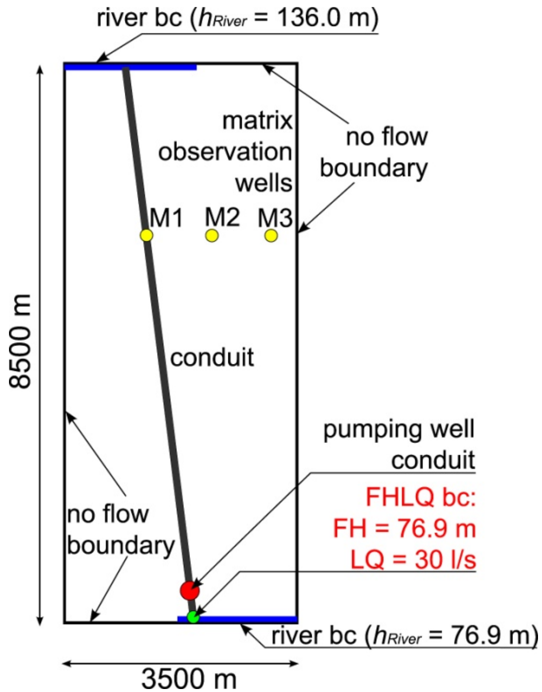
→ user friendly (input files, budgets, transport processes)

→ time dependent input possible (time series)

2. Flow enhancements

CFPM1 application – adaptation boundary conditions

Large-scale pumping test (Maréchal et al., 2008)



model enhancement:

- FHLQ boundary at the spring
- water abstracting through well boundary

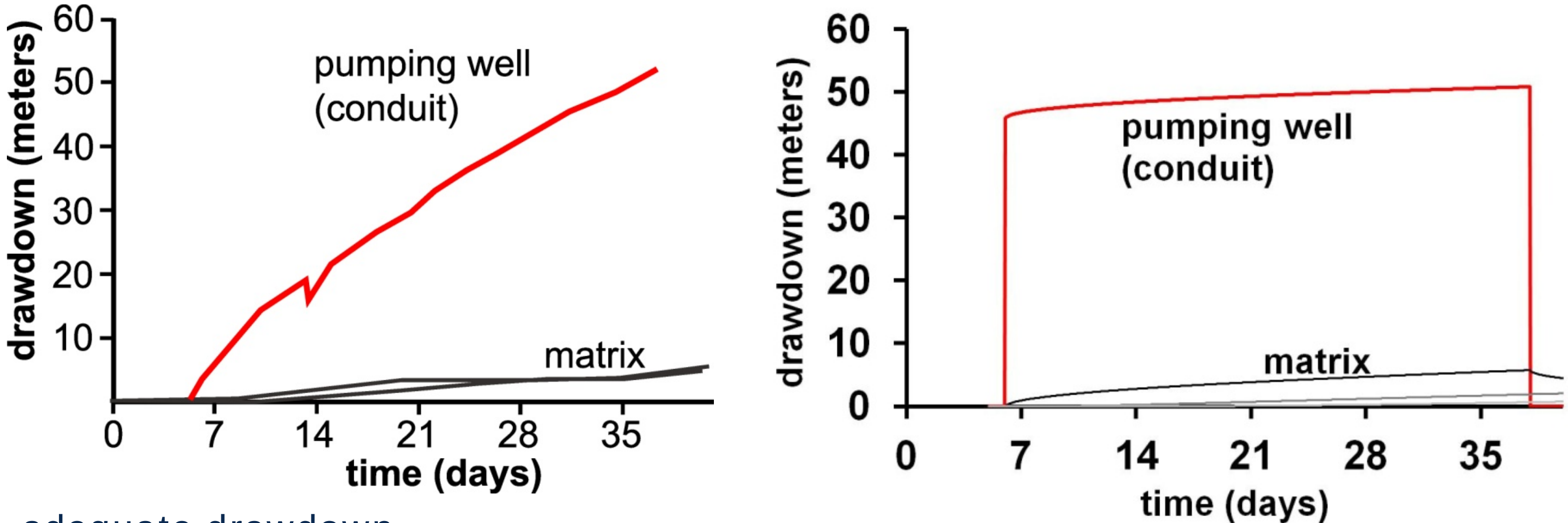
2. Flow enhancements

CFPM1 application – adaptation boundary conditions

Large-scale pumping test (Maréchal et al., 2008)

Intermediate results

observed *computed*



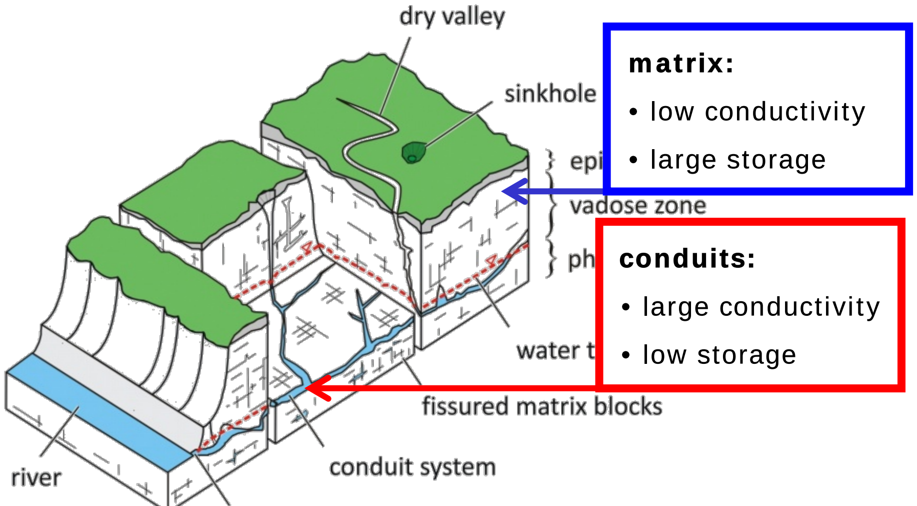
- adequate drawdown
- temporarily behavior not reflected (quasi-steady hydraulics in the conduit)

2. Flow enhancements

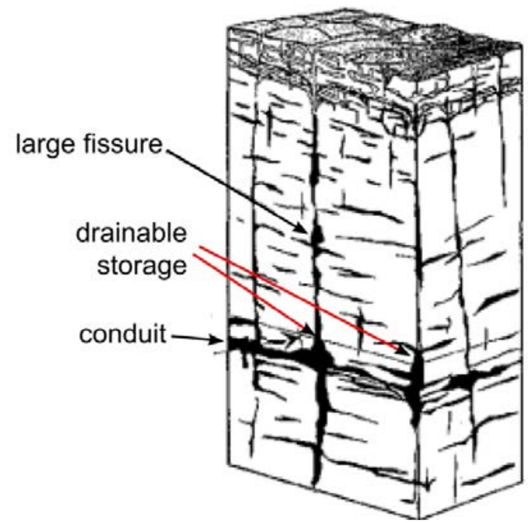
Conduit storage

Concepts

- actually: storage mainly provided by the matrix
- new suggestion: additional (fast reacting) storage associated with conduits (e.g. large fractures, voids, caves)



(from Geyer 2008)



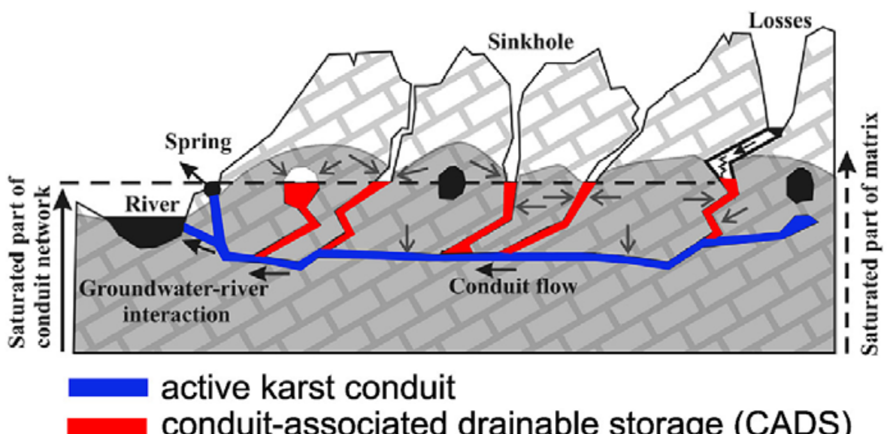
from Renner 1996

2. Flow enhancements

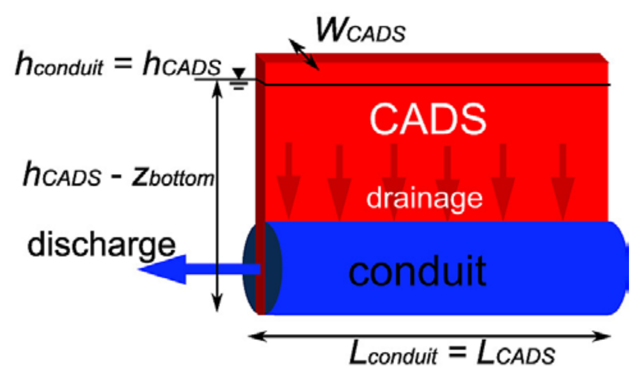
Conduit storage

New concept - implementation

- Conduit Associated Drainable Storage – **CADS**
- fully implemented in CFPM1 routines
- one additional parameter: CAD storage width W_{CADS}



Maréchal et al. 2008



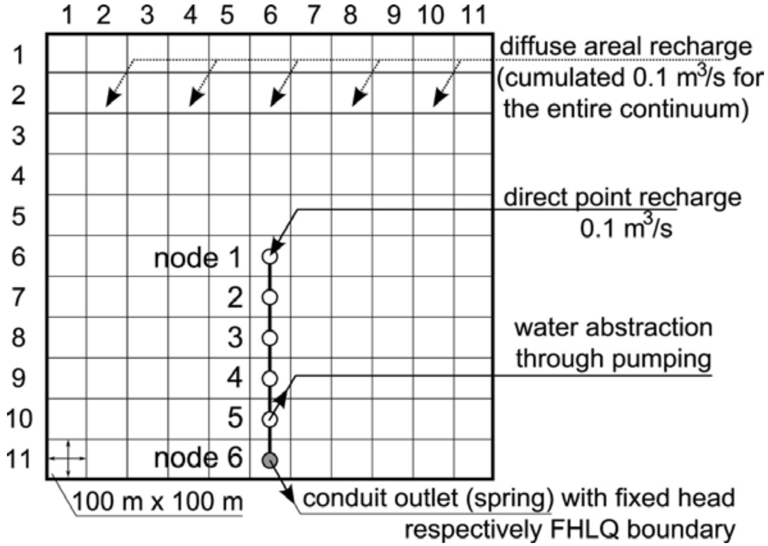
$$V_{CADS} = L_{CADS} W_{CADS} (h_{CADS} - z_{bottom});\ h_{CADS} > z_{bottom}$$

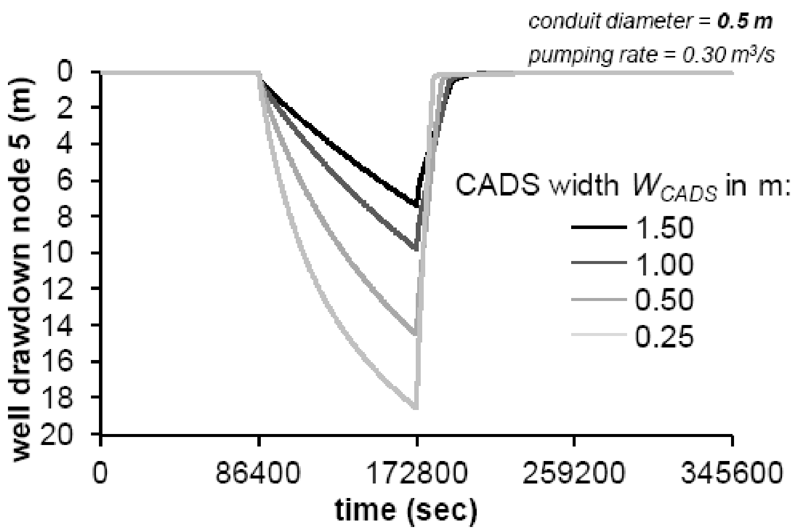
$$Q_{CADS} = \frac{V_t - V_{t-\Delta t}}{\Delta t}$$

2. Flow enhancements

Conduit storage

Functionality - testing



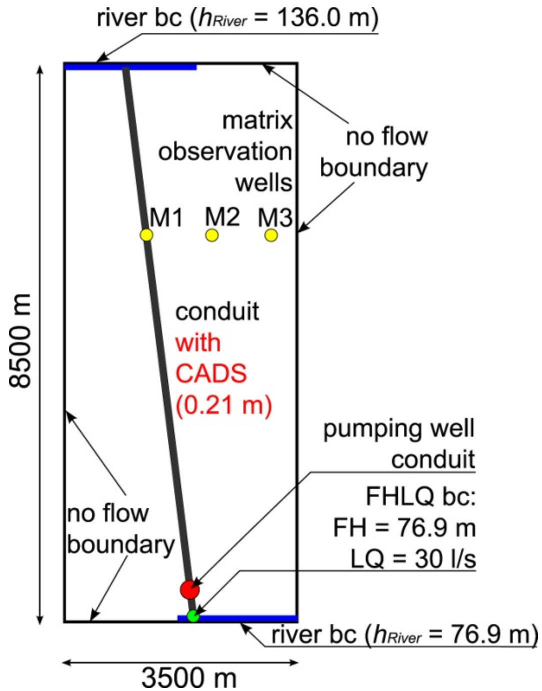


- CADS results in damping

2. Flow enhancements

CFPM1 application – conduit storage

Large-scale pumping test (Maréchal et al., 2008)



Model enhancement:

- FHLQ boundary at the spring
- pumping with well boundary
- conduit with CADS
- W_{CADS} **= 0.21 m** (from Marechal et al. 2008)

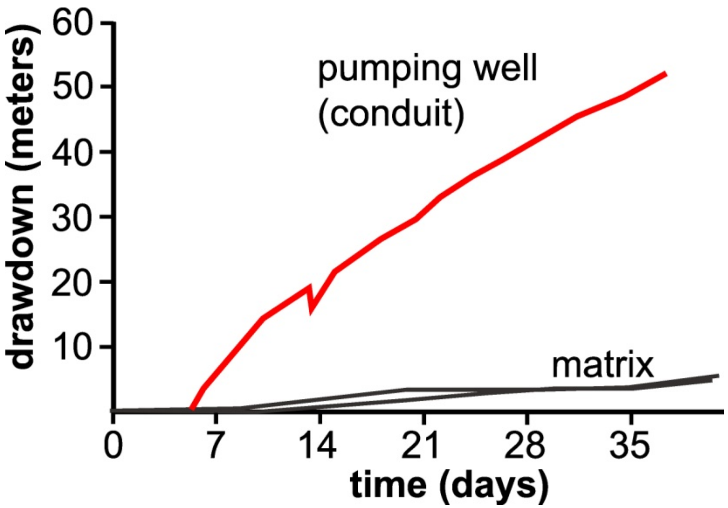
2. Flow enhancements

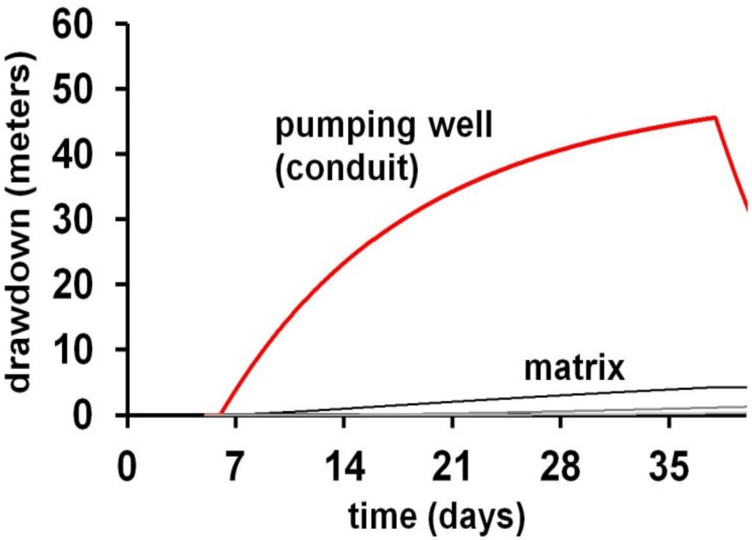
CFPM1 application – conduit storage

Large-scale pumping test (Maréchal et al., 2008)

Results

observed *computed*





- model (not calibrated) results in adequate drawdown / temporarily behavior
- catchment scale modeling is ongoing work

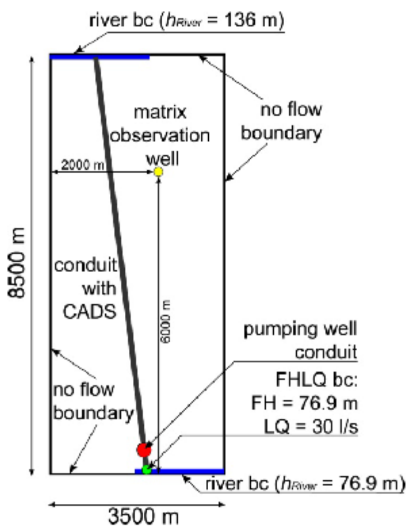
2. Flow enhancements

CFPM1 application – outlook

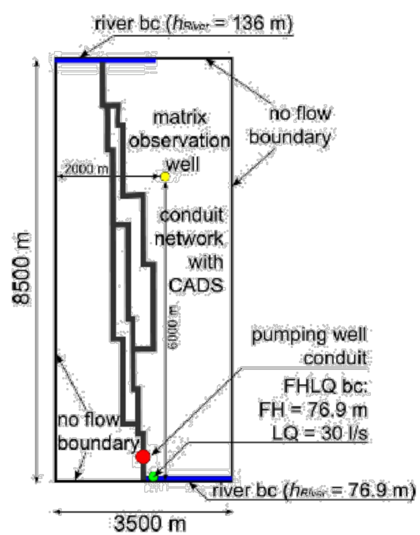
Inverse modeling / PEST

- example: different realizations for the conduit geometry
- adjustable parameters: K_{matrix}, S_{matrix}, α_{ex}

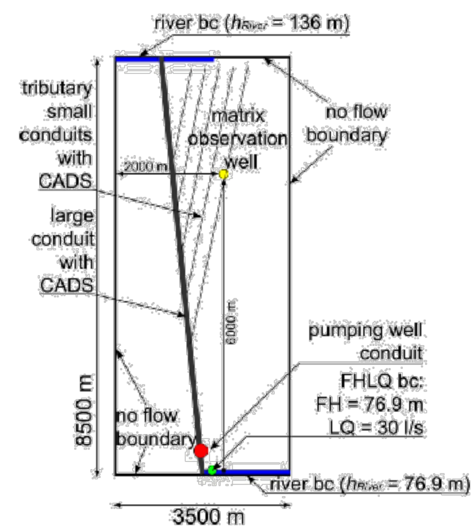
single conduit



meshed conduit



conduit with tributaries

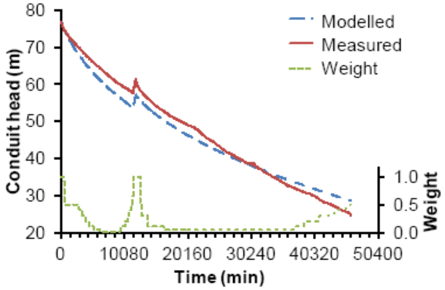


2. Flow enhancements

CFPM1 application – outlook

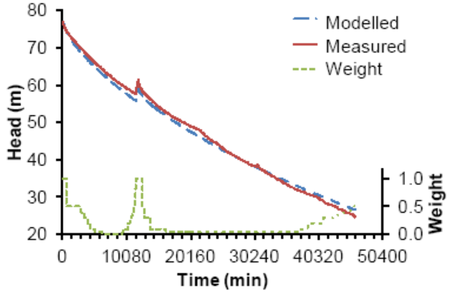
Inverse modeling / PEST

single conduit



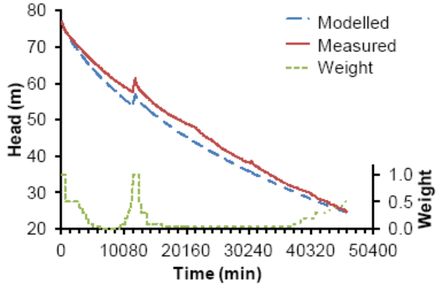
K_{matrix} 1E-6 m/s
S_{matrix} 2E-4
α_{ex} 2.94E-4 m^2/s

meshed conduit



K_{matrix} 5E-7 m/s
S_{matrix} 5E-4
α_{ex} 1.95E-4 m^2/s

conduit with tributaries



K_{matrix} 1E-7 m/s
S_{matrix} 1.2E-3
α_{ex} 3.36E-4 m^2/s

Further consideration:

- real field situation (catchment, boundaries, geology, ...)
- matrix observation wells
- pumping well: drawdown derivatives / flow dimension ...

2. Flow enhancements

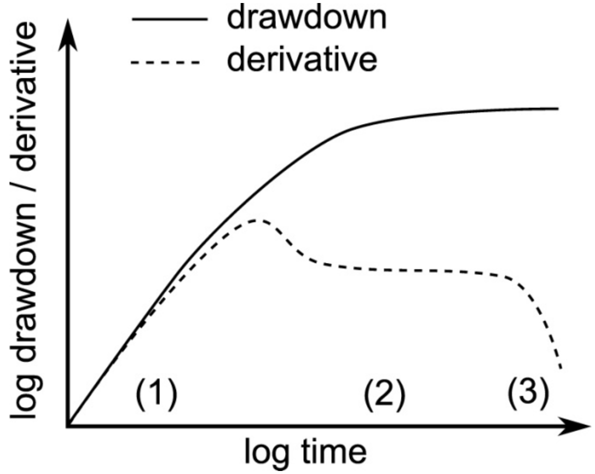
CFPM1 application – outlook

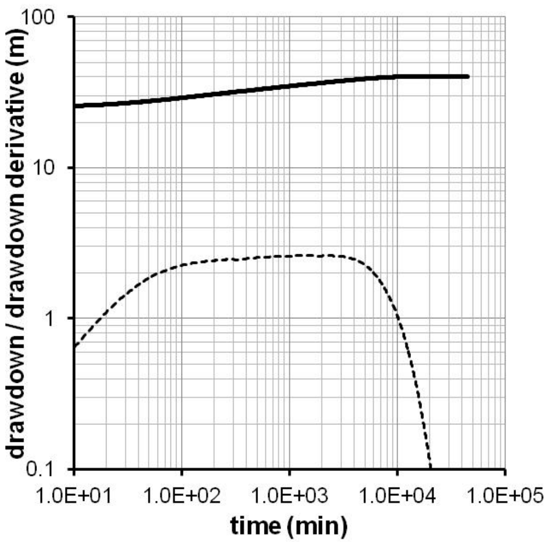
Drawdown derivatives / Flow dimension analysis

(1) Initial stage – well bore storage

(2) Intermediate stage – infinite system response

(3) Late stage – boundary conditions





Simple model

- 21 x 21 cells
- cell size 100 m x 100 m
- 1 layer
  - confined
  - 150 m thickness
- central conduit, 100 m long
- conduit pumping well
- without CADS

2. Flow enhancements

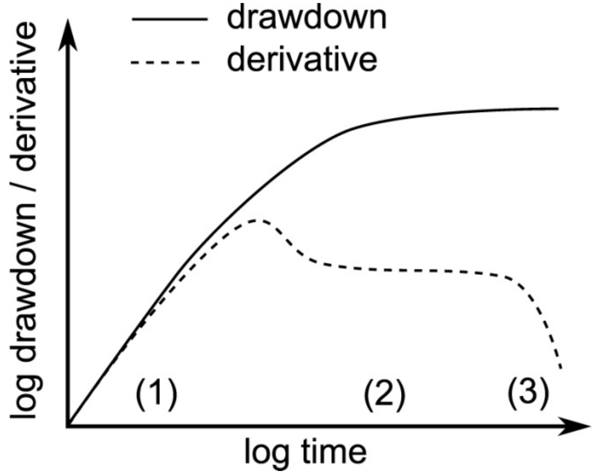
CFPM1 application – outlook

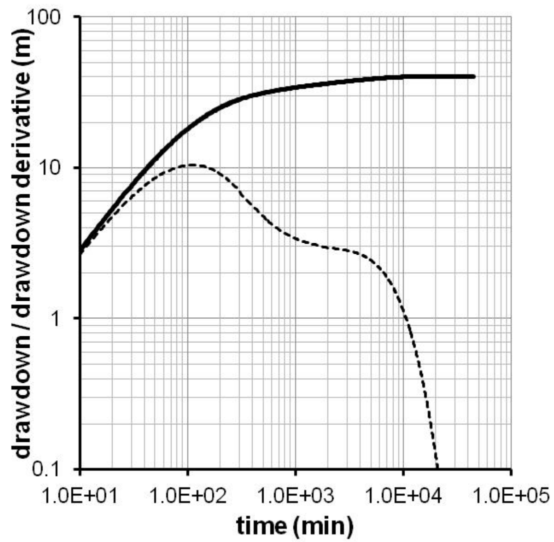
Drawdown derivatives / Flow dimension analysis

(1) Initial stage – well bore storage

(2) Intermediate stage – infinite system response

(3) Late stage – boundary conditions





Simple model

- 21 x 21 cells
- cell size 100 m x 100 m
- 1 layer
  - confined
  - 150 m thickness
- central conduit, 100 m long
- conduit pumping well
- additional CADS

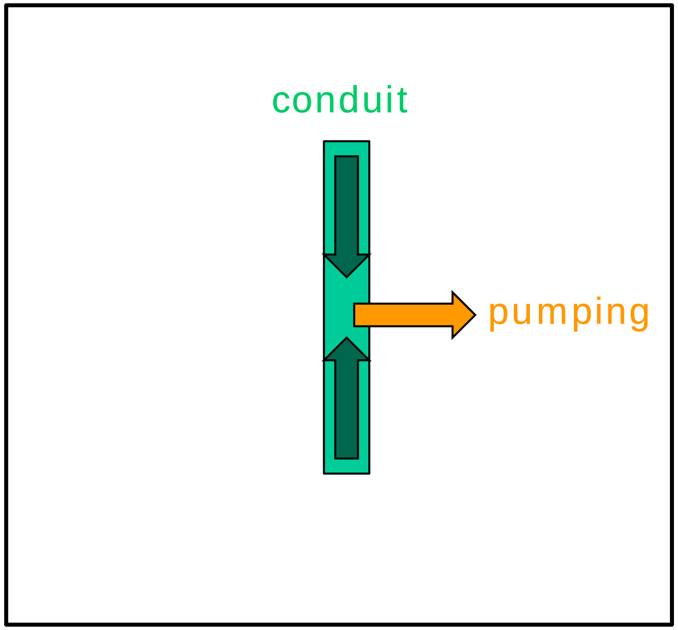
2. Flow enhancements

CFPM1 application – outlook

Drawdown derivatives / Flow dimension analysis

- flow dimension *n* can be computed from drawdown derivative
- additional tool to characterize conduit structure

top view



n = 0: well bore storage

n = 1: linear flow

n = 2: (pseudo)radial flow

n = 3: spherical flow

2. Flow enhancements

CFPM1 application – outlook

Drawdown derivatives / Flow dimension analysis

- flow dimension *n* can be computed from drawdown derivative
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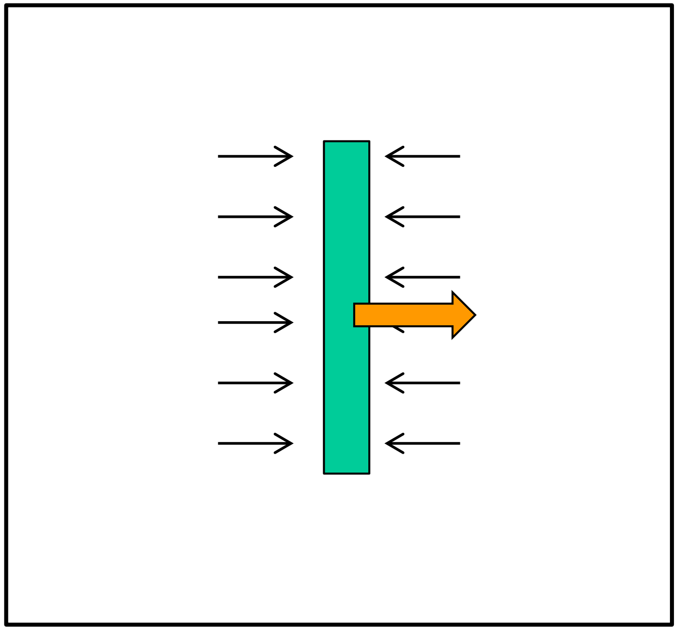
top view



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2. Flow enhancements

CFPM1 application – outlook

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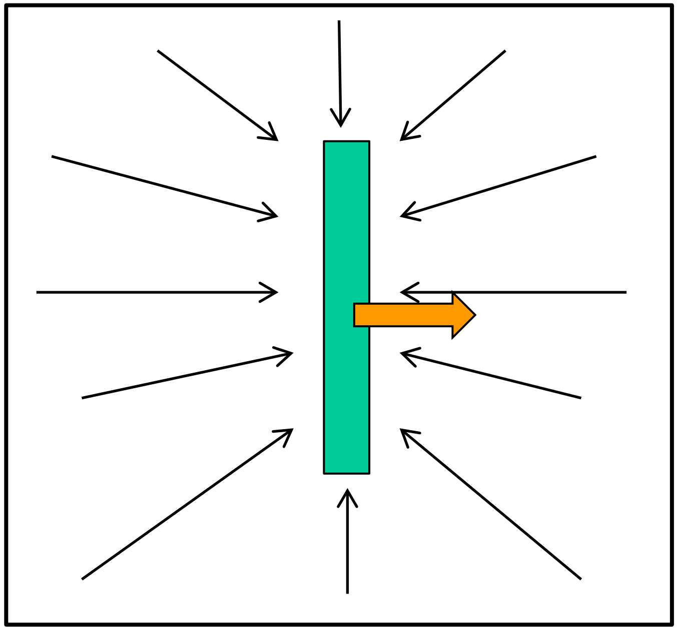

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2. Flow enhancements

CFPM1 application – outlook

Drawdown derivatives / Flow dimension analysis

- flow dimension *n* can be computed from drawdown derivative
- additional tool to characterize conduit structure

Example:

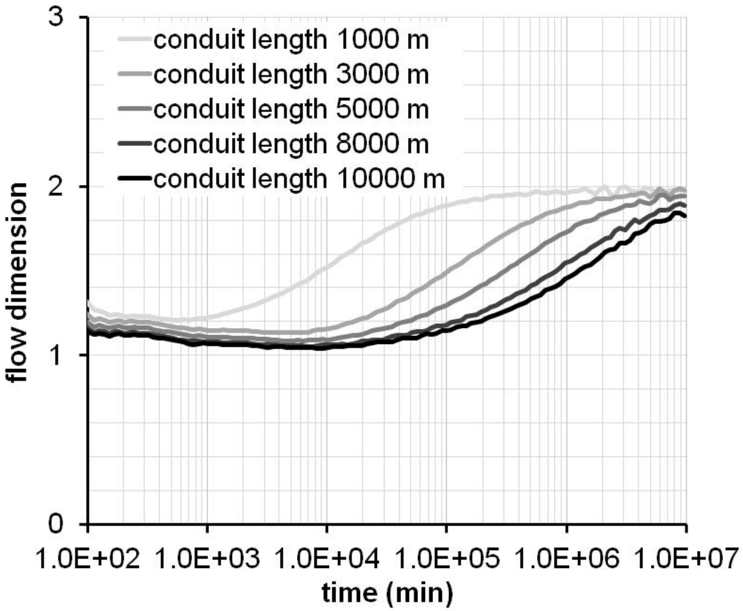
- single conduit, variable length up to 10 000 m
- conduit pumping well, centrally placed
- constant pumping rate
- quasi infinite matrix

n = 0: well bore storage

n = 1: linear flow

n = 2: (pseudo)radial flow

n = 3: spherical flow



Outline

1. Initial situation
2. Flow enhancements
   boundary conditions
   conduit storage
3. **Transport enhancements**
   solutes
   heat
4. Conclusion

3. Transport enhancements

Transport implementation

Approaches

(1) Conduit transport **included in CFP** subroutines

- transport computation alternate with flow computation (time step splitting)
- back coupling transport ⇆ flow possible

➝ heat transport module **HTM**

➝ solute transport module **STM**

(2) Conduit transport included in a **modified MT3D** ➝ UMT3D (Spiessl et al., 2007)

- flow transport link file included in CFP
- transport computation independent from flow model
- (actually simplified transport within conduits – no further consideration here)

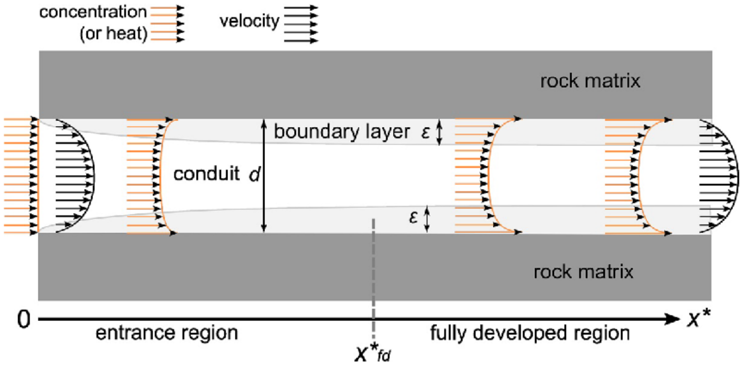
3. Transport enhancements

Heat and solute transport (HTM / STM)

Processes – interaction with rock matrix

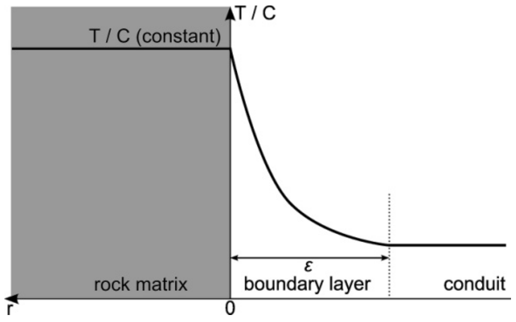
Boundary layer

- diffusive transfer matrix ⇆ conduit
- different behavior for lam. / turb.



Matrix diffusion

- considers influence of transfer processes on matrix conditions



3. Transport enhancements

Heat and solute transport (HTM / STM)

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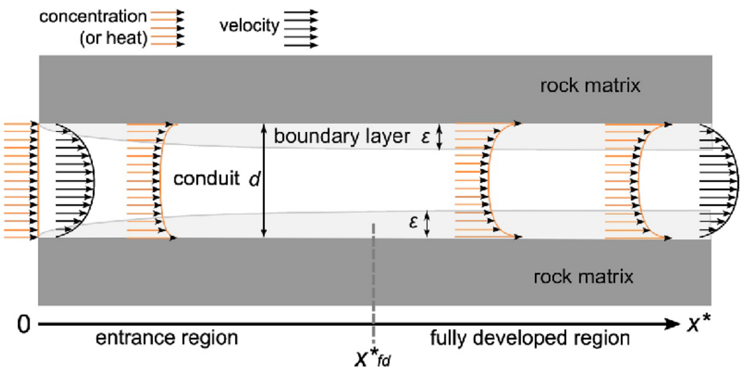
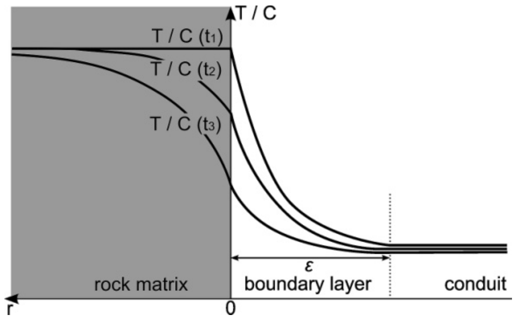
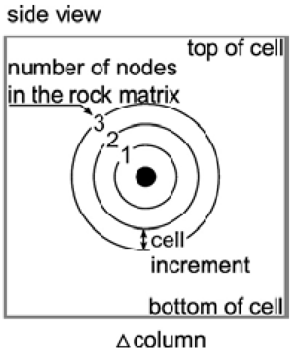


Matrix diffusion

- considers influence of transfer processes on matrix conditions
- 1D radial transport model around conduit (Birk 2003)





3. Transport enhancements

Heat and solute transport (HTM / STM)

Processes

HTM (heat)	STM (solutes)
convection in conduits	advection in conduits
	dispersion • fixed coefficient, or • Taylor dispersion (lam./turb.)
thermal boundary layer	concentration boundary layer
rock matrix conduction	rock matrix diffusion with retardation

$$\frac{\partial T}{\partial t} = -v\frac{\partial T}{\partial x} + S_T(x,t,T)$$

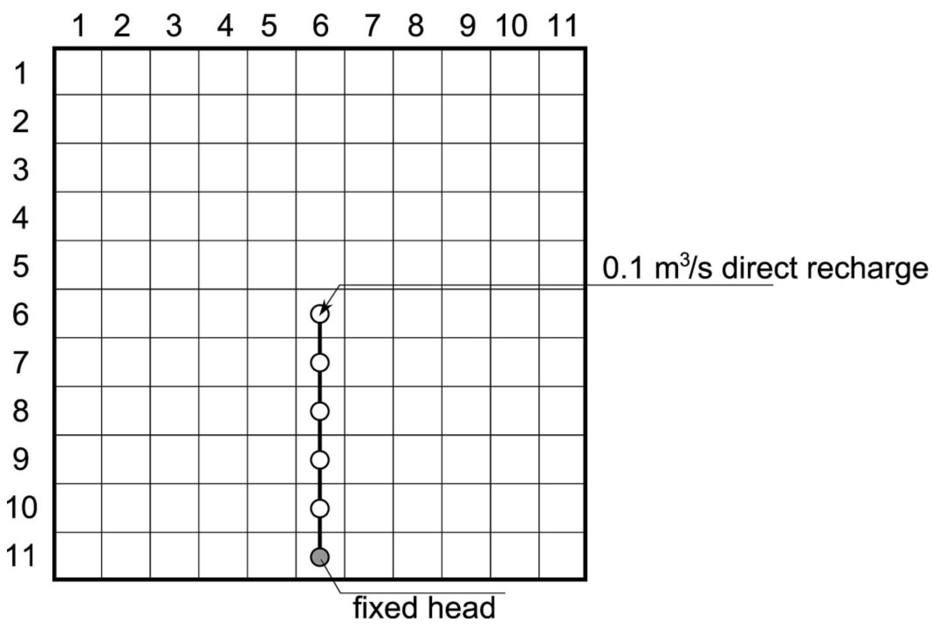
$$\frac{\partial C}{\partial t} = -v\frac{\partial C}{\partial x} + D_{dis}\frac{\partial^2 C}{\partial x^2} + S_C(x,t,C)$$

$S_{T/C}$ = source term (boundary layer)

3. Transport enhancements

Heat and solute transport (HTM / STM)

Some evaluation



Simple model

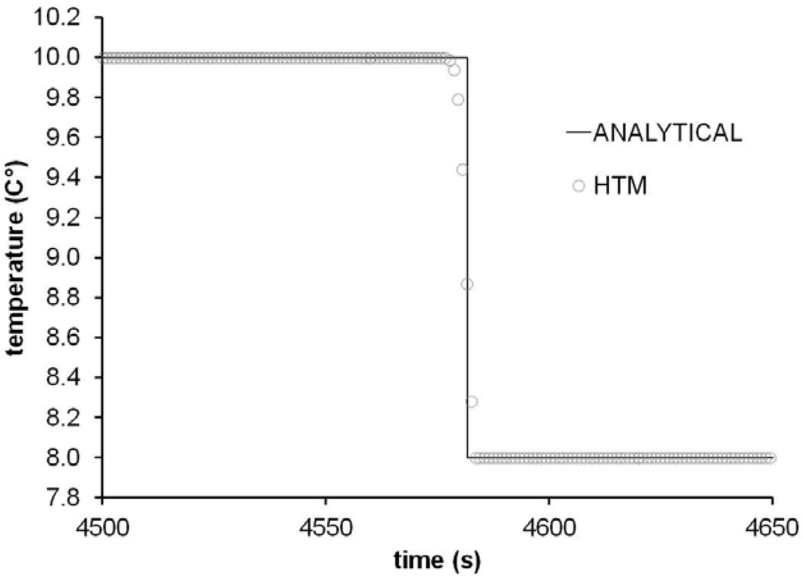
- decoupled conduit
- diameter 0.5 m
- initial temperature 10 °C
- direct recharge temperature 8 °C

3. Transport enhancements

Heat and solute transport (HTM / STM)

Some evaluation

convection only

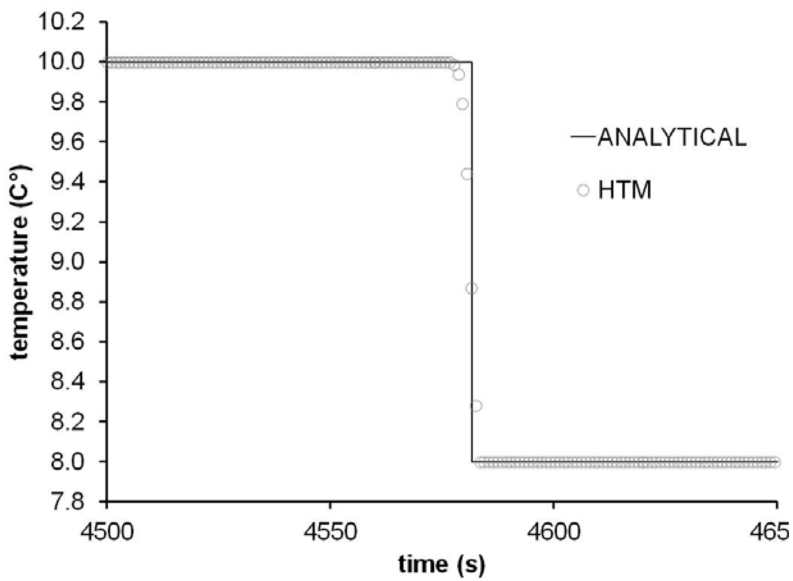


3. Transport enhancements

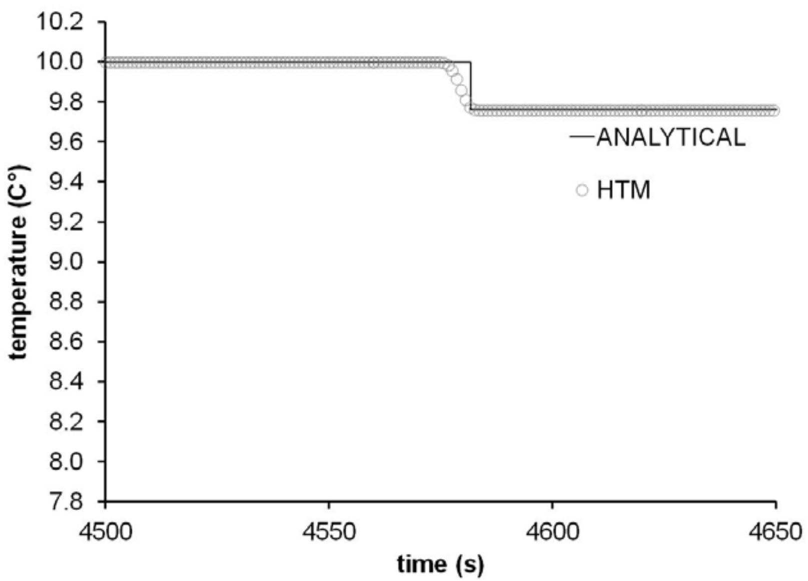
Heat and solute transport (HTM / STM)

Some evaluation

convection only



convection and thermal boundary layer

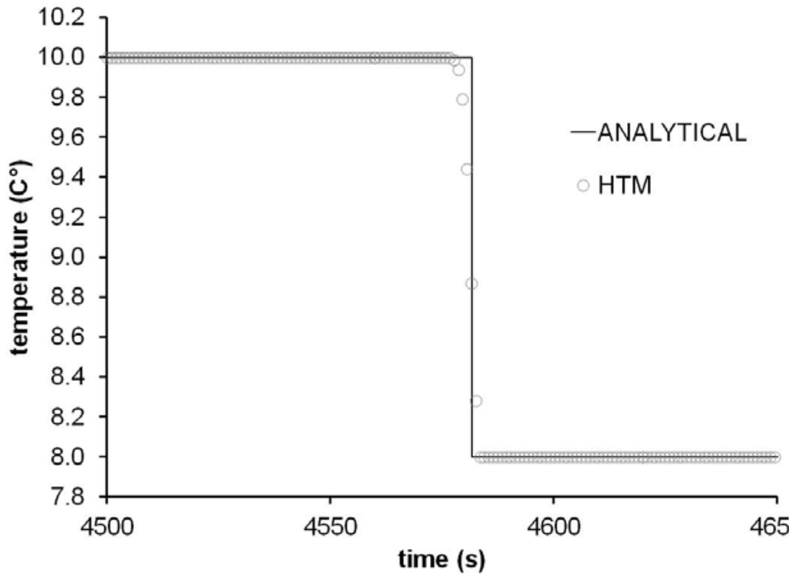


3. Transport enhancements

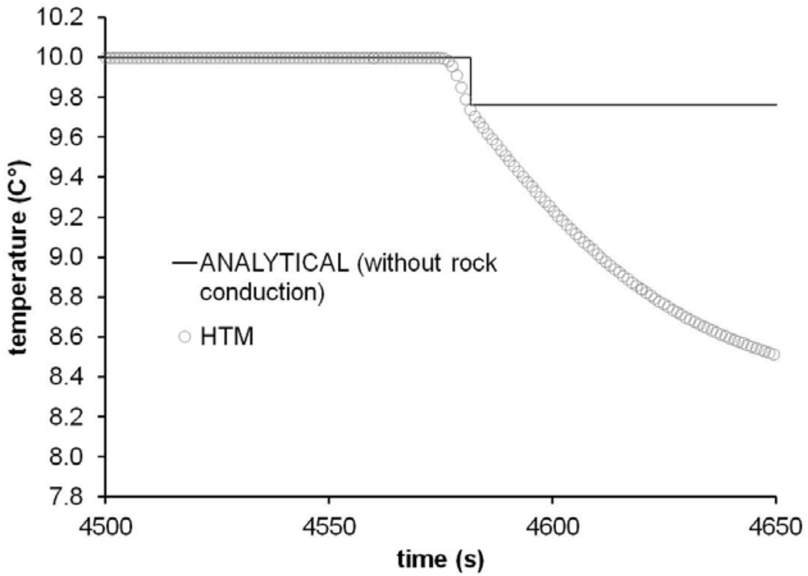
Heat and solute transport (HTM / STM)

Some evaluation

convection only



convection, thermal boundary layer, and rock conduction

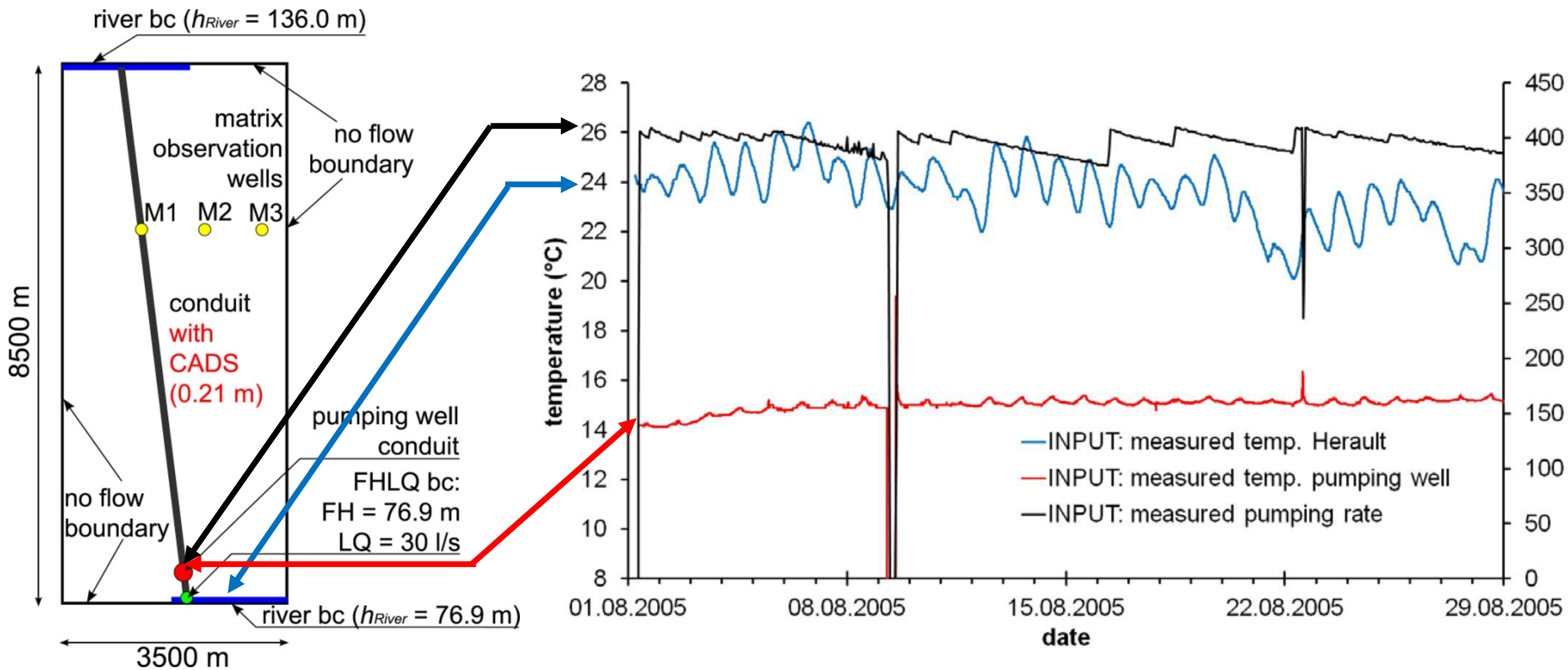


3. Transport enhancements

CFPM1 application

Temperature in pumping well

time dependent input: pumping rate, temperatures (river, pumping well)

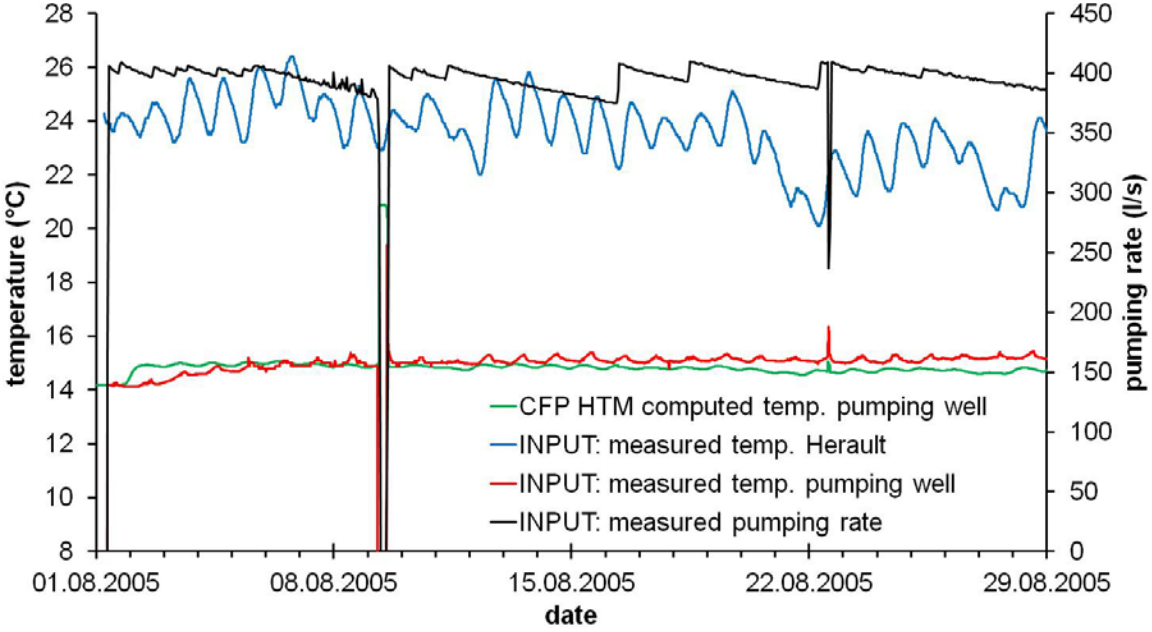


3. Transport enhancements

CFPM1 application

Some evaluation

first results (intention here: check model!) ➜ reasonable (not calibrated)



model run time:

~ 6 minutes

(5 year old notebook)

Outline

1. Initial situation
2. Flow enhancements
    boundary conditions
    conduit storage
3. Transport enhancements
    solutes
    heat
4. **Conclusion**

4. Conclusion

Addition and enhancement of flow and transport processes to CFP

Hydraulic enhancements

new boundary conditions

- Fixed Head Limited Flow (FHLQ) / Limited Head (LH) / Cauchy / Well
- time dependent input data
- applicable for solute / heat transport

enhanced concept: Conduit Associated Drainable Storage – CADS

- signal damping
- one additional parameter – CADS width

Possible use / application:

→ water abstraction scenarios (horizontal wells?)

→ pumping test analysis (drawdown, derivative analysis, flow dimensions)

→ inverse modeling (coupling with parameter estimation tools)

4. Conclusion

Addition and enhancement of flow and transport processes to CFP

Transport enhancements

two alternative approaches

(1) modified MT3D code and flow-transport link file within CFP

(2) HTM / STM package within CFP

- processes within HTM / STM: advection (convection), dispersion, boundary layer, matrix diffusion (conduction)
- fully integrated in CFP (boundary conditions, time dependent input, budgets)

Possible use / application:

→ karst characterization

→ tracer test evaluation

→ geothermal investigations

4. Conclusion

Addition and enhancement of flow and transport processes to CFP

Further information / contact

→ modified CFP executable with documentation available on request

→ CADS / FHLQ boundary: „Representation of water abstraction from a karst conduit with numerical discrete-continuum models"; Open Access Journal HESSD; interactive discussion until 3rd June 2013; doi:10.5194/hessd-10-4463-2013

→ www.tu-dresden.de/fghhigw: further tools (conduit network generator)

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DFG