Karlsruhe Institute of Technology

REKLIM
Helmholtz-Verbund Regionale Klimaänderungen

From the groundwater to the boundary layer: a fully-coupled hydro-meteorologic modeling approach for a catchment of the Alpine foothills

Benjamin Fersch[1], **Harald Kunstmann[1]**, and David Gochis[2]

(1) KIT Campus Alpin, Garmisch-Partenkirchen, Germany
(2) National Center of Atmospheric Research, Boulder, USA

INSTITUTE OF METEOROLOGY AND CLIMATE RESEARCH, ATMOSPHERIC ENVIRONMENTAL RESEARCH, IMK-IFU
Regional Climate and Hydrology

KIT-Campus Alpin
IMK-IFU: Atmospheric Environmental Research

Motivation

- WRF-Hydro, tool for cross-compartment water and energy budget simulations with the possibility for regional water cycle closure

- Water cycle closure requires a coupled system from the atmosphere to the groundwater with two-way interaction between
  - Atmosphere and Soils (unsaturated zone)
  - Soil and Groundwater
  - Groundwater and Channels

- Groundwater processes (baseflow generation) in WRF-Hydro is highly conceptual
  - Lumped storage approach
  - No lateral flow
  - No return flow from channels into the groundwater

WRF-Hydro Modeling System

Karlsruhe Institute of Technology

NCAR developed community model for the simulation of **coupled atmospheric and hydrological** processes (Gochis et al. 2013)

Available land surface models:

Noah-LSM

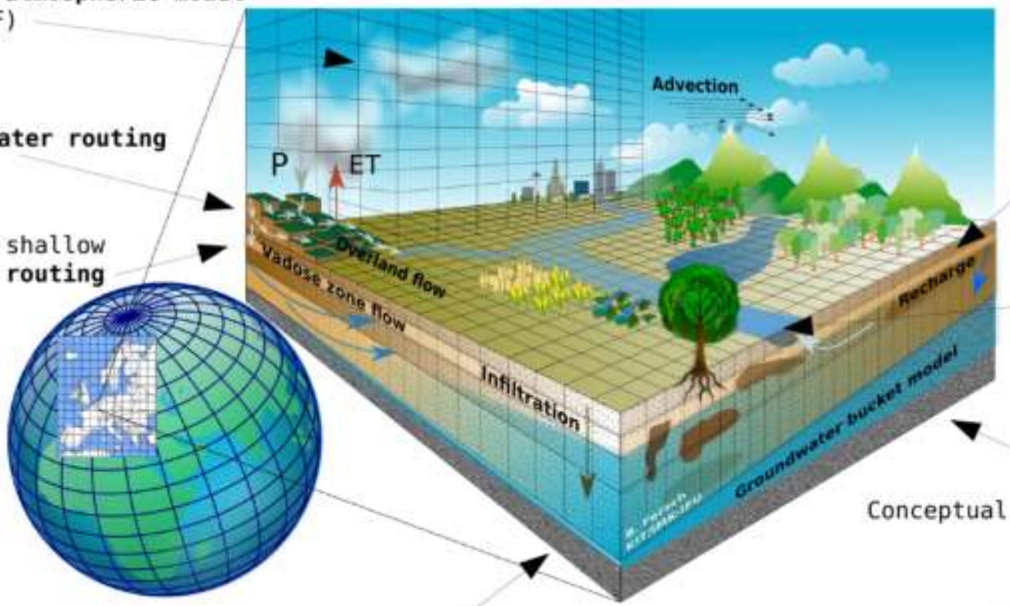
Noah-MP

CLM (Community Land Model)

Regional **atmospheric model** (e.g. WRF)

Surface water routing

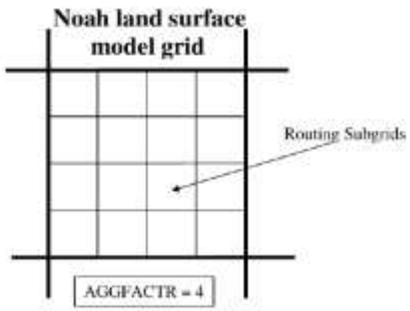
Horizontal shallow **subsurface routing**



Diffusive wave **channel routing**

Conceptual **groundwater bucket** storage

Free drainage percolation



WRF-Hydro Conceptual Bucket Model

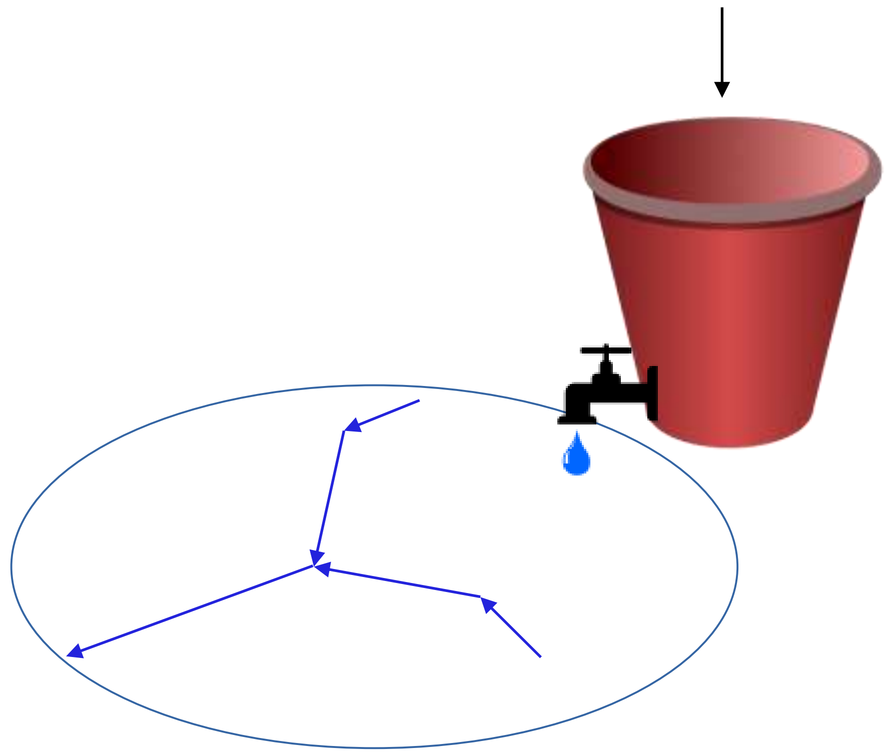
- Base-flow contribution for channel routing
- Individual calibration for sub-basins

$$Q_{base} = C_i e^{a_i z_i}$$

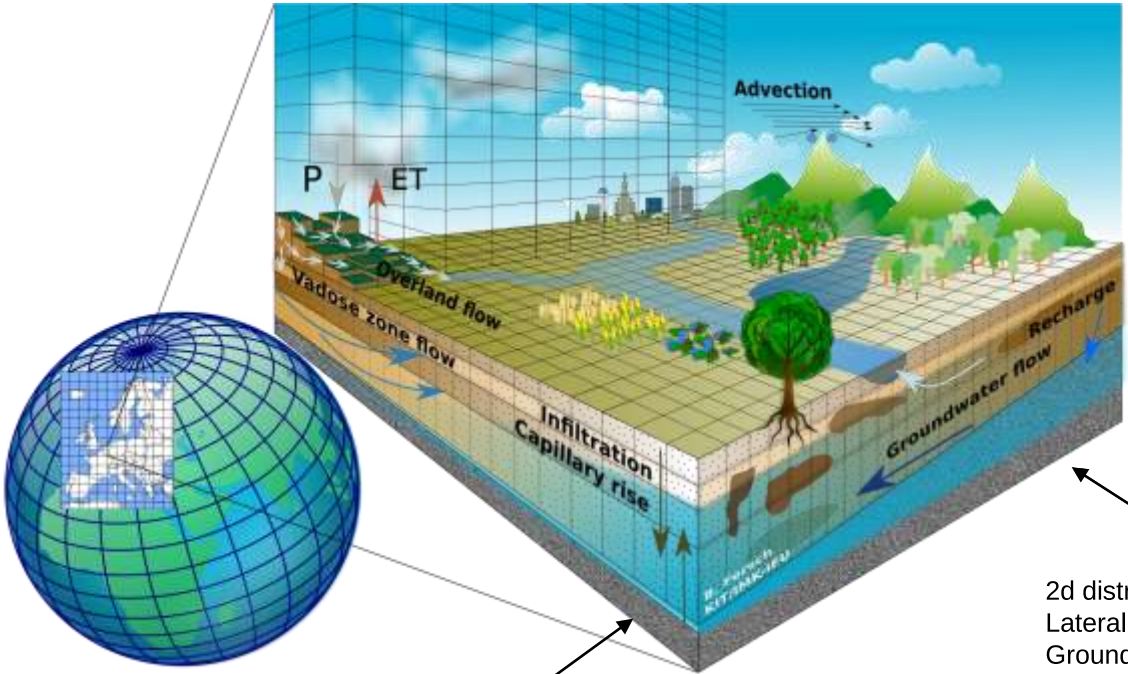
C = coefficient
a = bucket exponent
z = water depth

Basin	Coeff.	Expon.	Zmax	Zinit
1	0.7760	3.144	0.100	0.0982
2	0.0400	3.220	0.070	0.0358
3	0.4270	2.813	0.125	0.0678
4	0.0140	5.861	0.055	0.0358

LSM basin aggregated underground runoff



WRF-Hydro gw2d Groundwater Extension



2d distributed groundwater model
Lateral redistribution
Groundwater-channel interaction

State dependent, parameterized interaction
between unsaturated and saturated zone
Bi-directional vertical flow

2-D Single Layer Distributed Groundwater Model

Karlsruhe Institute of Technology

- Modified Prickett Lonnquist Aquifer Simulation Model (Prickett and Lonnquist 1971) for unconfined conditions

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}+Q$$

h = head
T = aquifer transmissivity
t = time

S = storage coefficient (porosity)
Q = sources and sinks
x,y → Cartesian coordinates

- Finite difference approximation of 2-d Boussinesq's equation

$$T_{i-1,j,2}\frac{(h_{i-1,j}-h_{i,j})}{\Delta x^2}+T_{i,j,2}\frac{(h_{i+1,j}-h_{i,j})}{\Delta x^2}+T_{i,j+1,1}\frac{(h_{i,j+1}-h_{i,j})}{\Delta y^2}+T_{i,j-1,1}\frac{(h_{i,j-1}-h_{i,j})}{\Delta y^2}=S\frac{(h_{i,j}-h_{t-1,i,j})}{\Delta t}+\frac{Q_{i,j}}{\Delta x\Delta y}-\frac{Q_n}{\Delta x\Delta y}$$

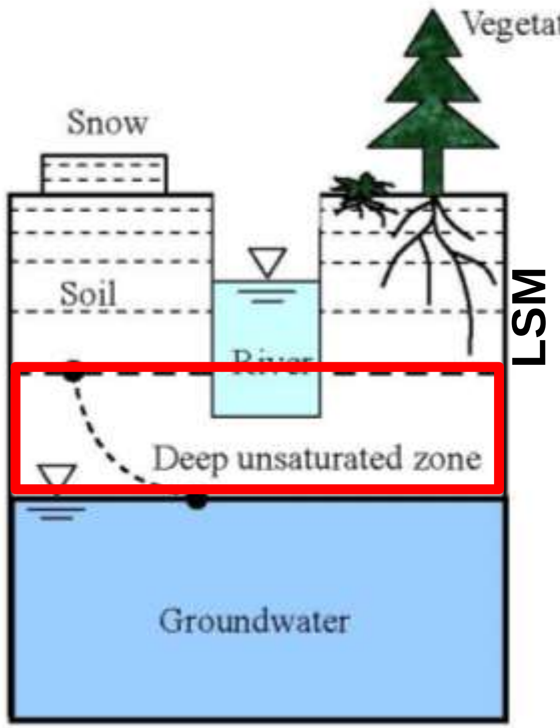
Solve equation for $h_{i,j}$ at every grid point with *Alternating Direction Implicit Method* (ADI) (MPI-parallel implementation)

Prickett & Lonnquist Selected Digital Computer Techniques for Groundwater Resources Evaluation State of Illinois, Department of Registration and Education, 1971

Groundwater – Unsaturated Zone Coupling

- Two way interaction & fluxes (e.g. capillary rise vs. gravity fluxes) between saturated and unsaturated zone

- Darcy flux boundary condition based on Bogaart et al. (2008)

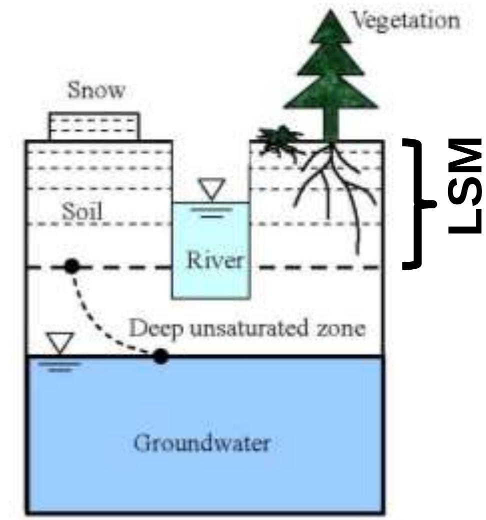


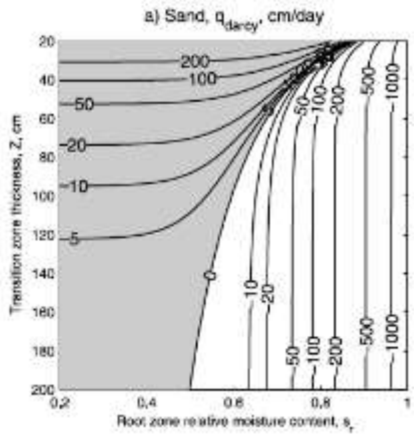
Bogaart, P. W., A. J. Teuling, and P. A. Troch. "A state-dependent parameterization of saturated-unsaturated zone interaction." Water resources research 44.11 (2008).

Groundwater – Unsaturated Zone Coupling

Darcy flux parameterized boundary condition

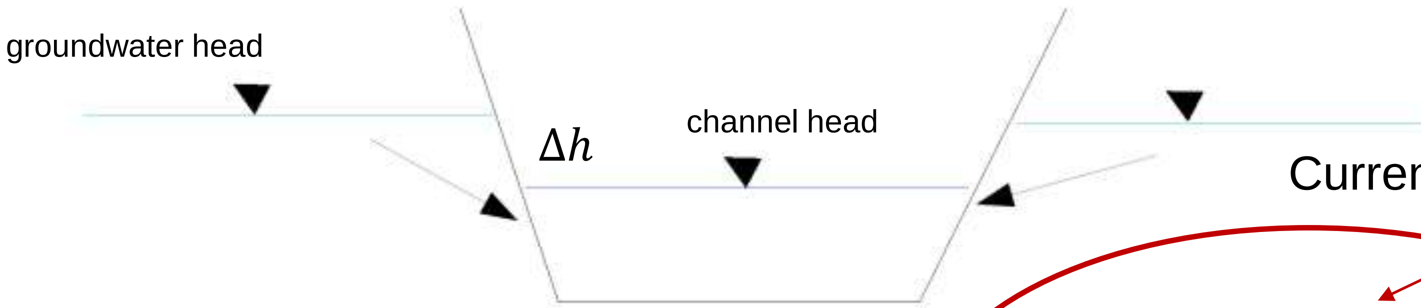
- Assumes a quasi steady-state moisture profile between groundwater head and lowest soil layer of the LSM.
- Darcy equation is used to describe flow through this transition zone depending on relative saturation at bottom of LSM
- Parameterization that approximates net Darcy flux qdarcy for different thicknesses of transition zone and different values of saturation for lowest LSM soil layer





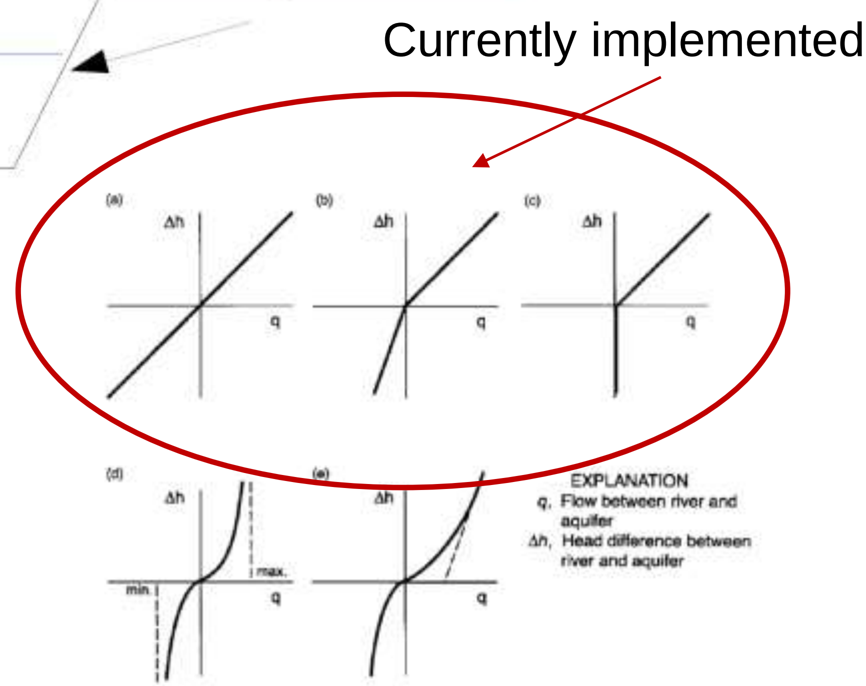
(From Bogaart et. al. 2008)

Groundwater – Channel Coupling



$$q = k\,\Delta h$$

q = groundwater-channel flow
k = streambed leakage factor
h = groundwater and channel head



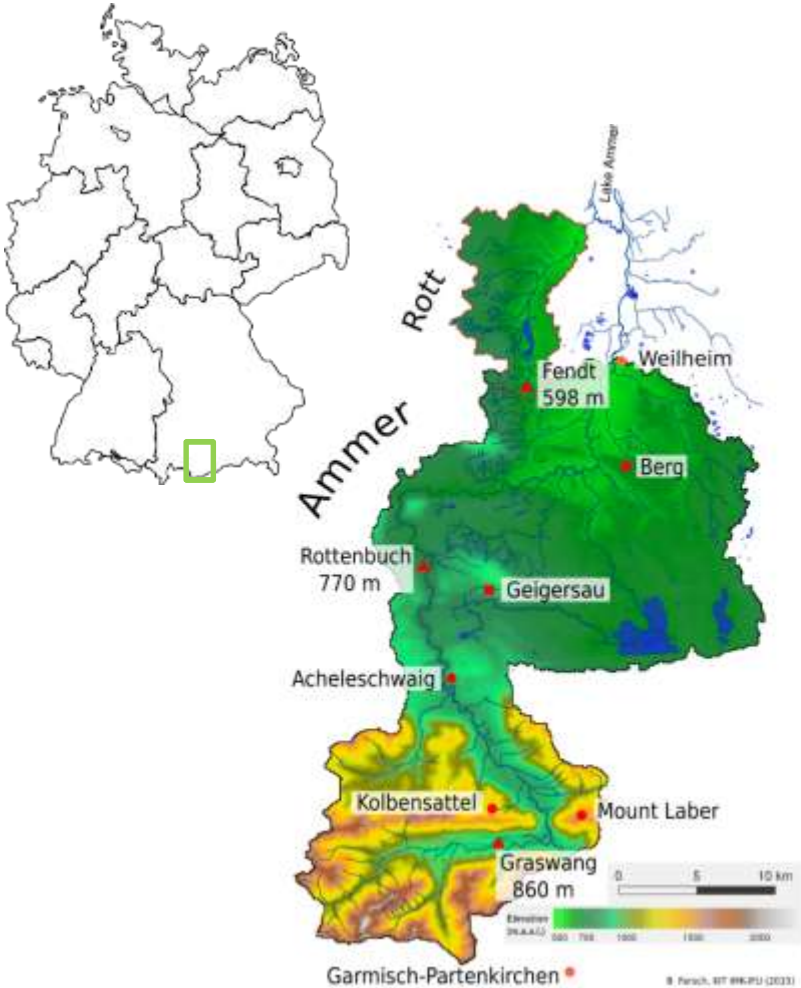
(From Sophocleous, 2002)

Sophocleous, Marios. "Interactions between groundwater and surface water: the state of the science." Hydrogeology journal 10.1 (2002): 52-67.

gw2d Innovations for WRF-Hydro

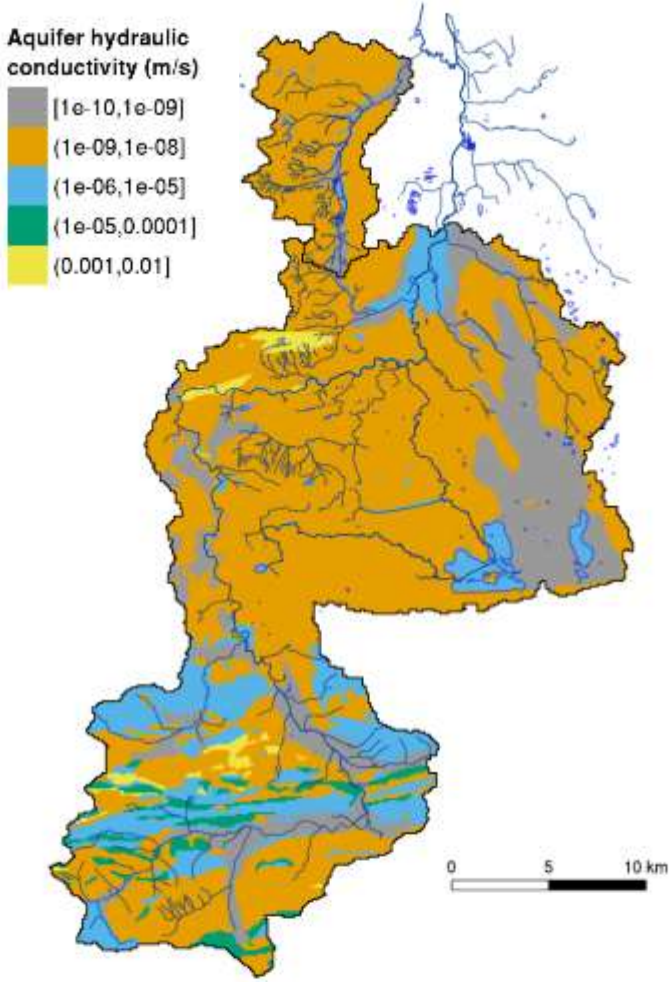
- 2-way groundwater – unsaturated zone coupling (one-way also possible)
- 2-d lateral groundwater flow for unconfined porous aquifers
- 2-way groundwater – channel coupling for baseflow creation
- Full closure and bi-directional coupling of the regional water cycle from the bottom to the top

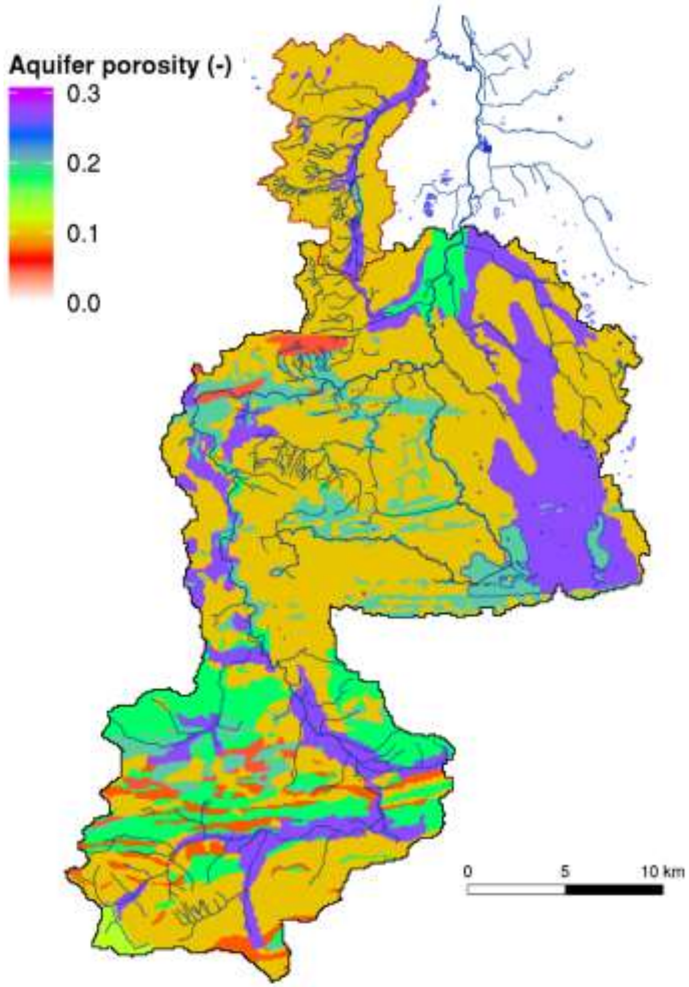
Model Application to Ammer Catchment



- Ammer catchment
  - ~800 km² up to gauge Weilheim
  - ~550 – 2000 m elevation
  - 700 – 1800 mm/a precipitation
  - Landuse: forest, grassland, cropland
- WRF-Hydro SA Model configuration
  - Driving: WRF-downscaling of ECMWF ERA-INTERIM (27 → 9 → 3 km)
  - Hydro routing grid 100 x 100 m²
  - Simulation period May to August 2008, one month spin-up for channels and soils
  - Groundwater model (gw2d) equilibrium spin-up
  - Basic calibration
    - Soil infiltration parameter (refkdt)
    - Manning channel roughness
    - Bucket model retention coefficients

Required Additional Aquifer Information

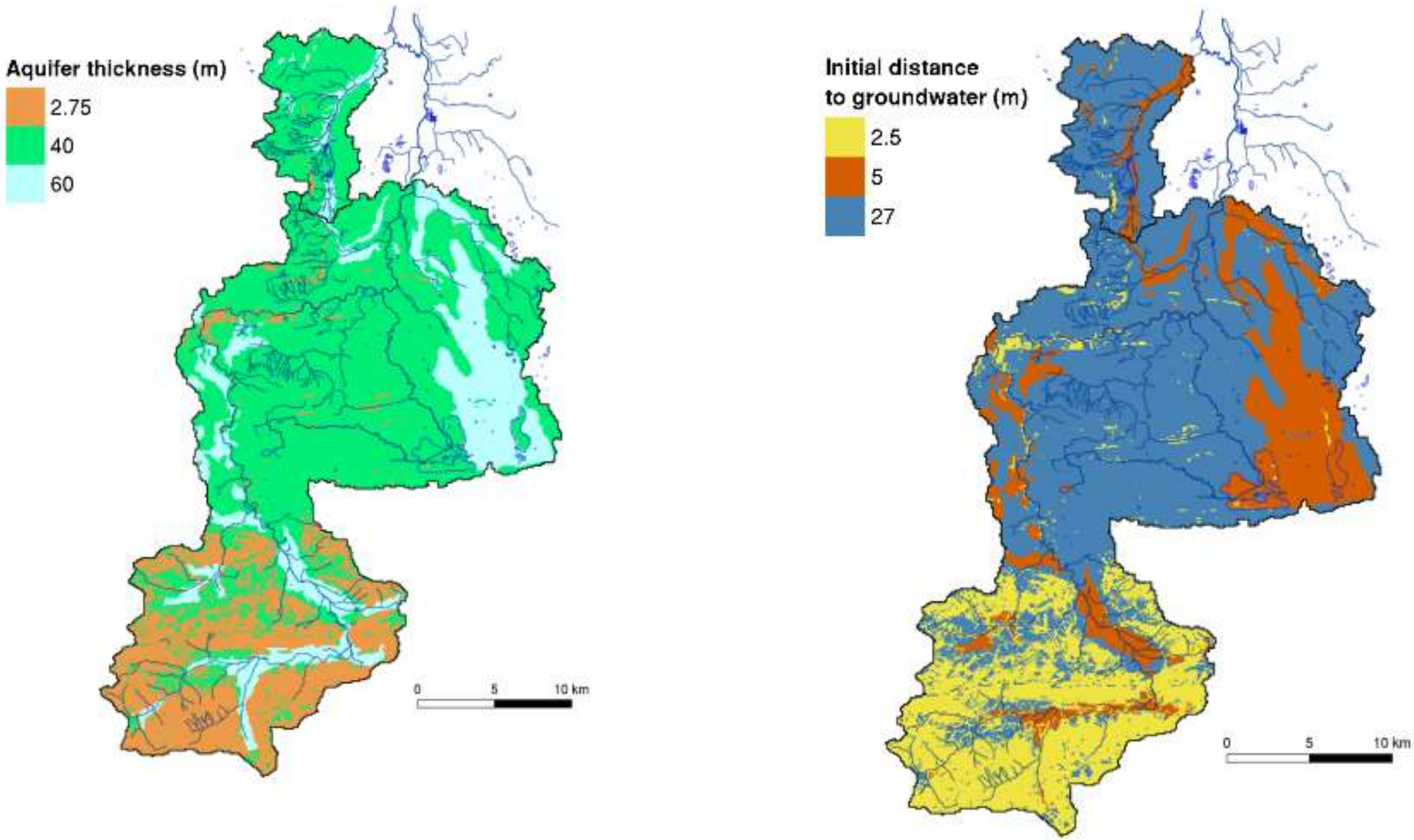




Derived from hydrogeological map of Bavaria (LfU)

Benjamin Fersch, Harald Kunstmann, David Gochis
EGU General Assembly 2016 – Vienna (EGU2016-7856)
Institute of Meteorology and Climate Research, IMK-IFU

Required Additional Aquifer Information



Derived from hydrogeological map of Bavaria (LfU)

Benjamin Fersch, Harald Kunstmann, David Gochis

GW Calibration & GW Spin-Up

$$q = k \Delta h$$

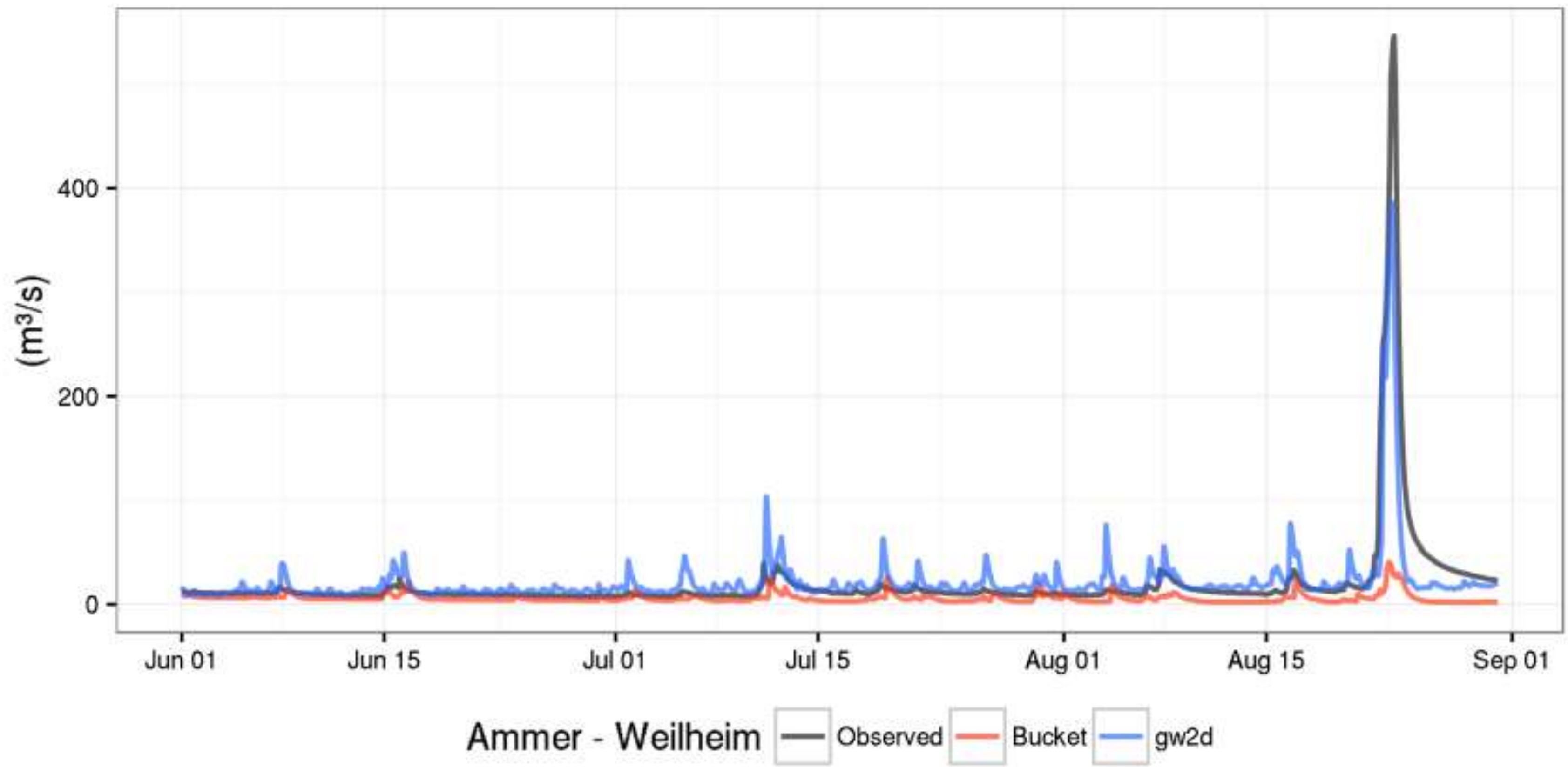
```
GwChanCondConstIn    = 1.0E-5  ! Conductivity constant for GWCHANCONDSW = 1
GwChanCondConstOut   = 1.0E-5  ! Conductivity constant for GWCHANCONDSW = 1

GwSpinCycles         = 1000    ! Number of forcing data  cycles for
                                 groundwater head initialization
GwPreCycles          = 10000   ! Number of pre-spinup cycles for
                                 groundwater model initialization
```

- Groundwater spin-up
  - 10,000 initial cycles with surface excess water removal
  - Climatological spin-up with cycled forcing data

- Calibration
  - Groundwater – channel conductivity constant
  - Aquifer depth
  - Aquifer initial water content

Preliminary Results: Discharge Bucket vs. Gw2d

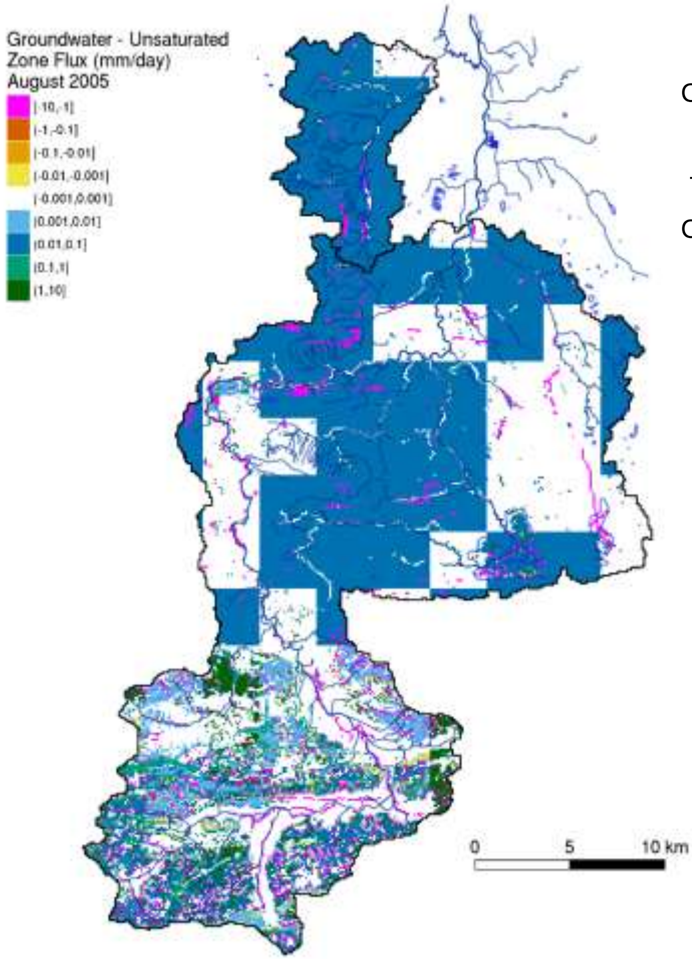


Benjamin Fersch, Harald Kunstmann, David Gochis
EGU General Assembly 2016 – Vienna (EGU2016-7856)
Institute of Meteorology and Climate Research, IMK-IFU
KIT-Campus Alpin
IMK-IFU: Atmospheric Environmental Research

Preliminary Results – WRF-Hydro gw2d SA

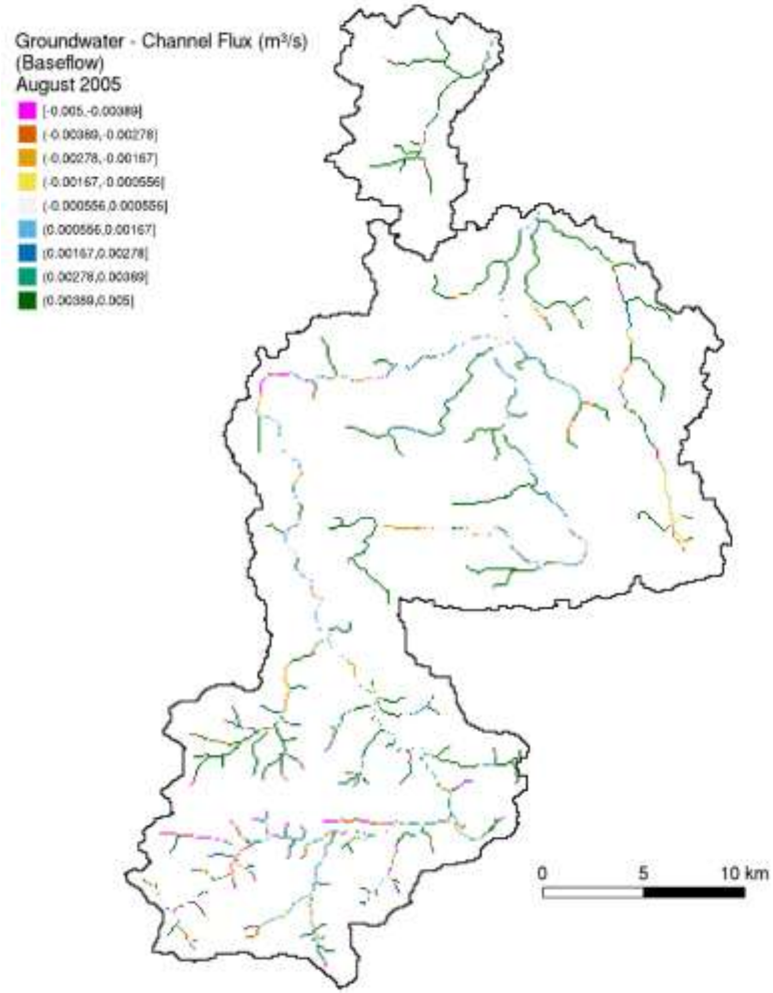
Capillary rise

Recharge



Channel loss

Channel gain



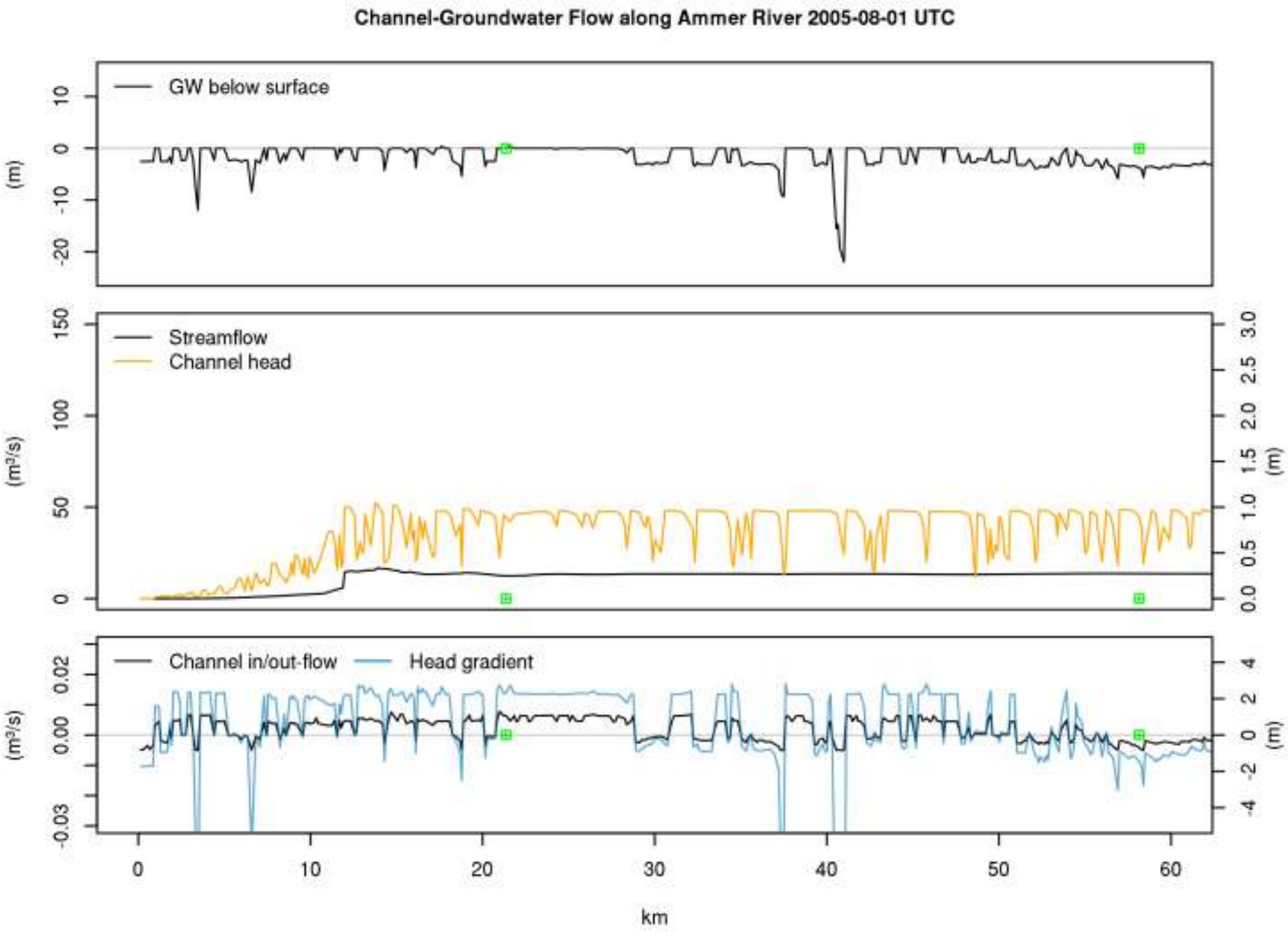
Benjamin Fersch, Harald Kunstmann, David Gochis

Summary and Outlook

- gw2d
  - Fully coupled groundwater extension for WRF-Hydro, lateral flow, channel and unsaturated zone interaction
  - Considerable calibration effort and spin-up are required
  - More reactive discharge simulation (representation of interflow)
  - Still challenging to apply at steep mountainous terrain

- Global applicability
  - Global data-sets for aquifer characteristics are slowly appearing in the community (e.g. GLHYMPS)
  - Not yet applicable to fractured aquifers, karst
  - Anthropogenic withdrawal / irrigation not yet implemented

Channel – Groundwater Coupling



Preliminary Results: Discharge Bucket vs. Gw2d