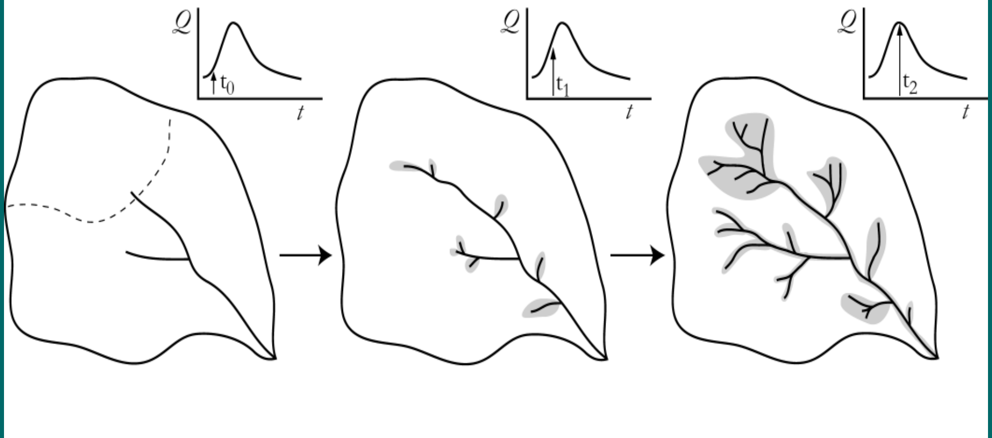
# Coupled modeling of groundwater/surface water interactions: successes and challenges from recent applications




**Claudio Paniconi**

*Institut National de la Recherche Scientifique, Centre Eau Terre Environnement (INRS-ETE)*

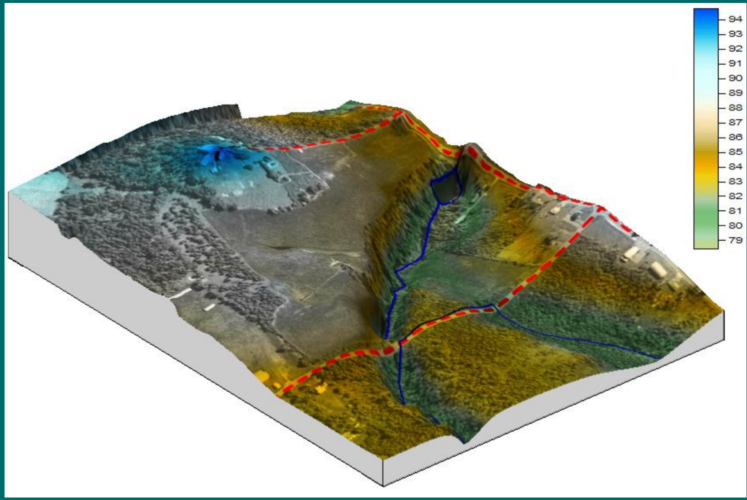
*Université du Québec, Québec, Canada*

*(claudio.paniconi@ete.inrs.ca)*

***WRF-Hydro Workshop, Cosenza (Italy), 11-13 June 2014***

## *Context*

Proper understanding and representation of hydrosphere interactions (between the atmosphere, land surface, soil zone, aquifers, rivers/lakes, and vegetation) is increasingly relevant to climate prediction, environmental protection, and water management




We are at a crossroads in hydrological modeling:

- models (of all flavors) are being integrated across many disciplines and over multiple scales, and they are being intercompared

- better datasets are increasingly being made available (for hypothesis testing and model validation) that provide observations (on the ground, airborne, and from space) of more processes, in more detail, and at higher accuracy

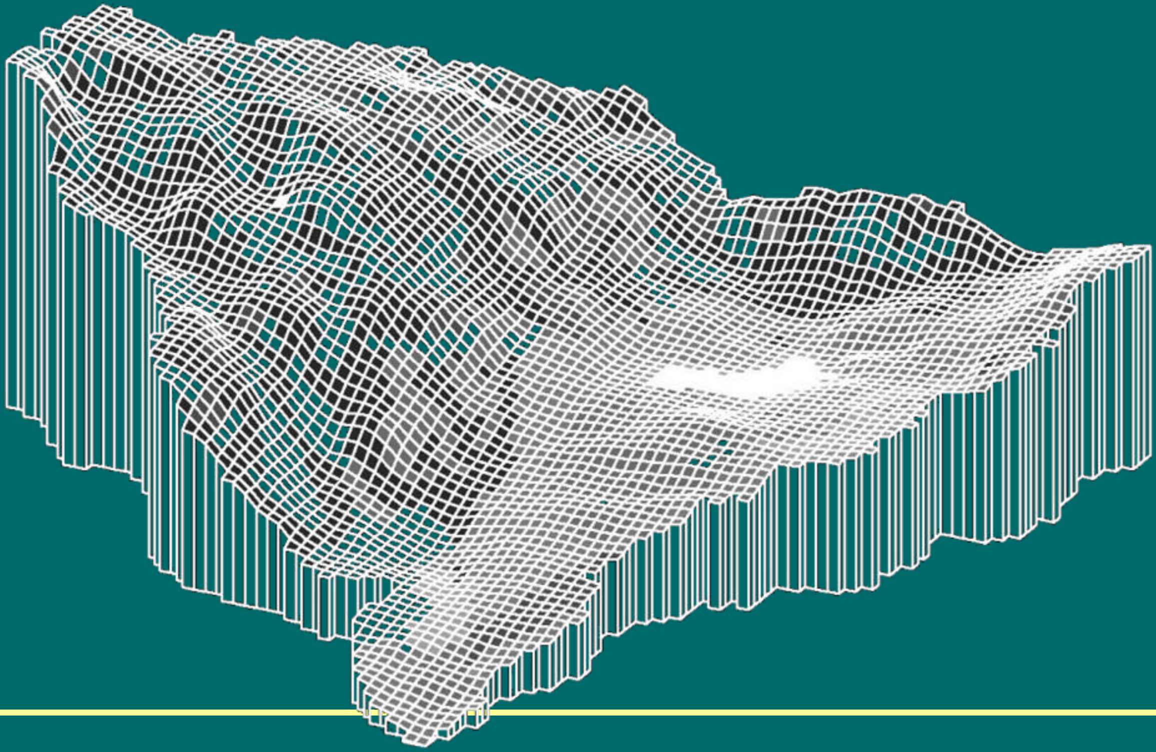
- computational boundaries are continually being pushed (cost and capabilities of systems, efficiency and robustness of algorithms), for easier and more effective data analysis and process simulation

## *Outline*

**CATHY (CATchment HYdrology) model description**

**Some recent studies (successes and challenges)**

**Extensions and evolution of the model**



## *CATHY (CATchment HYdrology) model description*

$$\sigma(S_w)\frac{\partial \psi}{\partial t} = \nabla \cdot \left[K_s K_{rw}(S_w)(\nabla \psi + \eta_z)\right] + q_s(h) \quad (1)$$

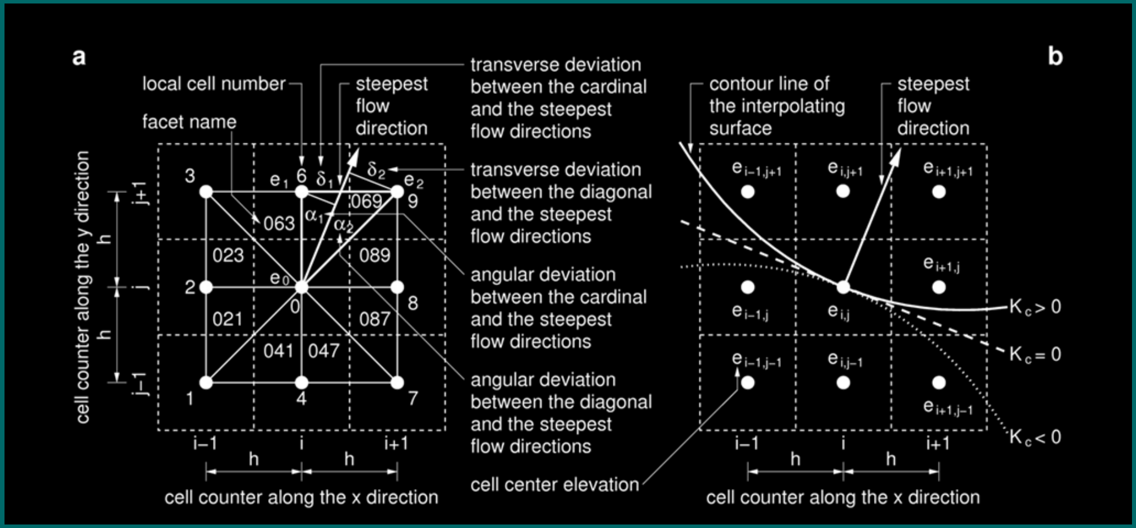
$$\frac{\partial Q}{\partial t} + c_k \frac{\partial Q}{\partial s} = D_h \frac{\partial^2 Q}{\partial s^2} + c_k q_L(h,\psi) \quad (2)$$

| | |
|---|---|
| $\sigma$ | general storage term [1/L]: $\sigma = S_w S_s + \phi(dS_w/d\psi)$ |
| $S_w$ | water saturation = $\theta/\theta_s$ [/] |
| $\theta$ | volumetric moisture content [$L^3/L^3$] |
| $\theta_s$ | saturated moisture content [$L^3/L^3$] |
| $S_s$ | specific storage [1/L] |
| $\phi$ | porosity (= $\theta_s$ if no swelling/shrinking) |
| $\psi$ | pressure head [L] |
| $t$ | time [T] |
| $K_s$ | saturated conductivity tensor [L/T] |
| $K_{rw}$ | relative hydraulic conductivity [/] |
| $\eta_z$ | zero in *x* and *y* and 1 in *z* direction |
| $z$ | vertical coordinate +ve upward [L] |
| $q_s$ | subsurface equation coupling term (more generally, source/sink term) [$L^3/L^3T$] |
| $h$ | ponding head (depth of water on surface of each cell) [L] |
| $s$ | hillslope/channel link coordinate [L] |
| $Q$ | discharge along *s* [$L^3/T$] |
| $c_k$ | kinematic wave celerity [L/T] |
| $D_h$ | hydraulic diffusivity [$L^2/T$] |
| $q_L$ | surface equation coupling term (overland flow rate) [$L^3/LT$] |

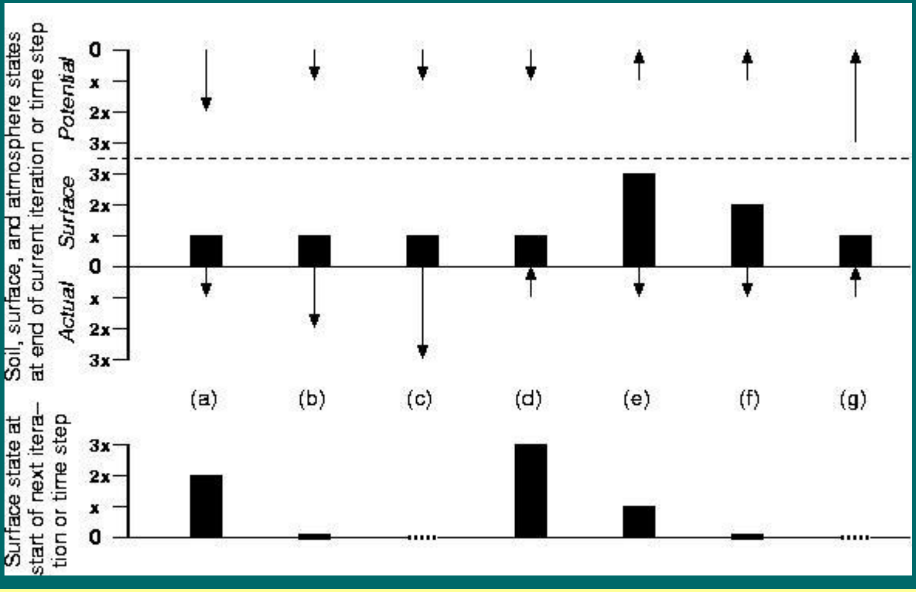
(1) *Paniconi & Wood, Water Resour. Res., 29(6), 1993 ; Paniconi & Putti, Water Resour. Res., 30(12), 1994*
(2) *Orlandini & Rosso, J. Hydrologic Engrg., ASCE, 1(3), 1996 ; Orlandini & Rosso, Water Resour. Res., 34(8), 1998*
(1)+(2) *Putti & Paniconi, CMWR Proceedings, 2004; Camporese, Paniconi, Putti, & Orlandini, Water Resour. Res., 46(W02512 ), 2010*

## *Main features of the model*

Path-based description of surface flow across the drainage basin; several options for identifying flow directions, for separating channel cells from hillslope cells (same governing equation), and for representing stream channel hydraulic geometry.




The coupling term for the model is computed as the balance between atmospheric forcing (rainfall and potential evaporation) and the amount of water that can actually infiltrate or exfiltrate the soil. This threshold-based boundary condition switching partitions potential fluxes into actual fluxes and changes in surface storage.



# *Subsurface flow module*

Various functional forms for $S_w(\psi)$ and $K_{rw}(\psi)$

Heterogeneities $(K_{sx}, K_{sy}, K_{sz}, S_s, \phi)$ by "zone" and by layer

DEM-based (uniform) grid or user-defined (nonuniform) surface grid input

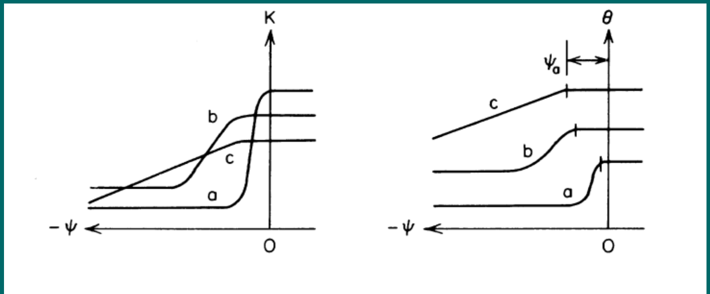
3D grid automatically generated with variable layer thicknesses and different base ("bedrock") shapes

Finite element spatial integrator (Galerkin scheme, tetrahedral elements, linear basis functions)

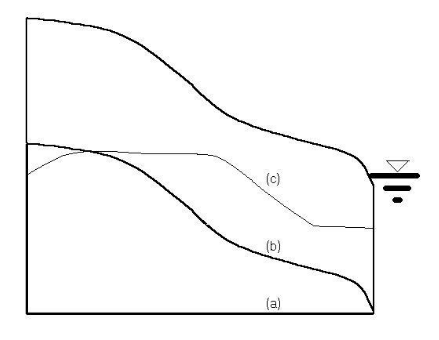
Weighted finite difference discretization in time

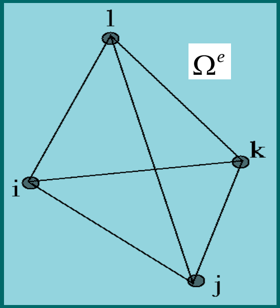
Time-varying boundary conditions: Neumann, Dirichlet, source/sink terms, seepage faces, and atmospheric fluxes

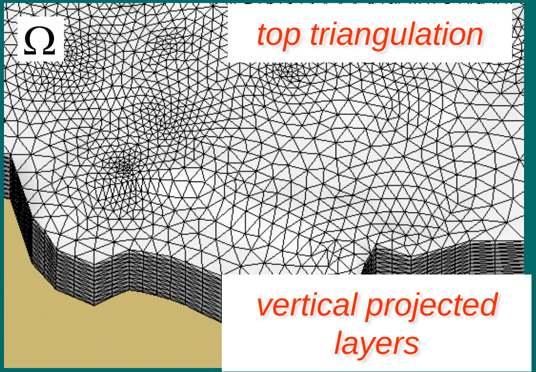
Adaptive time stepping; Newton and Picard linearization; selection of CG-type linear solvers; etc



(a) Uniform sand ; (b) silty sand ; (c) silty clay.



## *Surface flow module (cell differentiation, lake handling, other features)*

Overland (hillslope rills) and channel flow along *s*

DEM pre-analysis for definition of cell drainage directions, catchment drainage network and outlet, etc

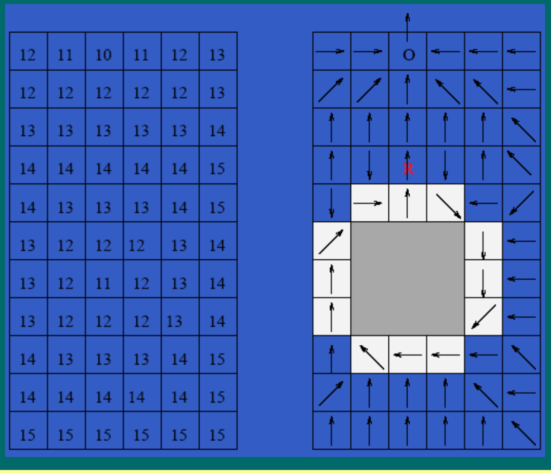
"Constant critical support area": overland flow ∀ cells with upstream drainage area $A < A^*$; else channel flow (2 other threshold-based options also implemented)

Leopold & Maddock scaling relationships; Muskingum-Cunge solution scheme (explicit and sequential); etc

"Lake boundary-following" procedure to pre-treat lakes

Storage and attenuation effects of lakes and other topographic depressions are accounted for by transferring with infinite celerity all the water drained by the "buffer" cells to the "reservoir" cell; level pool routing calculates the outflow from this cell:

$$\frac{\partial V}{\partial t} = I(t) - O(h^*)$$



# Surface flow module (drainage network flow characteristics)

*

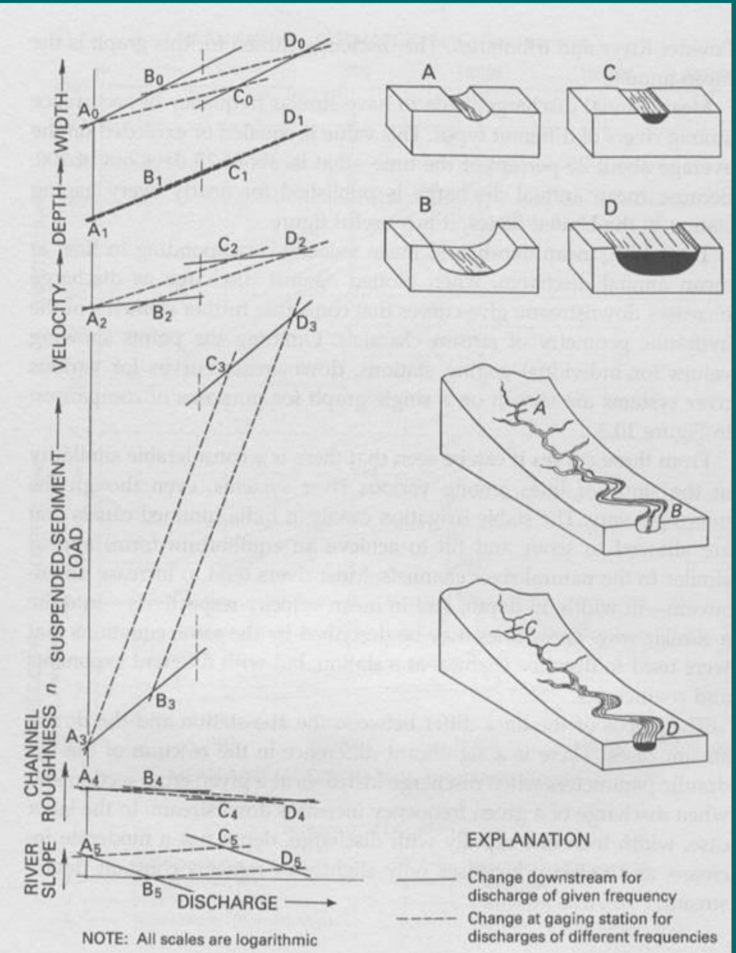



*Figure 10.4* Diagrammatic representation of relation of width, depth, and velocity to discharge at a station and downstream.

Surface runoff propagated through a network of rivulets and channels automatically extracted from the DEM.

Spatial (term I) and temporal (term II) variations of flow characteristics of the drainage network (stream channel geometry *W* and conductance coefficient $k_s$) derived from application of downstream (according to upstream drainage area) and at-a-station (according to flow discharge) fluvial relationships:

$$W(A,Q) = \overbrace{W(A_s,Q_f)Q_f(A_s)^{-b'}(A/A_s)^{w(b''-b')}}^{\text{I}}\overbrace{Q^{b'}}^{\text{II}}$$

$$k_s(A,Q) = \overbrace{k_s(A_s,Q_f)Q_f(A_s)^{-y'}(A/A_s)^{w(y''-y')}}^{\text{I}}\overbrace{Q^{y'}}^{\text{II}}$$

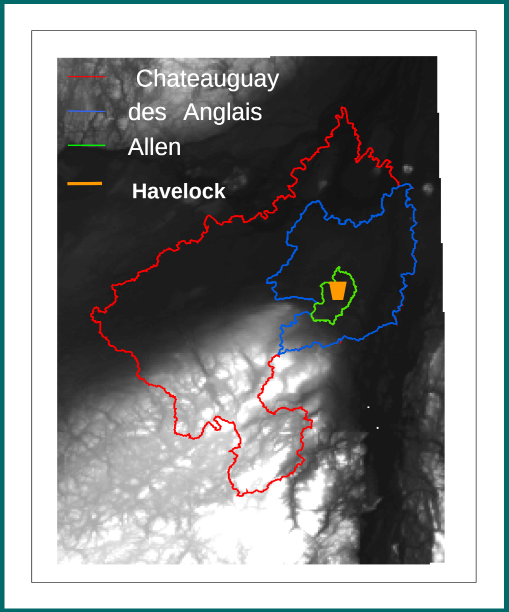

* *From L. B. Leopold and T. Maddock Jr. (1953), "The hydraulic geometry of stream channels and some physiographic implications", U. S. Geological Survey, Professional Paper no. 252*

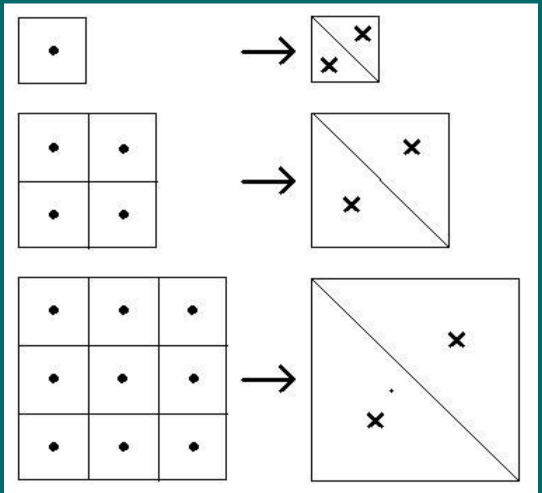
"Pond_head_min" threshold parameter accounts for microtopography

Coupled system solved sequentially*: surface first, for $Q^{k+1}$ and $h^{k+1}$; then subsurface, for $\psi^{k+1}$; finally overland flow rates $q_L^{k+1}$ are back-calculated from subsurface solution *[*sequential solution procedure but with iterative BC switching during subsurface resolution to resolve the coupling]*

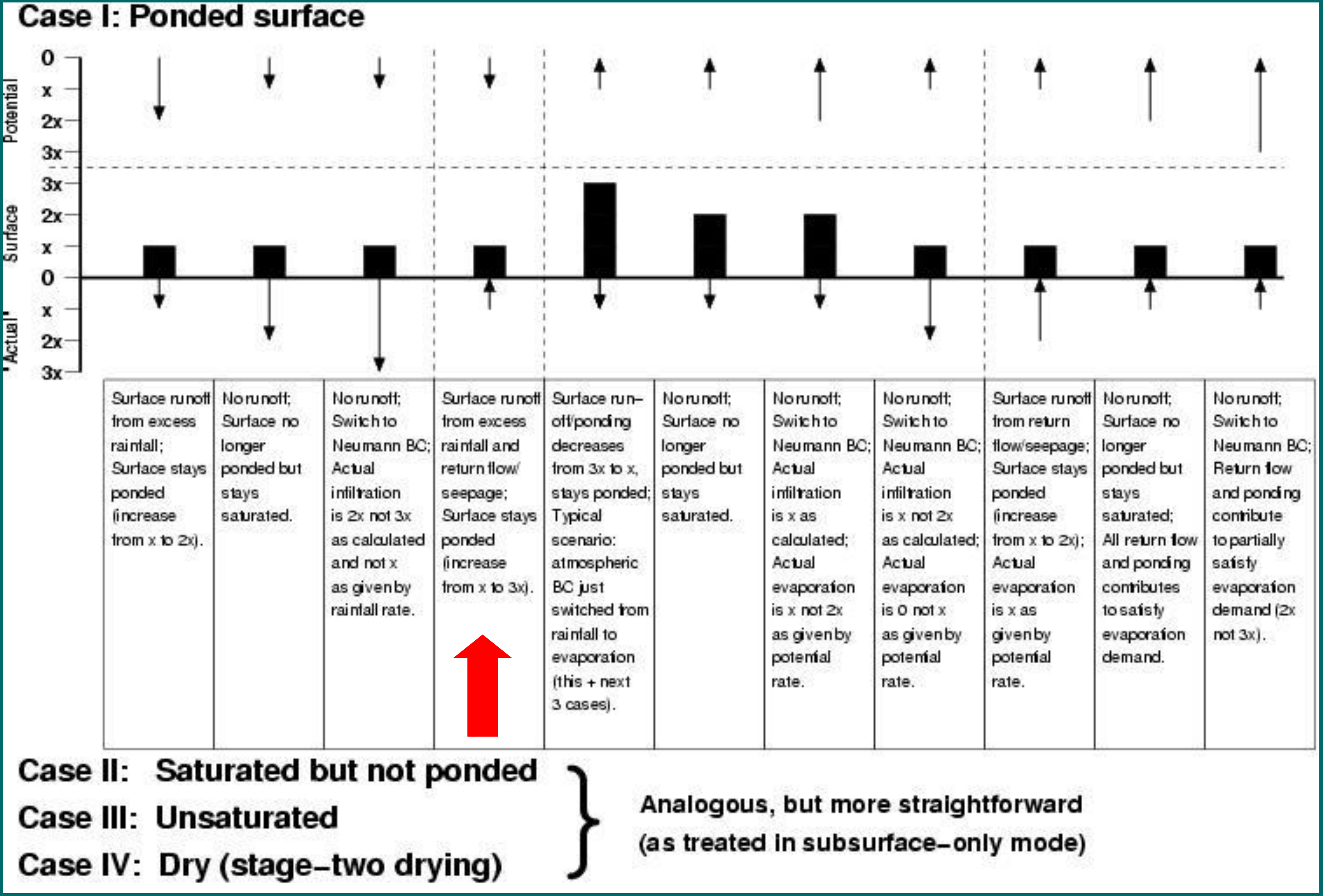
Nested time stepping: one or more surface solver time steps for each subsurface time step (based on Courant and Peclet criteria for the explicit surface routing scheme; also reflects typically faster surface dynamics compared to subsurface)

Interaction between cell-based surface grid and node-based subsurface grid includes input option for coarsening of latter grid. Allows us to exploit slower subsurface dynamics and looser grid constraints (implicit scheme), and can lower CPU and storage costs of 3D module

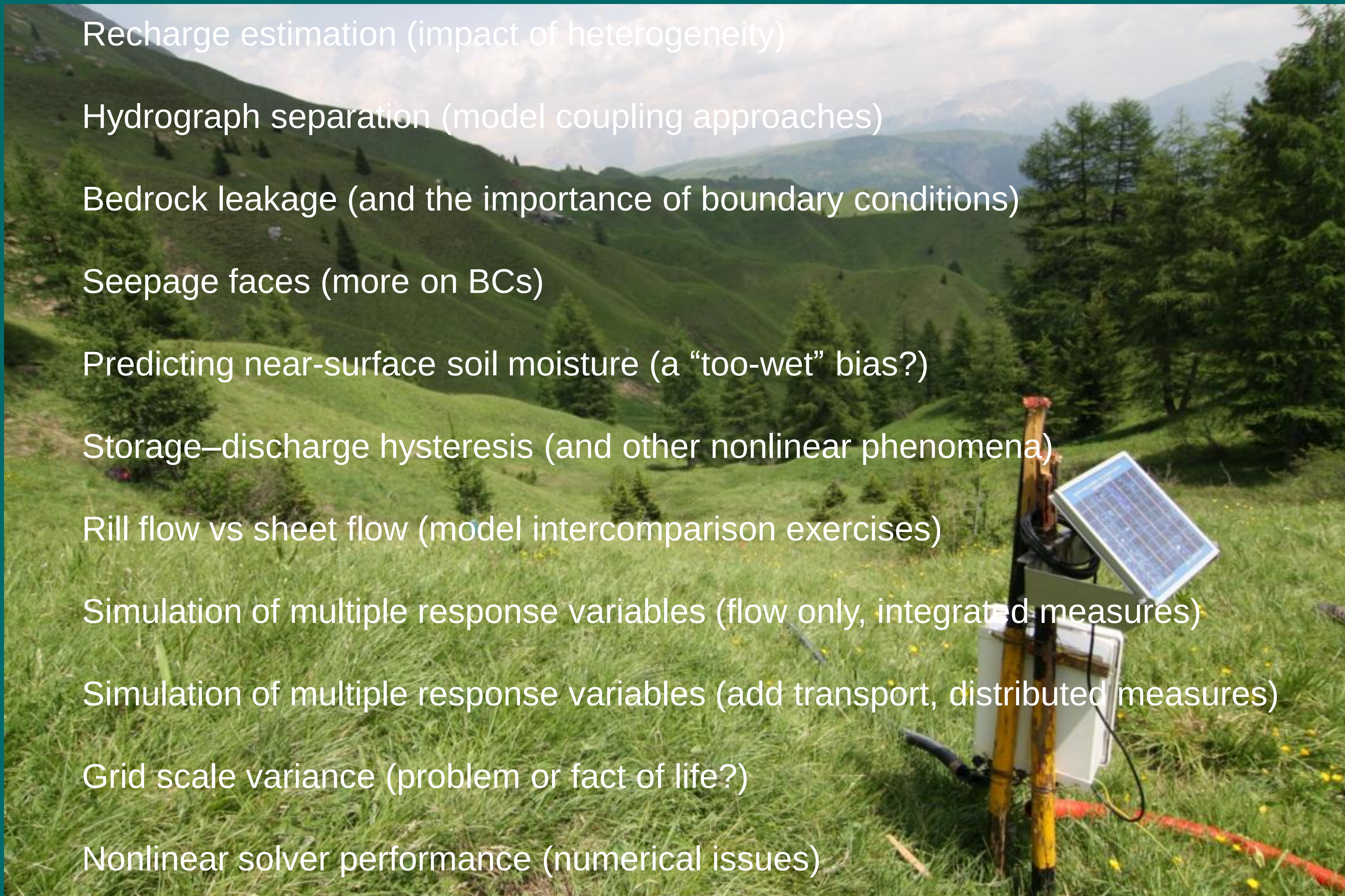


*Boundary condition-based coupling (surface BC switching procedure)*



## *Some recent studies (successes and challenges)*



Recharge estimation (impact of heterogeneity)

Hydrograph separation (model coupling approaches)

Bedrock leakage (and the importance of boundary conditions)

Seepage faces (more on BCs)

Predicting near-surface soil moisture (a “too-wet” bias?)

Storage–discharge hysteresis (and other nonlinear phenomena)

Rill flow vs sheet flow (model intercomparison exercises)

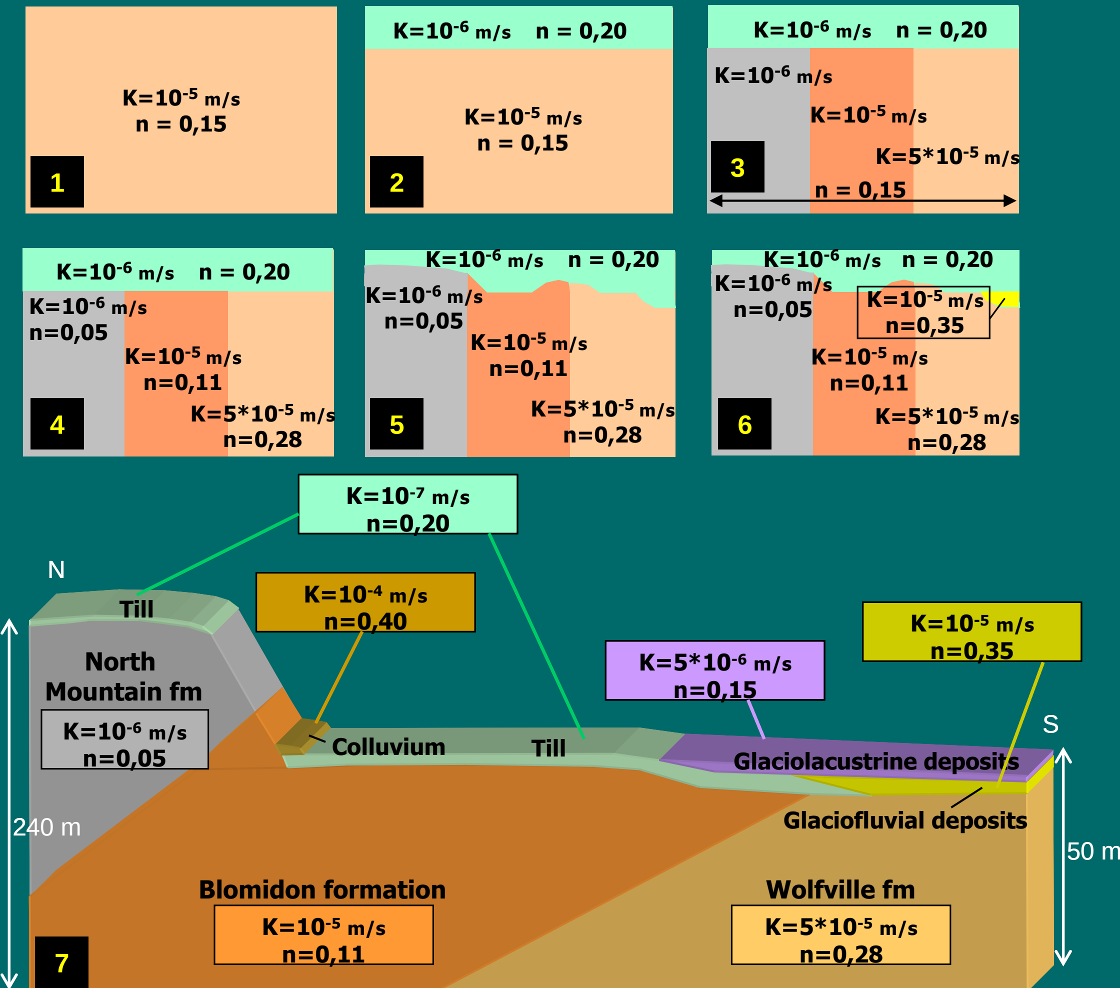
Simulation of multiple response variables (flow only, integrated measures)

Simulation of multiple response variables (add transport, distributed measures)

Grid scale variance (problem or fact of life?)

Nonlinear solver performance (numerical issues)

# *Recharge estimation (impact of heterogeneity): Thomas Brook catchment, Annapolis Valley, Nova Scotia*




*Higher-K colluvium and glacial deposits; smaller proportion of lower-K North Mtn fm*

*Increasing thickness (and nonuniformity) of surface layer*

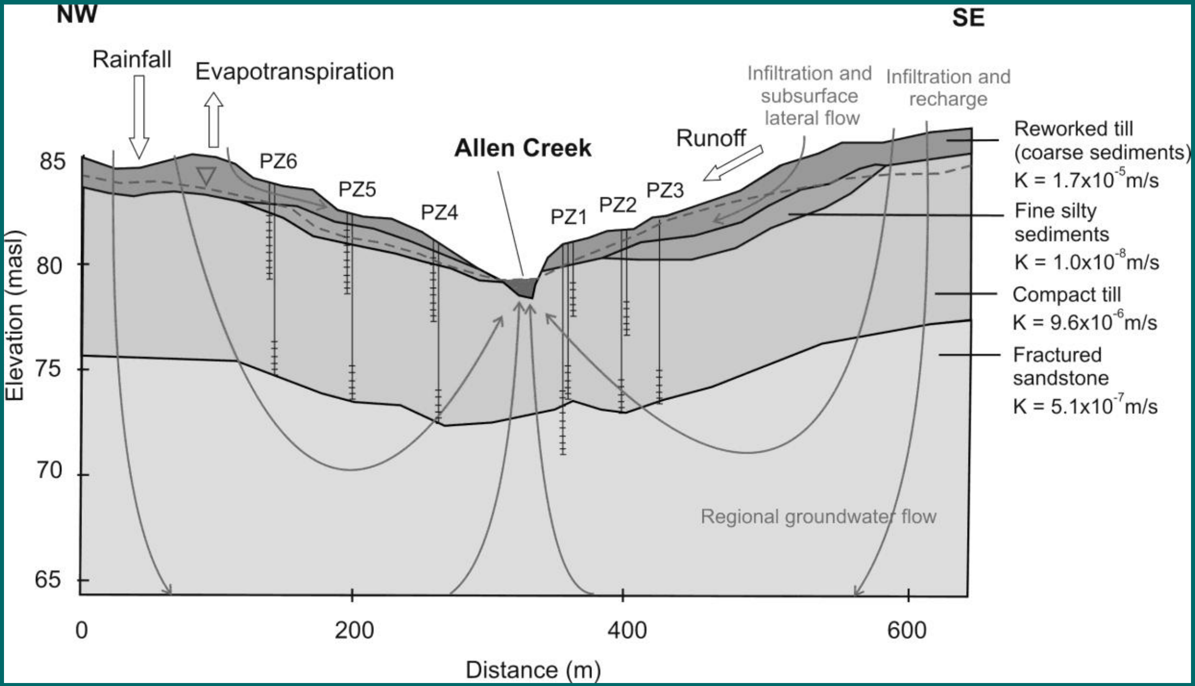
*Lower-K surface layer*

| Configuration | Average streamflow ($m^3$/s) | Annual Recharge (mm) |
|---|---|---|
| 1 | 0,252 | 567 |
| 2 | 0,243 | 439 |
| 3 | 0,180 | 457 |
| 4 | 0,177 | 449 |
| 5 | 0,167 | 375 |
| 6 | 0,158 | 514 |
| 7 | 0,223 | 675 |
| 8 (lower K 3 surf. fms.) | 0,180 | 368 |
| 9 (snow accumulation) | 0,176 | 349 |
| Mean | 0,195 | 466 |
| Std. dev. | 0,0347 | 105 |

*How do model-simulated values compare to other techniques?*
*What is the role of mechanisms such as reinfiltration or fill-and-spill?*

*Gauthier et al.: Hydrol. Earth Syst. Sci., 2009*

# *Hydrograph separation (model coupling approaches): Havelock hillslope, southwestern Quebec*

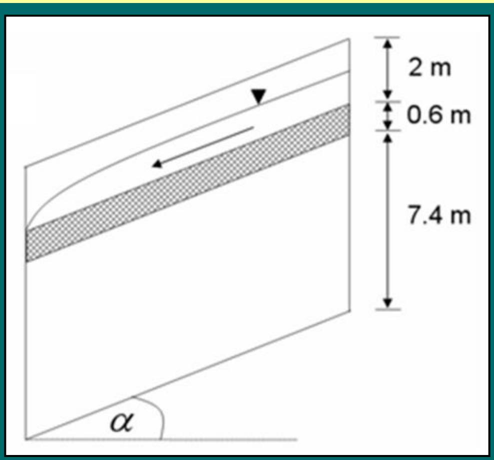


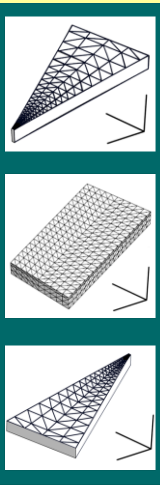

| Water budget component (mm/y) | HELP + FEFLOW | CATHY |
|---|---|---|
| Precipitation | 1038 | 1038 |
| Evapotranspiration | 556 | 556 |
| Recharge | 214 | 233 |
| Total Discharge | 456 | 500 |
| Surface runoff | 231 | / |
| Subsurface runoff | 36 | / |
| Baseflow | 189 | / |
| Exchange with regional fractured aquifer | | |
| +ve (reg.aq. to hillslope) | 4 | 77 |
| -ve (hillslope to reg.aq.) | 17 | 4 |
| Storage change | 14 | 55 |

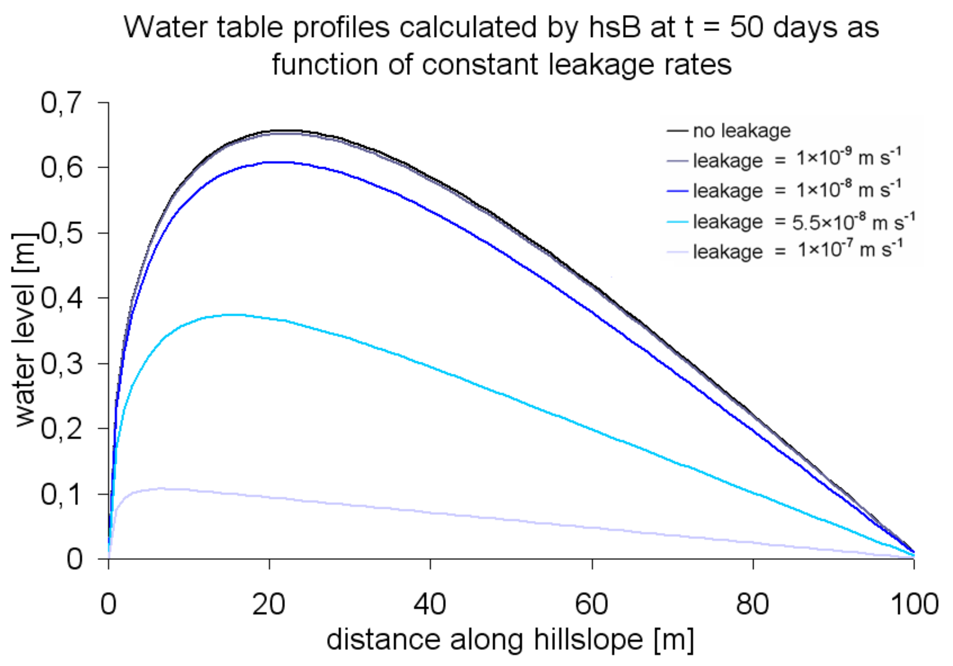
*Loose coupling (simplified model) vs CATHY:*
*is hydrograph separation really so straightforward?*

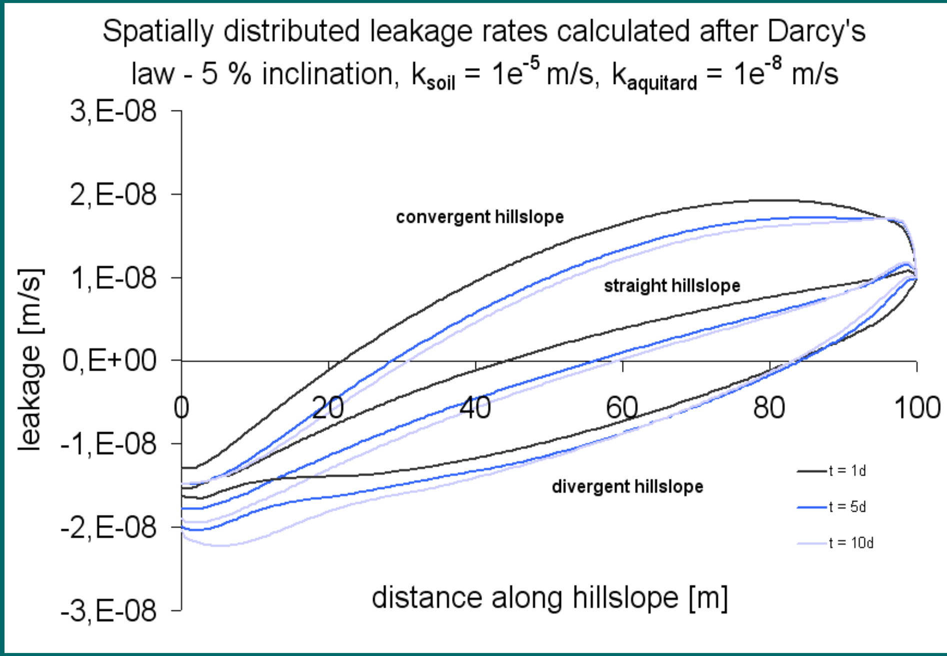
*Guay et al.: Hydrol. Process., 2012*

## *Bedrock leakage (and the importance of BCs): idealized hillslopes / sloping unconfined aquifers*





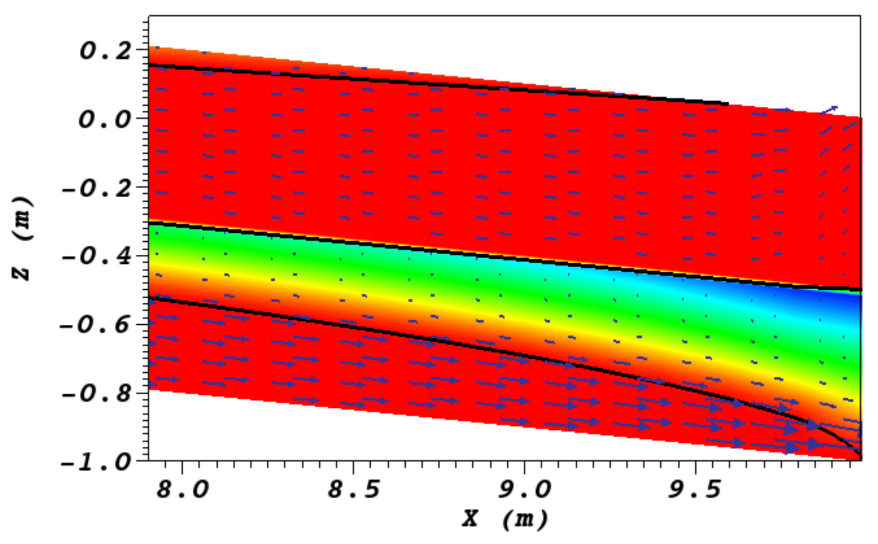



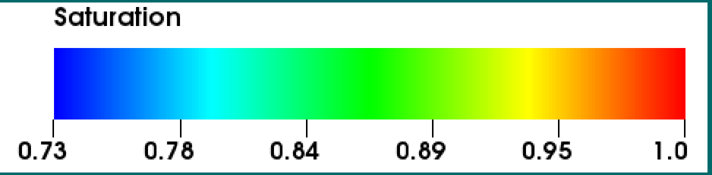

*Questioning a fundamental paradigm in hillslope hydrology.*

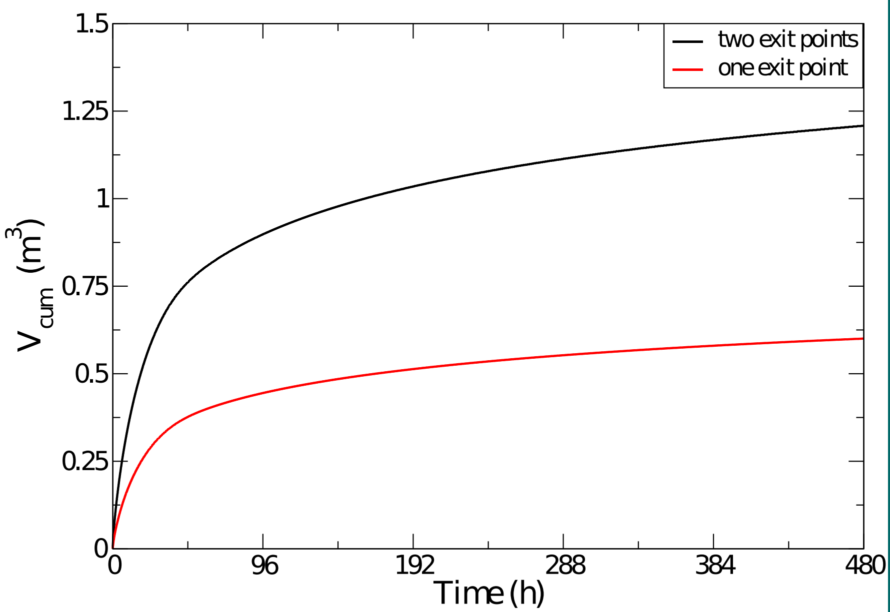
*Highly dependent on downslope BC treatment – not just a numerical issue.*

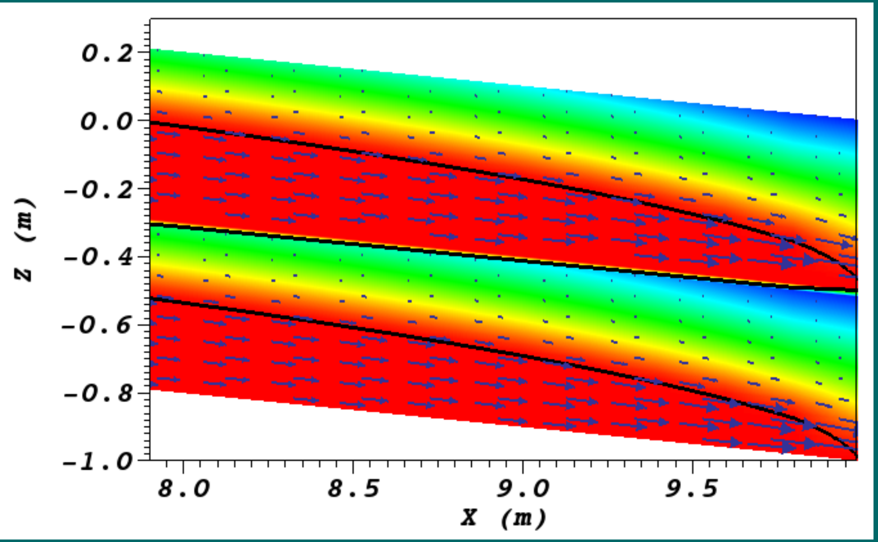
*Broda et al.: J. Hydrol., 2011*

## *Seepage faces (more on BCs): idealized hillslopes, Landscape Evolution Observatory (LEO)*



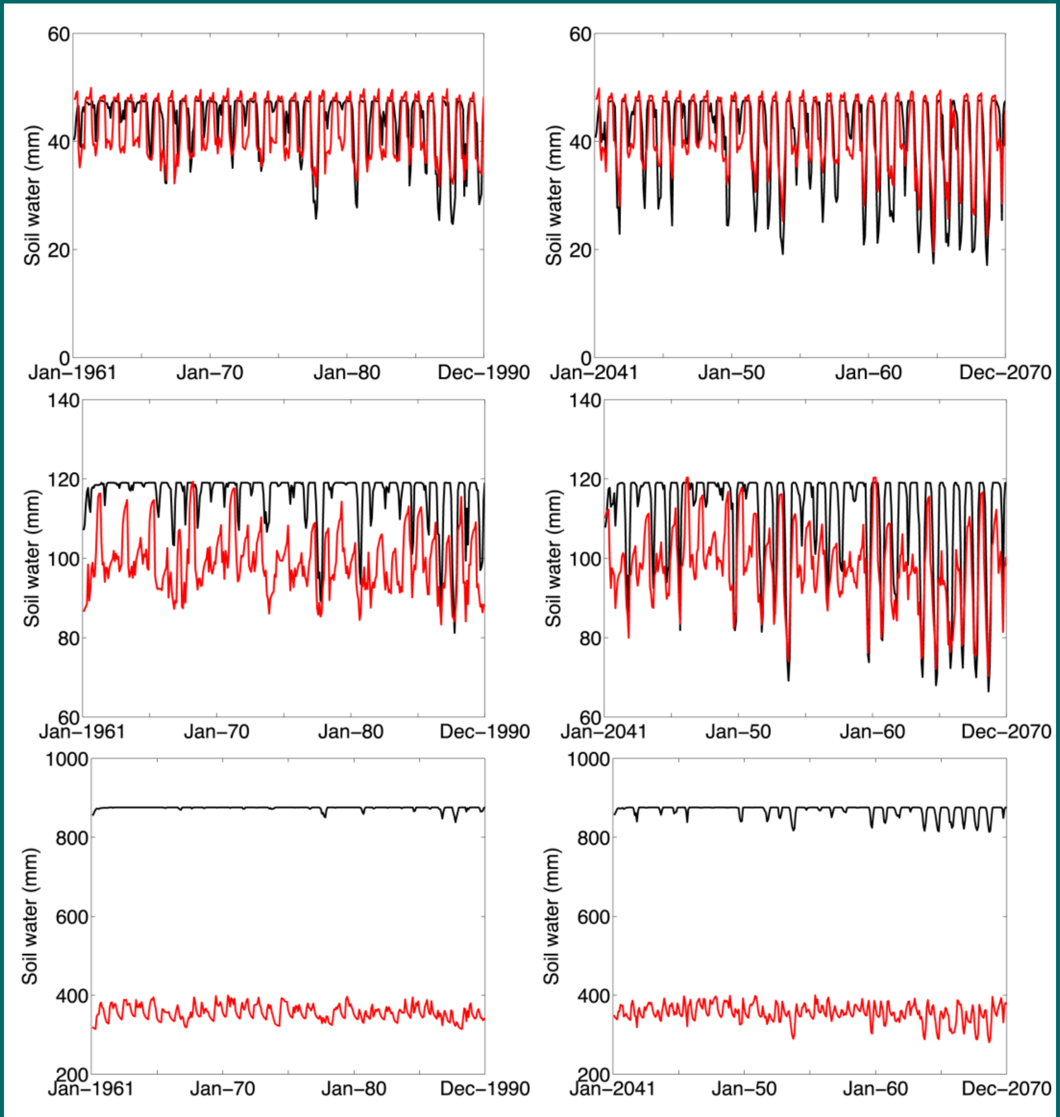




*Issues:*

- *seepage face vs Dirichlet BC treatment*
- *interaction between seepage face and catchment outlet*
- *SF algorithm for full (random) heterogeneity*

*Scudeler et al.: in preparation*

## *Predicting near-surface soil moisture (a "too-wet" bias?): des Anglais river basin, southwestern Quebec*




*CLASS (red) and CATHY (black) results for monthly soil water content at different depths (shallow to deep from top to bottom) and for past (left) and future (right) climate projections.*

*Is there a bias in the model?*
*Possible causes:*

*- surface BC handling (eg, need seepage faces along stream banks?)*

*- too-coarse temporal rainfall resolution (peak rain rates get smoothed out –> more infiltration, less surface runoff)*

*- missing transpiration*

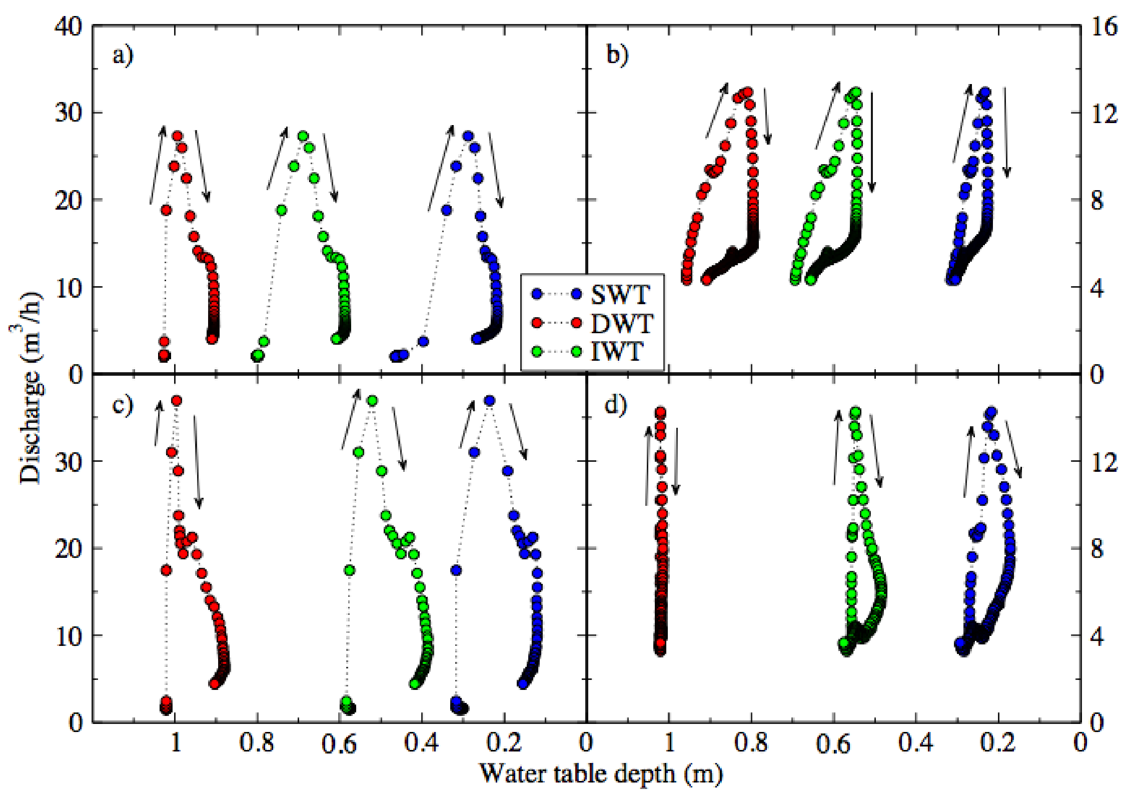
*- too-coarse grid around steep terrain (eg, Covey Hill) misses important dynamics*

*- missing agricultural (eg, tile) drainage*

*- …*

*Sulis et al.: Water Resour. Res., 2011*

## Storage–discharge hysteresis (and other nonlinear phenomena): Larch Creek catchment, northern Italy




CATHY can reproduce hysteresis and thresholding behavior observed in the relationship between the subsurface storage and discharge responses of a small catchment. No ad hoc parameterization is needed.

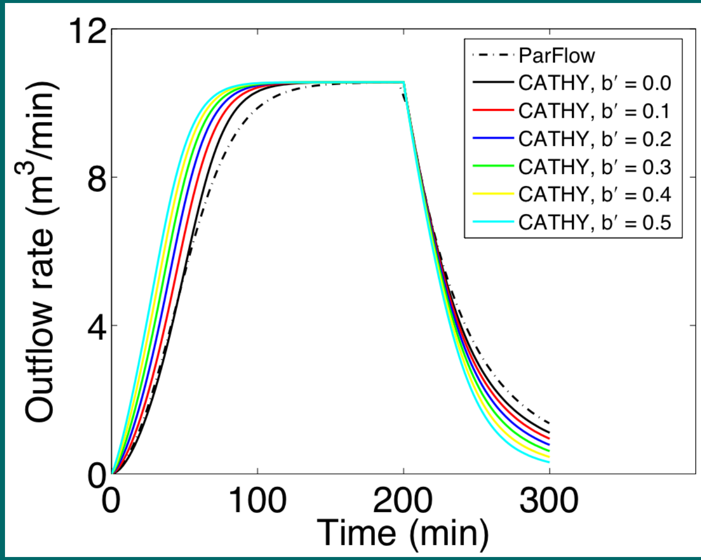
Is there any link to or contribution from unsaturated zone hysteresis?

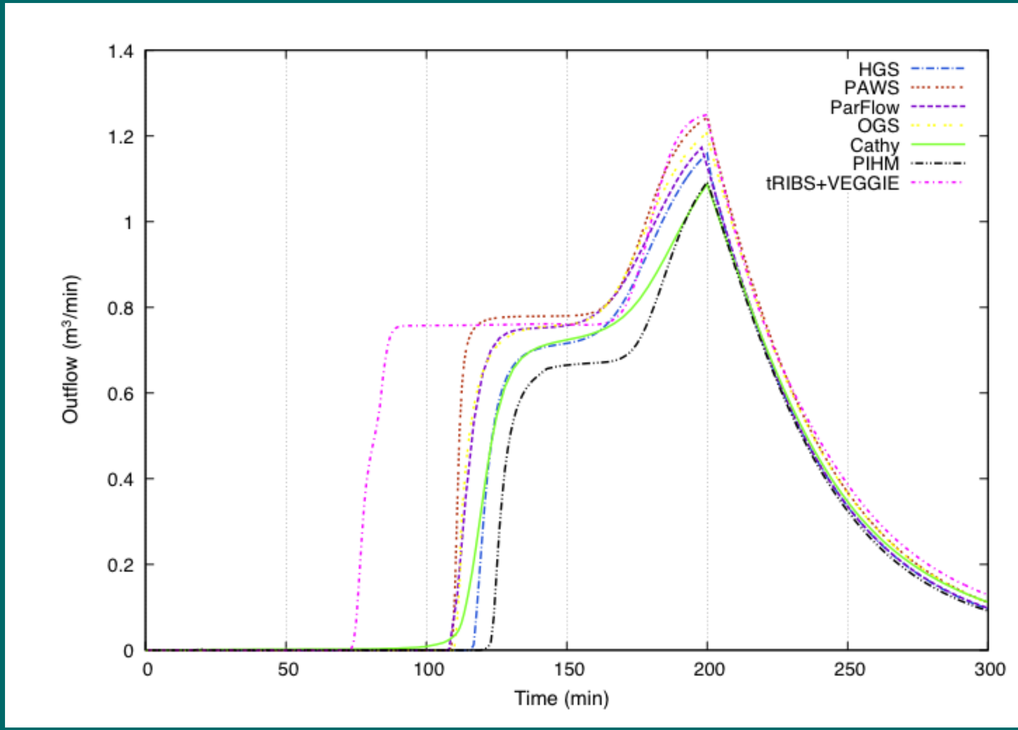
Nature and role of nonlinear phenomena in atmosphere–land surface–soil–aquifer interactions and feedbacks are poorly understood.

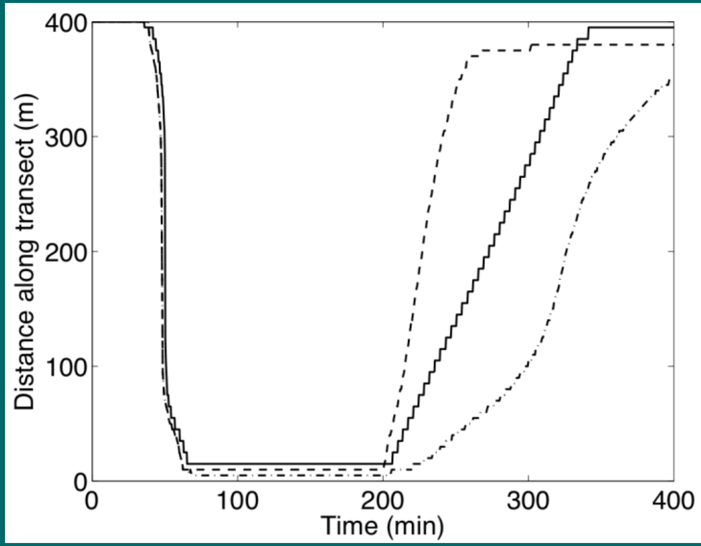
Simulated (top) and observed (bottom) responses in shallow, deep, and intermediate observation wells for 7-8 August 2009 (left) and 16-18 August 2009 (right) rainfall events.

Camporese et al.: Water Resour. Res., 2014

## *Rill flow vs sheet flow (model intercomparison exercises): benchmark problems*



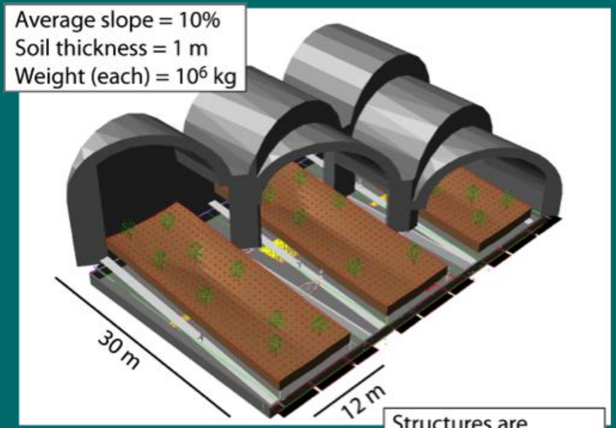

*Benchmarking is a complicated business even for synthetic test cases … Why and how do different models (even based on the same equations) perform differently? And what to do about it??*

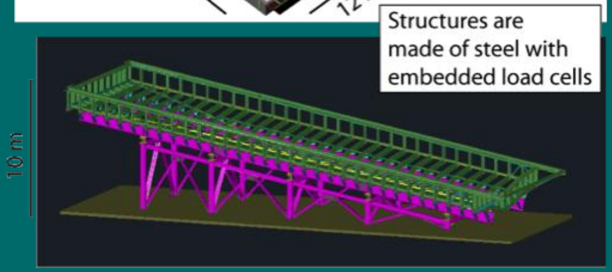
*Evolution of the point of intersection between the water table and the land surface for the sloping plane test case. The outlet face is at x = 400 m. ParFlow: solid line; CATHY: dashed-dotted (sheet flow) and dashed (rill flow).*

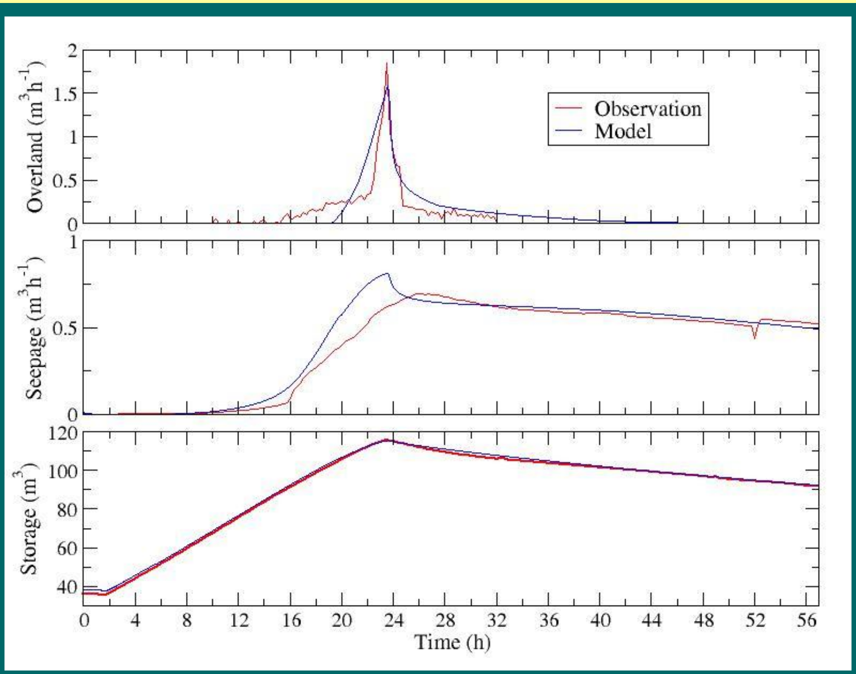
*Sulis et al.: Adv. Water Resour., 2010*

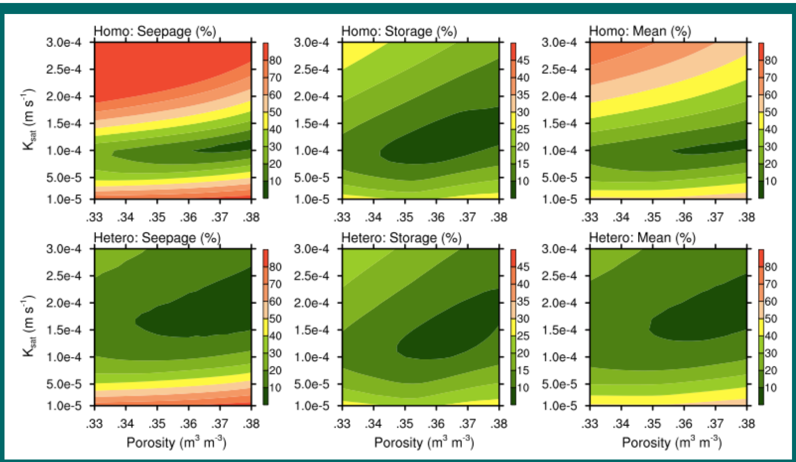
*Maxwell et al.: Water Resour. Res., 2014*

# *Simulation of multiple response variables (flow only, integrated measures): Biosphere 2 LEO*



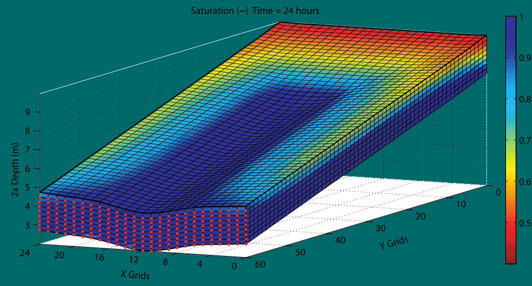



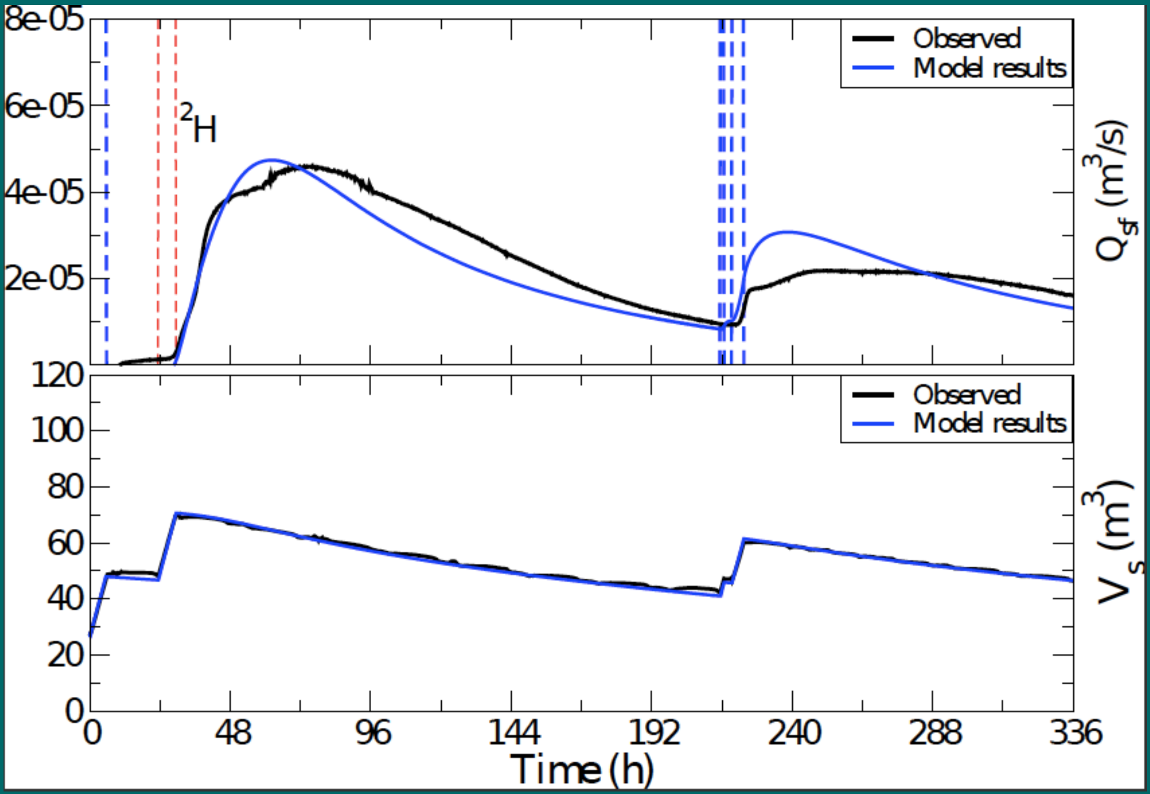

*Issue of equifinality: does the mechanism we invoke (incipient downslope heterogeneity) imply (sole) causation?*

*"Perfect knowledge" of the bottom BC … how much does this help?*

*Niu et al.: Hydrol. Earth Syst. Sci., 2014*

## *Simulation of multiple response variables (add transport, distributed measures): Biosphere 2 LEO*

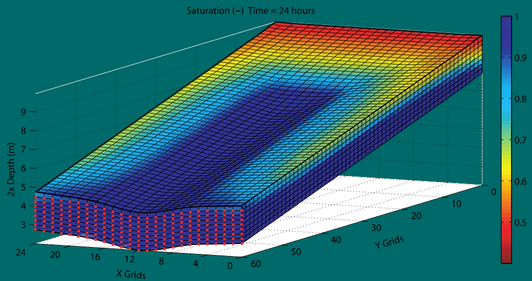


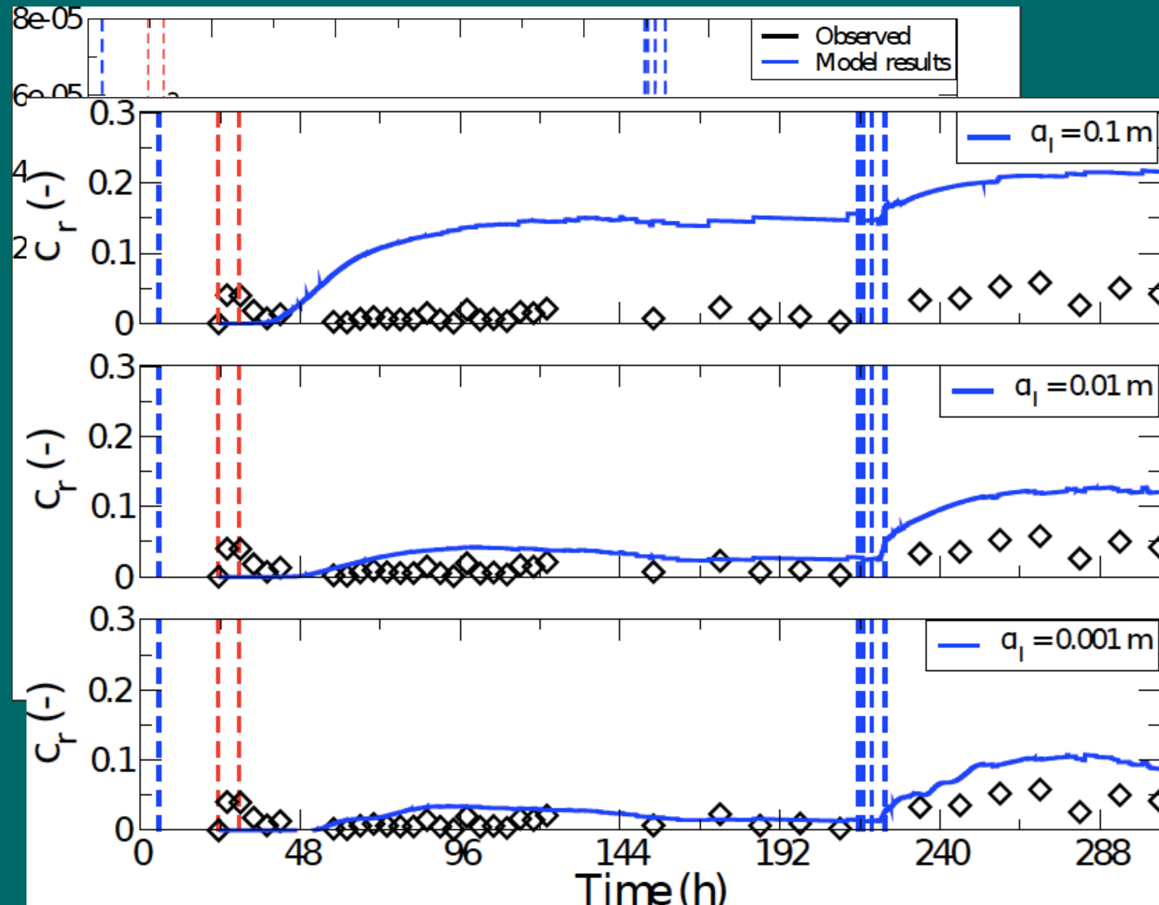




*All three variables on previous slide are integrated measures of the hillslope response. How does the model perform when we examine distributed responses? And what happens when we include solute transport? …*

*Scudeler et al.: in preparation*

## *Simulation of multiple response variables (add transport, distributed measures):* *Biosphere 2 LEO*

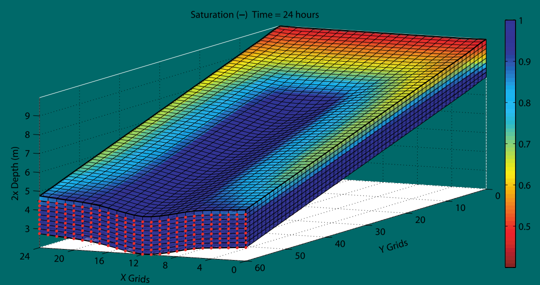


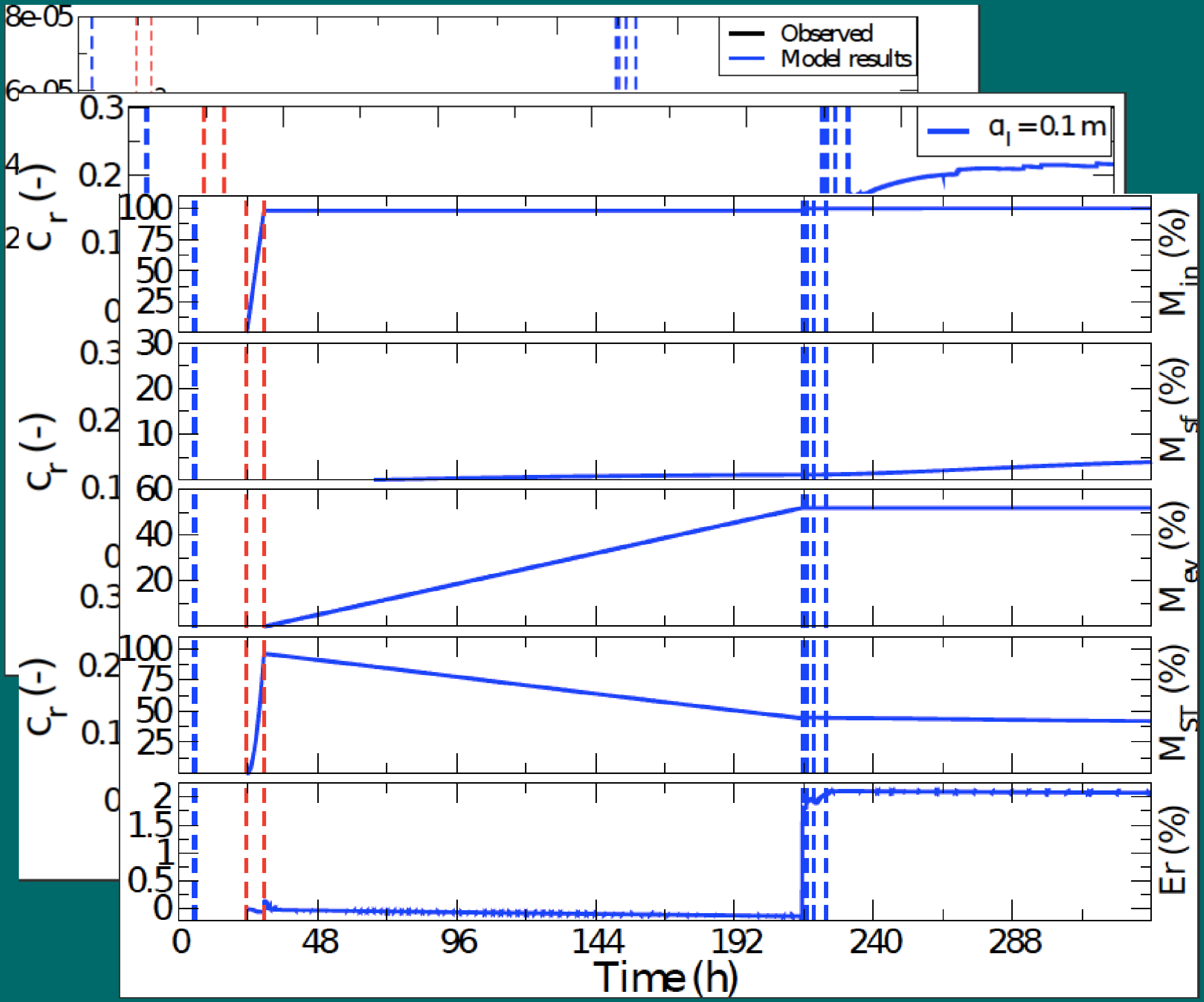




*All three variables on previous slide are integrated measures of the hillslope response. How does the model perform when we examine distributed responses? And what happens when we include solute transport? …*

*Scudeler et al.: in preparation*

## *Simulation of multiple response variables (add transport, distributed measures):* *Biosphere 2 LEO*

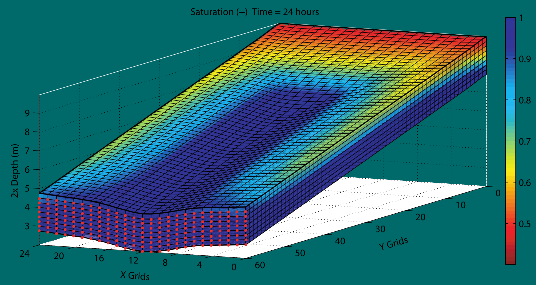


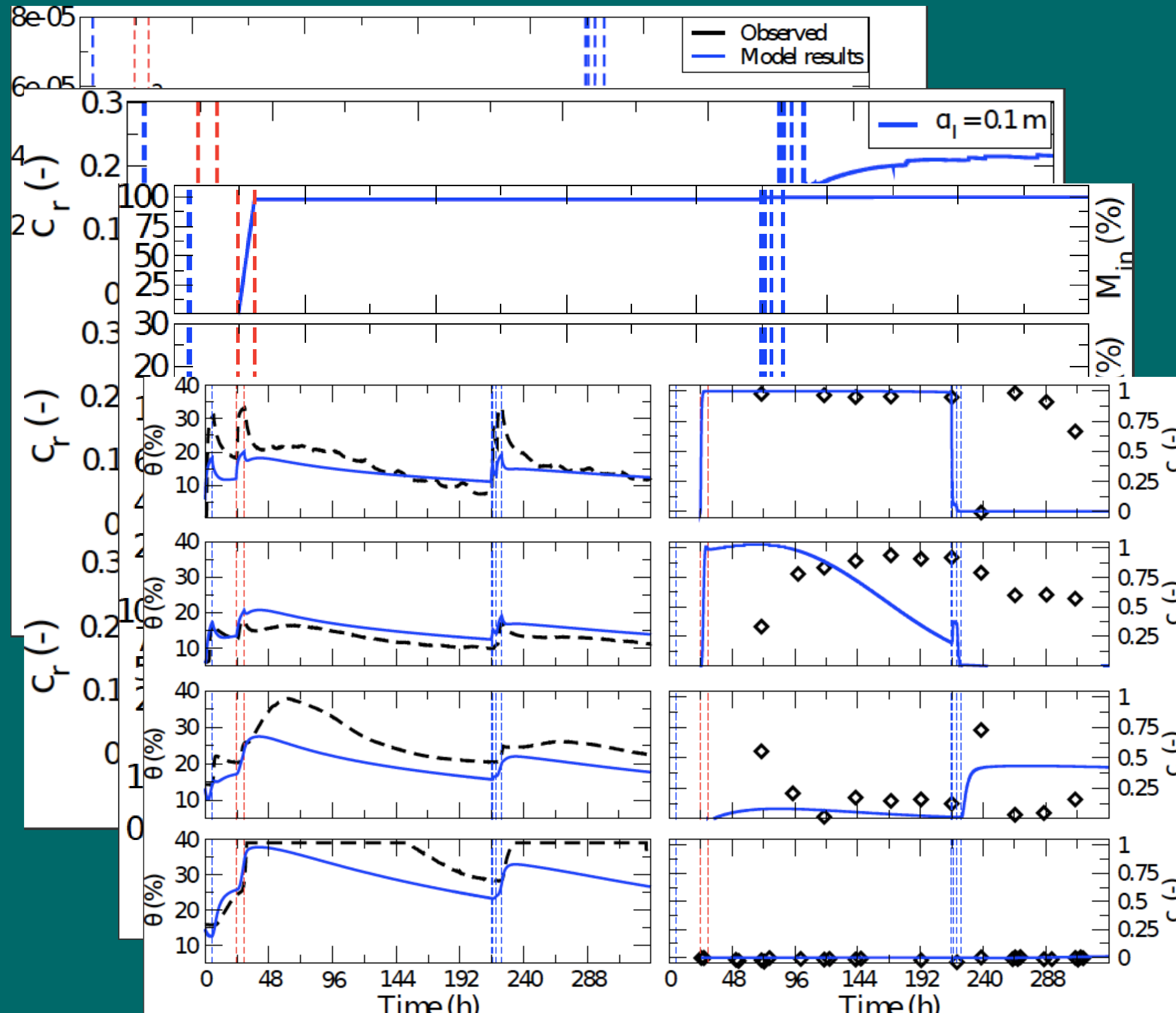




*All three variables on previous slide are integrated measures of the hillslope response. How does the model perform when we examine distributed responses? And what happens when we include solute transport? …*

*Scudeler et al.: in preparation*

# *Simulation of multiple response variables (add transport, distributed measures):* *Biosphere 2 LEO*

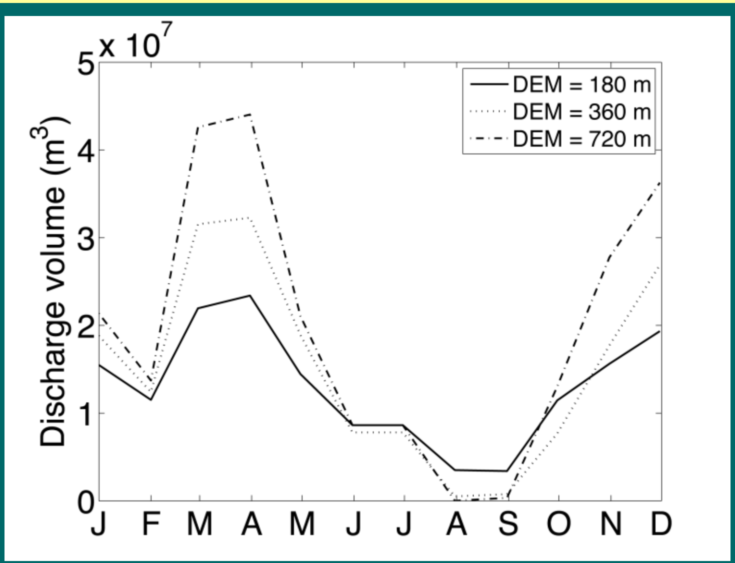


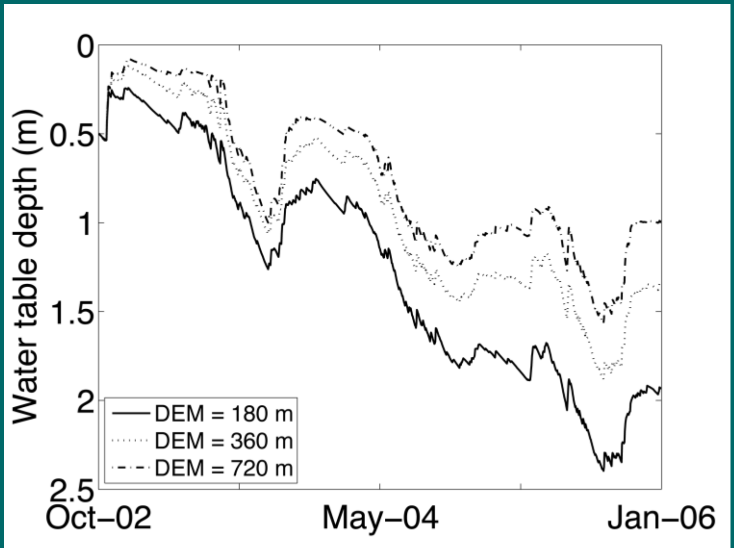



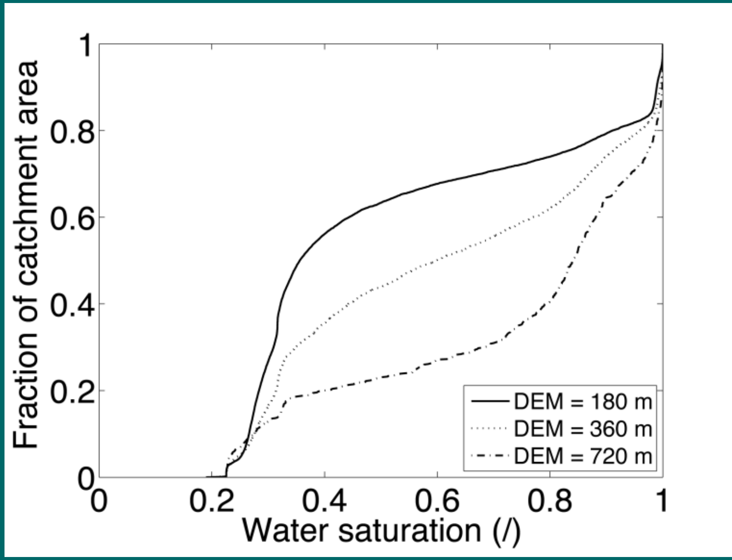

*All three variables on previous slide are integrated measures of the hillslope response. How does the model perform when we examine distributed responses? And what happens when we include solute transport? …*

*Scudeler et al.: in preparation*

# *Grid scale variance (problem or fact of life?): des Anglais river basin, southwestern Quebec*



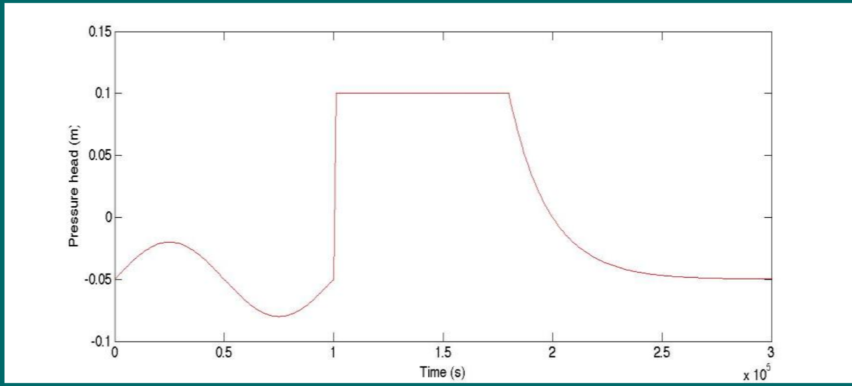



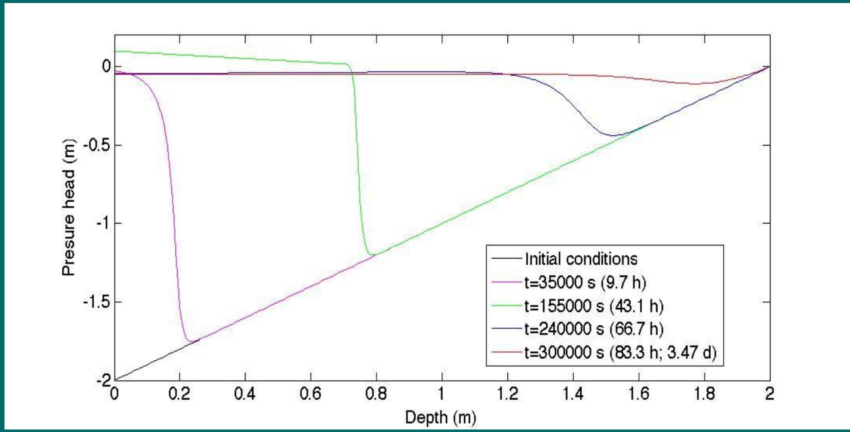

*Comparison of simulation results at 3 different DEM resolutions: average monthly streamflow discharge, catchment-averaged daily water table depth, and cumulative frequency distribution of surface soil saturation after a 10-day rain period.*

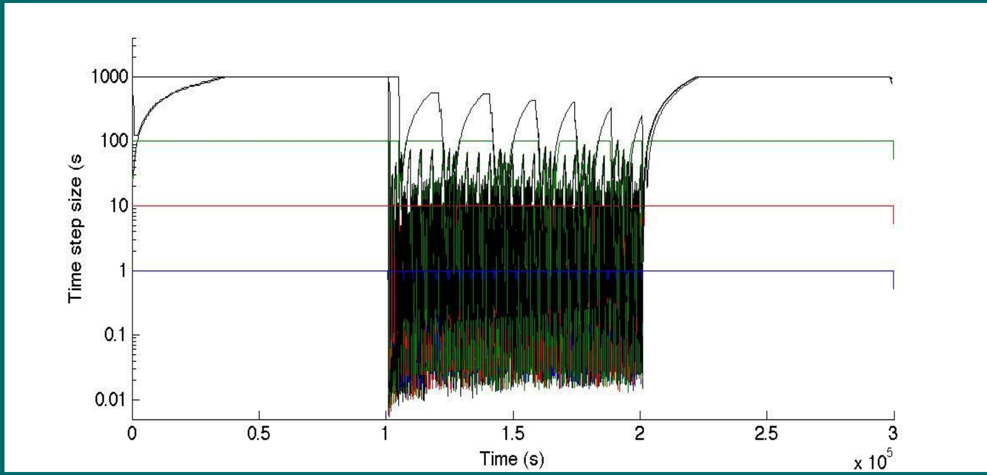
*There are many reasons (causes) for grid scale variance (and not limited to just the CATHY model). One of the most serious challenges in catchment-based hydrological / ecological modeling …*

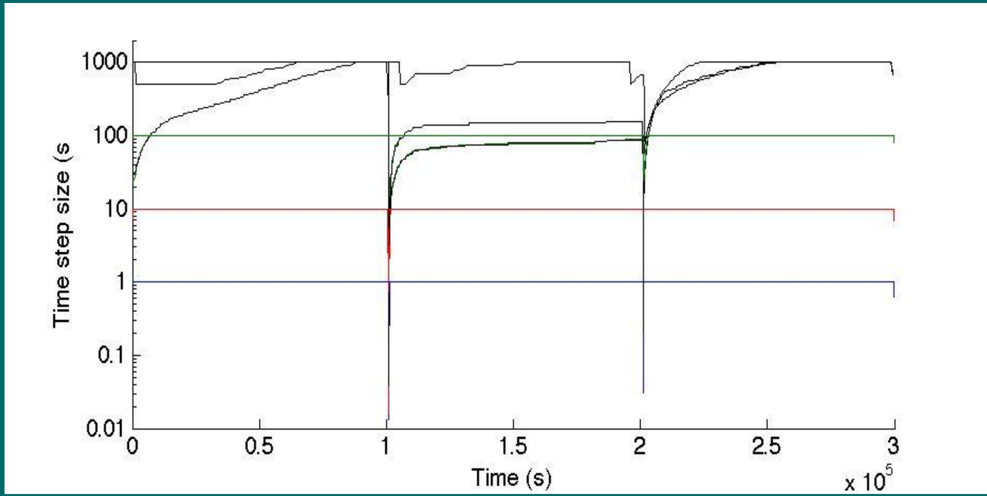
*Sulis et al.: Hydrol. Process., 2011*

# Nonlinear solver performance (numerical issues): *synthetic test case with dynamic ponding*




*Iterative schemes (Picard, Newton, nested Newton, …), mass conservation (including data assimilation considerations), accuracy of velocity calculations (especially important for gw recharge and for solute transport), etc – all still ongoing research topics!*

*Adaptive time stepping behavior for Picard (top) and Newton (bottom) at four different vertical discretizations (10, 50, 250, and 500 layers for black, green, red, and blue curves, respectively).*

*Paniconi et al.: EGU, 2012*

## *Extensions and evolution of the model (flow and transport; other processes)*

Flow (water quantity and distribution)

Surface

$$\frac{\partial Q}{\partial t} + c_k \frac{\partial Q}{\partial s} = D_h \frac{\partial^2 Q}{\partial s^2} + c_k q_s$$

Subsurface

$$\sigma(S_w)\frac{\partial \psi}{\partial t} = \nabla \cdot [K_s K_r(S_w)(\nabla \psi + \eta_z)] + q_{ss}$$

Transport (water quality and interactions with other substances)

Surface

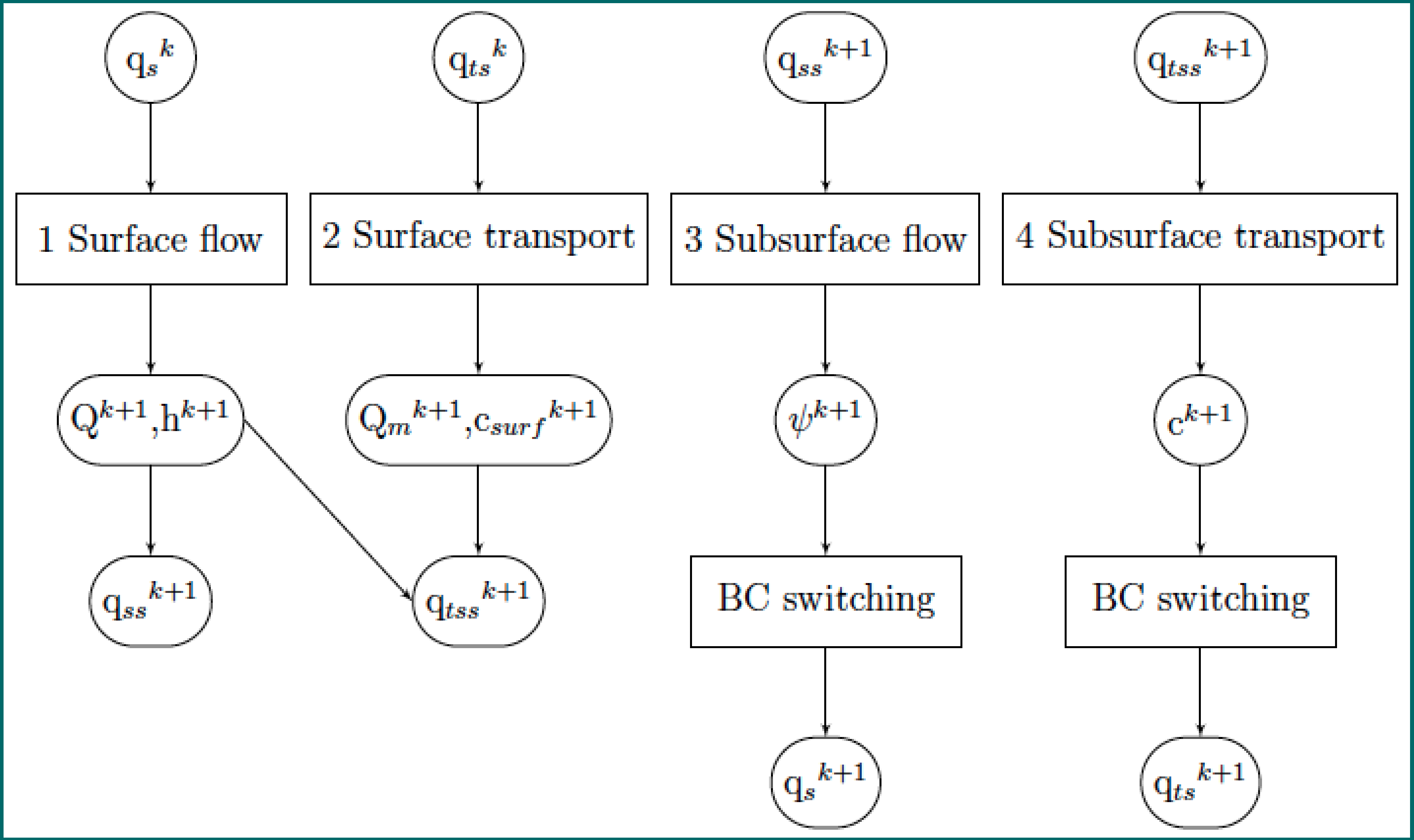
$$\frac{\partial Q_m}{\partial t} + c_t \frac{\partial Q_m}{\partial s} = D_c \frac{\partial^2 Q_m}{\partial s^2} + c_t q_{ts}$$

Subsurface

$$\frac{\partial \theta c}{\partial t} = \nabla \cdot [-qc + D\nabla c] + q_{tss}$$

*Weill et al.: Adv. Water Resour., 2011*

## *Coupling scheme (sequential; iterative BC switching provides updated information)*



*A physics-based building block approach; interactions and coupling*

**Atmospheric forcing**

land surface models

hydrostatic and nonhydrostatic LAM

**Water "quantity"**

surface flow
saturated flow
unsaturated flow
multiphase flow
preferential flow
root water uptake
…

**"Coupled" models**

surface-subsurface
reaction-transport-mechanics
erosion & sediment transport
DSS & cost-benefit analysis
saltwater & brines
vegetation & crops
water-solute-heat
…

**Water "quality"**

advection-dispersion transport
linear sorption and decay
reaction kinetics (non-LEA)
multi-component and -species
biodegradation
redox, precipitation/dissolution
…

# *Evolution of the model*

Catchment/DEM-based subsurface flow modeling
↓
Variable density transport (an early coupled model)
↓
Surface/subsurface flow coupling
↓
Advanced numerics
↓
Improved grid-based DEM analysis
↓
Data assimilation
↓
Surf/subsurf & flow/ transport coupling
↓
Ecohydrological modeling (LSM coupling, vegetation, energy balance, $CO_2$, nutrient cycles) – eg, CATHY-NoahMP
↓
Detailed experiments, geophysical inversion, parameter estimation, sensitivity & uncertainty analysis, model intercomparison, biogeochemistry & soil weathering, sediment transport & erosion, soil freezing & snowmelt, preferential flow, unstructured grids, RCM/NWP coupling (CATHY-NoahMP-WRF?), …


Paniconi, Wood: *A detailed model for simulation of catchment scale subsurface hydrologic processes.* **Water Resour. Res.,** 29, 1993

Paniconi, *Putti*: *A comparison of Picard and Newton iteration in the numerical solution of multidimensional variably saturated flow problems.* **Water Resour. Res.,** 30, 1994

Putti, Paniconi: *Picard and Newton linearization for the coupled model of saltwater intrusion in aquifers.* **Adv. Water Resour.,** 18, 1995

*Orlandini*, Rosso: *Diffusion wave modeling of distributed catchment dynamics.* [illegible]

Putti, Cordes: *Finite element approximation of the diffusion operator on tetrahedra.* **SIAM J. Sci. Comput.,** 19, 1998

Orlandini, Rosso: *Parameterization of stream channel geometry in the distributed modeling of catchment dynamics.* **Water Resour. Res.,** 34, 1998

Gambolati, Putti, Paniconi: *Three-dimensional model of coupled density-dependent flow and miscible salt transport.* **Seawater Intrusion in Coastal Aquifers,** chap. 10, Kluwer Academic, 1999

Paniconi, Khlaifi, Lecca, Giacomelli, Tarhouni: *Modeling and analysis of seawater intrusion in the coastal aquifer of eastern Cap-Bon, Tunisia.* **Transport in Porous Media,** 43, 2001

Bixio, Gambolati, Paniconi, Putti, Shestopalov, Bublias, Bohuslavsky, Kastelteseva, [illegible]: *Modeling groundwater–surface water interactions in the Chernobyl exclusion zone.* **Environ. Geol.,** 42, 2002

Paniconi, Marrocu, Putti, Verbunt: *Newtonian nudging for a Richards equation-based distributed hydrological model.* **Adv. Water Resour.,** 26, 2003

*Mazzia*, Putti: *High order Godunov mixed methods on tetrahedral meshes for density driven flow simulations in porous media.* **J. Comp. Phys.,** 208, 2005

*Camporese*, Ferraris, Putti, Salandin, Teatini: *Hydrological modeling in swelling/shrinking peat soils.* **Water Resour. Res.,** 42, 2006

Mazzia, Putti: *Three dimensional Mixed Finite Element-Finite Volume approach for the solution of density dependent flow in porous media.* **J. Comput. Appl. Math.,** 185, 2006

Putti, Sartoretto: *Linear Galerkin vs mixed finite element 2D flow fields.* **Int. J. Numer. Meth. Fluids,** 60, 2009

Camporese, Paniconi, Putti, Orlandini: *Surface–subsurface modeling with path-based routing, boundary condition-based coupling, and assimilation of multisource observation data.* **Water Resour. Res.,** 46, 2010

Orlandini, *Moretti*, Franchini, Aldighieri, Testa: *Path-based methods for the determination of nondispersive drainage directions in grid-based digital elevation models.* **Water Resour. Res.,** 39, 2003

D'Haese, Putti, Paniconi, Verhoest: *Assessment of adaptive and heuristic time stepping for variably saturated flow.* **Int. J. Numer. Meth. Fluids,** 53, 2007

Camporese, Paniconi, Putti, Salandin: *Ensemble Kalman filter data assimilation for a process-based catchment scale model of surface and subsurface flow.* **Water Resour. Res.,** 45, 2009

Orlandini, Moretti: *Determination of surface flow paths from gridded elevation data.* **Water Resour. Res.,** 45, 2009

*Sulis*, Meyerhoff, Paniconi, Maxwell, Putti, Kollet: *A comparison of two physics-based numerical models for simulating surface water–groundwater interactions.* **Adv. Water Resour.,** 33, 2010

*Weill*, Mazzia, Putti, Paniconi: *Coupling water flow and solute transport into a physically-based surface–subsurface hydrological model.* **Adv. Water Resour.,** 34, 2011

Sulis, Paniconi, Camporese: *Impact of grid resolution on the integrated and distributed response of a coupled surface–subsurface hydrological model for the des Anglais catchment, Quebec.* **Hydrol. Process.,** 25, 2011

Orlandini, Tarolli, Moretti, Dalla Fontana: *On the prediction of channel heads in a complex alpine terrain using gridded elevation data.* **Water Resour. Res.,** 47, 2011

Dagès, Paniconi, Sulis: *Analysis of coupling errors in a physically-based integrated surface water–groundwater model.* **Adv. Water Resour.,** 49, 2012

Pasetto, Camporese, Putti: *Ensemble Kalman filter versus particle filter for a physically-based coupled surface–subsurface model.* **Adv. Water Resour.,** 47, 2012

Guay, Nastev, Paniconi, Sulis: *Comparison of two modeling approaches for groundwater–surface water interactions.* **Hydrol. Process.,** 27, 2013

Weill, Altissimo, Cassiani, Deiana, Marani, Putti: *Saturated area dynamics and streamflow generation from coupled surface–subsurface simulations and field observations.* **Adv. Water Resour.,** 59, 2013

Niu, Paniconi, Troch, Scott, Durcik, Zeng, Huxman, Goodrich: *An integrated model of catchment-scale ecohydrological processes: 1. Model description and tests over an energy-limited watershed.* **Ecohydrol.**, 7, 2014

Camporese, Penna, Borga, Paniconi: *A field and modeling study of nonlinear storage-discharge dynamics for an Alpine headwater catchment.* **Water Resour. Res.,** [illegible]

Manoli, Bonetti, Domec, Putti, Katul, Marani: *Tree root systems competing for soil moisture in a 3D soil–plant model.* **Adv. Water Resour.,** 66, 2014

Maxwell, Putti, Meyerhoff, Delfs, Ferguson, Ivanov, Kim, Kolditz, Kollet, Kumar, Lopez, Niu, Paniconi, Park, Phanikumar, Shen, Sudicky, Sulis: *Surface–subsurface model intercomparison: A first set of benchmark results to diagnose integrated hydrology and feedbacks.* **Water Resour. Res.,** 50, 2014

Trudel, Leconte, Paniconi: *Analysis of the hydrological response of a distributed physically-based model using post-assimilation (EnKF) diagnostics of streamflow and in situ soil moisture observations.* **J. Hydrol.,** 514, 2014

Camporese, Daly, Dresel, Webb: *Simplified modeling of catchment-scale evapotranspiration via boundary condition switching.* **Adv. Water Resour.,** 69, 2014

Niu, Pasetto, Scudeler, Paniconi, Putti, Troch, DeLong, Dontsova, Pangle, Breshears, Chorover, Huxman, Pelletier, Saleska, Zeng: *Incipient subsurface heterogeneity and its effect on overland flow generation – Insight from a modeling study of the first experiment at the Biosphere 2 Landscape Evolution Observatory.* **Hydrol. Earth Syst. Sci.,** [illegible], 2014

## *Collaborators*

Mario Putti, Annamaria Mazzia,
Matteo Camporese, Gabriele Manoli, Sara Bonetti – *University of Padua, Italy*

Stefano Orlandini, Giovanni Moretti, Marcello Fiorentini – *University of Modena and Reggio Emilia, Italy*

Mauro Sulis – *now at University of Bonn, Germany*

Sylvain Weill – *now at University of Strasbourg, France*

Guo-Yue Niu – *University of Arizona, USA*

Cécile Dagés – *INRA-Montpellier, France*

Damiano Pasetto, Carlotta Scudeler – *INRS-ETE and University of Padua*

*many others (sensitivity tests, case studies, …)*