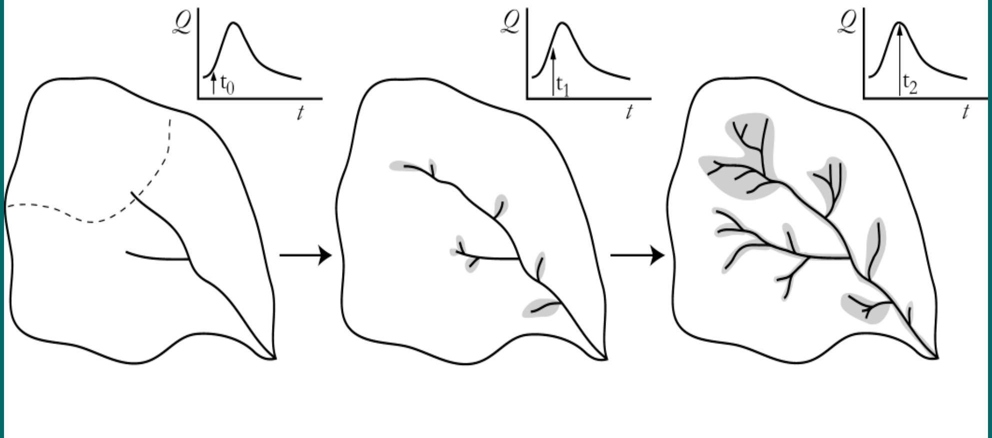
Modélisation numérique des interactions eaux souterraines / eaux de surface: défis et progrès récents



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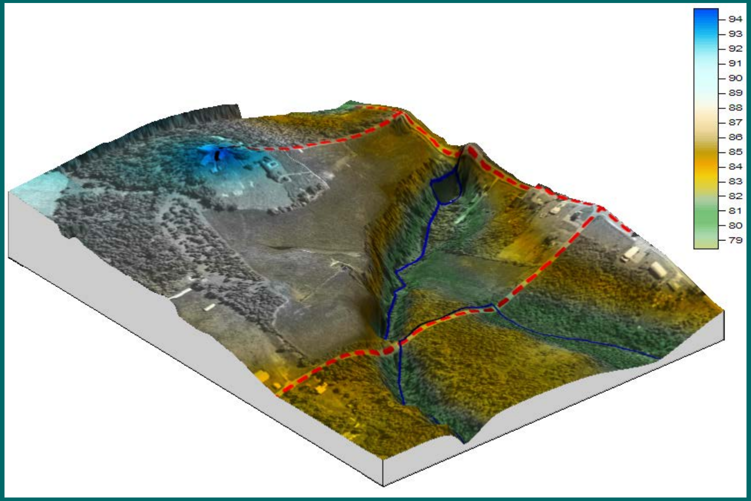
82e Congrès de l'ACFAS, Concordia University, 13 mai, 2014

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

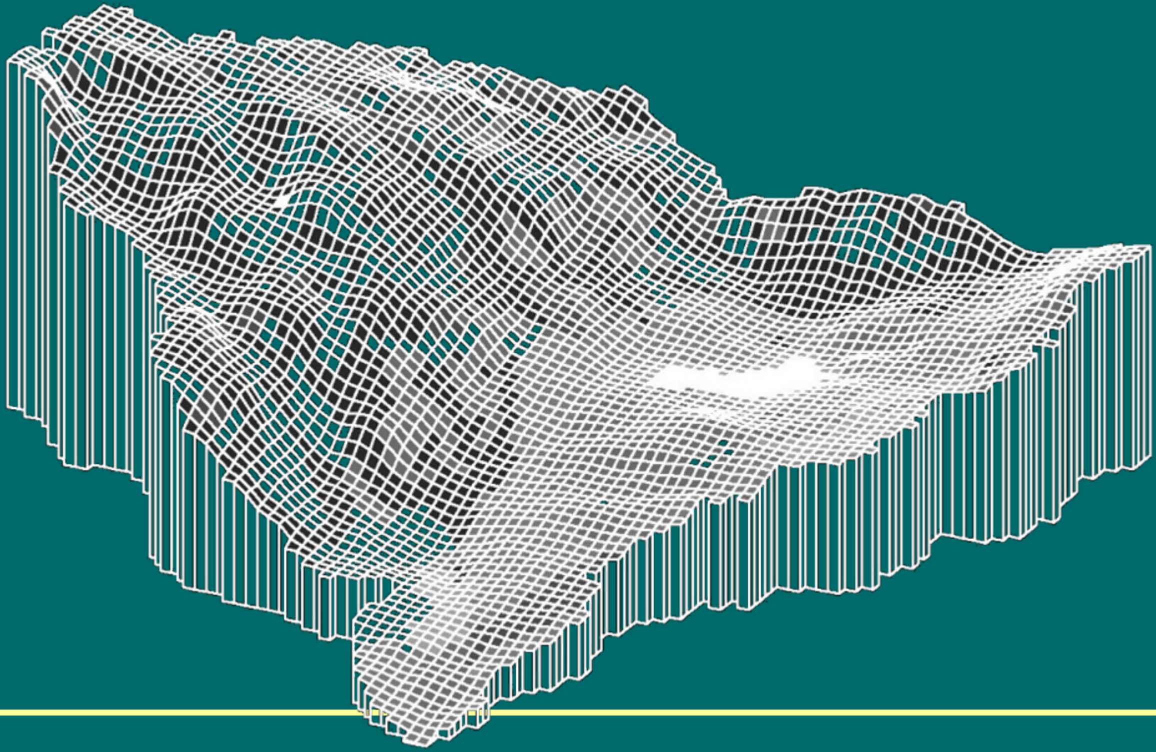
- computational boundaries are continually being pushed (cost and capabilities of systems, efficiency and robustness of algorithms), for easier and more effective data analysis and process simulation

Outline

CATHY (CATchment HYdrology) model description

Some recent studies (successes and challenges)

Extensions and evolution of the model



CATHY (CATchment HYdrology) model description

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

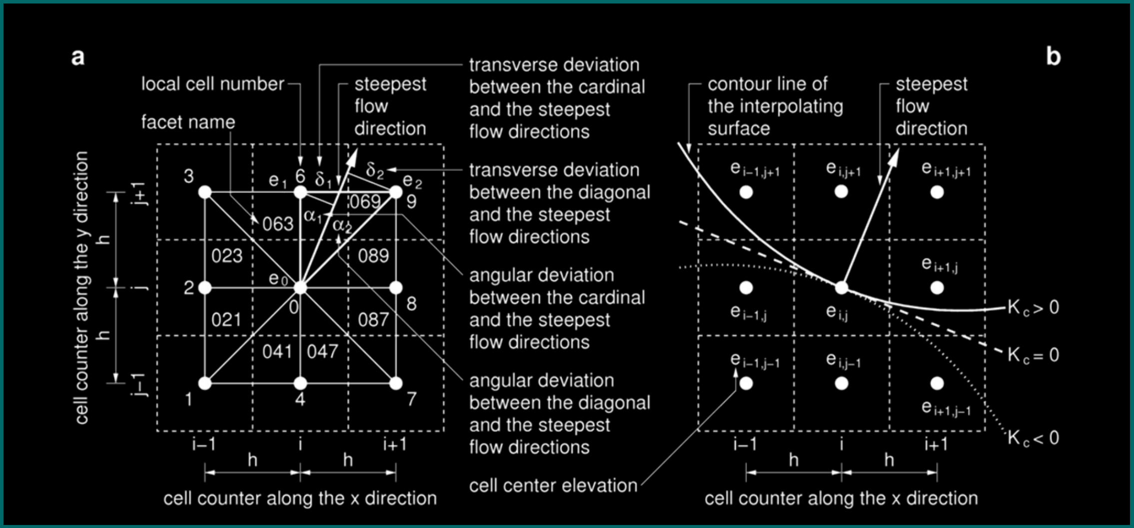
$$\frac{\partial Q}{\partial t} + c_k \frac{\partial Q}{\partial s} = D_h \frac{\partial^2 Q}{\partial s^2} + c_k q_L(h,\psi) \quad (2)$$

σ	general storage term [1/L]: $\sigma = S_w S_s + \phi(dS_w/d\psi)$
S_w	water saturation = θ/θ_s [/]
θ	volumetric moisture content [L^3/L^3]
θ_s	saturated moisture content [L^3/L^3]
S_s	specific storage [1/L]
ϕ	porosity (= θ_s if no swelling/shrinking)
ψ	pressure head [L]
t	time [T]
K_s	saturated conductivity tensor [L/T]
K_{rw}	relative hydraulic conductivity [/]
η_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]

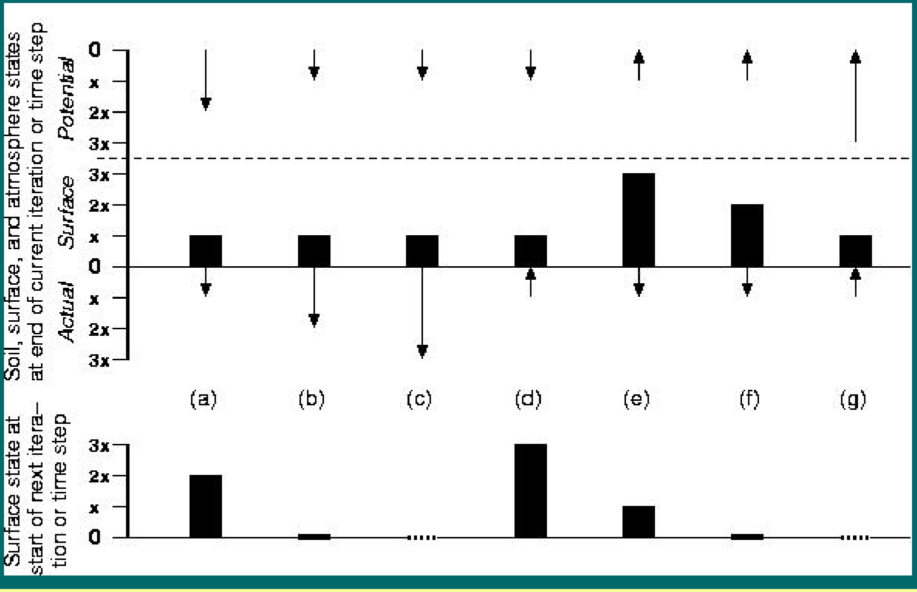
(1) *Paniconi & Wood, Water Resour. Res., 29(6), 1993 ; Paniconi & Putti, Water Resour. Res., 30(12), 1994*
(2) *Orlandini & Rosso, J. Hydrologic Engrg., ASCE, 1(3), 1996 ; Orlandini & Rosso, Water Resour. Res., 34(8), 1998*
(1)+(2) *Putti & Paniconi, CMWR Proceedings, 2004; Camporese, Paniconi, Putti,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

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

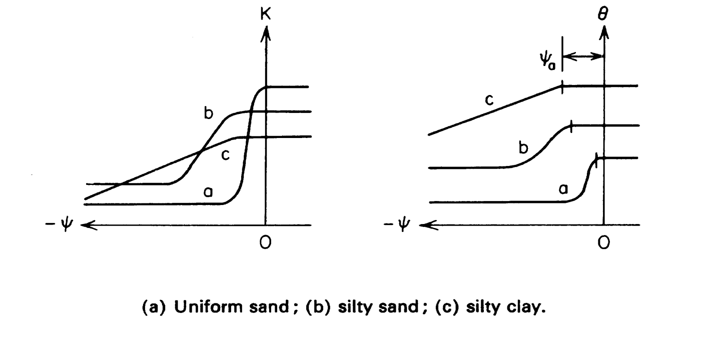
3D grid automatically generated with variable layer thicknesses and different base ("bedrock") shapes

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

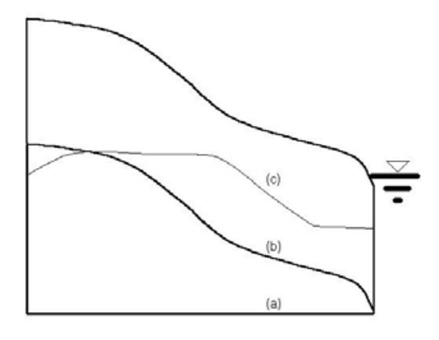
Weighted finite difference discretization in time

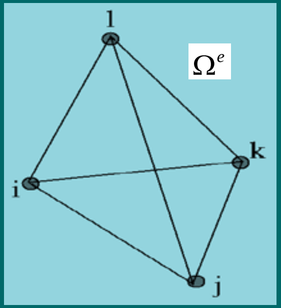
Time-varying boundary conditions: Neumann, Dirichlet, source/sink terms, seepage faces, and atmospheric fluxes

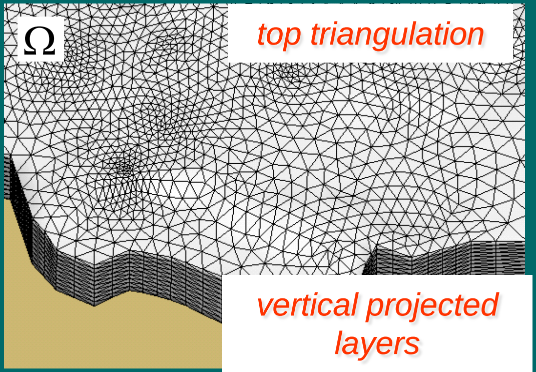
Adaptive time stepping; Newton and Picard linearization; selection of CG-type linear solvers; etc



(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

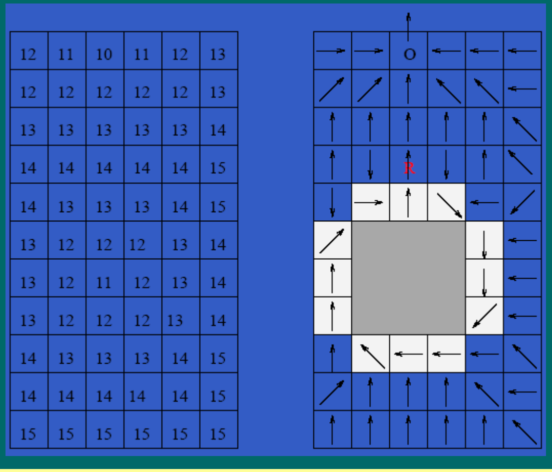
"Constant critical support area": overland flow ∀ cells with upstream drainage area *A* < *A**; else channel flow (2 other threshold-based options also implemented)

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)

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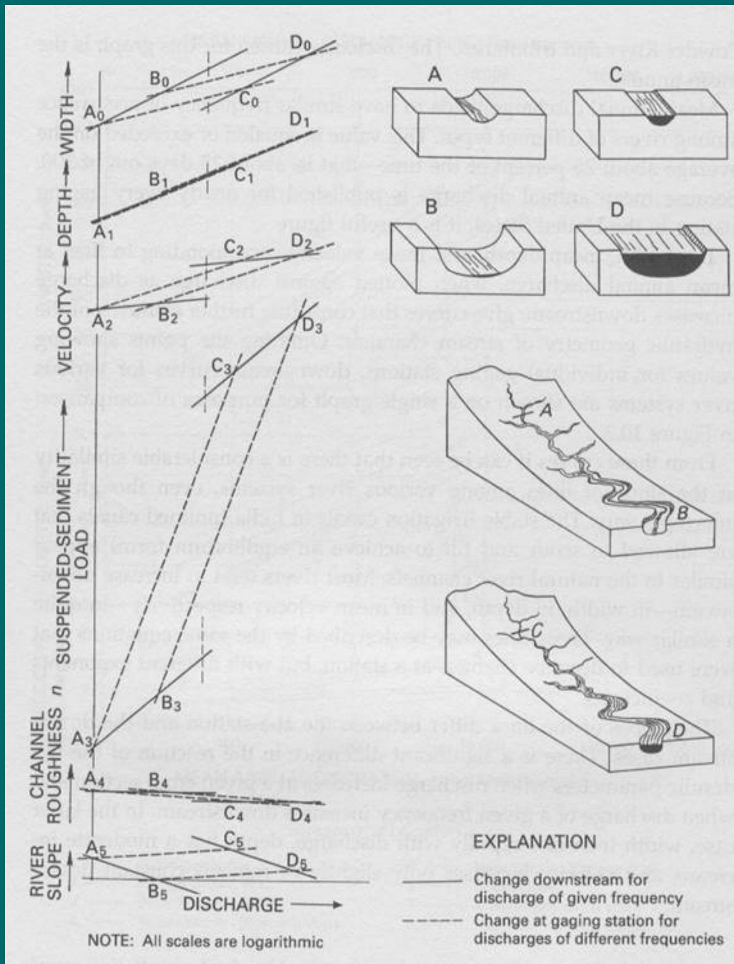


Figure 10.4 Diagrammatic representation of relation of width, depth, and velocity to discharge at a station and downstream.

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:

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

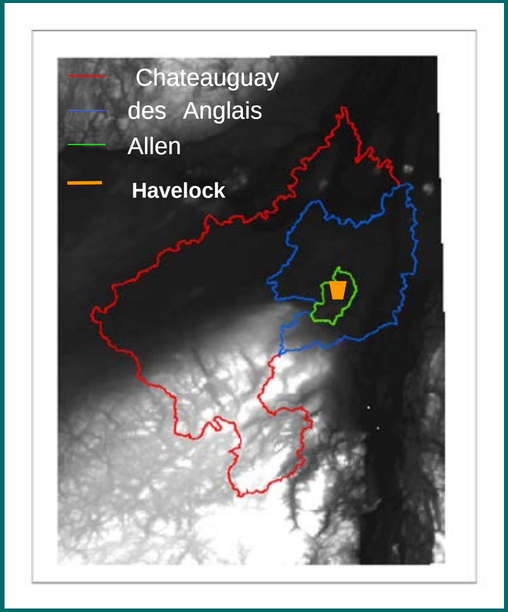
$$k_s(A,Q) = \overbrace{k_s(A_s,Q_f)\,Q_f(A_s)^{-y'}(A/A_s)^{w(y''-y')}}^{\text{I}}\,\overbrace{Q^{y'}}^{\text{II}}$$

* *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*

Coupling, time stepping, and iteration

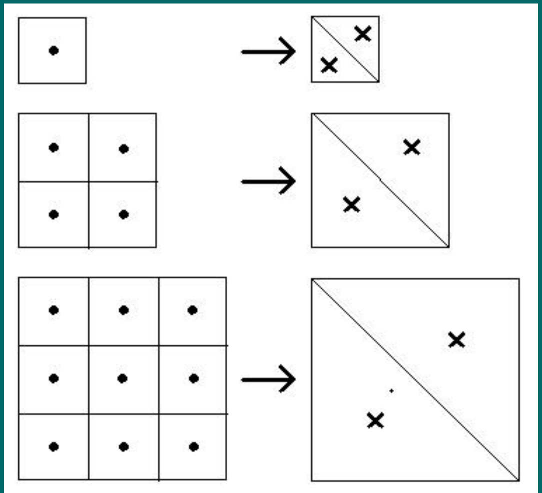
"Pond_head_min" threshold parameter accounts for microtopography

Coupled system solved sequentially*: surface first, for Q^{k+1} and h^{k+1}; then subsurface, for ψ^{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]*



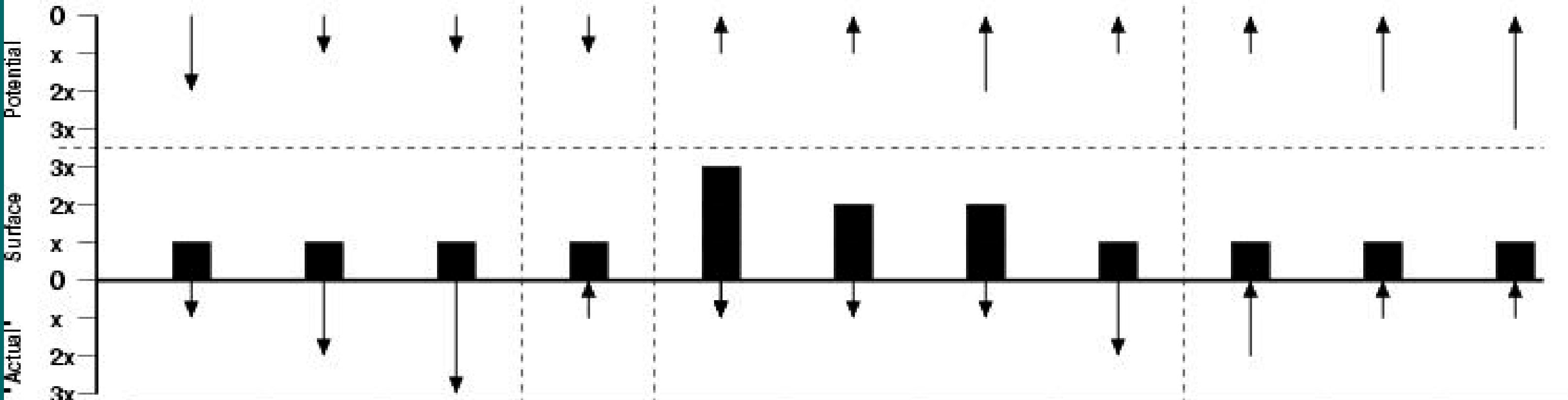
Nested time stepping: one or more surface solver time steps for each subsurface time step (based on Courant and Peclet criteria for the explicit surface routing scheme; also reflects typically faster surface dynamics compared to subsurface)

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)

Case I: Ponded surface



Surface runoff from excess rainfall; Surface stays ponded (increase from x to 2x).	No runoff; Surface no longer ponded but stays saturated.	No runoff; Switch to Neumann BC; Actual infiltration is 2x not 3x as calculated and not x as given by rainfall rate.	Surface runoff from excess rainfall and return flow/ seepage; Surface stays ponded (increase from x to 3x).	Surface run–off/ponding decreases from 3x to x, stays ponded; Typical scenario: atmospheric BC just switched from rainfall to evaporation (this + next 3 cases).	No runoff; Surface no longer ponded but stays saturated.	No runoff; Switch to Neumann BC; Actual infiltration is x as calculated; Actual evaporation is x not 2x as given by potential rate.	No runoff; Switch to Neumann BC; Actual infiltration is x not 2x as calculated; Actual evaporation is 0 not x as given by potential rate.	Surface runoff from return flow/seepage; Surface stays ponded (increase from x to 2x); Actual evaporation is x as given by potential rate.	No runoff; Surface no longer ponded but stays saturated; All return flow and ponding contributes to satisfy evaporation demand.	No runoff; Switch to Neumann BC; Return flow and ponding contribute to partially satisfy evaporation demand (2x not 3x).

Case II: Saturated but not ponded
Case III: Unsaturated
Case IV: Dry (stage–two drying)

} **Analogous, but more straightforward (as treated in subsurface–only mode)**

Some recent studies (successes and challenges)

Recharge estimation, impact of heterogeneity

Hydrograph separation, model coupling approaches

Bedrock leakage

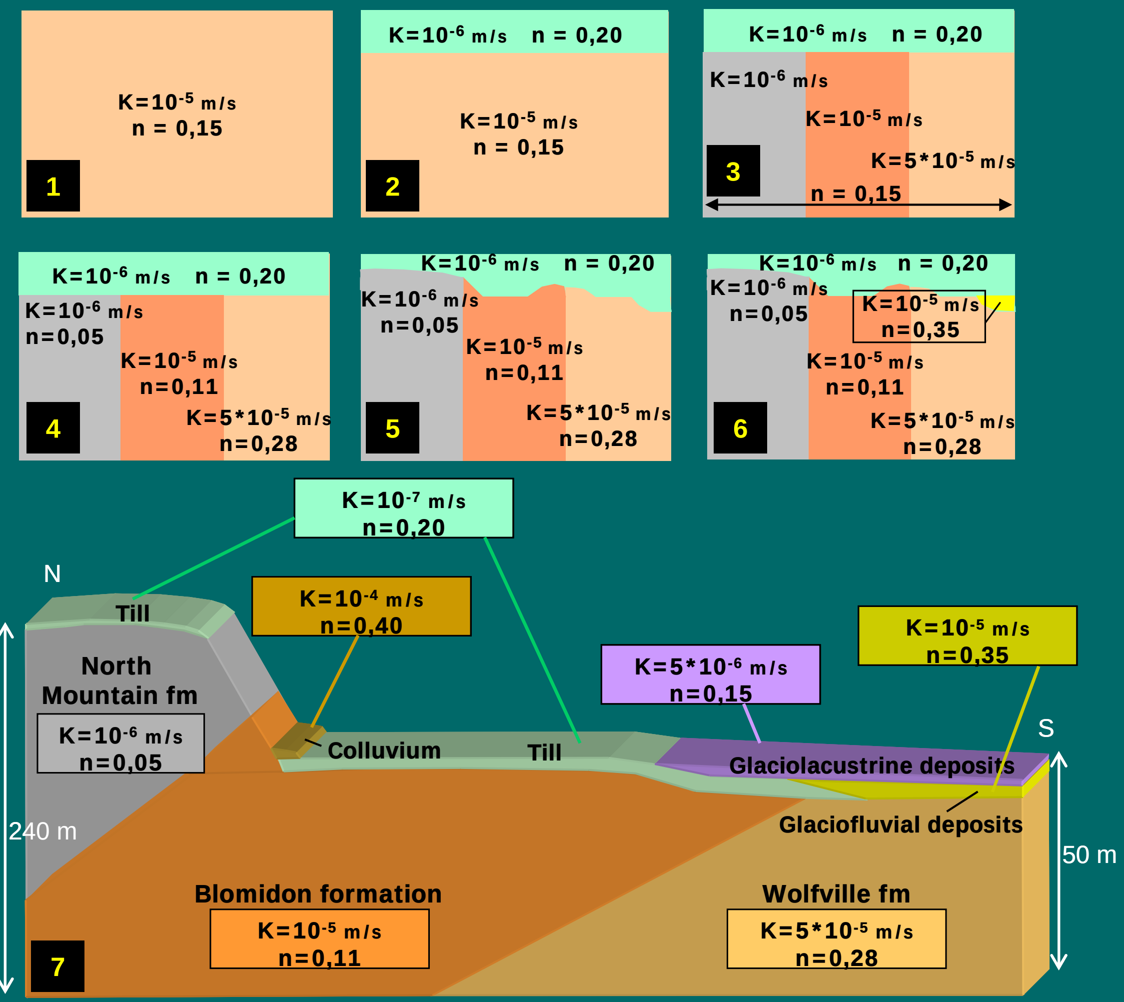
Predicting near-surface soil moisture state

Hysteresis in storage–discharge dynamics

Rill flow vs sheet flow

Simulation of multiple response variables

Problem of grid scale invariance



K=10-5 m/s
n = 0,15
1
K=10-6 m/s n = 0,20
K=10-5 m/s
n = 0,15
2
K=10-6 m/s n = 0,20
K=10-6 m/s
K=10-5 m/s
K=5*10-5 m/s
n = 0,15
3
K=10-6 m/s n = 0,20
K=10-6 m/s
n=0,05
K=10-5 m/s
n=0,11
K=5*10-5 m/s
n=0,28
4
K=10-6 m/s n = 0,20
K=10-6 m/s
n=0,05
K=10-5 m/s
n=0,11
K=5*10-5 m/s
n=0,28
5
K=10-6 m/s n = 0,20
K=10-6 m/s
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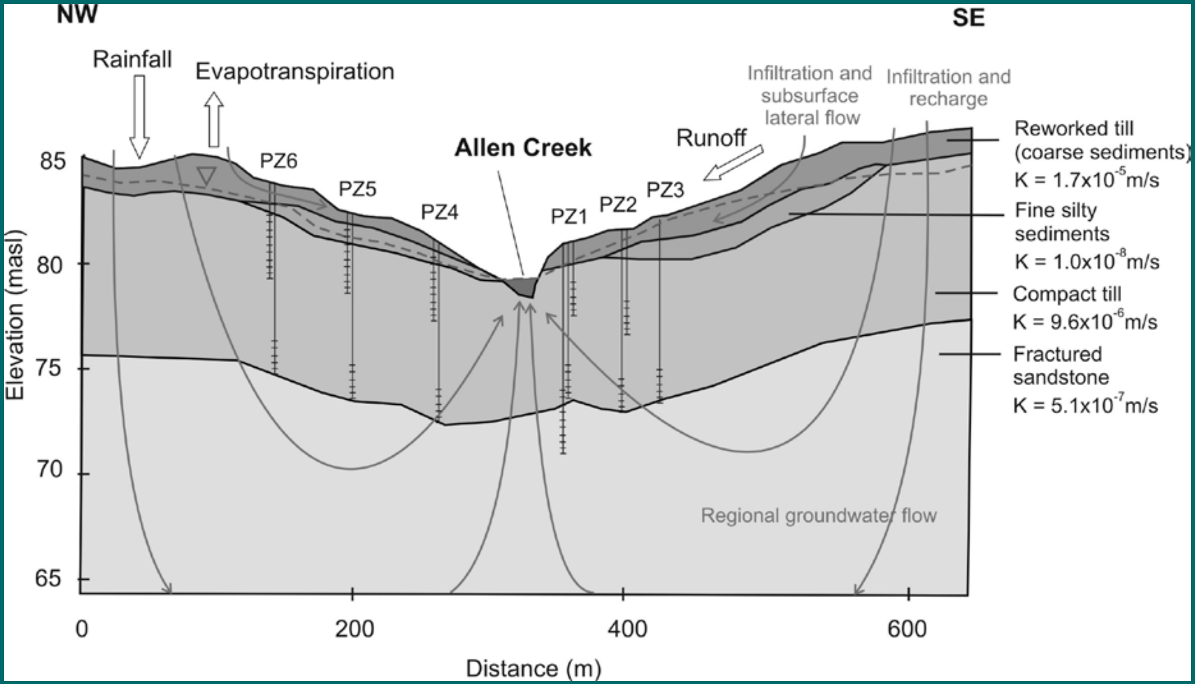
K=10-5 m/s
n=0,35
K=10-5 m/s
n=0,11
K=5*10-5 m/s
n=0,28
6
K=10-7 m/s
n=0,20
N
Till
K=10-4 m/s
n=0,40
North
Mountain fm
K=10-6 m/s
n=0,05
Colluvium
Till
K=5*10-6 m/s
n=0,15
K=10-5 m/s
n=0,35
S
Glaciolacustrine deposits
Glaciofluvial deposits
240 m
50 m
Blomidon formation
K=10-5 m/s
n=0,11
Wolfville fm
K=5*10-5 m/s
n=0,28
7

Hydrograph separation (Havelock hillslope, southwestern Quebec)

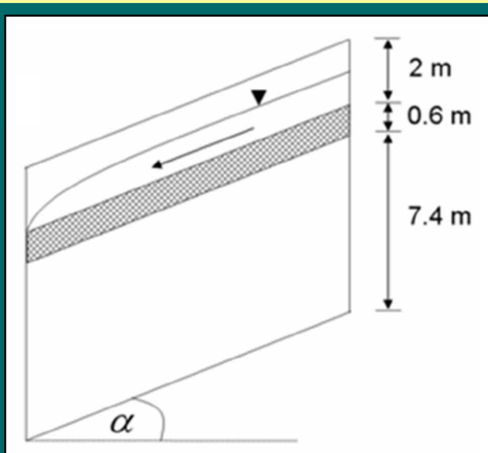


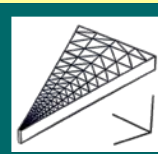
Water budget component (mm/y)	HELP + FEFLOW	CATHY
Precipitation	1038	1038
Evapotranspiration	556	556
Recharge	214	233
Total Discharge	456	500
Surface runoff	231	/
Subsurface runoff	36	/
Baseflow	189	/
Exchange with regional fractured aquifer		
+ve (reg.aq. to hillslope)	4	77
-ve (hillslope to reg.aq.)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

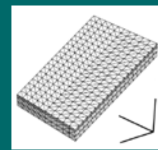
Loose coupling (simplified model) vs CATHY:
is hydrograph separation really so straightforward?

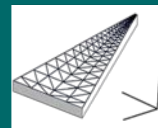
Guay, Nastev, Paniconi, Sulis: Hydrol. Process., 2012

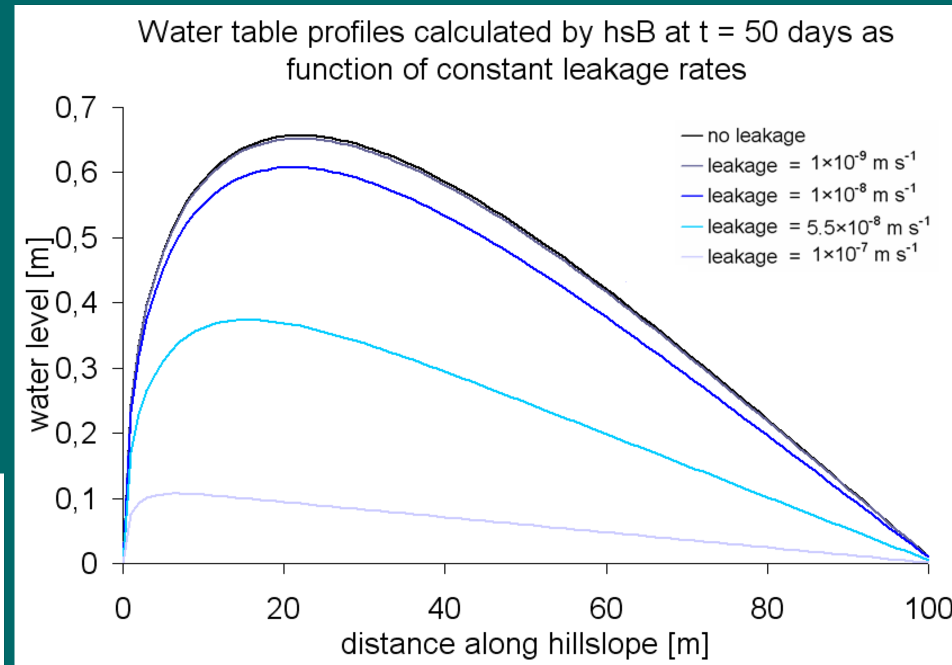
Bedrock leakage (idealized hillslopes / sloping unconfined aquifers)

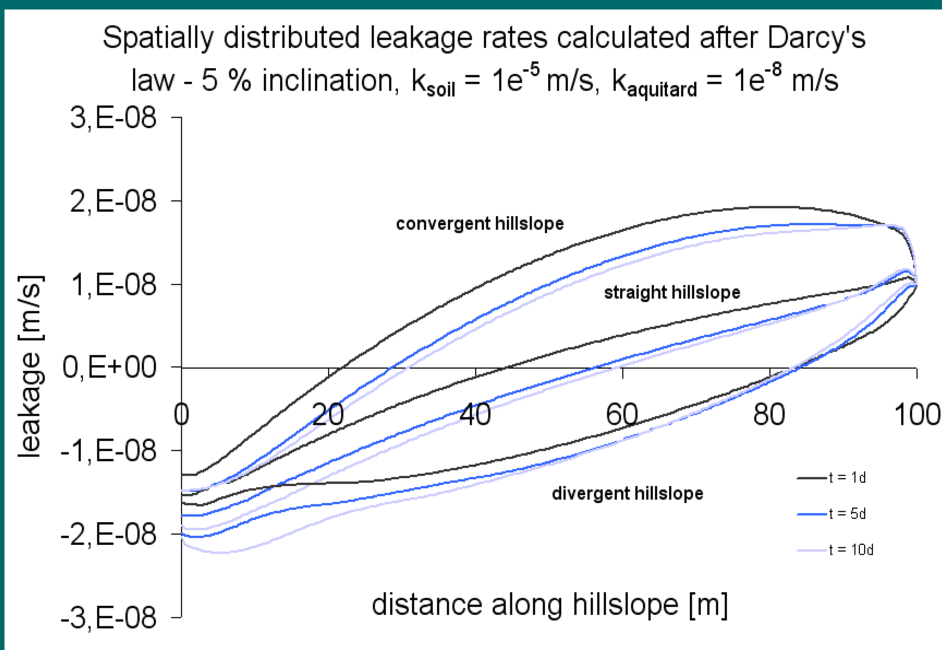










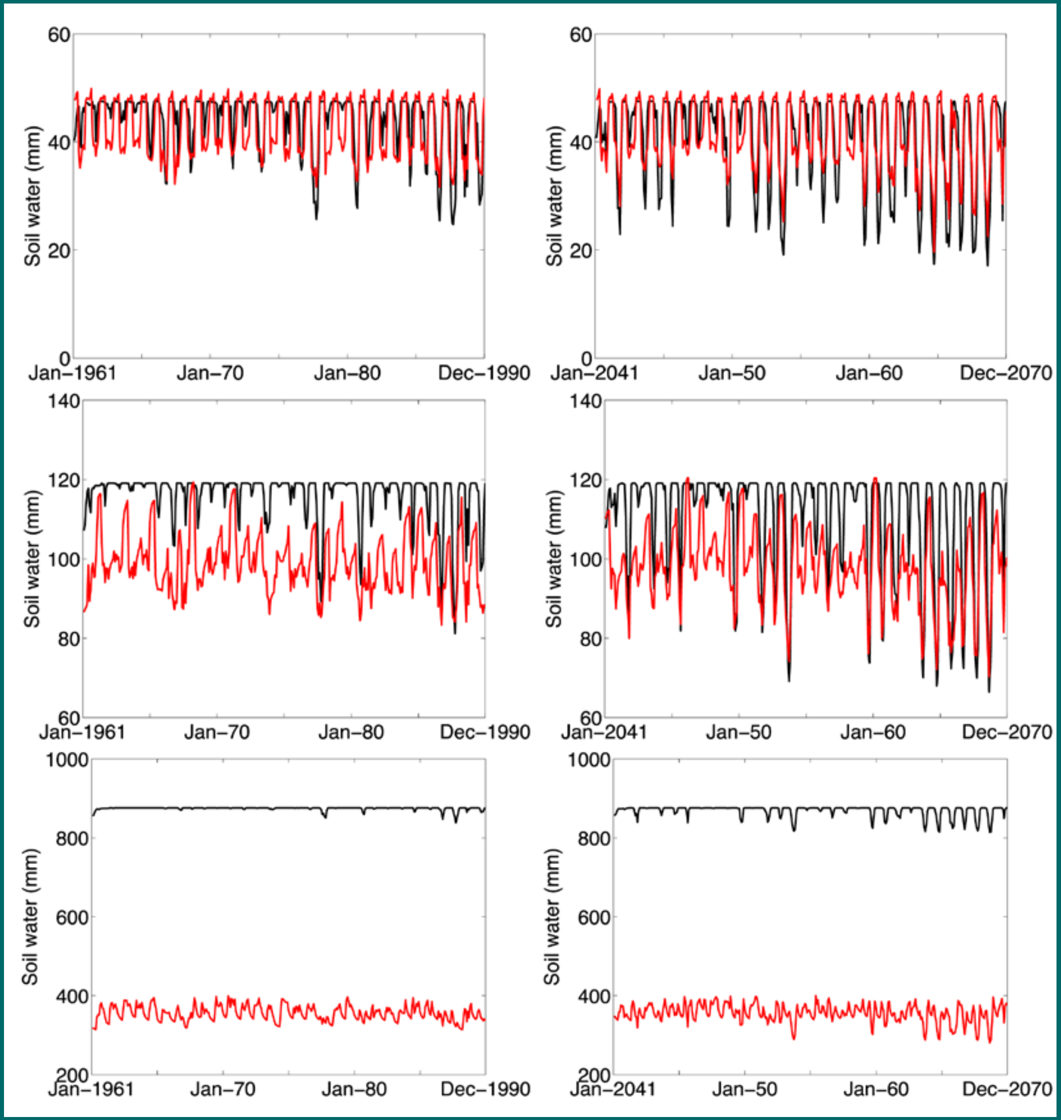


Questioning a fundamental paradigm in hillslope hydrology.

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

Broda, Paniconi, Larocque: J. Hydrol., 2011

Predicting near-surface soil moisture state (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;

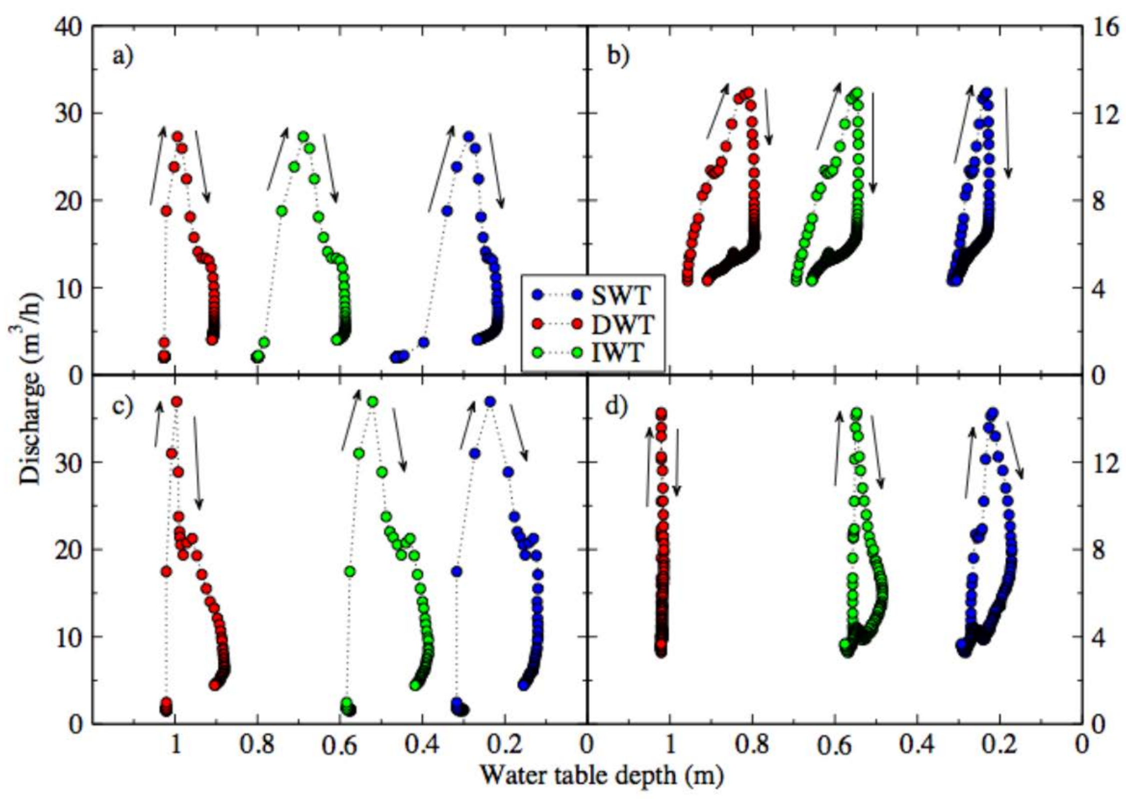
- too-coarse grid around steep terrain (eg, Covey Hill) misses important dynamics;

- missing agricultural (eg, tile) drainage;

- …

Sulis, Paniconi, Rivard, Harvey, Chaumont: Water Resour. Res., 2011

Hysteresis in storage–discharge dynamics (Larch Creek catchment, northern Italy)



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.

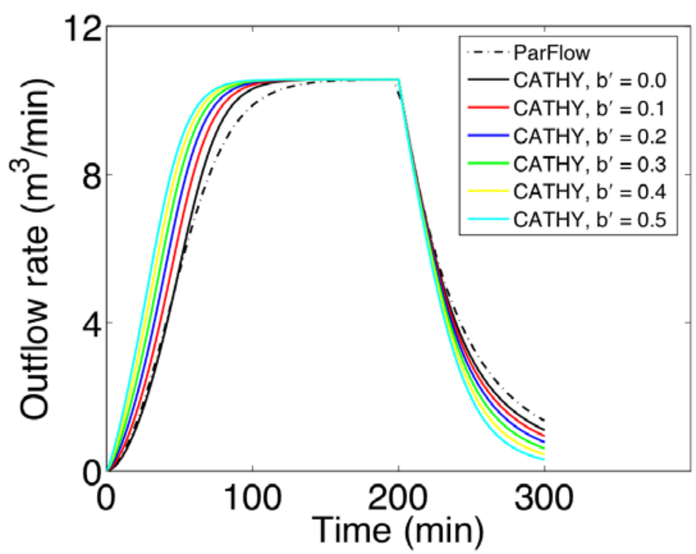
CATHY can reproduce hysteresis and thresholding behavior observed in the relationship between the subsurface storage and discharge responses of a small catchment. No ad hoc parameterization is needed.

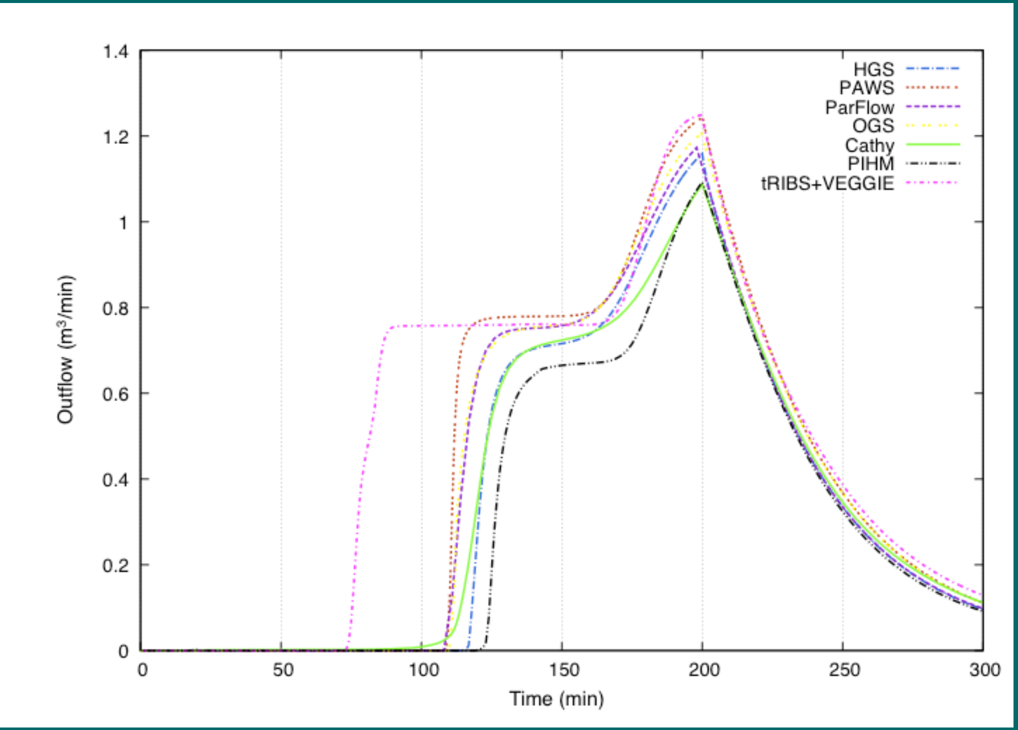
Is there any link to or contribution from unsaturated zone hysteresis?

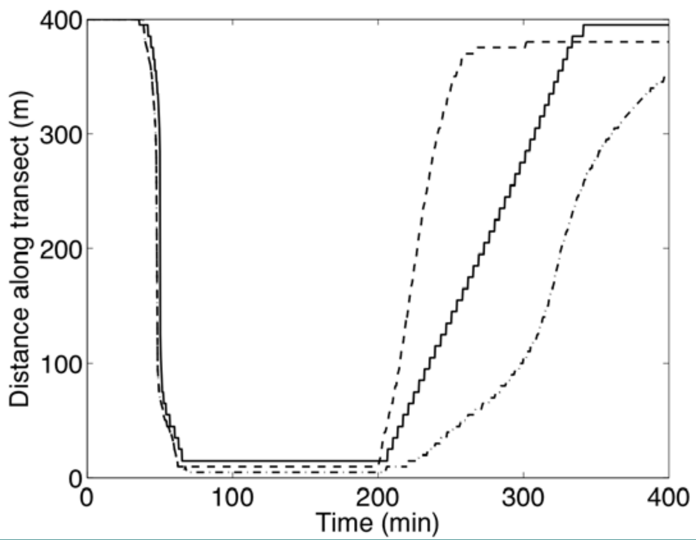
Nature and role of nonlinear phenomena in atmosphere–land surface–soil–aquifer interactions and feedbacks are poorly understood.

Camporese, Penna, Borga, Paniconi: Water Resour. Res., 2014

Rill flow vs sheet flow (benchmark tests for model intercomparison)





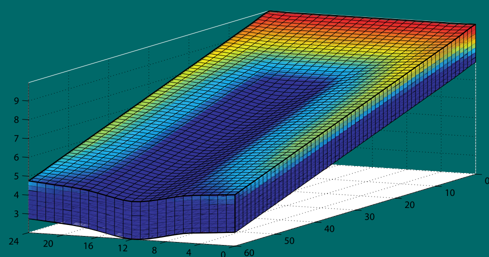


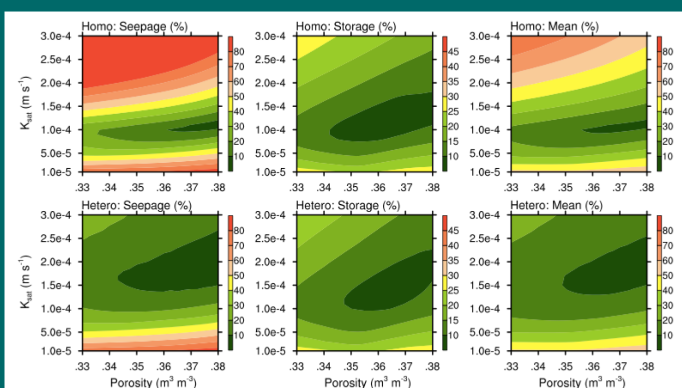
Benchmarking is a complicated business even for synthetic test cases … Why and how do different models (even based on the same equations) perform differently? And what to do about it??

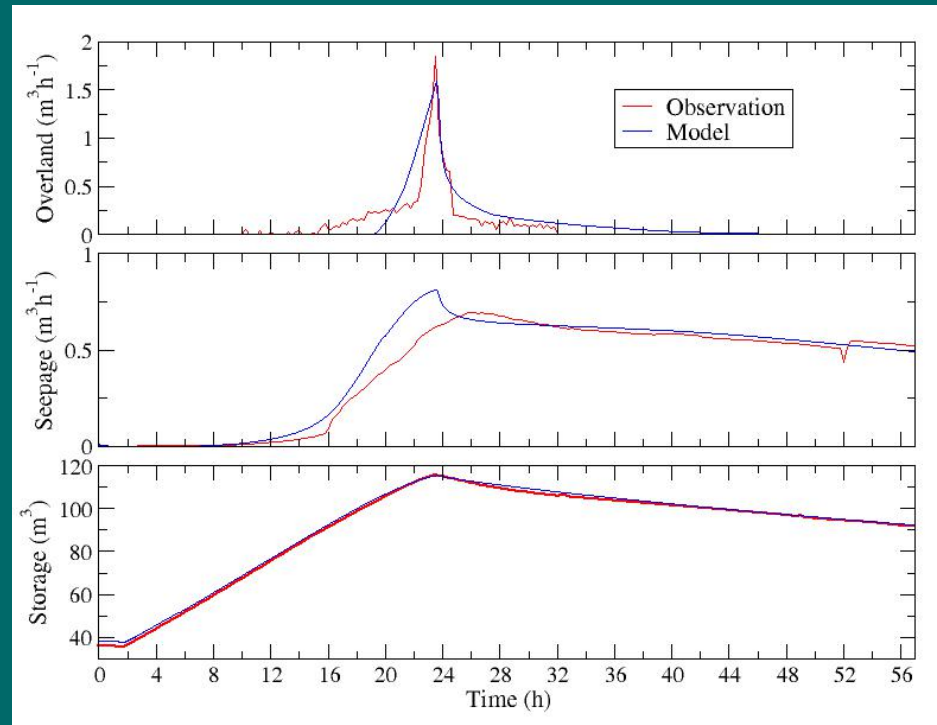
Evolution of the point of intersection between the water table and the land surface for the sloping plane test case. The outlet face is at x = 400 m. ParFlow: solid line; CATHY: dashed-dotted (sheet flow) and dashed (rill flow).

Sulis, Meyerhoff, Paniconi, Maxwell, Putti, Kollet: Adv. Water Resour., 2010
Maxwell, Putti, Meyerhoff, et al.: Water Resour. Res., 2014

Simulation of multiple response variables *(Biosphere 2 Landscape Evolution Observatory)*







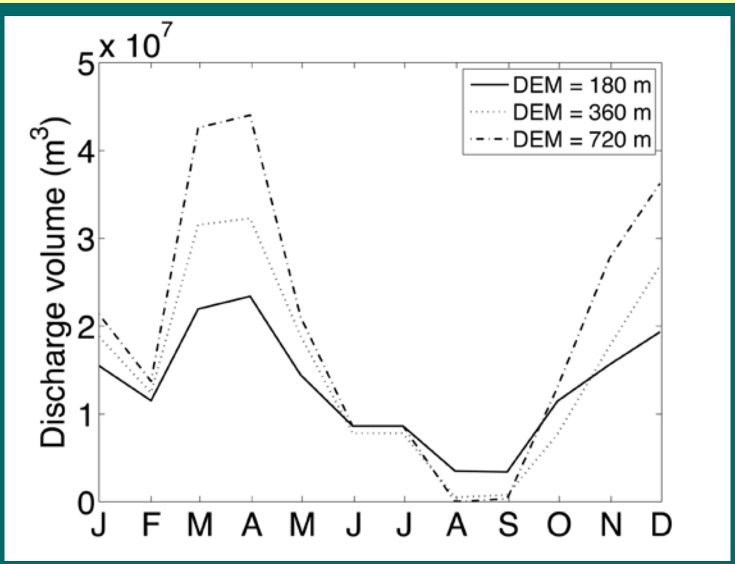
All three variables are integrated measures of the hillslope response. How does the model perform when we examine distributed responses? And what happens when we include solute transport?

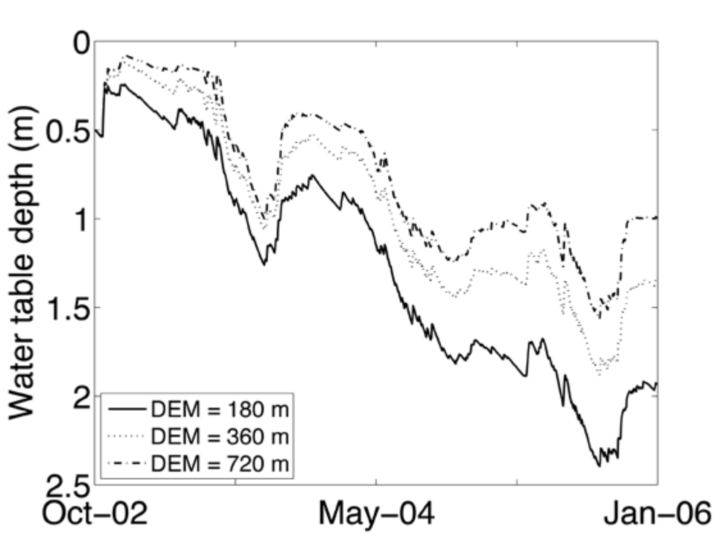
Issue of equifinality: does the mechanism we invoke imply (sole) causation?

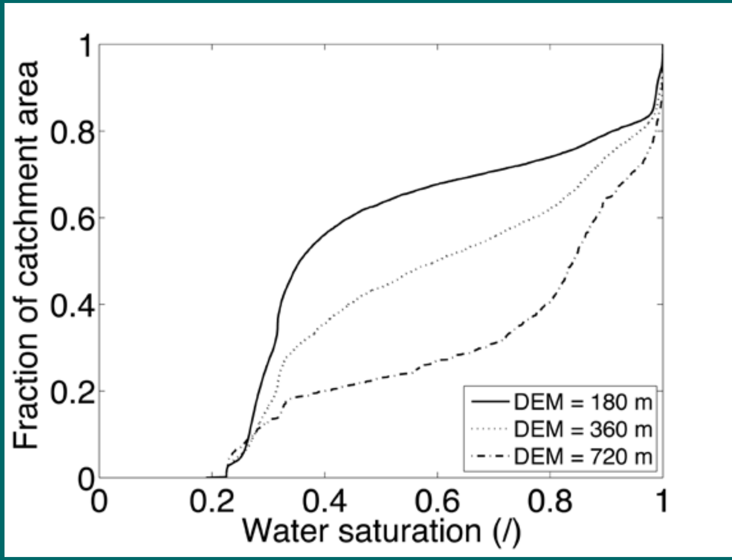
"Perfect knowledge" of the bottom BC … how much does this help?

Niu, Pasetto, Scudeler, Paniconi, Putti, Troch: Hydrol. Earth Syst. Sci., 2014

Problem of grid scale invariance (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 invariance (and not limited to just the CATHY model). One of the most serious challenges in catchment-based hydrological / ecological modeling …

Sulis, Paniconi, Camporese: Hydrol. Process., 2011

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

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

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

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

Weill, Mazzia, Putti, Paniconi: Adv. Water Resour., 2011

Evolution of the model

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.* **J. Hydrologic Engrg. ASCE,** 1, 1996

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, Kasteltseva, Rudenko: *Modeling groundwater–surface water interactions in the Chernobyl exclusion zone.* **Environ. Geol.,** 42, 2002

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Catchment/DEM-based subsurface flow modeling

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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)

↓

Detailed experiments, geophysical inversion, parameter estimation, sensitivity & uncertainty analysis, model intercomparison, biogeochemistry & soil weathering, sediment transport & erosion, soil freezing & snowmelt, preferential flow, unstructured grids, …

Collaborators

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