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Testing a process-based model of groundwater / surface water interactions at the hillslope, subcatchment, and watershed scales

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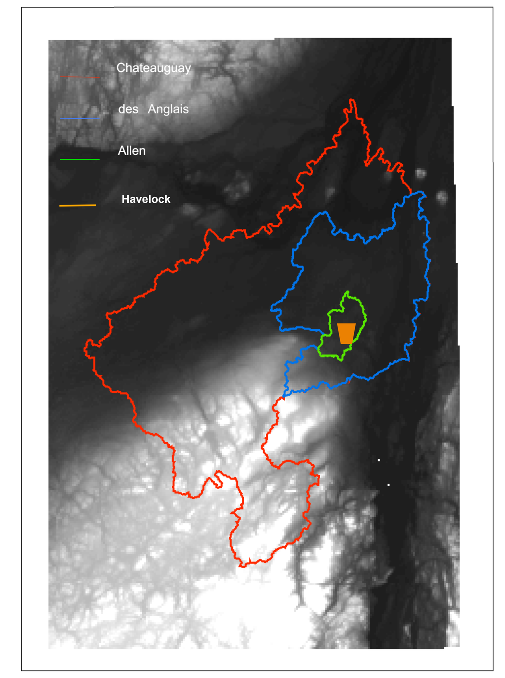
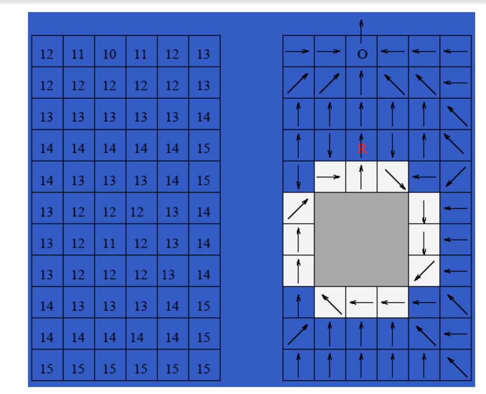
Introduction

A proper understanding and representation of the interactions between the different components of the hydrosphere (atmosphere, land surface, soil zone, aquifers) is increasingly relevant to climate prediction, environmental protection, and water management. These interactions can influence phenomena at the short temporal/small spatial scale (e.g., landslides and flash floods within a hillslope or small catchment) as well as over much longer periods and larger scales (e.g., replenishment of over-exploited regional aquifers). There is a variety of models and modeling approaches currently in use to model atmosphere/surface/subsurface interactions. Rigorous sensitivity testing, intercomparison, and performance assessment of available and emergent models is crucial. In particular, for coupled models that integrate different hydrosphere components, the hypotheses underpinning conceptualizations and parameterizations of the interaction terms, as well as the consistency between different process submodels, need to be continually assessed and improved.

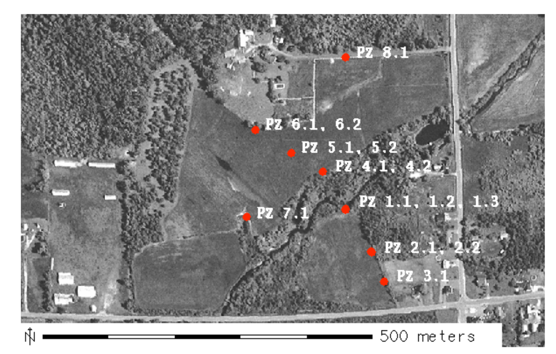
The work presented here is focused on the CATHY (CATchment HYdrology) model *(Camporese et al., 2010)* applied to settings from the hillslope to watershed scale. The coupling term for the model is computed as the balance between atmospheric forcing (rainfall and potential evaporation) and the amount of water that can actually infiltrate or exfiltrate the soil. Sensitivity tests, intercomparison studies, and other model applications are used to illustrate features and challenges for this particular model formulation, in relation also to other approaches. The tests examine processes and factors such as leakage, heterogeneity, grid resolution, hydrograph separation, climate change scenarios, and boundary conditions, and they consider the influence of these factors on streamflow, soil water storage, groundwater recharge, and other important determinants of a catchment's water balance. Some of the important challenges that emerge from this work relate to scale invariance, mass tracking and balance errors, model bias, and the validity and applicability of simplifying assumptions when modeling complex processes.

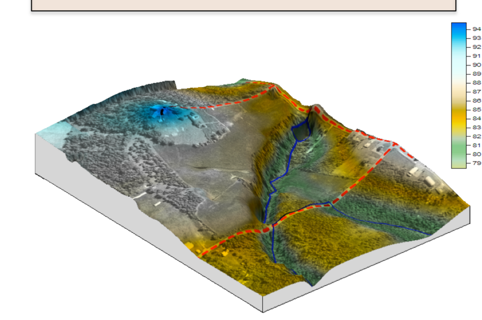
A detailed intercomparison study of the CATHY and ParFlow *(Kollet and Maxwell, 2006)* models has been previously presented *(Sulis et al., 2010)*. More recent work has been undertaken to compare CATHY against other popular modeling approaches for simulating hydrosphere interactions, including a loose coupling of the HELP *(Schroeder et al., 1994)* and FEFLOW *(Diersch, 1998)* models for recharge estimation, the CLASS land surface scheme *(Verseghy, 1991; Verseghy et al., 1993)* that is coupled to the Canadian regional climate model, and the HYDROTEL watershed model *(Fortin et al., 2001; Turcotte et al., 2003)* based on both subcatchment and hillslope response units. Some of this work will be addressed here as well.





Left: Nested study areas within the Chateauguay river basin, Quebec; below: boundary-following procedure for treatment of lakes in the CATHY model





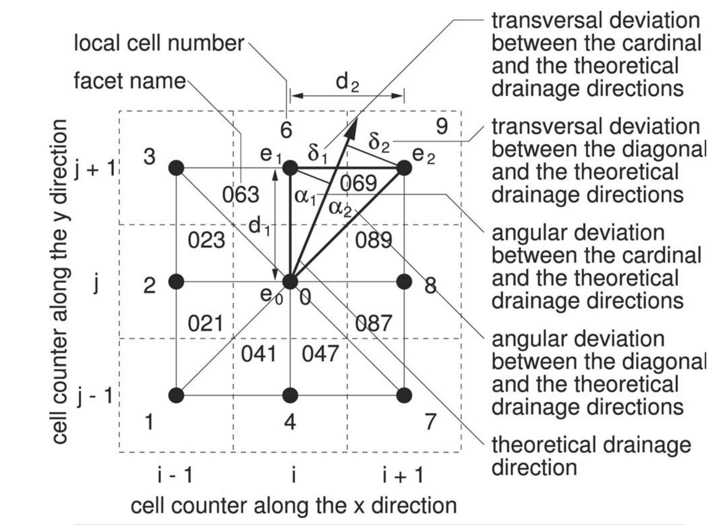
Below: Hillslope study site at Havelock, Quebec: piezometer transect (left) and overlaid topographic image (right)

Model description

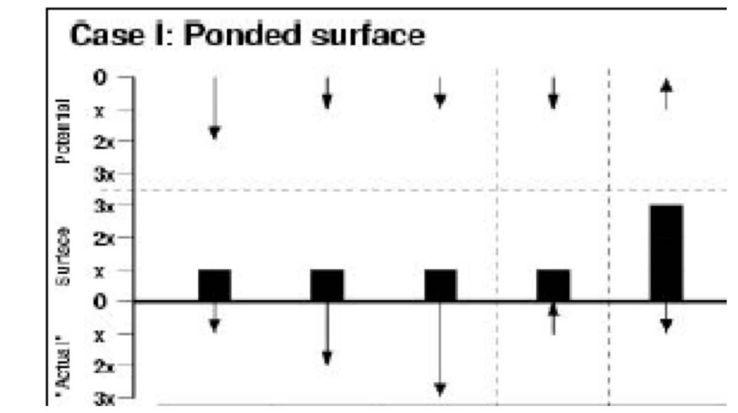
CATHY is a distributed-parameter, physically-based model. This class of models relies on theoretical principles (e.g., mass conservation) to describe the phenomena of interest and, it resolves the system response in a detailed manner (e.g., for each coordinate of a three-dimensional grid). In CATHY a finite element solver for the 3D Richards equation describing flow in variably saturated porous media *(Paniconi and Wood, 1993; Paniconi and Putti, 1994)* is coupled to a finite difference solver for a 1D diffusion wave equation describing surface flow propagation through a hillslope and stream channel network *(Orlandini and Rosso, 1996, 1998)*.

The main features of the model are:

- A path-based description of surface flow across the drainage basin is used, with several options for identifying flow directions, for separating channel cells from hillslope cells, and for representing stream channel hydraulic geometry *(Orlandini et al., 2003; see figure on the top right)*;
- Lakes and other topographic depressions are identified and specially treated as part of the preprocessing procedures applied to the digital elevation model (DEM) data for the catchment *(see figure on the left)*;
- Threshold-based boundary condition switching is used to partition potential (atmospheric) fluxes into actual fluxes across the land surface and changes in surface storage, thus resolving the exchange fluxes, or coupling, between the surface and subsurface modules *(see figure on the bottom right)*;
- Nested time stepping allows smaller steps to be taken for typically faster and explicitly solved surface runoff routing, while a mesh coarsening option allows larger grid elements to be used for typically slower and more compute-intensive subsurface flow;
- Sequential data assimilation schemes allow the model predictions to be updated with spatio-temporal observation data of surface and subsurface variables *(Paniconi et al., 2003; Camporese et al., 2009)*;
- The model has been recently extended to solute transport phenomena, with an advanced time-splitting procedure to solve the numerically difficult subsurface advection-dispersion equation *(Weill et al., 2011)*;
- The model has been coupled to a land surface model (Noah) that accounts for water, energy, and carbon flux exchanges between the atmosphere, land surface, and subsurface *(Niu et al., 2011)*.



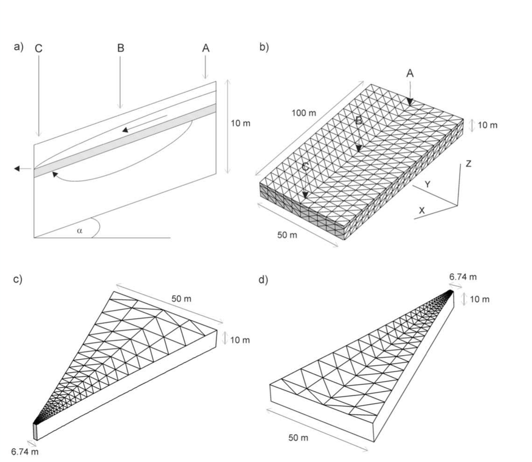
Flow path determination for a single DEM pixel



Atmosphere/land surface/subsurface exchange fluxes resolved via a boundary condition switching procedure

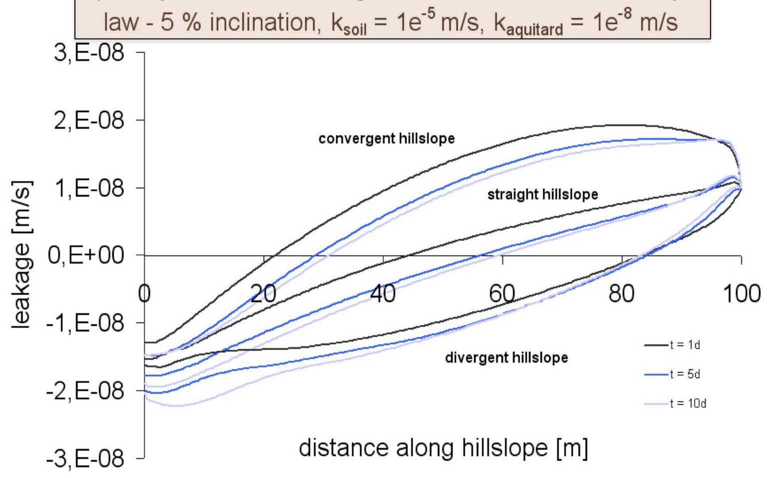
Sensitivity testing: Leakage and soil zone/aquifer interactions (validity of simplifying assumptions)

A sloping aquifer resting on impermeable bedrock is a common paradigm in hydrological modeling. The underlying assumptions of this paradigm were examined in a study of leaky hillslope systems for a synthetic hillslope composed of an unconfined and confined aquifer separated by an aquitard *(Broda et al., 2011)*. The CATHY simulations examined different configurations of aquifer and aquitard properties (conductivity, thickness), hillslope geometry (uniform, convergent, divergent), hillslope inclination (0.2, 5, and 30%) and boundary conditions (Dirichlet, seepage face), as well as the interplay between leakage, water levels, and outflow. The results show that leakage generally percolates in both directions, with downward (positive) leakage in upslope portions of the aquifer and upward (negative) leakage in downslope regions. Geometry is found to be a main determinant of the partitioning of leakage along a hillslope, with upward leakage in large portions of convergent slopes but only in a restricted downslope region for divergent slopes. In steep hillslopes, reverse leakage occurring downslope as a result of quick upslope drying represents a major component of the water budget. Boundary conditions also exert an important control, with the placement and extent of Dirichlet or seepage nodes along the outflow face being particularly influential.



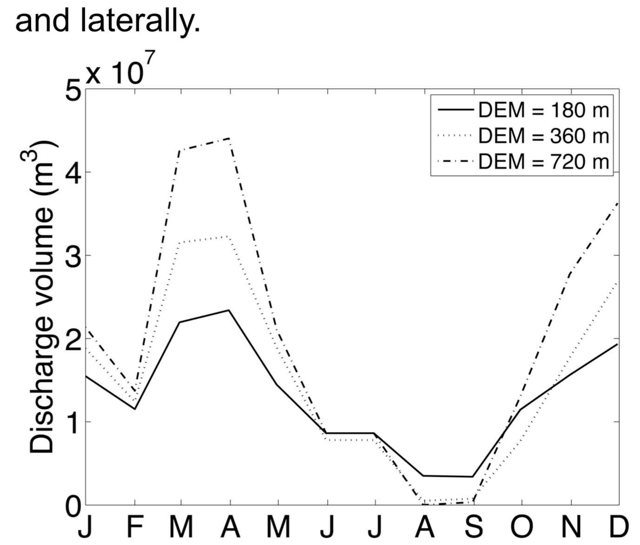
Vertical cross section of the layered aquifer system and views of the uniform, convergent, and divergent hillslopes

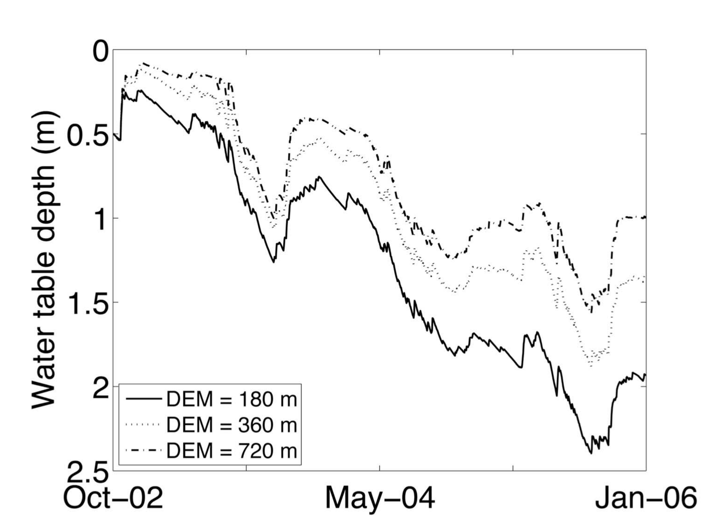
Spatially distributed leakage rates calculated after Darcy's law - 5 % inclination, $K_{soil} = 1e^{-5}$ m/s, $K_{aquitard} = 1e^{-8}$ m/s

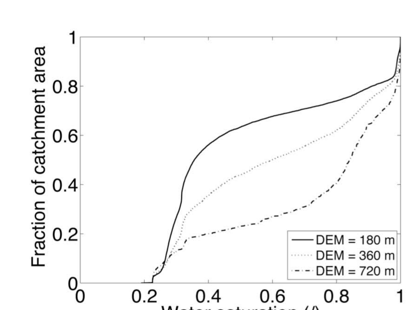


Sensitivity testing: Grid resolution and landscape representation (scale invariance)

Digital elevation models (DEMs) at different resolutions (180, 360, and 720 m) were used to examine the impact of different levels of landscape representation on the hydrological response of the 690 km^2 des Anglais subcatchment *(Sulis et al., 2011a)*. Frequency distributions of local slope, plan curvature, and drainage area were calculated for each grid size resolution. This landscape analysis reveals that DEM grid size significantly affects computed topographic attributes, which in turn explains some of the differences obtained in the CATHY simulations. In these simulations, the effects of grid size on both the integrated response of the catchment (discharge at the main outlet and at two internal points) and the distributed response (water table depth, surface saturation, and soil water storage) were examined. The results indicate that discharge volumes increase as the DEM is coarsened, and that coarser DEMs are also wetter overall in terms of water table depth and soil water storage. The reasons for these trends include an increase in the total drainage area of the catchment for larger DEM cell sizes, due to aggregation effects at the boundary cells of the catchment, and to a decrease in local slope and plan curvature variations, which in turn limits the capacity of the watershed to transmit water downslope and laterally.



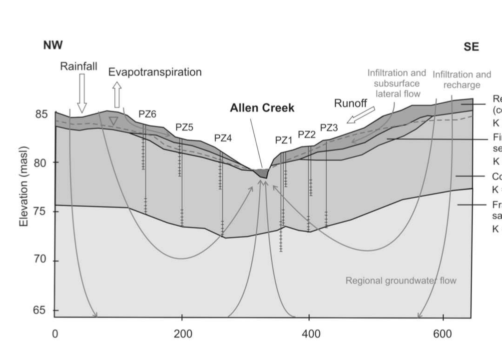


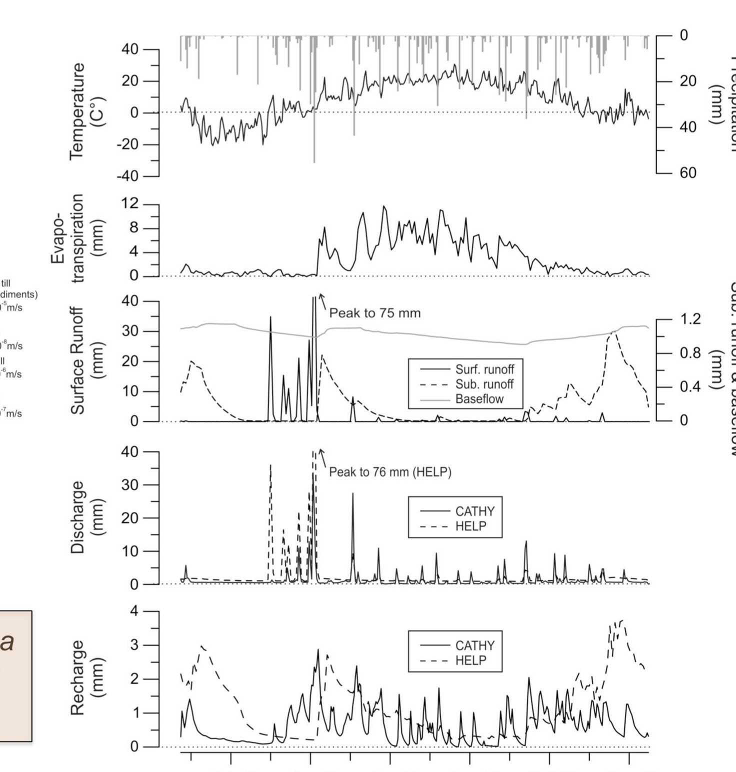


Comparison of simulation results at 3 different DEM resolutions: average monthly streamflow discharge (top left), catchment-averaged daily water table depth (top right), and cumulative frequency distribution of surface soil saturation after a 10-day rain period (left)

Model intercomparison (CATHY and HELP/FEFLOW): Hydrograph separation (mass tracking and mass errors)

An assessment of interactions between groundwater and surface water was carried out using two very different numerical modeling approaches applied to a small scale study area (0.2 km^2) in the municipality of Havelock situated within the Chateauguay basin *(Guay et al., 2011)*. The first approach was a two-step process: first the daily recharge rate was determined using a quasi 2D infiltration model, HELP; this recharge was then applied as an imposed flux to a 3D finite element groundwater model, FEFLOW. In the second approach the coupled model CATHY was applied in an integrated, one-step process. For equal annual rainfall and evaporation, the second approach yields a recharge rate of 233 mm/y, which is 9% higher than the first approach, and a simulated annual discharge at the outlet that is also reasonably close to that obtained in the second approach (5% difference). Based on the analyses performed, it was concluded that while the decoupled, two-model approach, with its separate compartments for surface, soil zone, and aquifer flows, can provide a useful but simplified picture of the different components of total discharge, the fully coupled model, in accounting for the complex water exchanges between the land surface, subsurface, and stream channel, ultimately produces a better match against distributed observation data.

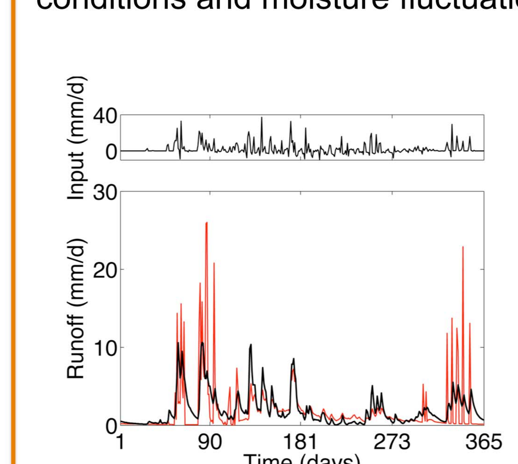


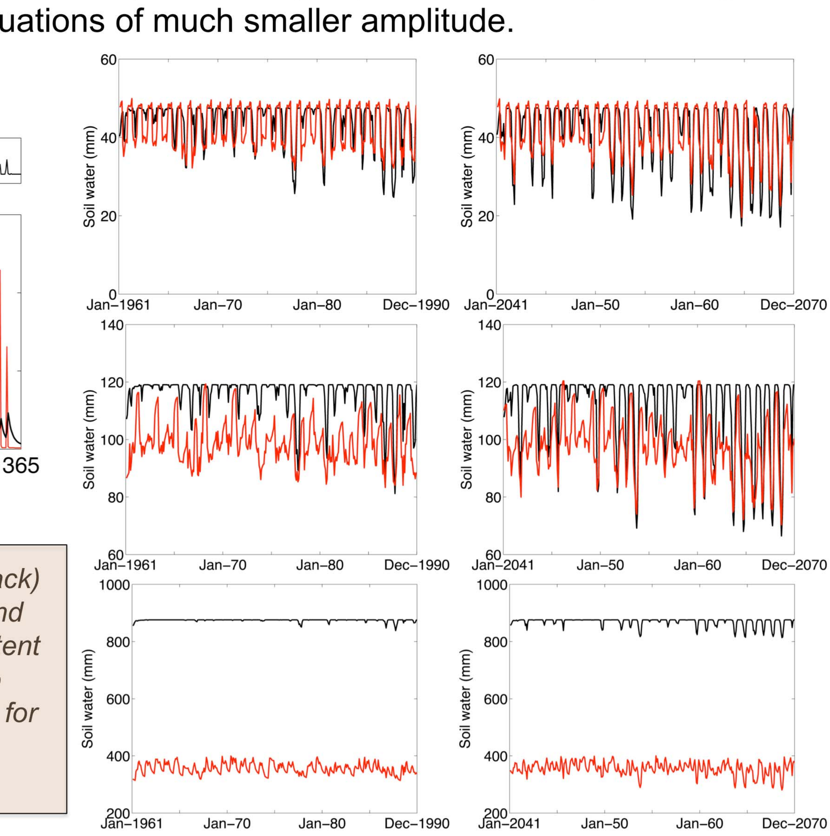


Vertical cross section of the study area (top) and time series of various water budget components (right)

Model intercomparison (CATHY and CLASS): Climate change impacts (model bias)

In a study of climate change impacts based on the IPCC SRES A2 scenario that was performed with the CATHY model for the des Anglais subcatchment *(Sulis et al., 2011b)*, a comparison was also made of the predictions obtained with CATHY and those derived from the land surface scheme (CLASS) that is coupled to the Canadian Regional Climate Model (CRCM). Land surface schemes have been extensively evaluated against observed data and intercomparison studies, but scale and other differences have thus far prevented comparison of these schemes to detailed groundwater/surface water models. The size of the selected study area, relatively large for a model such as CATHY and comparatively small for a land surface scheme, was deemed a convenient "meeting point" at which to investigate the importance of a 3D representation of a catchment that takes into account factors such as topography, lateral subsurface flow, and water table dynamics. The results reveal that CLASS produces biased (consistently higher) estimates than CATHY of surface and subsurface runoff; that for soil water storage the two models are in general agreement in terms of the intra-annual variability of moisture content at shallower soil layers; and that larger differences occur in deeper soil layers, with CATHY predicting wetter conditions and moisture fluctuations of much smaller amplitude.





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

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