Accounting for spatial heterogeneity in eco-hydrologic modeling for snow-dominated mountain systems

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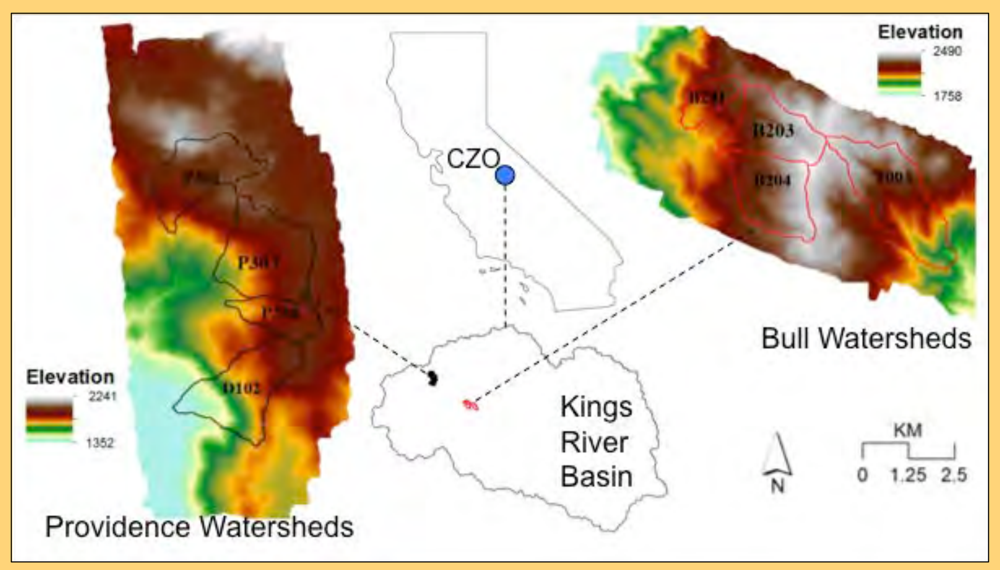
Introduction

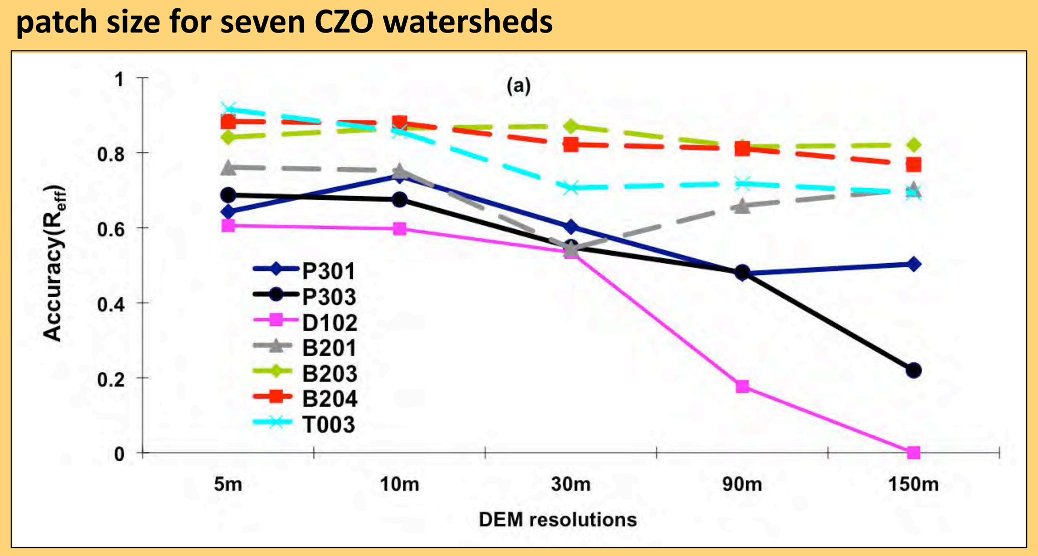
Controls on spatial-temporal patterns of land surface water and carbon fluxes at patch measurement scales are often quite distinct from those at hillslope and landscape scales. At patch scales, there is often significant fine-scale heterogeneity in snowmelt processes related to canopy architecture. Also, at the patch scale, soil moisture patterns respond to fine-scale snowmelt as well as micro-scale variation in topography, vegetation structure and soil drainage characteristics. At hillslope scales, topographically driven variation in micro-climate and radiation forcing, as well as hillslope drainage patterns become important. At even large scales, between watershed differences in underlying geology, as well as regional scale climate patterns can become dominate controls. While dominant controls on responses at particular scales are often well known and explicitly represented in models, the impact of finer-scale heterogeneity (below the typical model patch scale) is rarely assessed. For model applications at aggregate scales - from first-order watersheds to regions, an important question is how to account for sub-scale variability and any non-linear effects on estimates of aggregate fluxes including streamflow, net primary productivity and evapotranspiration. Explicit representation of heterogeneity involves tradeoffs related to computation time and limited data availability for parameterization. Here we assess how these tradeoffs may impact estimates of aggregate watershed moisture and carbon fluxes for snow-dominated systems, when working at 30m to 1km scales. We then demonstrate the utility of an intermediate scaling strategy that combines explicit and implicit representations of sub-watershed scale heterogeneity. We use explicit representation for patterns where spatial organization matters and implicit representation when the aggregate effect of heterogeneity is important but not its' spatial pattern. We argue that this new approach offers a more efficient method to account for spatial heterogeneity in mountainous snow-dominated systems and present some preliminary results of applying this new approach.

Sensitivity of eco-hydrologic flux estimates to model patch resolution: Sierra CZO case study

https://eng.ucmerced.edu/snsjho/files/MHWG/Field/Southern_Sierra_CZO_KREW/Photos/P301_Flux_Tower/imageGallery



Post-calibration model performance (accuracy), with increasing patch size for seven CZO watersheds



Model Accuracy (Streamflow)

$$R_{eff} = 1 - \frac{\sum_i (Q_{obs,i} - Q_{sim,i})^2}{\sum_i (Q_{sim,i} - \overline{Q_{obs}})^2}$$

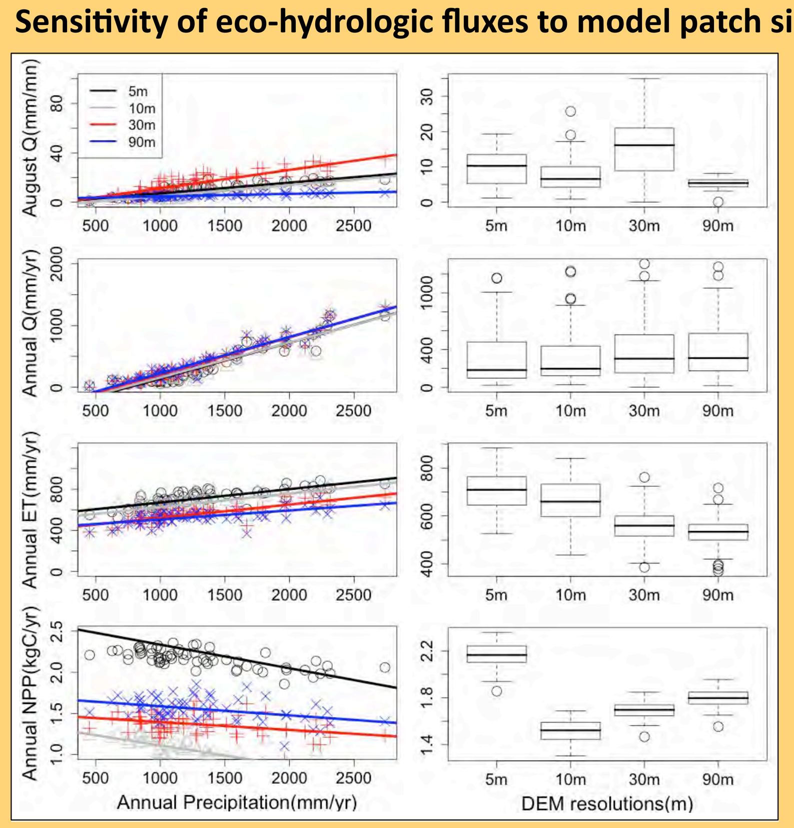
$$R_{\log eff} = 1 - \frac{\sum_i (\log(Q_{obs,i}) - \log(Q_{sim,i}))^2}{\sum_i (\log(Q_{sim,i}) - \log(\overline{Q_{obs}}))^2}$$

$$PerErr = \frac{(\overline{Q_{sim}} - \overline{Q_{obs}})}{\overline{Q_{obs}}} \times 100$$

$$Accuracy = R_{eff} \times R_{\log eff}) \times (1 - \left|\frac{PerErr}{100}\right|)$$

- Streamflow prediction accuracy declines with increasing patch resolution above 30m – even after calibration
- Some watersheds show much greater sensitivity to model patch size
- Watershed D102 is particularly sensitivity – D102 is the steepest sloped watershed and has the lowest elevation – in the sensitive rain-snow transition zone

Sensitivity of eco-hydrologic fluxes to model patch size for D102 (snow-dominated CZO watershed)



Predictions of Summer (August) low flows show complex (non-linear) relationship with model scale – with greatest inter-annual variation at intermediate (30m) scales

Estimates of ET decline with coarser resolution patches – may reflect higher ET in riparian areas which are not resolved for coarser resolution patches

NPP estimates are substantially greater for 5m resolution (and show a steeper decline with precipitation – associated with shorter growing season)

For CZO watersheds, accounting for finer scale heterogeneity (<90m patch resolution) leads to significantly different moisture and carbon flux estimates – scaling relations are non-linear

Regional Hydro-Ecological Simulation System (RHESSys)

RHESSys is a GIS-based, hydro-ecological modeling framework designed to simulate carbon, water and nutrient fluxes. By combining a set of physically based process models and a methodology for partitioning and parameterizing the landscape, RHESSys is capable of modeling the spatial distribution and spatio-temporal interactions between different processes at the watershed scale.

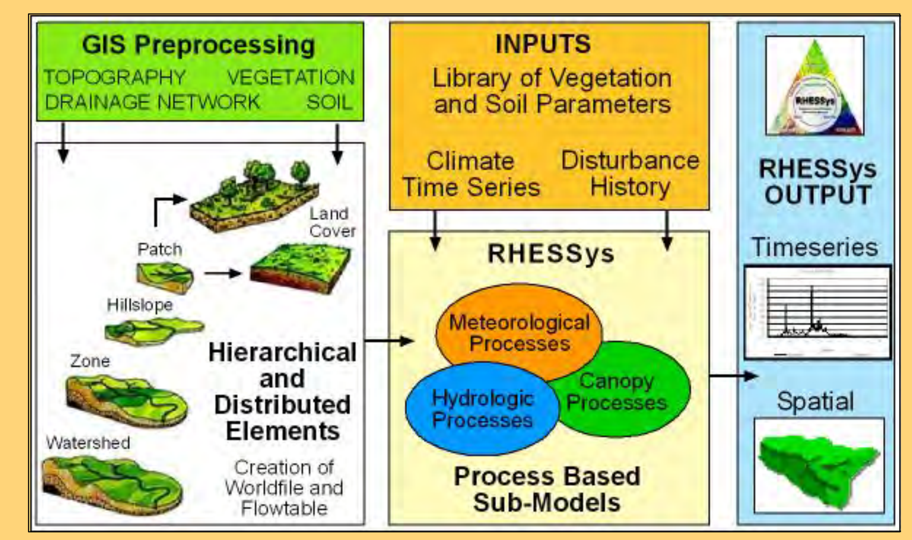
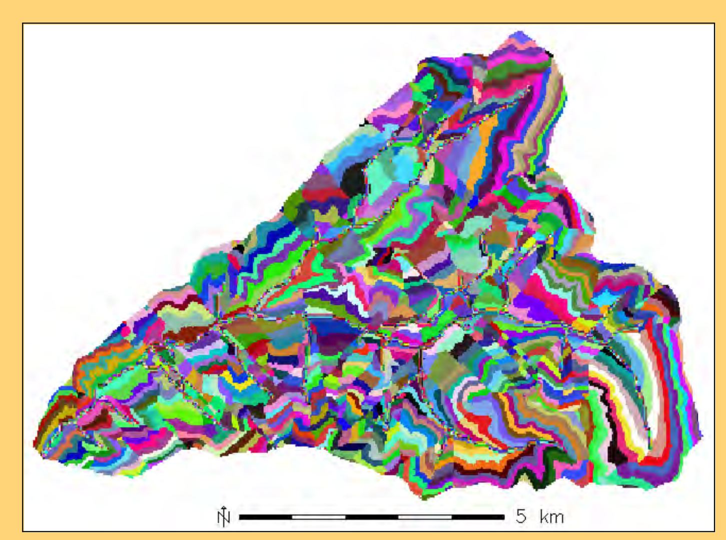


Illustration of aspatial patches embedded within a spatially explicit routing network – comparison with standard RHESSys patch structure

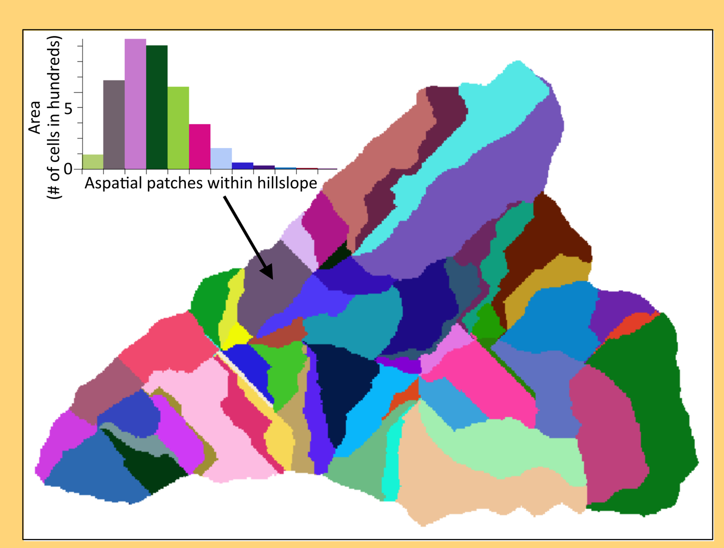


Original approach: Fully spatially explicit

Standard patch structure used in RHESSys
Most efficient approach is to have variable patch shapes

Variable patch size – selected to capture spatial variation in topography (elevation) and include fine-detail in riparian areas

Number of patches in this example: 4313



New approach: Aspatial embedded

Explicit routing objects are hillslopes

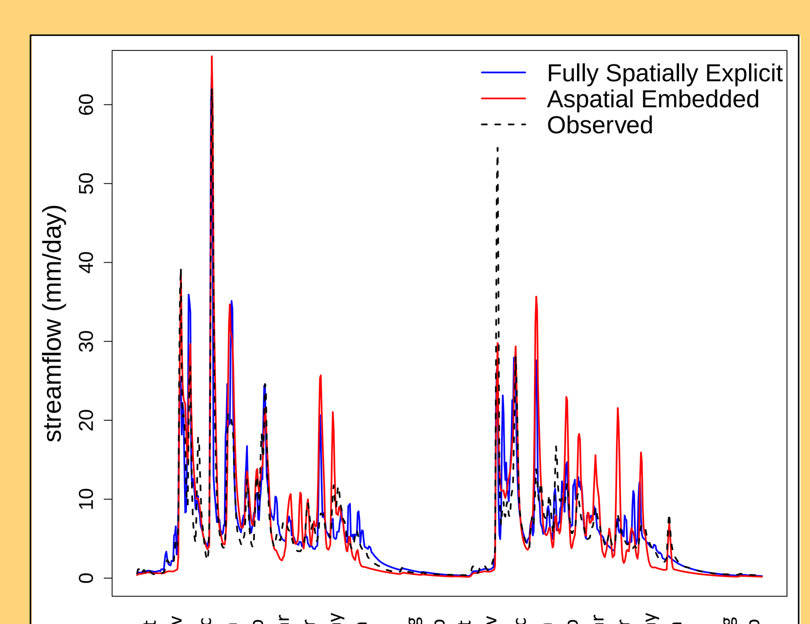
Aspatial patches within hillslopes (aspatial distribution based on wetness index distribution)
Similar to TOPMODEL *but* without Topmodel assumptions of continuous water table connectivity to stream (frequently not in mountain Western US watersheds)

Number of patches in this example: 633

Embedded aspatial approach performs similarly to the standard fully spatially explicit approach – performance degradation is small and computational efficiency is significantly improved

Time to run on Mac Pro for 1 simulation year:
Fully Spatially Explicit = 4 minutes 30 seconds
Aspatial Embedded = 14 seconds

Strategy	# patches	NSE	Log NSE	% error
Spatially explicit	4313	0.73 – 0.78	0.74 – 0.92	3.2 – 4.8
Aspatial Embedded	633	0.70 – 0.72	0.75 – 0.86	1.8 – 8.9



Representing fine scale heterogeneity in RHESSys

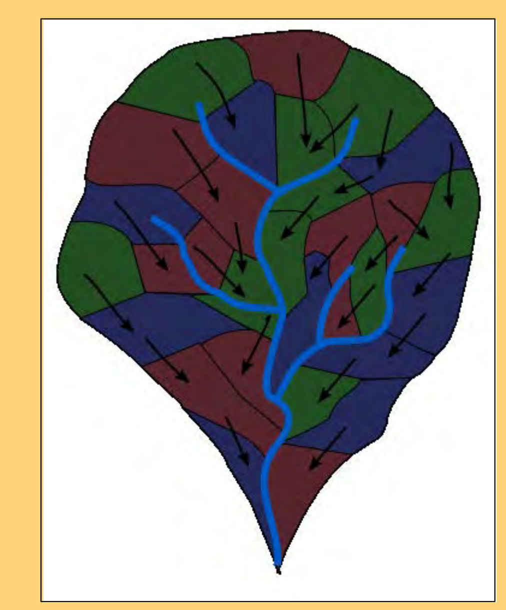
Heterogeneity between bare and vegetated areas

Heterogeneity between grass, trees, roads, houses

Spatial heterogeneity of landscape characteristics:

- Often occurs at a fine scale (<5m²)
- May be important to ecological processes
- Computationally intensive to represent if modeling at the watershed scale
- But, fine scale data is increasingly available

Can we take advantage of fine scale information about the landscape in a computationally efficient manner?



Current
- Patches are spatially explicit
- One value per landscape characteristic

Drawbacks
- Many computations required to capture variability in soil moisture, impervious surface, vegetation, etc.
- Not all data is available at a fine scale

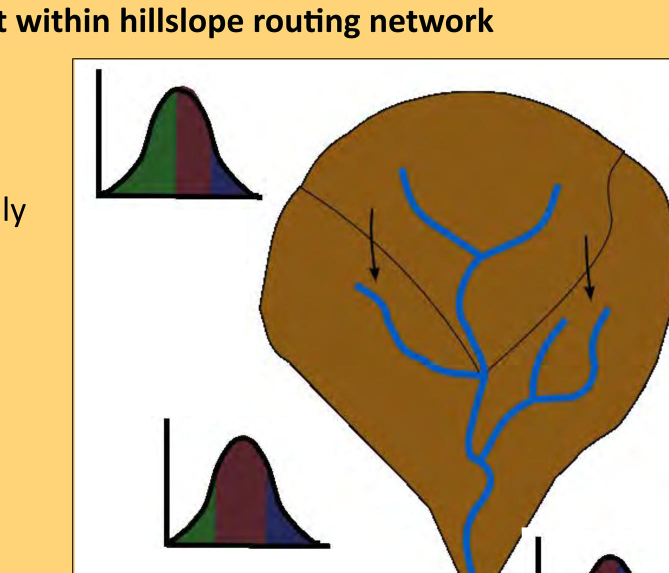
In this example: 29 patches
29 process calculations
29 sets of routing calculations

Aspatial patches embedded in a spatially explicit within hillslope routing network

Separate spatially explicit routing from landscape variables.
- Routing occurs in new coarser s-unit layer.
- Processes within s-units are lumped, not spatially explicit.
- Weighted by area fraction

Advantage:
- Capture landscape variability
- Maintain spatially explicit nature of RHESSys
- Computationally efficient

With s-unit: 3 explicit patches
3 routing calculations
9 process calculations (3 per patch)



Proposed modification: the s-unit

Including fine scale heterogeneity in hydrologic and carbon cycling models for forested snow-dominated watersheds can alter estimates of streamflow and carbon cycling (ET estimates for 5m patches were 25% greater than for 90m patches for one rain-snow transition watershed!)

Computation limits preclude 5-30m patches for large watersheds – so we need to account for heterogeneity implicitly inside explicit hillslope routing

Next Steps:

- Fully implement embedded aspatial approach as an option for lateral moisture redistribution in RHESSYs
- The improved computational efficiency will be critical for BioEarth integration of RHESSys for large scale Columbia River simulations