Report as of FY2008 for 2007MT150B: "Predictive Modeling of Snowmelt Dynamics: Thresholds and the Hydrologic Regime of the Tenderfoot Creek Experimental Forest, Montana"

Publications

- **Dissertations:**

- **Articles in Refereed Scientific Journals:**

- **Other Publications:**

- **Conference Proceedings:**
Final Report for USGS 104b Grant: Predictive Modeling of Snowmelt Dynamics: Thresholds and the Hydrologic Regime of the Tenderfoot Creek Experimental Forest, Montana

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Abstract
This project was aimed at advancing understanding of the first-order controls on snowmelt runoff processes for improved forecasting and water resource management. The need for this improved insight is particularly relevant given our reliance in the inland northwest region on mountain water resources, and our relatively poor understanding of thresholds and controls on runoff generation in mountain environments. We addressed these themes via a synthesis of field observations, data analyses and conceptual model development. We undertook our activities at a regional test watershed, the Tenderfoot Creek Experimental forest, located in the Little Belt Mountains in central Montana.

Our field observations and modeling approaches provided insight to the variables controlling runoff source areas and the utility of different data for quantifying these. Our analyses indicated topographic controls on runoff and the variability of this through time. We implemented a modular suite of 30 model structures to assess the relative importance of different elements of watershed runoff. Our results emphasize the importance of characterizing the spatial distribution of snowmelt (strongly correlated to aspect and elevation), and its temporal variability according to climatic indicators such as temperature and radiation. These results are transferable to other catchments and will help guide future conceptual models of watershed behavior in mountainous regions.

A self-contained graphical user interface was developed to integrate the modeling framework and associated analyses into a freely available modeling software package. The Simulation and Prediction Lab for Analysis of Snowmelt Hydrology (SPLASH) has been successfully programmed to perform model selection, parameter calibration, uncertainty analysis, and model evaluation.

This project provided training for two graduate students in field hydrology methods and modeling. These students were highly productive and successful over the duration of the project. Additionally, three journal manuscripts and numerous presentations disseminated the main scientific findings of this project to the greater scientific community.

Introduction and Overview
In mountainous areas across the western United States including Montana, winter snowpack controls regional water resources, supplying water to downstream, lower elevation valleys partially because of
reduced evaporation, greater water deposition, and storage until spring snowmelt. To date, little research has been conducted in the Montana region on the linkages between snow accumulation, melt timing, topographic structure, runoff source areas, and streamflow residence time. Although there is a strong desire to more efficiently predict and model snowmelt driven streamflow yield and timing, the primary controls on watershed runoff and flow dynamics are poorly understood.

Forecasting watershed response to incident and accumulated precipitation is more easily achieved via the use of simulation modeling. Such hydrological models play an important role in testing our understanding of the watershed response to precipitation, whether it is to elucidate more information on the unobservable processes occurring or to simulate past or future scenarios for better water resource management. In recent years, hydrologic modelers have increasingly recognized the importance of incorporating uncertainty in the modeling process. Modeling by its nature is only an approximation of the processes occurring and significant uncertainties arise in mathematically expressing complex non-linear watershed dynamics.

This project aimed to improve understanding and quantitative modeling of snow accumulation and melt, watershed streamflow generation, and the effect of watershed topographic structure on watershed processes. We focused our efforts on continued data collection, isotopic analyses of streamflow residence times, and conceptual model comparisons.

Research was conducted at Tenderfoot Creek Experimental Forest (TCEF). The TCEF was established in 1961, and consists of seven gauged watersheds (Figure 1). The forest is representative of the vast expanses of lodgepole pine found east of the continental divide and is the only USDA experimental forest formally dedicated to research on subalpine forests on the east slope of the northern Rocky Mountains.

**Objectives**

1. To synthesize extensive existing field observations at the Tenderfoot Creek Experimental Forest into a conceptual predictive modeling framework evaluating the first order controls on spatio-temporal runoff dynamics, new snowmelt/old groundwater runoff partitioning and the impact of terrain and forest practices.

*Figure 1. Site location and instrumentation of the TCEF catchment. (a) Catchment location in the Rocky Mountains, MT. (b) Catchment flumes, well transects, and SNOTEL instrumentation locations. Transect extents are not drawn to scale.*
2. To initiate watershed tracer experiments quantifying new snowmelt runoff direct contributions to streamflow and resident (old) groundwater contributions to spring runoff across sub-watersheds to explicate the residence time of new water within in each of 7 watersheds and better inform conceptual model underpinnings.

Methodology
This project focused on three main activities: hydrometric and isotopic data collection, analysis of detailed field measurements to inform conceptual modeling, and implementation of a modular predictive modeling framework.

Hydrologic Data Collection
This project helped support existing infrastructure and allowed for new data collection at the project test watershed. Under this project, continuing data collection included:

Stream flow
- Monitored discharge at the outlets of 7 nested watersheds
- Monitored real time specific conductance and temperature at 8 locations

Wells and piezometers
- Installed (many existing) and monitored (real-time water level data collection)
  - 100 wells
  - 20 piezometers

Lysimeters
- Installed recording snowmelt lysimeters

Rainfall
- Built and installed an incremental rainfall sampler
- Monitored 5 existing recording rain gauges

We additionally collected water samples for isotopic, dissolved organic carbon (DOC), and major ion analysis from stream flumes, groundwater wells, piezometers, snow and soil lysimeters, and rainfall sampler.

Data Analyses
Since the project inception (and following reviewer comments), the project evolved to consider topographic and water table data (additional to isotopic analyses) to help inform conceptual model underpinnings and to address major project objectives. In steep headwater catchments with shallow soils, topographic convergence and divergence is a hypothesized first-order control on the distribution of soil water and groundwater. Additionally, hillslope-riparian water table connectivity represents the linkage between the dominant catchment landscape elements (hillslopes and riparian zones) and the channel network. To explore these concepts, we combined digital elevation model (DEM) based terrain analyses with high frequency water table measurements. Using these, we tested the relationship between watershed topography and hillslope-riparian- stream shallow groundwater connectivity.
We quantified water table connectivity (Figure 2) based on 146 recording wells and piezometers distributed across transects within Tenderfoot Creek. Correlations were observed between the longevity of water table connectivity and the size of each transect’s upslope accumulated area (Jencso et al., 2009). We applied this relationship to the entire stream network to quantify landscape scale connectivity through time and determine its relationship to catchment scale runoff dynamics. We found that the shape of the estimated annual landscape connectivity duration curve was highly related to the catchment flow duration curve (Figure 2). This research suggests internal catchment landscape structure (topography and topology) as a 1st order control on runoff source area and whole catchment response characteristics.

We made additional analyses of isotopic data to discretize new (snowmelt runoff) and old (groundwater) contributions to streamflow. The model we implemented computes transfer functions for event water and pre-event water calculated from a time-variable event water fraction (Weiler et al., 2003). This undertaking helped to identify several obstacles in using traditional residence time analyses for a watershed system such as TCEF. The biggest stumbling block to these analyses is adequately characterizing the snowmelt contribution to runoff, due to the strong spatial variability of snow melt patterns across the watershed. Figure 3 illustrates the inability of classical transfer function models to capture patterns of

Figure 2. A) Upland-stream water table connectivity as a function of upslope accumulated area. This relationship defines the fraction of the stream network hydrologically connected to uplands and can be used either as a spatially explicit variable or as a space-time distribution. B) Flow duration curve and fractional upland stream connectivity curves for one TCEF subwatershed. Note relationship between connectivity and discharge.

Figure 3. Observed and predicted streamflow from runoff component of residence time model
runoff. These findings helped support conceptual model methodologies (detailed following). Our project evolved to focus on characterizing the variability in snow melt rates due to elevation and aspect across the watershed.

**Modeling**

We developed and implemented a modular modeling framework that applies model parameter estimation and uncertainty analysis quantification for a range of hydrologic models. We applied the modeling framework using existing observations from the Stringer Creek watershed, located within TCEF. Thirty unique modular structures, ranging in complexity from very simple to moderately complex, were developed and included in the modeling suite. The suite of models was constructed in a modular, component-wise fashion to allow for different conceptualizations of soil moisture accounting, runoff routing, and snowmelt accounting. We used findings from our data analyses to help guide conceptual modeling development, focusing on characterizing spatial variability in snowmelt rates, and spatial variability in runoff source areas.

In implementing the modeling approach we compared three recently developed Markov chain Monte Carlo algorithms necessary to for model calibration (parameter estimation) and uncertainty analysis under a Bayesian inferential approach (Smith and Marshall, 2008). The predictive modeling framework was used to assess the effect of model structural complexity on model predictive performance (Figure 4). We assessed each of the models based on their predictive performance, the uncertainty associated with the model simulations and parameters, and their ability to predict snow water equivalents (Smith and Marshall, 2009).

A self-contained graphical user interface was developed to integrate the modeling framework and associated analyses into a freely available modeling software package. The Simulation and Prediction Lab for Analysis of Snowmelt Hydrology (SPLASH) has been successfully programmed to perform model selection, parameter calibration, uncertainty analysis, and model evaluation. This software package simplifies the complexities required to implement a predictive modeling study and shifts the focus toward the modeling problem itself through the application of forward-looking methods in computational hydrology.
Figure 4. Modeling framework structural uncertainty and streamflow simulation for 'optimal' modular structure. Inset shows three model simulations corresponding to different conceptualizations of snowmelt.

Results and Conclusions

Overall, the project was successful and productive from three main viewpoints: scientific merit and furthering scientific understanding, graduate student training, and disseminating results via publications and presentations. These areas are detailed following.

Scientific Merit

Our analyses of water table connectivity strongly indicates topography (as represented by upslope accumulated area) controls upland-stream connectivity and that this drives runoff generation through time. The transformative nature of this research is strongly evident. How hillslope inputs along stream networks are linked to catchment-scale response has traditionally been poorly understood, with research efforts focused on a specific plot/stream reach. This project provides implications for watershed drivers that may be transferable to other catchments and allows development of general principles that can guide future conceptualizations of watershed models.

In undertaking conceptual model development at our test site, we focused on model selection, calibration, uncertainty analysis, and overall assessment. The results of this case study suggest that a modular framework is useful in identifying the interactions between and among different process representations and their resultant predictions of stream discharge. Such an approach can strengthen model building and address an oft ignored aspect of predictive uncertainty; namely, model structural
uncertainty. Our modeling approach offers insight into the interplay among the modular components and predictive performance for TCEF. The overriding conclusions are (1) precipitation semi-distribution methods did little more than provide another degree of freedom to the model structures; (2) net radiation is an important component in conceptualization of snowmelt accounting methods; and (3) a model based on topographic similarity may inhibit the overall calibration performance due to the model’s rigidity in structure.

While the research undertaken in this project has been focused at a local test-site, the methods and models developed are broad reaching and could be applied to other watersheds. This research should have significant impact for better understanding of the link between model reliability and predictive uncertainty in streamflow forecasting for mountainous snow driven watersheds, and for conceptualizing watershed response based on topographic structure.

**Student Training**
Two high achieving graduate students were trained under this project. Kelsey Jencso is pursuing a PhD degree in the department of Land Resources and Environmental Sciences under the tutelage of Dr Brian McGlynn. Kelsey’s work focused on hydrologic data collection and data analyses related to hydrologic connectivity. Kelsey has been very successful while working on this project, and was twice awarded the American Geophysical Meeting Outstanding Student Paper award. He recently published a high quality manuscript describing his work under this project and is continuing work focused at TCEF. Tyler Smith recently completed a Master’s degree and was advised by Dr Lucy Marshall. Tyler’s work focused on model development, model uncertainty assessment, and construction of the modular modeling software suite. Tyler published one paper describing the uncertainty methods used in this project, and has an additional manuscript under review describing the modeling framework. Tyler was additionally awarded and American Geophysical Meeting Outstanding Student Paper award. This is a highly competitive award, and it speaks highly of the quality of students supported under this project that both students received the award. Tyler is continuing his research efforts, and has recently commenced a PhD degree at Montana State University.

**Publications**
Several journal papers and numerous presentations resulted out of this project.

**Journal Manuscripts**


Presentations


References Cited


