MODELING SPATIAL DIFFERENCES IN SNOWMELT RUNOFF TIMING

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ABSTRACT

Discharge in small, tributary streams affects water table heights, riparian vegetation, and habitat in subalpine meadows. Because of this, meadows are very sensitive to the dates when the ephemeral streams go dry. This project investigates how topographic shading affects the advance of snowmelt onset and the date snow disappears as temperatures warm in Yosemite National Park, California. Observations show that in years where the temperature warms earlier in the season, south-facing sub-basins start melting over a week earlier than north-facing basins. Thus, meadow areas fed by sub-basins with southern aspects are expected to be much more sensitive to warming temperatures than areas fed by sub-basins with northern aspects. Traditionally, most future hydrologic simulations are run for large basins, and these effects would not be captured. The Distributed Hydrology Soil Vegetation Model (DHSVM) is used to test if high-resolution (150m) modeling containing a topographic shading component can represent these observed differences in various sub-basins and meadow regions. Additionally, the Snow-17 model is modified to test if simpler, less data-intensive methods can yield similar results. The findings help define the model complexity needed to properly represent the effects of shading in mountainous terrain.

INTRODUCTION

In high-elevation areas with a Mediterranean climate, the majority of precipitation falls in the winter, and the timing and duration of spring snowmelt exercise a significant influence over the local ecosystem. Water table heights, vegetation, and habitat in subalpine meadows are all dependent upon the timing of discharge in small, tributary streams. With warmer winter and spring temperatures leading to earlier snowmelt (Stewart et al., 2005), it is essential to be able to properly represent the spatial and temporal variability of melt processes feeding these meadows.

The Tuolumne River basin in Yosemite National Park provides a favorable setting to experiment with new approaches modeling snowmelt. This 316 km^2 westward-draining basin has an elevation range of about 2000 – 4000 m and contains both north and south-facing subbasins in complex terrain (Figure 1). Also, the granite geology and shallow soils allow for reasonable simplifications in the water balance. As a result, this area allows for many aspects of the snowmelt modeling process to be analyzed, including topographic shading, snowpack heterogeneity, and effects of aspect and elevation. Observations show that in years where the temperature warms earlier in the season, south-facing subbasins start melting over a week earlier than north-facing subbasins (Lundquist and Flint, 2006). Thus, meadow areas fed by subbasins with southern aspects are expected to be more sensitive to warming temperatures. The Gaylor Creek (south-facing) and Budd Creek (north-facing) subbasins show evidence of these effects. This projection highlights the need for a model that is able to show the spatial differences in melt timing.

This paper analyzes two distributed snowmelt models and their ability to capture those differences. Snow-17 model (Anderson, 1973) is the snowmelt component of an operational hydrology model used by the National Weather Service for river forecasting. It was developed as a temperature-index-driven point model, but can be distributed across a basin using spatially interpolated input grids. The Distributed Hydrology Soil Vegetation Model (DHSVM, Wigmosta et al., 1994) is a physically-based hydrology model that performs a full energy and mass balance. DHSVM allows for terrain-specific input such as shading, skyview, and elevation maps. The **Data** section of this paper describes the data used to drive and test the models. Next, **Preliminary Snow-17 Model** tests the distribution of input data and highlights some of the shortcomings of a simple coarse-resolution model. The **DHSVM** section shows the method and results of setting up a more complex model at a higher resolution. The **Revisiting Simple Models** section provides a plan for future work and preliminary results from making modifications to the Snow-17 model. **Summary and Conclusions** covers the general findings from the experiment and considerations for future work on the project.

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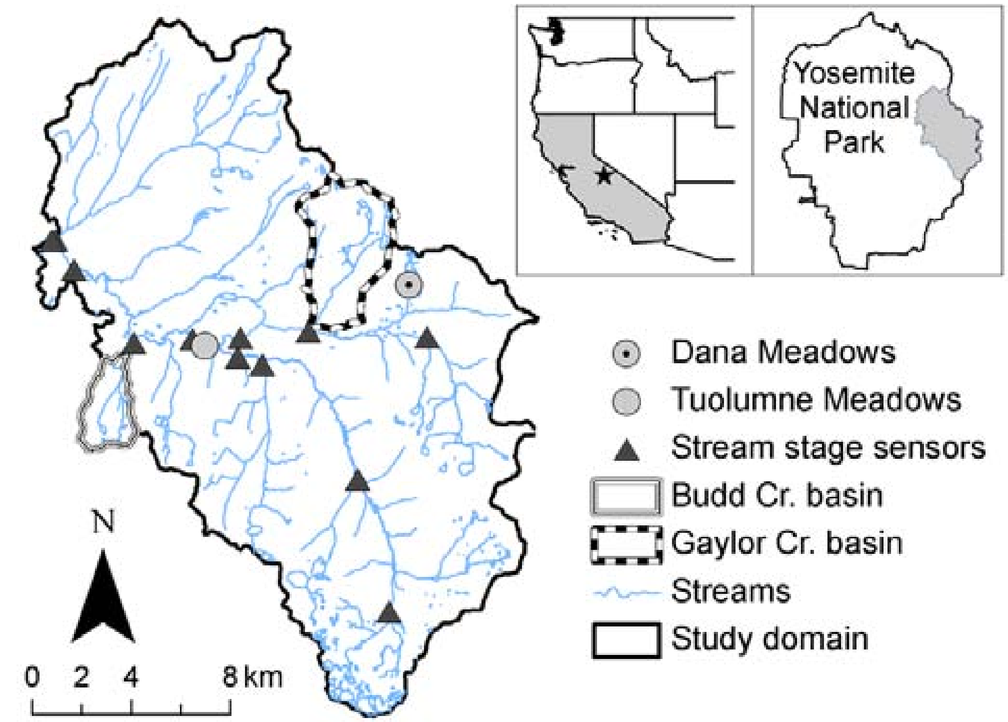

Figure 1. Study area and monitoring sites in the upper portion of the Tuolumne River.

DATA

Meteorological Data

Meteorological data for the project was obtained from the Dana Meadows and Tuolumne Meadows monitoring stations (Figure 1), which are maintained by the California Department of Water Resources (CA DWR). Data from these stations is available through the CA DWR California Data Exchange Center (CDEC) at http://cdec.water.ca.gov. Snow water equivalent (SWE) records from snow pillows at the sites are based are based on the weight of accumulated snow. Hourly records of temperature, wind speed, wind direction, and incoming shortwave radiation are available. Wind data was measured with a cup-anemometer. Shortwave radiation is measured by a Li-Cor silicon pyranometer. Precipitation is measured via an accumulating gage at the Tuolumne Meadows station or estimated from accumulation in SWE at the site. The climatology of the region causes most of the precipitation to fall during the winter months, meaning that the colder, higher elevation sites record practically all of their precipitation in the form of snow. The Dana Meadows station was used to drive the models since it had the most complete record. The Tuolumne Meadows station was used to check the quality of the input data distribution methods.

Stream stage sensors

There are about a dozen Solinst Levelogger stream gages in the study domain. The sensors measure stage every half hour using a pressure transducer and the data record is corrected for barometric pressure fluctuations by a logger kept in open air at the Tuolumne Meadows station. Rating curves for the streams are updated each summer as with new stage and discharge measurements. Most flow measurements are taken between May and October, when the park is open. As a result, some of the higher seasonal flows are not captured. The rating curve for the Tuolumne River at CA Route 120 has the most measurements and has been found to be reliable in recent years, so it was used to compare against model outflow results. When flow approximations are not available, the stream logger records provide information on melt timing in the basin. A distinct rise in stream stage marks the beginning of snowmelt, and the return to dry or baseflow conditions in late summer can be estimated from the stream level.

Spatial Datasets

The Physical Science Group of Yosemite National Park's Resource Management Division provided many of the spatial datasets used in the modeling. This included a 10-meter resolution digital elevation model, vegetation maps, soil surveys, and stream maps. The digital elevation map was aggregated to coarser resolutions in ArcGIS using the areal mean elevation.

Thirty-year (1971-2000) monthly normal precipitation maps from the PRISM (Parameter-elevation Regressions on Independent Slopes Model, available at http://www.prism.oregonstate.edu) project were used to distribute station precipitation data. The 30-year, monthly normals compared well with the monthly datasets and are provided at a higher resolution of 800 meters.

For the 2004-2005 water year, a processed MODIS dataset was provided by Dr. Bob Rice (UC Merced) and Dr. Jeff Dozier (UC Santa Barbara). The MODIS data has been filtered and interpolated across space and time to give the best continuous estimate of fractional snow-covered area (SCA) and albedo (Dozier et al., 2008). The dataset spans the Tuolumne and Merced River basins at a 500-meter resolution. The MODIS SCA data is useful for approximating the disappearance date of snow cover from a particular grid cell. This provides an independent check on distributed model performance.

A clear-sky solar irradiance model developed by Flint and Childs (1987) provided daily shortwave radiation maps for comparison against those generated by DHSVM. The Flint and Childs model takes into account surrounding topography and calculates potential incoming solar radiation, while DHSVM splits measured station data into direct beam and diffuse components and distributes the values across the basin. The Flint and Childs model provides a physically-based upper bound to check against.

PRELIMINARY SNOW-17 MODEL

Snow-17 was chosen as a preliminary testing model due to its relative simplicity and previous application in the Sierra Nevada (Lundquist and Flint, 2006; Shamir and Georgakakos, 2006). The model requires temperature and precipitation as driving data. Melt at each 6-hour timestep is calculated based on temperature and a varying melt factor. The melt factor for each day is based on a sine curve, with the minimum and maximum values set by the user to reflect seasonal variability at the site. The model then approximates the snowpack energy balance using a "heat deficit" term to determine if meltwater refreezes or leaves the snowpack. The snowpack is treated as a single layer containing both ice and liquid water components. The liquid water capacity is determined based on a user-specified holding capacity. The snowpack is accounted for in terms of millimeters of SWE.

The assumptions about Snow-17 and MODIS also needed to be justified before continuing. The model was run for the 2005 water year at the grid cell location where observed data was available. It was found that the modeled SWE was in good agreement with the observed data and small-scale fluctuations were captured. Both the model and the observed data show SWE disappearing on the same date. For the MODIS data, using a cutoff of 5% snow-covered area to classify a cell as being snow-free matches the disappearance of SWE at the snow pillow.

Then, the model was run across a 500-meter gridded domain to test the temperature and precipitation distribution methods. They were checked against the MODIS SCA data to compute error at each grid cell. From the meteorological reference cell at Dana Meadows, temperature was distributed using a constant lapse rate of -6.5°C/km. On average, this rate was found to work well in the Sierra Nevada (Lundquist and Cayan, 2007). The station precipitation data was distributed using ratios derived from the PRISM 30-year normal monthly precipitation grids. This was done in order to preserve the complex spatial relationship between precipitation and location. Precipitation is non-linear with elevation, so using a constant lapse rate method like the one used for temperature would introduce error. The ratio of precipitation values between a grid cell and the reference (Dana Meadows) cell in each month's PRISM map was used to scale the station precipitation amount to the new location. Initial parameter values for the model were chosen according to the work of Lundquist and Flint for the region (Lundquist and Flint, 2006).

The results from the 500-meter, 2004-2005 Snow-17 model run showed that the precipitation and temperature distribution methods brought the model within a reasonable range of error. 50% of the cells in the basin lost snow cover within a week of the MODIS observations (Figure 2). The model had a basin-average bias of melting snow away about 6 days earlier than MODIS observations and a RMSE of 9 days. Sources of error in the model can be attributed to the resolution, which is too coarse to capture many of the headwater cirques and steep valleys in the basin, as well as the model lacking an energy balance or topographic influence component. While the melt factor parameter in the temperature-index model implicitly accounts for fluctuations in radiation and the energy balance, the complex terrain of the basin leads to errors when a single set of parameters are used for all grid cells. To address these errors, a distributed model with an energy balance component was implemented.

DHSVM

The Distributed Hydrology Soil Vegetation Model applies a full energy and mass balance across a basin. Stemming from that are higher input data requirements, with the model requiring maps of elevation, skyview, terrain shadowing, vegetation, soil type, soil depth, and the same PRISM precipitation maps used in the preliminary Snow-17 model. In addition to temperature and precipitation, the model requires wind speed, relative humidity, wind speed, wind direction, shortwave radiation, and longwave radiation. The snowmelt component of the model uses a two-layer energy balance. The model resolution for this run was increased to 150 meters and the timestep was increased to three hours.

DHSVM performed well at a point, compared to the Dana Meadows measured SWE (Figure 3), and across the basin as a whole, generating 101% of observed streamflow volume (Figure 4). While the volume of water matched well, the timing of the model melt showed larger peaks earlier in the season and lower late-season flows. This indicated that early spring snowmelt rates may be too high. When looking at the Gaylor Creek and Budd Creek subbasins, the differences became more evident. In the spring of 2004, observations show the onset of snowmelt in Budd Creek basin occurring eight days after melt began in the Gaylor Creek basin [*Lundquist and Flint*, 2006]. However, the results from DHSVM are just the opposite, with the onset of snowmelt in Budd Creek appearing about ten days before Gaylor Creek.

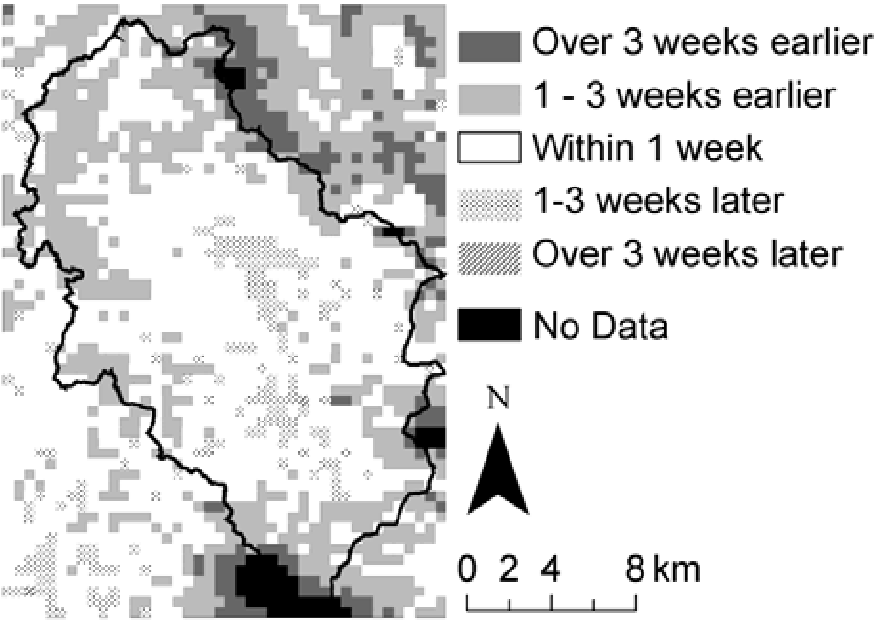

Figure 2. Snow-17 model snow disappearance compared to MODIS observations in 2005.

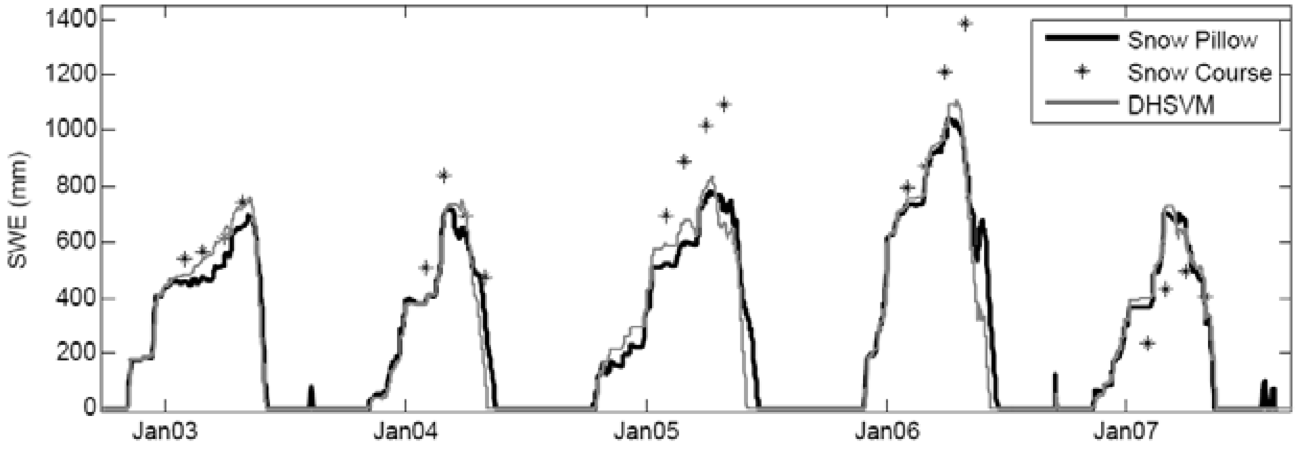

Figure 3. Comparison between observed and modeled (DHSVM) SWE at the Dana Meadows snow pillow.

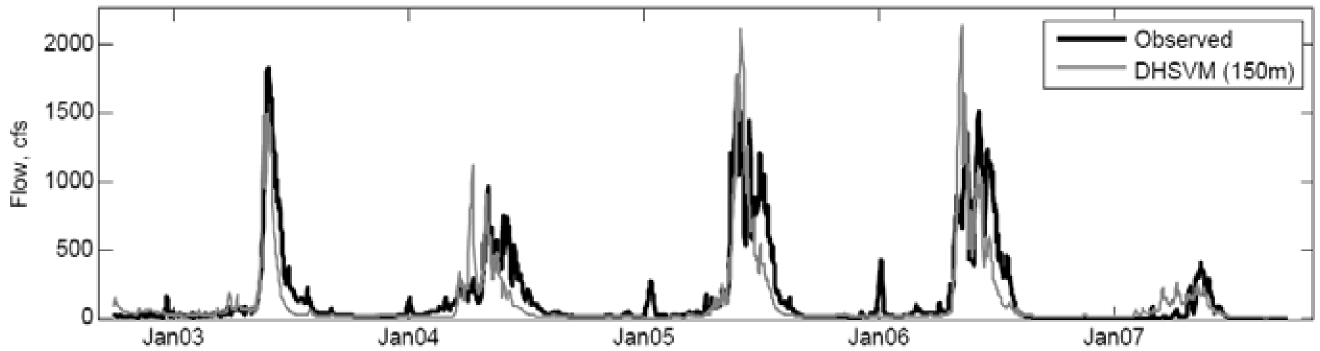

Figure 4. Observed and modeled (DHSVM) average daily flow at the Tuolumne River (at CA-120)

As a check, shortwave radiation maps for March 1st from DHSVM were compared to those generated with the Flint and Childs [1987] clear-sky irradiance algorithm. In the headwater cirques and steep portions of the subbasins, DHSVM tended to overestimate the amount of incoming shortwave radiation by up to 5 MJ/day. This amount comes to a potential melt difference of about 15 mm per day (based on water's latent heat of fusion, $3.34(10^8)$ J m^{-3}). For an isothermal snowpack in early spring, the difference may raise the internal energy of the snowpack enough to initiate melt.

DHSVM introduced more options and complexity to the modeling process. As a result, it becomes more difficult to track individual processes and isolate problems. For the issue of snowmelt timing, a return to a simpler framework seemed to offer a better chance to create an accessible modeling approach.

REVISITING SIMPLE MODELS

While the full energy balance approach used by DHSVM performed well for the basin on average, the input demands may not be appropriate for application in basins lacking extensive field data. Simple models were reconsidered as a starting point for exploration of controlling processes in the Tuolumne River basin. Besides the more basic framework, the speed of simple models allows for quick tests of modifications. The importance of radiation in years with an early spring in the Sierra, the influence of surrounding topography, and the impact of snow heterogeneity on melt timing (Luce et al., 1998) were all considered important for this basin. The Snow-17 model and the Utah Energy Balance (UEB, Tarboton and Luce, 1977) are two approaches that are designed to fit within larger models. The UEB is a physically-based energy balance approach that can utilize radiation data or make estimations from daily temperature ranges.

The first attempt to modify a simple model was to write MATLAB code to run Snow-17 over the entire modeling domain at each timestep instead of running the model at each individual cell for the full length of the modeling period. Also, the main model functions were split up to ease modifications and an option to run over basin masks was added. Future plans for the model include incorporating radiation indices (similar to Cazorzi and DallaFontana, 1996), and cell-based changes to the melt factor. Shamir and Georgakakos (2006) found that aspect corrections to a distributed SNOW-17 model resulted in good agreement with snow sensor and MODIS snow extent datasets, with errors in the driving precipitation data causing a significant portion of the model uncertainty.

Changes to the melt factor on the basin scale were the first modification tested. Since the melt factor implicitly accounts for seasonal variations in solar radiation and energy balance terms, it is an appropriate way to represent differences due to basin aspect. While the initial values worked well on the total basin average, tests were run to find the change needed in the subbasins to match observations. For the early spring year of 2004, changing the melt factor by 25% moved the modeled melt onset date closer to the observed dates for the Budd and Gaylor Creek basins (Table 1). However, in a more typical year such as 2005 where shading does not exert as much influence, changing the melt factor will affect how deep-piled snowpacks will carry late-season flows. This process is independent of aspect, and Table 2 shows the same change in melt factor would match observed snow disappearance dates in the two basins.

Table 1. 2004 melt onset dates using a modified melt factor.

Basin	**Observed melt onset**	**Modeled Snow-17 melt onset using basin averaged melt factor**	**Modeled Snow-17 melt onset using modified melt factor**
Budd Creek (north-facing)	16 March	11 March	15 March (-25% MF)
Gaylor Creek (south-facing)	8 March	13 March	11 March (+25% MF)

Table 2. Changes to the Snow-17 to match melt completion dates in 2005.

Basin	**Observed (via MODIS) snow disappearance**	**Modeled Snow-17 snow disappearance**	**Change in melt factor needed to match observed snow disappearance date**
Budd Creek (north-facing)	1 July	25 June	-12 %
Gaylor Creek (south-facing)	8 July	3 July	-12%

SUMMARY AND CONCLUSIONS

Complex topography at high elevations presents an extra challenge in modeling. Many more processes need to be taken into consideration to properly represent melt behavior. Temperature-index models work well over a large area, but in high-elevation headwater cirques, where shading plays an important role, a complete energy balance is needed to avoid overestimating the amount of melt. Larger models such as DHSVM require more input data and preparation, and for this basin, only minimal gains in accuracy over a simple model were achieved when used at a resolution of 150 meters. Still, changing the model resolution improves energy simulations the most in places where the energy balance is important due to the detail in topography.

It is important to consider the needs of a project when choosing a model framework. The scientific community is asking more of its models. Many of the fundamental approaches to snow modeling were developed decades ago and are still relatively accurate and reliable. Changes to models require an understanding of the controlling processes in the region to avoid impacting parts of a model that work satisfactorily. The implicit nature of temperature-index models limit the extent of changes that can be made without completely restructuring the framework. An energy balance model is necessary to represent many of the processes controlling snowmelt in years where spring arrives early. The data requirements may be higher, but Walter et al. [2005] argue that estimating parameters for an energy balance model using the same data that would be used to drive a temperature-index still provide more accurate results. Future work on this topic will explore ways of integrating energy balance and topography-dependent snowmelt processes of complex terrain into simpler model frameworks.

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