AN EXPERIMENTAL AND MODELING INVESTIGATION OF THE IMPACT OF SILVICULTURAL MANIPULATION ON SNOW HYDROLOGY IN THE CEDAR RIVER WATERSHED, WA

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ABSTRACT

Over the past 80 years, forest harvesting throughout the western U.S. has resulted in a shift in the dominant forest structure to young, dense forests. Meanwhile, declining trends in mountain snow water equivalent (SWE), summer river flow, and earlier snowmelt have largely been attributed to climate with little consideration of the impact of the concurrent changes in vegetation from forestry practices. Silvicultural manipulation has the potential to increase snow water storage, change snowmelt timing and restore ecological processes that might normally be adversely affected by climate change. This study is primarily concerned with snowmelt timing, since it is crucial to watershed management in basins with limited reservoir storage. Any delay in snowmelt from silvicultural manipulation could reduce winter flood hazards and increase summer runoff when water demand for cities and agriculture is the highest. This study commenced in the 2009 water year and takes place in the Cedar River Watershed, WA, located in the climate-sensitive intermittent snow zone. Using a combination of distributed field measurements and point and distributed hydrologic models, we are investigating i) the heterogeneity of snow accumulation and melt in different forest structures, and ii) which forest changes are of comparable magnitude to climate change in their effects on snow hydrology. (KEYWORDS: snow water equivalent, seasonal runoff, runoff timing, timber harvest effects, Cedar River)

INTRODUCTION

Climate-related trends associated with snow, which provides approximately 40% of the world's fresh water, are harbingers of water troubles in future years (Barnett et al., 2008). Since 1950, the extent, depth, and snow water equivalent (SWE) of the April 1st snowpack have declined in the Western U.S., and snowmelt is occurring one-to-three weeks earlier (Hamlet and Lettenmaier, 1999; Mote, 2003; Hamlet et al., 2005). Earlier snowmelt means there will be greater runoff in the winter, when water is a flood hazard, but less in the summer, when water demand for cities and agriculture is the highest. Approximately 20% of watersheds in the western U.S. are in the transient snow zone, where winter precipitation falls as both rain and snow (Maurer et al., 2002). Climate models predict that these regions will experience the most dramatic shift towards earlier melt, compared to either snow- or rain-dominant zones. The Pacific Northwest relies heavily on mountain snowpacks for snow storage to augment small-sized man-made reservoirs (Mote et al., 2005; Barnett et al,. 2008). In these regions, early or abrupt snowmelt is a "loss of reservoir storage," resulting in economic loss, ecological disruption, and an inability to meet human water demands.

Vegetation affects snowmelt timing via two main processes: sheltering from solar radiation and wind, which decreases melt rates, and canopy interception. Depending on the density of forest vegetation and related physical factors, snow may be retained more or less effectively on the landscape. Snowmelt timing can be advanced or delayed several weeks by forest structure change, and rates of interception can range from 30 to 60% of snowfall (Pomeroy and Schmidt, 1993; Pomeroy et al., 1998; Storck et al., 2002). As human and ecological demands for late-summer water increase, it will be advantageous to optimize snow retention through silvicultural manipulation. Runoff shifts over the past century cannot be evaluated without considering changes in both climate and vegetation. Over the same period of mean temperature increase, forests of the western U.S. and British Columbia have experienced intense timber harvesting (Bowling et al. 2000; Jones and Post 2004; Thorne et al. 2006). Immediately following harvest and the attendant burning of slash, interception is eliminated, but ground-level melt rates are maximized. As forests grow back, tree density is high and there is a period of canopy closure, which maximizes snow interception. The majority of Northwest forests are in the 30-80 year age class, with dense and near-uniform canopies. After approximately 200 years, structurally diverse forests with a wide range of tree ages and densities develop (Franklin et al., 2002). Because forest structure affects snowpack accumulation and melt rates, silvicultural manipulation has the potential to increase snow water storage, change the timing of snowmelt, and restore related ecosystem services, such as river flow patterns and water temperatures that are favorable to salmon.

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FIELD EXPERIMENTATION

The study is located in the Cedar River Municipal Watershed (CRMW) along the western slope of the Washington Cascades. The CRMW, owned by the city of Seattle and managed by Seattle Public Utilities (SPU), provides approximately 70% of water for the 1.4 million people of the Seattle metropolitan area. In addition to providing water for municipal consumption, SPU manages stream flow regimes to secure habitat for salmonid species under its Habitat Conservation Plan (City of Seattle 2000). Sustainable forest management practices that optimize water quantity and quality in numerous catchments like the Cedar will become more important across North America (Wiley and Palmer, 2008).

Previous snow-vegetation studies have lacked detailed information about forest canopy form and structure (e.g., Jost et al., 2007). We have integrated our study with ongoing research on the effects of spatial structure and ecological thinning on forest development. In each 40 m x 40 m treatment unit, the location, diameter, and species of every tree has been surveyed to construct stem maps, allowing forest structure to be quantified and used in spatially explicit models to quantify the distribution of light under the canopy and test the effect of restoration treatments on light distribution. This study explicitly includes a spatial component (13,585 trees have been surveyed to a positional accuracy of ± 10 cm).

This spatially explicit data set provides a unique opportunity to study how variance in forest structure affects variability in snow accumulation, melt, and ultimately, snow retention on the forest floor. We are studying five nearby sites: i) Clearing site (740 m), ii) Old Growth Forest (780 m and 200+ yr. forest), iii) Control site in the secondary forest (630m and ~55 yr. forest), iv) Gap site in the secondary forest (640 m and ~55 yr. forest), and v) Thinned site in the secondary forest (640 m and ~55 yr. forest).

A calibrated meteorological station is located in the clearing site to obtain full energy balance data without canopy effects. In addition to temperature, relative humidity, wind speed and direction, shortwave radiation, net radiation and precipitation instruments, the station is also equipped with an acoustic snow depth sensor. In each of the four forested sites there is a small meteorological station measuring temperature, relative humidity, and wind speed.

To measure the spatial variability of light beneath the canopy, HOBO pendants have been placed at 10-meter intervals near the ground surface in the control and gap forests. HOBO light pendants are also located in the clearing site for calibration. We will also use the light model developed by Douglas Sprugel, University of Washington.

Temperature variability of the ground is being measured using 10 iButtons buried in each forested plot. Because of the insulating effects of snow, the ground temperature remains near- constant while covered with snow but oscillates diurnally when the snow disappears, providing a clear indication of the snow disappearance date (Lundquist and Lott 2008). Thus, groups of these sensors provide an innovative technique for determining the spatial variance in snow retention on the landscape. Additionally, there is a fiber optic cable that rests on the ground surface throughout the secondary forest plots, capable of measuring temperature at fine spatial and temporal scales.

Unfortunately, the 2009-2010 winter season had too little snow to manually measure. However, in subsequent years, we will manually measure the spatial variability of snow interception and retention within the different forest plots using a Model 3600 Federal snow sampling tube at 20 random locations within each forest plot each week when snow is present. In addition to manual measurements, there are two ultrasonic snow depth instruments per plot.

MODEL SENSITIVITY

In order to test the sensitivity of the snowpack to changes in vegetation, we have recoded the Distributed Hydrologic Soil Vegetation Model (DHSVM) as a point model using Matlab ®. Recoding is still in progress, but the model is a single-layer interception and two-layer energy balance model with canopy and surface layers.

With the exception of interception and wind speed calculations (influenced by understory in the DHSVM), the mathematical calculations of the energy balance, radiation, snow accumulation and melt are unchanged from the original DHSVM (see Wigmosta et al., 1994 for a further description of calculations).

Considering a snowpack on the ground, the energy available for snowmelt, Q_M, (W/m^2), can be calculated as

$$Q_{M}= (1-\alpha)Q_S + Q_L - \varepsilon\sigma T_S + Q_E + Q_R + Q_G - \frac{dU}{dt}$$

where Q_S is the incoming shortwave radiation (W/m^2), α is the albedo (dimensionless), ε is the snow emissivity (dimensionless), Q_L is the incoming longwave radiation (W/m^2), σ is the Stefan-Boltzman constant (W/m^{2}K^4), T_S is snow surface temperature (K), Q_E is the sensible heat flux (W/m^2), Q_H is the latent heat flux (W/m^2), Q_R is the energy transferred to the snowpack from deposited snow or rain, Q_G is the ground heat flux (W/m^2), and $\frac{dU}{dt}$ is the change in the internal energy of the snowpack (W/m^2) (Gray and Prowse, 1992; Pomeroy et al., 2003). The sign convention is such that all fluxes of energy to the snowpack are positive. The sensible and latent heat fluxes depend on the vertical temperature and vapor pressure gradients, respectively, above the snowpack, and both depend critically on the local wind speed. The ground heat flux depends on the subsurface temperature gradient.

The goal of the sensitivity testing is to determine the relative effects on snow accumulation and melt when changing vegetation parameters, climate, or both. The important vegetation parameters in the model include fractional vegetation coverage, albedo, Leaf Area Index (LAI), maximum interception storage, tree and trunk heights, radiation attenuation, wind attenuation and displacement heights.

SUMMARY

The 2009-2010 data collection was thwarted by a dry winter with very little snow. However, the study sites are equipped with instruments to measure the components of the energy balance and snow accumulation and melt for subsequent years. The model has been tested and is undergoing revisions to be used in forested environments at a point scale for future sensitivity studies.

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