Modeling snow processes and streamflow generation under forest canopy and on a forest clearing

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Abstract The objective was to use hydrological models to quantify the effect of forest clear-cutting on snow processes and snowmelt runoff. Snow water equivalent, snow depth, and micrometeorological variables were measured below canopy in a small forested catchment (0.18 km^2), and on an adjacent clear-cut opening in Southern Finland. Additional data on streamflow were available from the forested catchment. Snow accumulation and melt on the ground were modeled by using an energy balance approach adopted in UEB [Tarboton et al., 1995]. The snow model used hourly measured micrometeorological variables as input data, and the model results were assessed against the measurements of snow water equivalent. The average energy fluxes at the snow surface during the winter indicated an upward net radiation flux in the open, and a downward net flux in the forest. The turbulent fluxes were suppressed by the low wind speeds below the canopy. The calculated snowmelt outflow was used to drive a rainfall-runoff model. The dominant interactions of water between soils, vegetation, and atmosphere were modeled at a hillslope scale. The runoffs generated by the hillslope scale water balance model were taken as an input to a linear reservoir acting as a simple streamflow routing procedure. The model was calibrated by adjusting the routing parameters only. The hillslope parameters were fixed relying on the available information of catchment properties. The calibrated model was used to simulate spring runoff after hypothetical clear-cutting of the study catchment. The results indicated that the peak snow water equivalent was only slightly affected, but the peak flow rates and the total discharge increased significantly after the clear-cutting. The case study showed that a priori defined characteristic hillslopes proved useful in modeling the hydrological processes of the study area.

1. INTRODUCTION

Experimental studies have indicated that deforestation generally increases, and afforestation decreases streamflow [Calder, 1990; 1992, Troendle and King, 1987]. It is difficult to draw strict conclusions on the hydrological effects of the forest harvesting if experimental data are limited [Jones and Grant, 1996; Thomas and Megahan, 1998]. Forest cutting may affect several hydrological processes such as snow accumulation and melt, snow distribution patterns, interception, evapotranspiration, runoff flow paths and streamflow. This calls for a combined use of process-oriented hydrological modeling and experimental data. The demands on the hydrological modeling are extensive, because runoff processes occur at different scales and are affected by the areal inhomogeneity of land use.

In a cold temperate climate where spring snowmelt produces major streamflows, the effect of forest treatments on snow processes is important. Harding and Pomeroy [1996] reported that winter time energy balance over a boreal landscape experiences big differences between forest covered and open areas. The differences must be recognized in order to identify the sources of energy causing snowmelt. Lundberg et al. [1998] addressed the importance of snow interception in trees, because considerable snow losses may occur due to sublimation of intercepted snow. Significant differences may be absent in the peak snow water equivalent after clearcutting, but the timing and efficiency of snowmelt can be changed [Troendle and King, 1987].

This study aims to show how hydrological modeling can be used to predict the effects of land use changes such as forest clear-cutting. A special focus in the present work is directed on snow processes and winter and spring time streamflows. The modeling system is composed of process models, which include a snow energy balance routine to calculate snow melt on the ground, a soil water routine to derive vertical and horizontal water distribution along prescribed hillslopes, and a simple streamflow routing procedure. Interception is not modeled in this study, because data are used to estimate net precipitation below the forest canopy.

2. SITE DESCRIPTION AND DATA

Snow, runoff and meteorological measurements were carried out during 1997-99 in a forested catcment (Rudbäck, 18 ha) and in an adjacent clear-cut area (about 3 ha) in Siuntio, southern Finland (Figure 1). The topography in the area varies in the elevation range from 34 m to 65 m.

The catchment is covered by a mature forest stand dominated by Norway Spruce. The clearing has a few pine trees left for seeding and small spruces planted after the harvest. Bedrock is exposed on the hilltops of the area and soils are composed of silty and sandy moraines with an average depth of 1-2 m to bedrock. More details on the site information are published in Lepistö [1994] and Lepistö and Kivinen [1997].

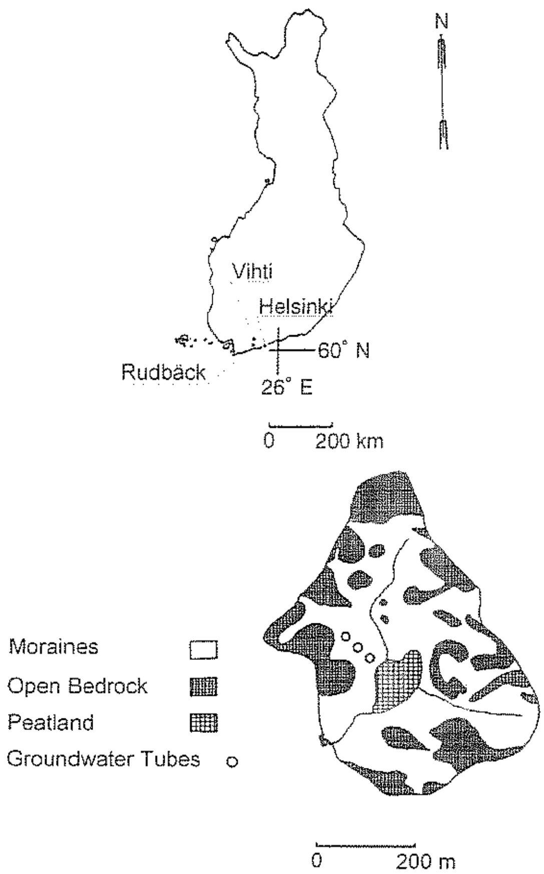

Figure 1. Location of the Rudbäck catchment and the Vihti climate station, measurement sites, and soil types of the catchment.

Local climate in Siuntio is cold temperate and characterized by rainfalls of relatively low intensity. Mean annual precipitation (uncorrected) during 1991-96 was 700 mm, which includes 15-25 % of snowfall. Snowmelt dominates the annual maximum runoff.

A matrix of 12 snow sticks was set up in the clearing, and a total of 22 sticks were placed in the forest to manually measure snow depth on the ground. Snow water equivalent was measured at three points in both clear-cut and forested sites. Micrometeorological data at a height of 2 m were recorded on the clearing and in the forest below the canopy to provide input for a snow energy balance model. Half-hourly data include air temperature, relative humidity, wind speed, and downward and reflected short-wave radiation in both sites, and precipitation in the open. Precipitation below the canopy in the forest was measured manually at 6 points approximately once per week. Atmospheric long-wave radiation was measured in the open until January 1999, then the sensor was moved under forest canopy to measure the downward flux. Additional temperature measurements were recorded at a distance of –0.5 - +0.5 m from the soil surface and at a height of 10 m in the forest. Streamflow measurements were available from February 1998 until April 1999 in a stream draining the forested catchment.

2.1. Input data check and modifications

The meteorological data were checked and edited to provide continuous hourly input data for a hydrological model. Air temperature was compared to manually measured readings to correct for a systematic bias and for large errors during malfunctioning of the measurement system after prolonged periods of cold temperatures. In February 1999, the air temperature sensor in the forest ceased to operate and the vegetation temperature at a height of 10 m was used to cover for the missing data. Relative humidity was scaled not to exceed 100%. The solar radiation sensors became occasionally covered with snow and the corresponding readings were corrected using the measured upward short-wave radiation and an estimate of new snow albedo of 0.85. The long-wave radiation measurements were excluded after snowfalls, and the missing values were estimated using the procedure suggested by Satterlund [1979] and an estimate of cloudiness, which was derived from the ratio of the measured short-wave radiation and the simulated clear-sky radiation. For the forested site, a sky-view-fraction of 0.85 was used to estimate the contribution of the canopy to the downward long-wave radiation on the ground.

The operation of the anemometers was occasionally hampered by intensive snowfalls. The wind speed was not measured in the forest between 21 Oct 98 and 25 Jan 99, when the forest wind speed was taken as the open values reduced by 79%, which was the average difference between the winter-time wind speed in the open and forested sites.

Precipitation in the open was corrected using the procedure recommended for the Finnish H&H measurement gauge in Førland et al. [1996]. The manually operated precipitation gauges in the forest accumulated throughfall that occurred between the field visits. The average of the 6 gauges was assumed to represent the cumulative net precipitation in the forest. Stemflow was assumed negligible in this case. The hourly precipitation measured in the open was scaled down to match the average manually measured accumulations in the forest.

3. METHODS

3.1. Snow model

Snow modeling was based on the energy balance approach as implemented over a snow surface in many earlier studies [Price and Dunne, 1976; Anderson, 1976; Tarboton et al., 1995]. The present model treats the snowpack as one layer, which exchanges energy with the atmosphere and conducts heat down to soil. The radiative energy transfer is calculated using the measured net short-wave radiation, the measured or estimated downward long-wave radiation, and the upward long-wave radiation as a function of the calculated snow surface temperature. The turbulent energy exchange follows the flux-gradient method given in Tarboton et al. [1995], which involves a simple correction scheme for the atmospheric stability.

The snow surface temperature was iterated by balancing the heat conduction into snow with the net energy input above the snow surface. After the snowpack reaches the temperature of 0 °C, the net energy input is used to melt snow. Snowmelt increases the liquid water content in the snowpack until the liquid water holding capacity is exceeded, and meltwater is discharged out of the snowpack.

The heat conduction within snow and the computation of the soil heat content were modified from the approach used in Tarboton et al. [1995]. We defined a thermally active top soil layer as in Tarboton et al. [1995], but calculated the heat conduction to the soil as a steady-state flux using the modeled temperatures at the snow surface and in the bulk top soil layer [Stähli, 1997]. Given the heat flux from the snowpack to the soil, the average temperature of the top soil layer was iterated by taking into account the latent heat effects of soil water phase changes. Soil water content was assumed constant during the winter. The snow thermal conductivity and snow density were calculated following Anderson [1976].

3.2. Rainfall-runoff model

The rainfall runoff modeling is based on a subdivision of a catchment into hydrologically similar units as presented in Karvonen et al. [1999] and Kokkonen et al. [this publication]. Hydrological similarity can be defined according to catchment properties, such as land-use, soil type, and topography. The water balance of each unit is modeled using a characteristic profile, where the interactions of water between soils, vegetation, and atmosphere are described. For natural areas, such as forests, the characteristic profile is a hillslope corresponding to a longitudinal cross-section from a water divide down to a stream channel.

The snow energy balance scheme can be coupled in a hillslope model to provide input (meltwater flow out of the snowpack) to the soil water processes. The soil water movement along the hillslope was modeled as given in Koivusalo et al. [1998]. The hillslope is subdivided longitudinally into a number of columns, where the vertical water movement is assumed to be dominant in the unsaturated soil, and the corresponding soil moisture distribution is modeled using similar principles as in DRAINMOD [Skaggs, 1980; McCarthy et al., 1992]. The horizontal downslope water movement between the columns occurs in the saturated soil and is calculated using the Darcy's law. The downslope end boundary condition is a constant water level in the stream channel. Surface runoff is generated as a saturation overland flow [Dunne and Black, 1970] at any part of the hillslope which becomes saturated by water. Surface runoff is not routed along the hillslope, but discharged instantaneously to the stream network. Summer time transpiration from the root zone is a function of soil moisture and potential transpiration. Potential transpiration is set equal to an estimate of potential evapotranspiration reduced by interception.

The calculated response from the set of hillslopes is the input to the streamflow routing routine, which is a single linear reservoir.

4. RESULTS AND DISCUSSION

4.1. Snow modeling

Snow model was applied separately for the open and forest (under canopy) conditions. The model parameters were taken as suggested in Tarboton et al., [1995], except for the liquid water holding capacity of snow (0.1) and soil thermal conductivity (3.6 kJ/m/°C). The correction for the atmospheric stability was used in a restricted mode as suggested in Koivusalo and Heikinheimo (1999). The snow model was calibrated to forest conditions by adjusting the roughness length (0.005 m in open, 0.09 m in forest) to match the measured average snow water equivalent during winter 1998-99.

Figure 2 shows the measured and calculated snow water equivalent in the clearing and below the forest canopy during the two winters 1997-1999. The range of measurements at both sites show a considerable variation around the average, which is due to spatially variable accumulation and melt of the snowpack. The periods with lasting snowpacks show good correspondence between average measured and modeled values, but the prediction for the winter 1997-98 with temporary melts in the open was less successful.

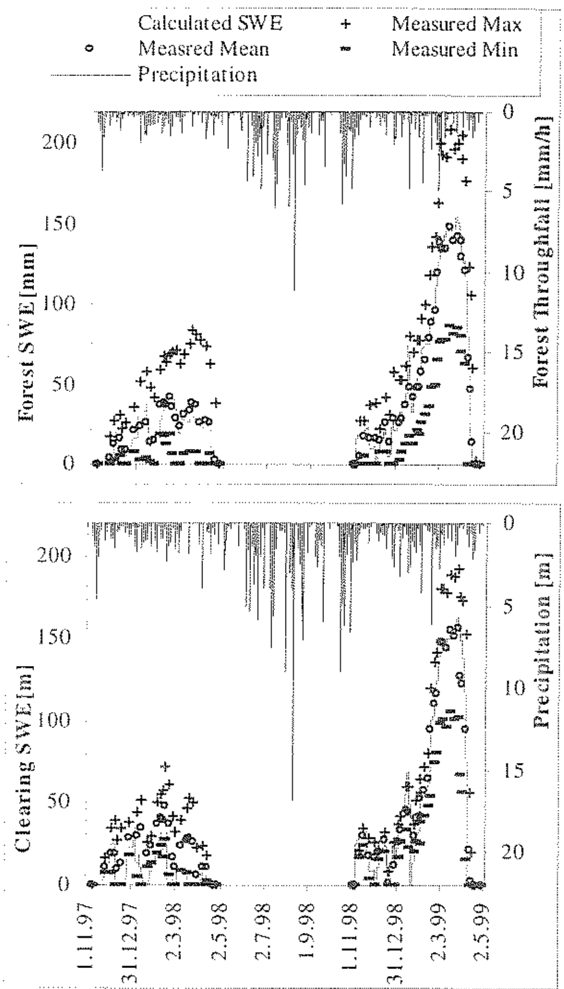

Figure 2. Precipitation and measured and calculated snow water equivalent in open and in forest during 1997-99.

Figure 3 shows the cumulative fluxes of net radiation and turbulent energy in the open and forested sites. The forest had a prominent shadowing effect decreasing effectively the short-wave radiation input on the snow surface below the canopy. The effect was most pronounced during the mid-winter when the zenith angle is high. The canopy increased greatly the long-wave radiation input down to the snow surface from the canopy cover. The energy fluxes on the snow surface during the mid-winter indicated mostly an upward net radiation flux in the open, and a slightly downward net flux in the forest. The wind speeds were effectively reduced in the forest, which made the overall magnitude of the turbulent energy exchange higher in the open than in the forest.

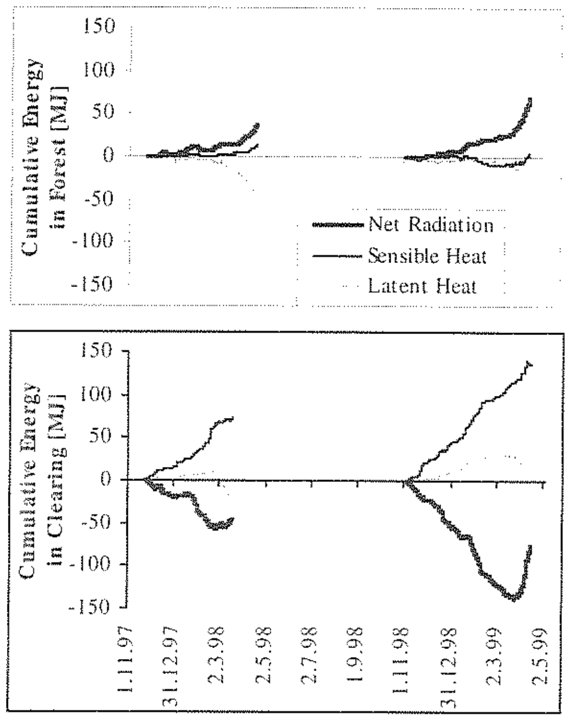

Figure 3. Cumulative fluxes of net radiation, latent heat, and sensible heat in open and in forest during winters 1997-99.

4.2. Rainfall-runoff modeling

The number and shape of characteristic hillslopes for the forested catchment were identified using a digital elevation model (5×5 m^2). The geometry of the hillslopes was defined by computing water travel paths from the water divide down to the nearest stream channel [see Kokkonen et al., this publication]. The computation revealed four typical shapes and lengths of the hillslopes and the relative shares of each group. Other physical parameters of the hillslopes, such as the hydraulic conductivity of saturated soil (0.62 m/d), the root zone depth (0.4 m) and the soil surface storage capacity (0.005 m), were assumed similar for each hillslope and were taken as suggested in earlier studies [Koivusalo et al., 1998]. The depth to bedrock along the hillslope was determined using the information on average depth to bedrock and the estimated percentage of exposed bedrock areas (40 %) as given in Lepistö [1994]. The lower 60 % of the hillslope was assigned a depth of 1.5 m and the upper 40 % a depth of 0.1 m to the bedrock. The soil water retention curves were taken from Koivusalo et al. [1998] and were based on the measurements taken in the forested hillslope next to the studied catchment.

The calculated snowmelt outflow below the canopy was used as a driving variable for every hillslope. The hillslope parameters were not calibrated but fixed to represent the catchment conditions as well as possible. The model calibration was done systematically for the streamflow routing parameters only (a retention coefficient and a weighing coefficient in the implicit finite difference solution). The streamflow routing parameters were calibrated first for the autumn period Sep-Oct 1998, and then for the winter period Mar-Apr 1999. The rest of the data were used to test the performance of the model. Figure 4 presents the calculated and measured runoff and their difference, and Table 1 presents the coefficients of efficiency [Nash and Sutcliffe, 1970] for different calibration and testing periods. The results showed that the routing parameters calibrated for the autumn conditions did not apply well for the winter conditions, whereas the parameters calibrated for the winter conditions produced moderate predictions for all testing periods. The difference between the seasons is probably due to the effect of snow and frozen ground on the runoff flow paths.

Table 1. Coefficients of efficiency between measured and calculated runoff using two different calibration periods

	Calibration	Validation	Validation
	Sep-Oct 98	Summer	Winter
Coeff. Efficiency	0.89	0.78	-0.08
	Mar-Apr 99	Summer	Winter
Coeff. Efficiency	0.75	0.72	0.71

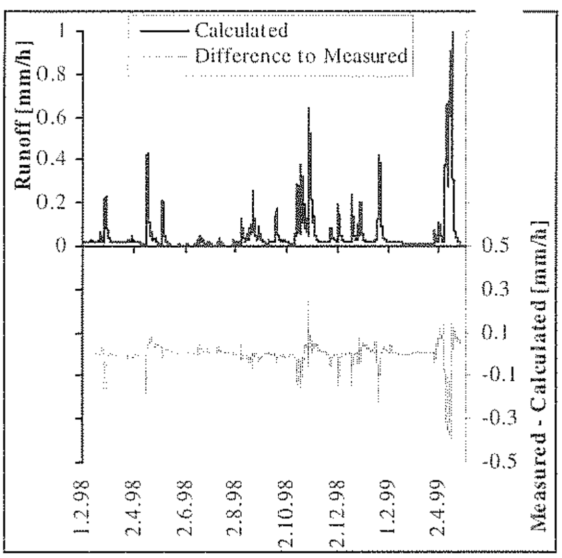

Figure 4. Calculated runoff and difference to measured runoff. Parameters were calibrated for period Sep-Oct 1998.

After the application in the forested catchment, the model was run using the calculated meltwater outflow in the open site as an input. The routing function used the parameters calibrated for the winter period. Figure 5 compares the runoffs from the forested and a hypothetically clear-cut catchment during Nov 1998 – Apr 1999. The model predicted increases of 43% in the peak flow and 32 % in the total stream flow, whereas the calculated peak snow water equivalent was 6 % higher in the open than in the forest. Precipitation in the open was estimated 26 % higher than the forest throughfall during the corresponding period.

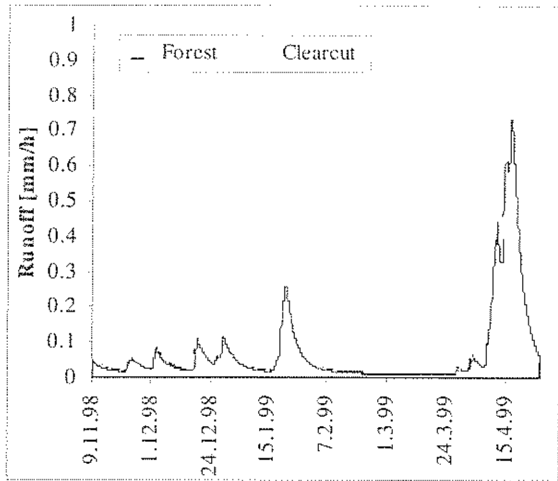

Figure 5. Calculated runoff from the forested catchment and the difference to a hypothetically clear-cut catchment during winter 1998-99. Routing parameters for the winter conditions were used.

5. CONCLUSIONS

This study shows how hydrological modeling can support the use of measurements in estimating the effects of land use change. The characteristic hillslope approach proved useful in understanding and quantifying catchment hydrological processes. The model produced reasonable results using a priori defined hillslope parameters, even though deficiencies were found in the streamflow routing scheme which did not account for differences between the winter and summer/autumn conditions.

The model and the measurements indicated small differences in the peak snow water equivalent between the open and forested sites. The model suggested that the runoff peaks and the total discharge would increase and the timing of the peak would be shifted earlier in the small catchment, if the forest was clearcut.

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