Parameterisation and application of a hillslope model to assess hydrological impacts of forest harvesting

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Abstract: This paper combines an empirical paired-catchment method with hydrological simulation techniques in quantifying and explaining the influence of forest removal on streamflow generation. The pair of catchments (56 and 29 ha) is located in a northern boreal zone in eastern Finland. As the first part of the study, measured streamflows from the two catchments, of which one has been partially clear-cut (35%) and one has not been treated (control), were analysed to detect differences in streamflows preceding and following the logging. Subsequently, canopy and snow process models were calibrated to characterise land surface processes in the forested areas of the study site. In clear-felled areas the canopy routine was simply not active in simulation runs. Output from the canopy and snow models provided an input for a hillslope hydrological model, which was parameterised for the two catchments. Parameterisation was based on spatial data on topography, soil types, soil depths, and location of treated areas with respect to the stream network draining the catchment. The hillslope hydrological model was calibrated against streamflow measurements, and the paired-catchment analysis was repeated using the simulated streamflows. Results inferred from a direct data analysis and model simulations were compared to address mechanisms that could explain the observed difference in the hydrological behaviour of the two catchments. According to the model, decreased interception and increased snowmelt were largely responsible for the observed differences in timing of the spring flood and volumes of total streamflow.

Keywords: *Forest harvest; Hydrology; Mathematical modelling; Paired-catchment*

1. INTRODUCTION

Forest harvesting can significantly affect hydrological behaviour of a catchment by changing land surface mass and energy fluxes. Removal of a forest stand affects accumulation of water in the snowpack over the winter through reducing interception losses and through changing depositional patterns of precipitation. Also, timing and intensity of spring snowmelt change as the snow cover becomes exposed to increased solar radiation and turbulent energy fluxes. During the growing season transpiration is affected as the understorey vegetation becomes the sole transpiring surface.

Hydrological effects of forest harvesting have experimentally been quantified using paired-catchment studies, where measurements from a treated catchment preceding and following the treatment are compared with measurements from an untreated control catchment (see e.g. Seuna, 1988, 1999; Troendle and King, 1987; Whitehead and Robinson, 1993). Effects of forest removal can be seen as a greater accumulation of snow in small openings compared with the surrounding forest, earlier onset of snowmelt and higher snowmelt intensity in the open, and higher elevation of ground water levels in the clear-cut areas (Päivänen, 1982; Troendle, 1983). Increased annual water yields have been reported when substantial portions of a catchment have been clear-felled (Stednick, 1996). Also, spring flood peaks in partially logged areas may decrease due to a longer time span of snowmelt arising from earlier snowmelt in logged than in forested areas (Heikurainen and Päivänen, 1970).

When planning forest management practices, long time series of hydrological data from paired catchments are seldom available for predicting effects of a treatment in the area subject to changes. Coupling of hydrological simulation models with the available experimental data constitutes one avenue to predicting hydrological effects of forest management in ungauged sites (Thomas and Megahan, 1998).

Role of the canopy in forest hydrology has been studied with aid of hydrological simulation models in e.g. Link and Marks (1999) and Storck (2000). Before a hydrological model can be expected to have credibility in producing predictions of forest harvesting effects, it must be tested against measured data. When data only from the treated catchment are used in a modelling exercise, effect of the treatment can easily be masked by errors arising from uncertainties in the driving meteorological data, model structure, and estimated parameter values. Consequently, it may not be possible to validate the modelled hydrological influence of a forest removal.

Aim of the current paper is to combine the empirical paired-catchment method with hydrological simulation techniques in quantifying and explaining the influence of forest removal on streamflow generation. At the first stage, measured streamflows from two catchments, of which one has been partially clear-cut (35%) and the other one has not been treated (control), are analysed. At the second stage, a hydrological model is calibrated against measurements from both catchments, and a paired-catchment analysis is repeated using the simulated streamflows. Results gained from the empirical data and simulation runs are compared to address mechanisms that can explain the observed difference in the behaviour of the two catchments.

2. SITE AND DATA DESCRIPTION

The Kangasvaara (56 ha) and Kangaslampi (29 ha) catchment pair located in eastern Finland (63º 51' N, 28º 58' E) was instrumented as part of the VALU project commenced in 1992 (Finér et al. 1997). This paper utilises meteorological and snow data from January 1992 to December 2001, and streamflow data from January 1992 to June 2000. The Kangasvaara forest is dominated by an old-growth mixed coniferous stand (97% of the area). In late 1996 35% of the catchment area was clear-cut. The logging was carried out according to a normal forest management plan where only stands of certain development classes were felled and logging up to the stream was not allowed. In the adjacent Kangaslampi catchment both young (67% of the area) and old-growth coniferous forests (33% of the area) can be found. Kangasvaara and Kangaslampi catchments comprise 92% and 91% till soils, respectively, and the remaining land area is covered by peat. Elevation in the area ranges from 184 to 238 metres above the mean sea level. Spatial data on the topography and soil depths were available in a 10x10 m^2 grid. Till soil hydraulic characteristics reported in Möttönen (2000) were available for the current study. Long-term mean annual precipitation and air temperature in the area are 700 mm and 1.5 ºC, respectively.

Hourly meteorological data to drive the simulation models were compiled from on-site measurements of air temperature, relative humidity, global radiation, wind speed, and precipitation together with records obtained from the nearest (ca. 20 km) weather station operated by the Finnish Meteorological Institute. Daily series of streamflow from Kangasvaara and Kangaslampi, and measurements (1-2 times per month) from three snow courses residing in an old-growth forest within the catchments were available for the purposes of this study. Mean annual streamflows are shown in Table 1.

Table 1. Mean annual streamflows MQ_a at Kangasvaara and Kangaslampi catchments preceding and following the treatment.

	Kangasvaara MQ_a [mm/a]	Kangaslampi MQ_a [mm/a]
Pre-treatment	308	274
Post-treatment	349	252

3. METHODS

3.1. Canopy model

The canopy model estimates at an hourly time scale solar radiation, long-wave radiation, wind speed, and throughfall beneath the canopy from an input characterising meteorological conditions above the canopy. Relative humidity and air temperature are assumed not to be affected by the canopy. Detailed description of the canopy model can be found in Koivusalo and Kokkonen (2002).

3.2. Snow model

The snow model used in the current study is based on the energy balance approach, and it has been described in detail in Koivusalo et al. (2001). The model is one-dimensional and it simulates at an hourly time scale accumulation and compaction of snow, snowmelt, liquid water retention in snow, melt water discharge out of a snowpack, and heat conduction through the snow into the soil.

3.3. Characteristic profile model

The characteristic profile model (CPM) describes soil water movement and runoff generation processes along a typical longitudinal section (hillslope) from a water divide to a stream. It takes as an input daily series of throughfall/snowmelt and potential transpiration. The CPM (Karvonen et al., 1999; Koivusalo and Kokkonen, 2003) is a quasi-two-dimensional model in the sense that vertical and lateral water fluxes are computed alternately. The characteristic profile is divided into vertical soil columns, which are further divided into soil layers. Vertical fluxes in all columns are computed by approximating the Richards equation with successive steady-state solutions of the pressure head distribution (Skaggs, 1980). Infiltration into a soil column is controlled by the available air volume in the column. Water that cannot infiltrate is transported downslope the profile as surface runoff and it either reaches the stream, or infiltrates if the air volume further down along the profile allows it.

After the vertical fluxes and the resulting groundwater levels have been resolved, lateral groundwater flow between vertical soil columns is computed from Darcy's law. Groundwater flow from the column next to the stream constitutes the slowly responding baseflow component. When groundwater level in any column rises above the soil surface, the model generates exfiltration which – similarly to surface runoff – is transported downslope the profile. Sum of all runoff components – surface runoff, exfiltration, and baseflow – is passed through a linear storage, which describes delay of water flowing in a stream.

4. RESULTS AND DISCUSSION

4.1. Paired-catchment approach: observed streamflows

Differences in streamflow between the partially logged Kangasvaara catchment and the Kangaslampi control catchment were examined to detect changes in hydrological response following the harvest in Kangasvaara. Figure 1 shows average differences in cumulative daily streamflows for the data measured before (black) and after (grey) the treatment. Averaging was performed in the following way. Differences were calculated for each year, and for two seasonal periods which extended from January to June and from July to December. In mathematical terms the difference D_t at day t of any particular year reads:

$$D_t = \sum_{i=i_0}^{t} \left(q_{Kv,i} - q_{Kl,i} \right) \qquad (1)$$

where $q_{Kv,i}$ is streamflow in Kangasvaara at day i, $q_{Kl,i}$ is streamflow in Kangaslampi, and i_0 is the first day of the period (January 1 or July 1) of any particular year. Averaging the differences (D_t) gained for the individual years during the pre-treatment or post-treatment period produced the graphs shown in Figure 1. Rationale behind separation of the year into two periods is that the first period includes spring flood and its recession, and the second period accounts for late summer and autumn streamflow events.

Examination of the first half-yearly periods in Figure 1a clearly indicates that before the harvest spring flood commences earlier in Kangaslampi than in Kangasvaara. The flashier response in Kangaslampi may simply result from its smaller catchment area. After the harvest onset of the flood is almost concurrent in both catchments. In addition to the change in spring flood timing, differences between cumulative depths of streamflow by the end of June have increased when comparing periods preceding and following the harvest. From the data for the second half-year periods (Figure 1b) it can be seen that even before the logging cumulative streamflow in Kangasvaara is higher than in Kangaslampi throughout the period. After the harvest this difference clearly increases.

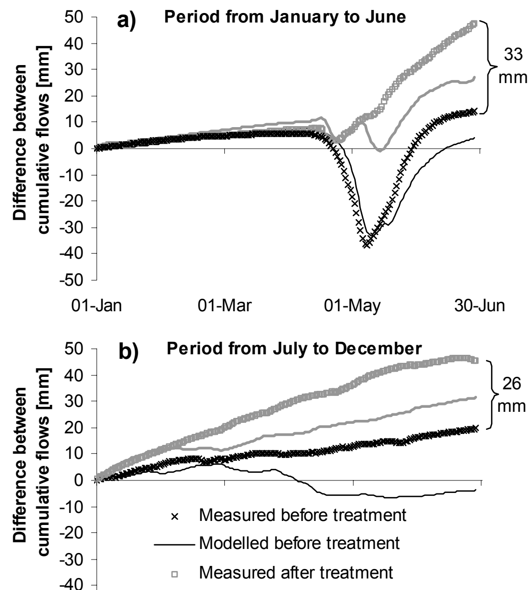

Figure 1. Differences in cumulative streamflows between Kangasvaara and Kangaslampi catchments for the first (a) and second (b) half-yearly periods.

In the following sections we describe the application of a hydrological simulation model to both catchments and repeat the paired-catchment analysis with simulated streamflows.

4.2. Parameterisation of the hydrological model

A digital elevation model (DEM) was used in determining how many characteristic profiles were formed for each of the two catchments, and in identifying the surface topography, width and length of these profiles. For each pixel distance along the flowpath to a stream pixel was determined using the steepest descent method. Then the elevation difference between a pixel and its receiving stream pixel was computed. Figure 2 plots the elevation difference as a function of distance from a stream. According to the result shown in Figure 2 one profile was identified for the Kangasvaara catchment and two for the Kangaslampi catchment. Length of a profile was taken as the longest distance to a stream, width was calculated from the number of pixels at a given distance, and shape of the soil surface along a profile was determined as a median elevation of pixels residing at a given distance. Depth to the bedrock along a profile was estimated in a similar fashion to the estimation of the surface topography from a raster presenting spatial distribution of soil thickness within the catchments.

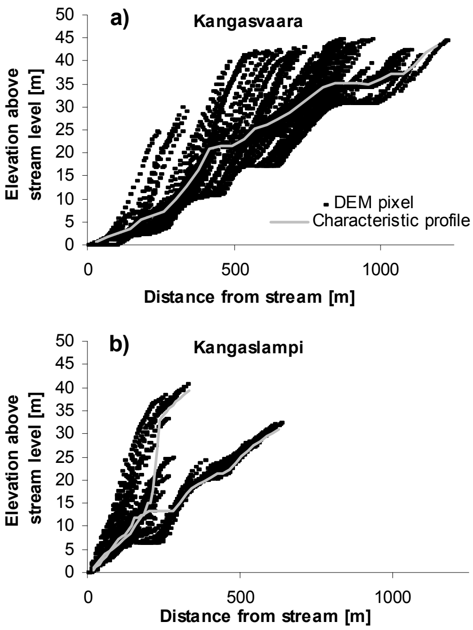

Figure 2. Elevation above the stream level for all grid cells as a function of distance from a stream, and surface topography of the characteristic profiles for Kangasvaara (a) and Kangaslampi (b).

Land use types described in the model were a clear-cut and a mature forest. It was assumed that all forests in both catchments behaved in the hydrological sense similarly to a mature forest. Changes in hydrological behaviour resulting from forest growth were neglected. Assigning forest and clear-cut areas on the Kangasvaara profile was based on the spatial distribution of distance of treated/untreated areas from a stream.

Soil types along the profile were assigned according to peat land and till fractions reported in Raekallio (2001). In Kangasvaara and Kangaslampi 8 and 9%, respectively, of the downslope end of the profiles were peat land. Vertical distribution of the soil hydraulic properties was adopted from Möttönen (2000).

In the model parameterisation the following hypotheses accounted for the hydrological effects of forest harvest. In the logged part of the profile the canopy model was absent and hence no forest interception losses could occur and the canopy did not affect radiative and turbulent energy fluxes. Consequently, net precipitation increased both during summer and winter, and there was more energy available for snowmelt in the spring. To account for the effect of forest removal on transpiration, different levels of potential evapotranspiration were used in forested and clear-felled parts of the profile.

4.3. Paired-catchment approach: simulated streamflows

The canopy and snow models were calibrated against the mean snow water equivalent of three snow courses located within a mature forest (autumn 1993 to spring 1997), and validated for the period from autumn 1997 to spring 2001. Calibration of the canopy and snow models was conducted by adjusting parameters that affect the rate of interception, and control the amount of energy available for snowmelt beneath the canopy. Figure 3 graphs measured and calculated snow water equivalents for the calibration and validation periods. Snow processes in the clear-cut areas were described by running the snow model with the meteorological input without first passing it through the canopy routine. No snow measurements were available from clear-cut areas for a model validation.

Streamflow measurements from Kangasvaara and Kangaslampi were utilised to calibrate the CPM and the routing model. In Kangasvaara potential evapotranspiration, saturated lateral hydraulic conductivities, and the retention coefficient of the routing model were adjusted using data from the period preceding the harvest. Data from the post-treatment period were used to calibrate potential evapotranspiration in the harvested part of the profile. In Kangaslampi only the retention coefficient of the routing model was calibrated (against the period 1991-2000) while soil hydraulic parameters and estimate of potential evapotranspiration were adopted from the Kangasvaara model. Table 2 lists Nash and Sutcliffe (1970) efficiencies and biases for the pre-treatment and post-treatment periods.

Table 2. Nash and Sutcliffe (1970) efficiencies (NS) characterising the model fit to observed daily streamflow, and difference between measured and simulated cumulative streamflow (Bias).

	NS [-]		Bias [mm]	
	Pre	Post	Pre	Post
Kangasvaara	0.83	0.82	84	24
Kangaslampi	0.71	0.70	-63	-97

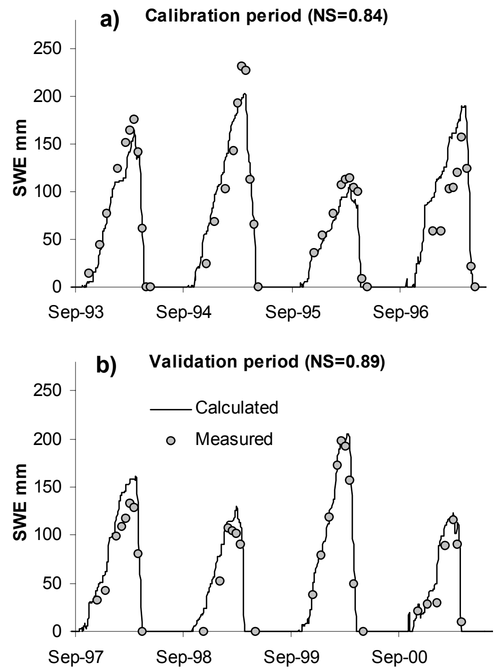

Figure 3. Measured and calculated snow water equivalents **(**SWE**)** for calibration (a) and validation (b) periods. Measured SWE is an average value from three snow courses. Nash and Sutcliffe (1970) efficiencies (NS) are also shown.

In addition to the measured data, Figure 1 also shows average differences in simulated cumulative daily streamflows before and after the treatment in Kangasvaara.

When examining results from the first half of the year (Figure 1a), the timing difference in spring flood visible in the measured streamflow data preceding the treatment is also clearly present in the model simulation results. In the post-treatment period, both observed and simulated stramflow show that this timing difference almost disappears. The model seems to be capable of accounting for the increase in snowmelt intensity in the clear-cut areas simply by bypassing the canopy routine in the clear-cut part of the profile. Absence of the canopy routine leads to a more intense snowmelt as snowpack on the ground is exposed to increased solar radiation and turbulent heat exchange. Before the treatment the observed cumulative streamflow at Kangasvaara is on the average 14 mm higher than at Kangaslampi and after the treatment this difference has increased by 33 mm (Figure 1a). The simulated increase is 23 mm, which arises from absence of forest interception in the harvested part of the profile. Reduction in interception losses in Kangasvaara due to the forest harvest may not be the only factor explaining the observed difference between the catchments. It should be pointed out that influence of forest growth over the study period was not considered, although most of the Kangaslampi catchment is covered with young forest. Gradual increase in interception in Kangaslampi would affect the observed difference in the same way as the forest harvest in Kangasvaara does.

Examination of results for the second half of the year (Figure 1b) reveals that according to both observations and model simulations the average difference in late summer/autumn streamflow depths between Kangasvaara and Kangaslampi has increased after the harvest. This increase is 26 mm for the measured streamflows (Figure 1b), and 35 mm for the simulated streamflows. This change is explained in the model as decreased interception and transpiration losses in the clear-cut part of the profile.

5. CONCLUSIONS

From the paired-catchment analysis it can be concluded that, before the partial logging spring flood occurs in Kangasvaara later than in the Kangaslampi control catchment. Total volumes of streamflow are also higher in Kangasvaara for both seasonal periods (Jan-Jun, Jul-Dec). Following the logging in Kangasvaara, onset of the flood becomes almost concurrent in both catchments and the difference between total flood volumes increases.

Difference in timing of the spring flood was explained by increased snowmelt intensity in the clear-cut areas. The increase in total streamflow volumes resulted from decreased interception and transpiration losses due to removal of the forest canopy.

This study summarises preliminary modelling results of forest logging effects at Kangasvaara. In further analyses it will be necessary to assess how the forest growth both in the treated and in the control catchment affects the observed response differences between the catchments.

6. ACKNOWLEDGEMENTS

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