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Cumulative Effects of Forest Management on Peak Streamflows During Rain-on-Snow Events

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INTRODUCTION

Initial studies on forest harvesting impacts on storm hydrographs focused on impervious areas associated with roads, skid trails and landings within small watersheds (Harr et al 1975). Some National Forests use indices of impervious area, equivalent road area, to analyze cumulative effects in some regions.

Work by Christner and Harr (1982) raised the issue of forest harvesting impacts on peak flows generated from rain-on-snow. Small plot studies (Berris and Harr 1987, Harr and Coffin 1992 this issue) offer substantial evidence that water inputs to the soil surface over short time periods can be significantly increased due to forest harvesting. The Washington State Department of Natural Resources is currently reviewing forest practice applications with regard to harvest intensity within the rain-on-snow zone.

This paper presents an approach for analyzing cumulative watershed effects (CWE) from multiple harvest units within a large watershed under rain-on-snow (ROS) conditions. Furthermore, initial results from applying the approach are given. In particular, we focus on sources of spatial variation affecting ROS impacts. The spatial variations considered are energy inputs as affected by forest cover, energy inputs as affected by location within the watershed, channel routing, and harvest pattern. We do not evaluate CWE through time.

Our approach uses observed snowpack outflows of Coffin (1991) and simulated outflows based on an energy balance equation similar to Anderson (1976) to drive a conceptual rainfall-runoff model. The H.J. Andrews (HJA) Experimental Forest in Oregon is used as the model drainage basin. The rainfall-runoff model is calibrated on HJA-10 and channel routing is determined from measured cross-sections within Lookout Creek (LOC) basin. Hypothetical harvesting is then imposed on the LOC basin and the resulting peak flows are analyzed.

METHODS

Conceptual Rainfall-Runoff Model

The Streamflow Synthesis and Reservoir Regulation Model (SSARR; U.S. Army Corps of Engineers 1976) is used in this study

(Figure 1). Although it is typically used for very large drainage basins, the model is suited for this analysis because it is capable of simulating a linked hillslope and channel system. The inputs and parameters for each hillslope and channel segment may vary independently of the others.

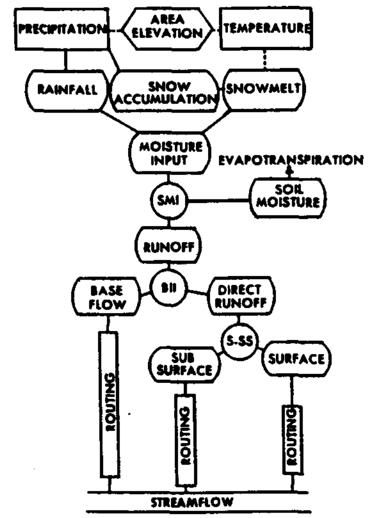

Figure 1. Schematic representation of SSARR.

Analysis focuses on the three LOC subbasins, A,B,C, noted in Figure 2. The entire LOC basin is broken into 190 hillslope segments and 190 channel segments of sizes approximately 32 ha and 200 m, respectively. The hillslope sizes vary with topography but were chosen to approximate the size of individual harvest units. The channel segment sizes were then chosen to correspond to the adjacent hillslopes as just defined.

Spatial Variation in Energy

In this study, SSARR is driven by observed energy conditions measured by Coffin (1991) during ROS. Six sets of input were used to evaluate the effects of spatial variations in energy due to forest cover, aspect and elevation (Table 1). Simulated snowmelt for the six cases was calculated from Anderson's (1976) model with wind speed adjusted for forest cover as given in Dunne and Leopold (1978). In all cases we assumed the snowpack was ripe and of sufficient thickness so that all energy would result in melt. Furthermore, no lag was considered for water percolation through the snowpack. The resulting snowpack outflows, consisting of both

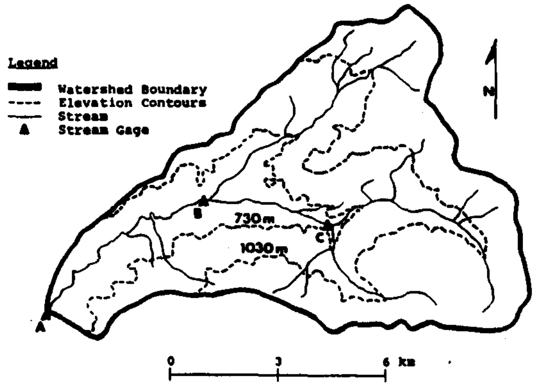

Figure 2. Lookout Creek watershed in the H.J. Andrews Experimental Foest. Subwatersheds are defined by gages A,B, and C.

rain and snowmelt, were then used to drive an individual hillslope segment in SSARR. The energy balances, snowpack outflows and resulting hydrographs are compared and discussed.

Table 1. Six energy cases.

Case #	Forest Cover	Aspect	Elevation
1	open	high wind	low temperature
2	forest	high wind	low temperature
3	open	low wind	low temperature
4	forest	low wind	low temperature
5	open	high wind	high temperature
6	forest	high wind	high temperature

Spatial Variation in Hillslope Response

Each hillslope segment was initially assigned identical SSARR parameters determined by calibration on HJA-10. Calibration was done using only fall rainstorms in 1977. To study the importance of spatial variation in hillslope response we used three values of the parameter "subsurface time of storage" (SSTS), 4, 8 (calibrated values) and 12 hrs. This parameter affects the routing of subsurface flow within SSARR. Smaller values of SSTS cause higher peak flows and steeper rising and recession limbs.

Spatial Variation in Channel Routing

The channel routing in SSARR is based on two parameters, KTS and p, which can be approximately related to channel geometry and

roughness. The values of KTS and p were determined from cross-section measurements at various places within LOC and Manning's equation. To study the importance of spatial variation in channel characteristics, we varied KTS and p together as (.38,.28), (1.43,.40), and (.11,.25). These represent physical situations of the measured cross-sections, a wide rectangular channel, and an incised triangular channel, respectively. A hydrograph was then routed down these three channels, and the attenuation of the peak discharge and the travel times were evaluated at downstream distances of 1.6, 8 and 15 km.

Spatial Variation in Harvest Patterns

A fundamental issue in evaluating CWE is the effect of spatial intensity and distribution of harvesting on peak flows. To study this issue, we imposed nine harvesting patterns on LOC (Table 2, Figure 3). Each of these patterns was driven by 11 ROS events measured by Coffin (1991) (Table 3).

Table 2. Forest harvesting patterns.

Case #	Description
1	10 % of the area above gage C, aggregated near gage C
2	10 % of the area above gage C, aggregated away from C
3	10 % of the area above gage C, dispersed
4	10 % of the area above gage B, aggregated near gage B
5	10 % of the area above gage B, aggregated away from B
6	10 % of the area above gage B, dispersed
7	10 % of the area above gage A, aggregated near gage A
8	10 % of the area above gage A, aggregated away from A
9	10 % of the area above gage A, dispersed
10	no harvest

For these simulations LOC was divided into three elevation bands: 420 - 730 m, 730 - 1030 m, and 1030 - 1520 m. The lower band is considered snow-free, and only the observed rainfall is used to drive SSARR. The upper band is considered to have a deep, cold snowpack so that ROS yields no input to the soil surface. Forest harvesting was confined to the middle elevation band. Each hillslope segment was treated as either completely forested or completely open. All hillslope segments were assigned identical SSARR parameters.

Peak flows from 11 ROS events, and nine harvest patterns are compared for the three LOC subbasins.

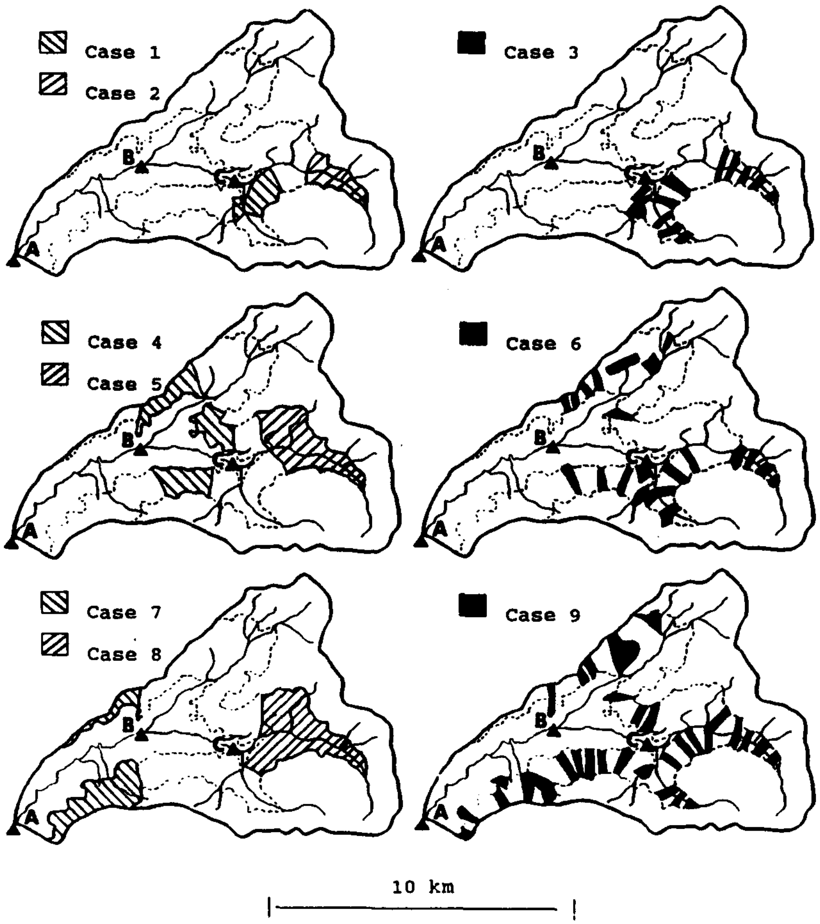

Figure 3. Nine different harvesting patterns on the Lookout Creek basin in the H.J. Andrews Experimental Forest.

Table 3. Rain-on-snow events from Coffin (1991).

Event #	Duration (hrs)	Forest Outflow (mm)	Open Outflow (mm)	Difference %
1	32	69	114	+65
2	27	46	90	+96
3	28	85	106	+25
4	24	57	81	+42
5	24	38	46	+21
6	7	31	53	+71
7	24	26	62	+138
8	24	53	84	+58
9	24	36	64	+78
10	24	76	94	+24
11	24	55	87	+58

RESULTS AND DISCUSSION

SSARR Calibration and Verification

The SSARR model adequately reproduced observed hydrographs and peakflows from HJA-10. Figure 4 shows a typical calibration hydrograph and the results from the verification runs.

Spatial Variations in Energy

Figures 5a,b show the total energy input for four different locations (cases 1-4, Table 1). The differences are due to only changes in wind speed. The resulting snowpack outflows as predicted by the snowmelt model, and the resulting hydrograph from SSARR for a 16-ha hillslope segment are shown in Figures 5c-f.

Figures 5a,b show that the energy input at a fixed location can be substantially affected by the presence or absence of forest cover. The reduction in wind in the forest results in a difference of total energy of 197 cal/cm^2 under high wind conditions and of 87 cal/cm^2 under low wind conditions.

Figures 5a,b also show that there is substantial variation in energy related to location when forest cover is held constant. This effect is due primarily to the aspect of the hillslope relative to the overall storm direction. Differences in total energy are 27 cal/cm^2 for forested conditions and 137 cal/cm^2 for open conditions.

The resulting snowpack outflows (melt plus rainfall) are shown in Figures 5c,d. The large inputs of rainfall cause the relative differences in snowpack outflows to be smaller than the

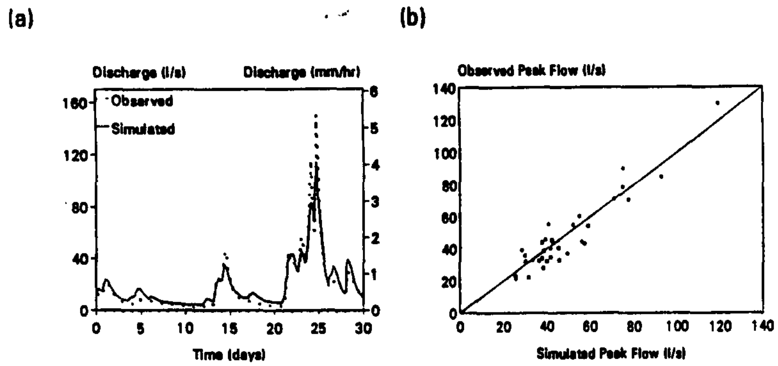

Figure 4. Calibration and verification of SSARR; (a) typical calibration hydrograph, (b) observed and simulated peak flows for verification runs.

relative differences in energy. The difference in snowpack outflow between forested and open conditions at a fixed location decreases from 24 mm under high wind conditions to 11 mm under low wind conditions. Snowpack outflows at different locations increase from 4 mm under forest conditions to 17 mm under open conditions.

The resulting hillslope hydrographs are shown in Figures 5e,f. Differences in peak flows closely follow the snowpack outflows. At a fixed location, differences in peak flows between forested and open areas are 34 l/s under high wind and 14 l/s under low wind. At different locations, differences in peak flows are 3 l/s under forest cover and 23 l/s for open areas.

Figures 6a,b show the total energy input calculated from cases 1,2 and 5,6 (Table 1). In this case, the inputs differ in both temperature and wind speed. The changes in wind speed are identical to the previous runs, reflecting differences in forest cover. This discussion focuses on the temperature changes which are due to elevation.

Figure 6b shows the energy at a site 300 m lower in elevation At a fixed location the difference in energy between forested and open conditions increases from 197 to 267 cal/cm^2, under low and high temperatures, respectively. Between locations with fixed cover the difference in energy increases from 52 to 122 cal/cm^2 under forest and open conditions, respectively.

The resulting snowpack outflows are shown in Figures 6c,d.

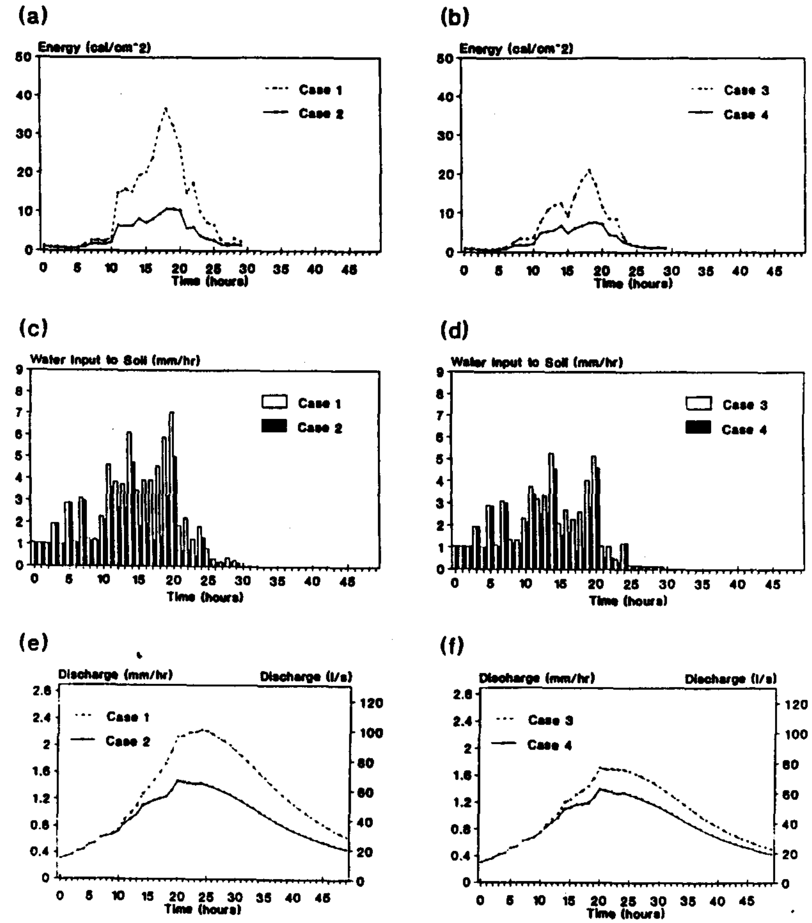

Figure 5. Energy, snowpack outflow, and resulting hydrograph for cases 1-4, Table 1.

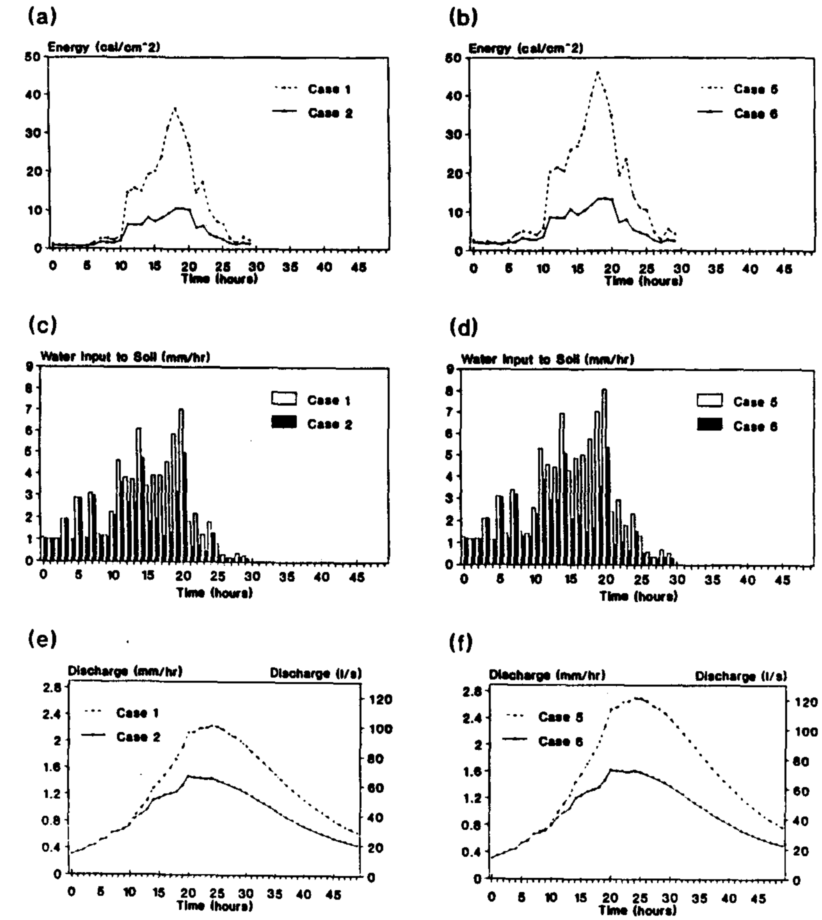

Figure 6. Energy, snowpack outflows, and resulting hydrographs for cases 1,2 and 5,6, Table 1.

Again, differences in snowpack outflows are smaller because of the large addition of rainfall. At a fixed location the difference in outflows between forested and open conditions increases from 24 to 34 mm under low and high temperature, respectively. Between locations with fixed cover the difference in outflows increases from 6 to 16 mm under forest and open conditions, respectively.

The hillslope hydrographs are shown in Figures 6e,f. The difference in peak flows for a fixed location increase from 34 to 48 l/s under forested and open conditions, respectively. For different locations the differences in peak flows increases from 7 to 21 l/s under low and high temperature, respectively.

Spatial Variation in Hillslope Response

Figure 7 shows the outflow hydrographs in response to energy conditions described by cases 1,2 (Table 1) for the three different values of the SSARR parameter SSTS. The peak discharge from the forested areas varies between 55 and 90 l/s. The peak discharge from open areas varies from 80 to 145 l/s.

Spatial Variation in Channel Routing

Input and routed hydrographs are shown in Figure 8 for the three channel configurations. The hydrographs show only modest attenuation of peak flows, the maximum being 9 l/s to 8 l/s or 11 %. These results are consistent with the effects described by Dunne and Leopold (1978) for steep mountain channels. These results suggest that SSARR is not sensitive to channel description over the range of conditions tested.

The analysis also shows that the travel times down the stream system are quite short. The entire 15-km is traversed in one to three hours. This suggests that channel routing is unlikely to cause desynchronization, and thus lessening, of harvest effects on peak flows.

Summary of Spatial Variation

The changes in peak flow resulting from changes in forest cover, aspect and elevation are quite similar in magnitude. Furthermore, these results show that highly productive sites, either from an energy balance or runoff production perspective, yield a greater response to forest harvesting in both absolute and relative terms. Therefore, the concept of a threshhold harvest level is invalid. Rather, the actual location relative to energy inputs and hydrologic response must be considered.

The changes in peak flow due to channel routing effects and channel representation appear to be minimal in this case.

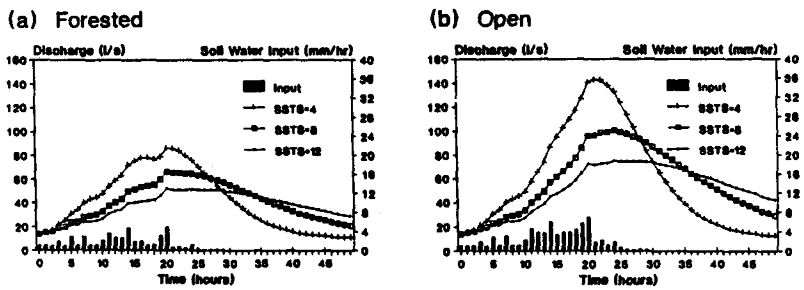

Figure 7. Resulting hydrographs from variation in SSTS parameter.

Effects of Harvest Pattern

Figure 9 shows peak flows from the different harvest patterns on the three subbasins. The results show no effects of harvest pattern. This is consistent with the previous results and discussion on channel routing in terms of both attenuation and desynchronization of peak flows.

Aggregation of harvest units in the upper or lower parts of the watersheds yield the same peak flows as dispersing of units for all three subbasins.

Figure 10 shows the peak flows for events 1,5,6 and 8, normalized by the peak flow from a totally forested basin as a function of harvest intensity for the three subbasins. The results have significant scatter with peak flows increases ranging from less than 10 % to more than 200 %. This is due to the differences between storms. For a particular storm the increase in peak flow is highly correlated with harvest intensity. The increasing scatter with increasing harvest intensity reinforces the previous discussion that harvest intensity alone is not a good indicator of harvest effect. The simulations shown in Figure 10 included only forest cover effects, not elevation, not aspect and not hydrologic response. We would expect even greater variation at a fixed harvest intensity if these other effects were included.

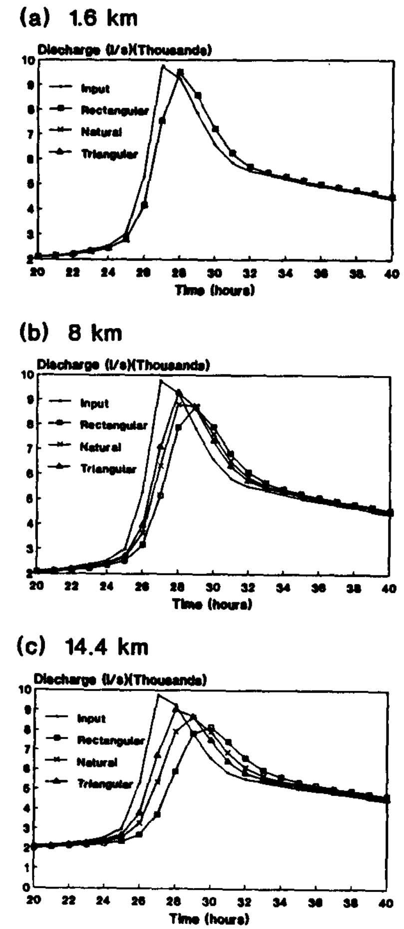

Figure 8. Hydrographs routed down the three channels.

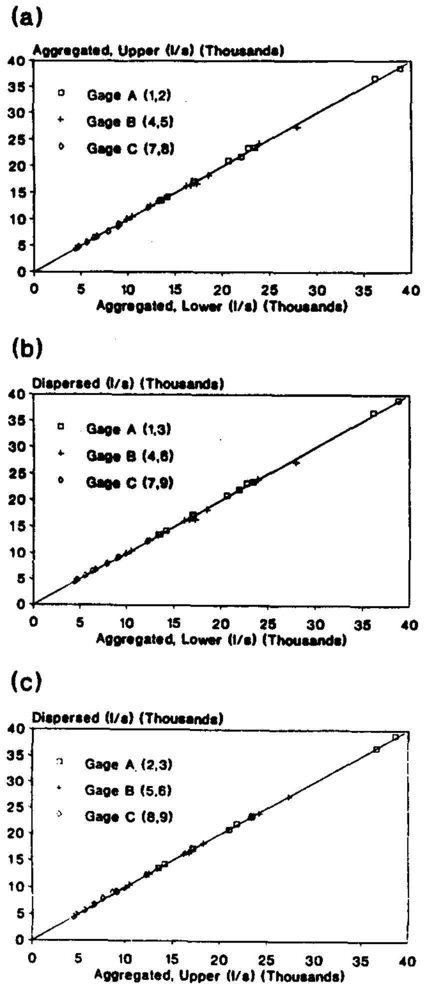

Figure 9. Effects of harvesting pattern on peak flows.

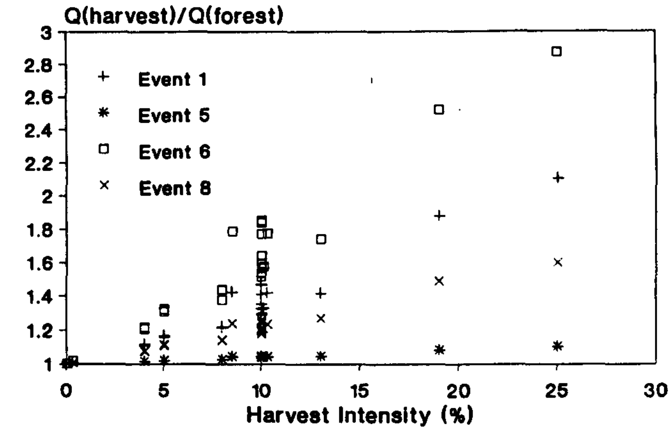

Figure 10. Normalized peak flows for events 1,5,6 and 8 as a function of harvest intensity.

SUMMARY AND CONCLUSIONS

The SSARR model, driven by observed data, was used as a tool for evaluating forest harvesting impacts on peak flows during rain-on-snow events. Because of SSARR's ability to represent a linked hillslope and channel system it appears to be a viable option for CWE analyses. Ideally, further work should consist of multiple small basins within a nested monitoring system to test the variation in hydrologic response and channel routing. Also, we need to have more detailed monitoring of energy inputs, particularly wind, throughout the watershed.

Simulation results showed that several sources of spatial variation are important. The effects of variation in forest cover, aspect, elevation and hydrologic response are large and of similar magnitude. The effects of channel routing are minimal. The analysis showed significant increases in peak flows from forest harvesting. While the effects increase with increasing harvest intensity, harvest intensity alone does not appear to be an adequate predictor of the effect.

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