# SIMULATING THE IMPACT OF ROAD CONSTRUCTION AND FOREST HARVESTING ON HYDROLOGIC RESPONSE

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# ABSTRACT

This paper incorporates a conceptual model of the effect of roads and forest harvesting on hillslope soil moisture and runoff production into a hydroecological modelling system and discusses model results for a range of scenarios for a small catchment in the Western Oregon Cascades, USA. The model is used to explore the implications of road cut depth and road drainage patterns on seasonal hydrologic responses including runoff production, soil moisture and ecological processes such as evapotranspiration. By examining hydrologic response within a seasonal and hillslope context, we illustrate the complex role played by roads in terms of both the spatial and temporal persistence of the effects of an increase in local drainage efficiency associated with particular road segments. Model results are compared with observed outflow responses for a paired catchment study using the test case watershed. (catchment area in UK terminology). Results show the potential for an ecologically significant change in soil moisture in the area downslope from the road. These changes are mediated by the drainage patterns associated with roads, specifically whether road culverts serve to concentrate or to diffuse flow. Field verification of these findings presents an avenue for further research. The modelled effects on seasonal outflow response are less significant but do show clear temporal patterns associated with climate pattern, hillslope drainage organization and road construction. Comparison between modelled and observed outflow response suggests that the model does not yet capture all of the processes involved in assessing the effects of forest road construction. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: road construction; drainage organization; seasonal hydrologic response; hydroecological modelling; streamflow; soil moisture distribution; forest harvesting

# INTRODUCTION

Forest roads have been associated with increased peak flows for a number of monitored catchments in the Pacific Northwest, USA. Plot-level studies illustrate the ability of forest roads to intercept and route both subsurface and saturated overland flow more efficiently to the stream (Wemple *et al.*, 1996) as well as to generate additional surface runoff as a result of reduced infiltration capacity of the road surface (Luce and Cundy, 1994). This paper uses an ecosystem model, the Regional Hydro-Ecological Simulation System (RHESSys), to address the effects of forest roads on hydrologic response within both a catchment and a seasonal context. We use the model to generate hypotheses about the broader spatial and seasonal effect of roads, which include impacts on summer low flow and on winter storm flow responses. We compare these modelling results with available field data and propose additional field testing.

The connection between forest harvesting and hydrology continues to be an important scientific and forest management issue in the Pacific Northwest. Both field-based and modelling approaches have explored changes in the magnitude, timing and inter-catchment variability of hydrologic response following harvest. Roads in themselves have the potential to alter hydrologic response and may also act synergistically with forest harvesting. Case studies, such as Jones and Grant (1996), Wright *et al.* (1990), Harr *et al.* (1975), King and Tennyson (1984) and Keppeler and Ziemer (1990), indicate that roads can have significant effects on peak flow; however, these results vary significantly across sites, different road construction patterns, storm

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events and seasonal precipitation. Spatially distributed modelling provides a technique to organize the interacting effects of these different controls on hydrologic response thereby helping to explain observed variability in watershed (catchment area in UK terminology) responses to road construction.

In many field and modelling studies, the exploration of the effect of roads has centred on peak flow response (e.g. Storck *et al.*, 1998). In this paper, we include consideration of the seasonal and spatially distributed effects of roads. Variability in peak flow response due to roads may in part be explained by examining this seasonal context. In the Pacific Northwest, there is a distinct seasonality to precipitation, with a significant percentage of precipitation falling during winter months followed by a dry period during the summer. In addition, effects of forest harvest disturbance on summer low flow can have significant ecological consequences related to streamflow quality and quantity, both of which support aquatic habitat and human uses of streams (Hicks *et al.*, 1991; Johnson, 1998). Disturbances may also affect soil moisture, which is a control on plant evapotranspiration, photosynthesis and species competition, especially in water-limited environments.

To examine the role played by roads, we incorporate a conceptual model of road impacts into a spatially distributed hydroecological modelling system, RHESSys. Simulations are developed for an experimental watershed in the H.J. Andrews Experimental Forest in the Western Oregon Cascades. A range of scenarios is used to generate hypotheses about the variability of hydrologic response to roads. Simulation results are also compared with results from an empirical study in the H.J. Andrews watershed in order to assess how well the model captures the processes of interest.

# CONCEPTUAL MODEL

Wemple *et al.* (1996) proposed that connectivity of road ditches and culverts with stream networks increases the impact of roads on peak flow. Wemple *et al.* (1996) suggest that road–stream connectivity effectively increases the drainage density of the watershed and consequently can increase peak flow. They observed that roads may be hydrologically connected to the stream either through culverts which drain directly into the stream channel or via culverts which drain into a system of gullies incised below culvert outlets. These gullies, during storm events, can act as channels to connect flow intercepted by the road to downslope stream channels. Wemple *et al.* (1996) observed that for two basins in the Western Oregon Cascades, 76 per cent of the surveyed road length was hydrologically connected to the stream network either directly or via gully channelization.

Our conceptual model also includes consideration of impacts where roads are not directly linked to a stream but still route and therefore concentrate flow in particular areas below the road as shown in Figure 1.

Thus, we are interested not only in increased outflow due to the increased hydrological connectivity to the stream, but also in:

- (1) hydrologic effects on areas below the road which receive less recharge due to the redirection of flow into ditches; and
- (2) outflow and soil moisture response in cases in which road culverts drain into areas not hydrologically connected to the stream.

The reduction in recharge to areas below the road will result in a decrease in downslope soil moisture. It may also result in a decrease in saturated subsurface throughflow. From the perspective of catchment outflow, it is the combination of the effects from areas below the road and the increase in drainage efficiency due to redirection by the road that will create the net change in streamflow. The relative timing and spatial distribution of these two effects will probably be different, since road-redirection effects are fast relative to effects on subsurface throughflow in the area below the road. The combined effects will create a temporally complex pattern with contrasting effects in different areas of the hillslope.

The above discussion applies in the case where water is redirected by the road into culverts and gullies which are hydrologically connected to the stream. In many cases, however, road culverts serve only to



Figure 1. Road drainage pattern alternatives: routing to highest wetness index; routing to the lowest wetness index

concentrate the flow in particular areas below the road. The effect of this concentration of flow will depend upon the characteristics of the receiving areas. As shown in Figure 1, intercepted flow may be concentrated in a relatively wet area below the road. This would correspond with road culverts draining into downslope hollows, which may increase and concentrate saturated subsurface throughflow. The potential to increase peak flow effects is similar to the situation where culverts are hydrologically connected to the stream, although effects may be diminished if the flow is not channelled. Alternatively, road culverts may redirect the flow to relatively dry areas, as shown in Figure 1, and essentially act to diffuse the flow by transferring water to areas that otherwise would receive the least amount of upslope flow. In this case, we would expect potentially higher evapotranspiration in the discharge area and an overall reduction in outflow as opposed to the preceding two cases in which flow is concentrated or channelled directly to the stream.

In addition to connectivity, road cut depth can vary depending upon local slope and road width. Road cut depth directly controls the amount of subsurface runoff that is intercepted by the road, as shown in Figure 2, and therefore the magnitude of road effects.

# THE SIMULATION MODEL

To illustrate the various effects of roads on hydrologic response, we apply the above conceptual model in RHESSys, the Regional Hydro-Ecological Simulation System. RHESSys is a modelling system which combines distributed flow modelling with an ecophysiological canopy model, based on BIOME\_BGC



Figure 2. Interception of subsurface and surface flow by road cut bank where increasing the depth of the water table decreases the proportion of subsurface flow that is intercepted by the road

(Running and Hunt, 1993) and a climate interpolation scheme based on MTN\_CLIM (Running *et al.*, 1987). In RHESSys simulations, explicit distributed routing is performed using a modified version of the Distributed Hydrologic Soil Vegetation System (DHSVM) algorithm (Wigmosta *et al.*, 1994) which has been adjusted to consider irregular patch areas. Patches are topographically defined simulation units. The smallest patch size is a 30 m grid cell. Process algorithms used in the current version of RHESSys are described in Tague *et al.* (1998).

Implementation of a road network in the RHESSys framework makes the following assumptions.

- The amount of subsurface throughflow intercepted by the road is a function of the road cut depth and the current saturation deficit (or depth to water table) of the area immediately upslope from the road (see Figure 2).
- The intercepted flow is redirected to one of three downslope patches, specified by the user: the nearest stream; a relatively wet adjacent downslope patch; or a relatively dry adjacent downslope patch. Relative wetness is determined by using the TOPMODEL wetness index (Beven and Kirkby, 1979).

The wetness index is used here to determine a priori measures of relative wetness for downslope patches. It is not used to simulate the pattern of flow since TOPMODEL would be unable to account for the spatially explicit rerouting of water by roads.

The wetness index (WI) is calculated as:

$$WI = \ln A / \tan \beta T$$

where A is accumulated area above the patch per unit contour length,  $\tan \beta$  is local slope and T is the patch soil transmissivity.

Lateral hydrologic fluxes are modelled using the modified DHSVM explicit routing approach. Any surface flow or infiltration excess is assumed to leave the patch within the daily time step. The amount of subsurface

water flux from a given patch is computed as:

$$q(t) = \{T(t) \tan \beta \omega\}$$
(1)

where q(t) is water flux from the patch at time t; tan $\beta$  is local slope;  $\omega$  is patch boundary length and T(t) is transmissivity at time t. Transmissivity is computed as:

$$T = \int_{z_i}^{\infty} K_o \mathrm{e}^{\left(-\frac{z}{m}\right)} \mathrm{d}z \tag{2}$$

where  $K_0$  is local saturated hydraulic conductivity at surface,  $z_i$  is local depth to saturation and *m* is a soil parameter, which scales hydraulic conductivity with depth.

If the patch contains a road, all surface flow is intercepted by the road. The amount of subsurface flow that is intercepted by the road is a function of road cut depth (*D*). If the depth to saturation,  $s_i$ , is greater than the road cut depth, the intercepted subsurface flow is zero. If the depth to saturation is less than the road cut depth then the amount of intercepted flow is computed using Equation 1 where transmissivity, *T*, is calculated as:

$$T = \int_{z_i}^{D} K_o \mathrm{e}^{\left(-\frac{z_i}{m}\right)} \mathrm{d}z \tag{3}$$

If the patch contains a road, the intercepted subsurface and surface flow is routed to one of the following downslope patches as specified by the user:

- (a) the nearest downslope stream patch;
- (b) the wettest adjacent downslope patch (as calculated by the wetness index);
- (c) the driest adjacent downslope patch (as calculated by the wetness index).

The remaining subsurface flow, i.e subsurface flow from Equation 1, that is deeper than the road cut and therefore not intercepted by the road is directed to adjacent downslope patches. The percentage of subsurface flow apportioned to any given downslope patch is based upon relative gradients as described in Wigmosta *et al.* (1994).

The model can be applied using estimates of road culvert positions and routing characteristics if a detailed survey of individual road culverts is not available. This paper examines simplified scenarios at the ends of a continuum where roads can connect directly to the stream, concentrate flow in hollows below the road or diffuse flow to drier areas below the road. An algorithm for determining road connectivity will be implemented in later versions of the model. Wemple *et al.* (1996) propose a relationship between road connectivity (to stream channels) and road and topographic characteristics including slope and the road length draining the culverts.

## METHOD

We apply this model to Watershed 3 in the H.J. Andrews Forest in the Western Oregon Cascades. Elevation within the 101 ha watershed ranges from 400 to 1000 m. Mean annual precipitation is greater than 2000 mm and shows a clear seasonal variation with most of the precipitation falling between October and April. Precipitation and temperature inputs are taken from a single base station within the catchment. Variation in incoming radiation with elevation and aspect is adjusted using MTN\_CLIM (Running *et al.*, 1987) which estimates radiation based on latitude, slope, aspect and estimates of atmospheric transmissivity (Bristow and



Figure 3. Stream and road network for Watershed 3: H.J. Andrews Experimental Watershed

Campbell, 1984). Spatially variable precipitation lapse rates with elevation are derived from a precipitation map of the H.J. Andrews Forest, which was derived using the precipitation distribution model PRISM (Daly

Watershed 2, 1958-1959



Figure 4. Daily outflow for Watershed 2 and Watershed 3; simulated vs. observed

*et al.*, 1994) developed for mountainous landscapes in this region. Spatially variable temperature lapse rates with elevation are taken from Rosentrater (1997) for the H.J. Andrews basin based on information from multiple climate stations within the H.J. Andrews site.

Soils are gravelly clay loam with high infiltration capacities and high hydraulic conductivity (>80 m/day). Vegetation is dominated by Douglas Fir (*Pseudotsuga menziesii*). Figure 3 illustrates the position of roads relative to the stream drainage pattern in the watershed. Road construction on Watershed 3 began in April 1959. In August 1962, 25 per cent of the forest was clearcut and then burned in February 1963.

The model was calibrated using data from a neighbouring unharvested watershed, Watershed 2, using daily outflow from 1963. Lateral saturated hydraulic conductivity,  $K_{sat}$ , was used as the sole calibration parameter. An initial set of spatially distributed  $K_{sat}$  values were assigned based on soil texture maps for the area. For calibration, all  $K_{sat}$  values were scaled by a single multiplier. Thus calibration alters the magnitude of basin hydraulic conductivity but not the spatial distribution. The calibration procedure used the Simplex method (Nelder and Mead, 1965) to maximize the Nash–Sutcliffe (1970) efficiency measure to compare the correspondence between observed and modelled outflow. A maximum Nash–Sutcliffe efficiency measure of 0.77 was obtained for Watershed 2 outflow for 1963. Simulation results for the calibration year are shown in Figure 4.

The model calibration achieves a reasonable correspondence between observed and modelled outflow, although the model underestimates response to early autumn precipitation events as shown in Figure 4. Soil information is the main source of error in the model. Spatial variation in soil parameters is difficult to infer from available soil maps, and calibration does not adjust the spatial variation in soil characteristics. In addition, McDonnell (1990) has shown that effective saturated hydraulic conductivity may vary under

different conditions due to the accessing of macropore flow. These factors may account for some of the differences noted between observed and modelled outflow.

Watershed 3 scenarios were run using the same  $K_{sat}$  multiplier that was calculated through calibration on Watershed 2. Figure 4 compares resulting modelled and observed outflow for Watershed 3 for a predisturbance year, 1959. Watershed 3 also exhibits a reasonable correspondence, i.e. a Nash–Sutcliffe efficiency of 0.7, between observed and modelled outflow.

In order to illustrate the implications of the conceptual model, we tested the effects of two road construction scenarios.

- (1) *Road cut depths.* We begin by exploring an extreme 'worst case' scenario with a road cut depth of 5 m and all roads are assumed to be hydrologically connected to the stream. Simulations are repeated for a more moderate cut bank depth of 0.5 m and differences in response noted.
- (2) Road-stream connectivity. We assess three scenarios with respect to road connectivity as discussed above. We consider a 'worst case' scenario where all roads are hydrologically connected to the stream. We also model two scenarios where intercepted flow is redirected to downslope areas through culverts that drain to high or low wetness index downslope patches.

The above scenarios are used to assess the implications of the proposed model on the spatial and temporal persistence of road construction effects on hydrologic response. We are also interested in comparing these results with empirical data. Paired catchment comparisons between Watershed 3 and the control unharvested Watershed 2 provide information on outflow differences between responses with and without both roads and forest harvesting. We compare these empirical differences with simulation results for scenarios with and without roads.

# RESULTS

#### Simulated annual and summer outflow

Table I summarizes model predictions of the percentage change in annual outflow and evapotranspiration due to disturbance for the various road construction scenarios. All recorded changes illustrate the differences in outflow from Watershed 3 for simulations run with two different land use scenarios (with roads, and with both roads and harvesting) in comparison to a baseline 'no disturbance' simulation.

*Pre-harvesting (roads only) period.* Three periods for comparison are considered. The first is the comparison between simulations with roads and without roads for the pre-harvest (1959–1962) period. For this period, changes in simulated annual flow are small (<2 per cent) for all road construction alternatives. Increases in annual flow due to roads are balanced by a reduction in evapotranspiration.

Post-harvesting period. We also examine the period in which both forest harvesting and roads occur

	Change in annual outflow (evapotranspiration) (%)			
Road construction	Road effects during pre-harvest period	Road effects during harvested period	Combined disturbance effects	
0.5 m cut bank; route to stream 5 m cut bank; route to stream 5 m cut bank; route to highest WI 5 m cut bank; route to lowest WI	$\begin{array}{c} 0.5 \ (-0.4) \\ 1.7 \ (-1.6) \\ 0.2 \ (-0.1) \\ -0.0 \ (0.0) \end{array}$	$\begin{array}{c} 0.2 \ (-0.3) \\ 1.6 \ (-1.9) \\ 0.0 \ (0.0) \\ -0.0 \ (0.0) \end{array}$	$\begin{array}{c} 6.7 \ (-7.1) \\ 8.0 \ (-8.6) \\ 6.4 \ (-6.8) \\ 6.3 \ (-6.7) \end{array}$	

Table I. Change in simulated outflow in response to different road construction and forest harvesting scenarios

(1962–1969). We limit this period to the early response of forest harvesting before significant regrowth has occurred. Table I summarizes both the combined effects of roads and harvesting and a scenario that isolates the contribution of roads during this time period.

The effect of forest removal contributes a 6 per cent increase in annual flows independent of the effects of roads. The net effect of harvesting versus road construction dominates in all scenarios. To disaggregate the effect of roads from harvesting, we compare scenarios with roads and without roads during the harvested period. These scenarios illustrate the potential for any synergistic effects due to harvesting on the response due to roads. Results summarized in Table I suggest that the effects of roads on annual outflow are similar for pre- and post-harvest periods. (Note that percentage effects diminish slightly due to the higher flow volumes in post-harvesting periods but the net effect of roads does not change.)

*Effect of road–stream connectivity.* When water is concentrated in areas below the road, rather than directly routed to the stream, the effect of roads becomes negligible on both outflow and evapotranspiration. This is consistent with the conceptual model where roads routing directly to the stream produce the largest effects due to flow channelization. Routing culverts to local areas below the road diminishes the effects on both annual outflow and evapotranspiration. No significant difference between routing to highest versus lowest wetness index was found for modelled annual evapotranspiration and outflow responses.

### Within-season outflow dynamics

The within seasonal effects are also of interest, since they illustrate temporal dynamics. Figures 5 and 6 illustrate cumulative outflow differences for simulations with roads and without roads for 1959, for the 0.5 and 5 m cut bank, respectively. Superimposed on a net seasonal increase in outflow, both cut depths show a repeated cycle of increase and decrease in outflow differences during the spring and winter periods. For a given storm, a scenario with roads may produce more outflow as a result of subsurface throughflow interception by the road and more efficient routing of this flow to the stream. The consequence of this redirection, however, is a reduction in subsurface recharge to areas below the road. In inter-storm and subsequent storm periods, these downslope areas may then contribute less outflow to adjacent streams. For these periods, Figures 5 and 6 show a partial recovery which occurs following increases in the cumulative difference. The timing of this recovery will depend upon the history of storm events and the hillslope characteristics. These simulation results show that for Watershed 3, the decrease in flow associated with roads, following increases during high flow events, occurs within the winter season and with a similar frequency for moderate and low cut banks.

Figures 5 and 6 also show that the magnitude of effects on cumulative outflow varies significantly with road cut depth. The larger cut depth (5 m) produces a peak cumulative outflow almost five times that produced using the 0.5 m cut bank.

This pattern of recovery occurs, with diminished magnitude, when intercepted flow is routed to the highest wetness index. For routing to the lowest wetness index, effects are further diminished and, for the low cut bank, are the inverse of what is found with routing directly to the stream or to the highest wetness index. This inverse and diminished pattern associated with routing to the lowest wetness index supports the conceptual model that routing to the lowest wetness index acts to diffuse rather than to concentrate flow. In the 5 m cut depth cases, the additional interception by the high cut bank overshadows these diffusive characteristics.

It should be noted that the scenarios tested here assume a single culvert for each 30 m of road length. Varying the concentration of culverts and therefore the magnitude of flow concentration/diffusion may produce more or less significant results. Estimation of culvert density is required to be able to use this model in areas where detailed road surveys are not available. Use of the 30 m spacing provides a model to allow comparison of other road variables. Figure 7 illustrates the impact of increasing culvert spacing in the model. Results show that the outflow difference associated with roads follows a similar seasonal pattern. For



Figure 5. Cumulative outflow difference on Watershed 3 for simulations with roads and base line (no road) simulations assuming a 0-5 m road cut depth

individual events, the increase in outflow associated with roads is slightly (<1 mm) more flashy with the larger culvert spacing. This reflects the larger contributing area (and therefore magnitude of intercepted flow) associated with larger culvert spacing. For one particular storm event, the 90–120 m culvert spacing produces a change in the timing of response in comparison to the 'no road' scenario (i.e storm outflow occurs one day earlier in the scenario with road, producing the two sequential spikes in the outflow difference between scenarios). Use of the daily time step in the model results in this apparent dramatic difference in outflow. To explore the effect of roads on timing in more detail, a subdaily time step would be required.

## Spatially distributed soil moisture

The spatial extent of the reduction in recharge to areas below the road and to the hillslope drainage features will have an impact on hydrologic response characteristics. To explore this, we examine the spatial pattern of the effect of roads on saturation deficit. Figure 8 maps the spatial distribution of the differences in saturation deficit and evapotranspiration for a representative summer day for scenarios with and without roads. Differences in saturation deficit are highest immediately below the road but extend from the area immediately below the road to the stream network. This illustrates the spatial persistence of road effects to adjacent stream areas that control subsurface routing to the stream. The impact of a change in saturation deficit on subsurface throughflow (and eventually streamflow) is mediated by associated changes in evapotranspiration. In Figure 8, differences in evapotranspiration show a smaller spatial extent than differences in soil moisture. This pattern arises because evapotranspiration does not respond linearly to soil moisture, and because in lower, wetter areas and wetter periods, evapotranspiration may not be limited by soil moisture. Significant



Figure 6. Cumulative outflow difference on Watershed 3 for simulations with roads and base line (no road) simulations assuming a 5 m road cut depth

differences (i.e. >50 per cent in some local cases) in evapotranspiration near the road (i.e. within 200 m) also illustrate the potential for ecologically significant consequences on downslope vegetation.

Figure 9 illustrates the generalization of these results through time and space. Figure 9a shows the mean and standard deviation of the daily increase in saturation deficit due to roads as a function of flowpath distance from the road for March to October 1959. This graph illustrates the pattern of spatial persistence of effects on saturation deficit, showing that the greatest effects occur within the first 100 m below the road and a continued increase in saturation deficit for a significant distance downslope. Figure 9c illustrates the corresponding pattern for the reduction in downslope evapotranspiration due to roads. A similar, although muted, reduction in the mean decrease in evapotranspiration with downslope distance is shown. The higher variance associated with evapotranspiration is due to the non-linear relationship between soil moisture and evapotranspiration such that a reduction of soil moisture in relatively dry periods will have significantly greater effects on evapotranspiration than in wetter periods. In local areas, effects on evapotranspiration can be quite high with maximum difference in evapotranspiration of greater than 3 mm observed for areas near to the road and a difference of greater than 2 mm for areas more than 500 m downslope. Figure 9b and d illustrate the temporal persistence of road effects on downslope saturation deficit and evapotranspiration respectively. Effects on saturation deficit tend to increase from wet periods in March and April, where differences between road and non-road simulations are dominated by differences in outflow rather than soil moisture. Differences increase into mid-summer and then drop off as evapotranspiration differences, as shown in Figure 9d, begin to reduce soil moisture differences. Evapotranspiration differences due to road construction are most pronounced during dry, late summer periods, again due to the higher sensitivity of evapotranspiration effects during dry periods.



Figure 7. Comparison of coarse (90 m) and fine (30 m) culvert spacing showing cumulative outflow difference for simulations run with roads and base line (no road) simulations assuming a 5 m road cut depth

#### Empirical paired catchment comparisons

We now compare model results with empirical data. We analyse variation in observed daily and annual outflow from Watershed 3 against the neighbouring undisturbed Watershed 2 and another neighbouring Watershed 1 in the H.J. Andrews basin. Watershed 1 was 100 per cent harvested in 1963 without any prior road construction. Hicks *et al.* (1991) develop a least-squares regression relationship for summer and annual watershed yields for pre-harvesting periods for both Watershed 1 and Watershed 3 against the control watershed, Watershed 2. Using this regression relationship to examine post-harvesting differences in the relationship between the control and disturbed catchments, they indicate a significant increase in summer low flow response following harvesting for both watersheds. In their development of regression relationships, Hicks *et al.* (1991) include the 'road only' period in Watershed 3, from April 1959 to August 1962, in the predisturbance period. Given our interest in the effects of roads on seasonal flow, we repeat this regression using only the pre-road period of record from 1954 to 1958.

Table II summarizes results from a linear regression analysis that relates annual outflow from Watershed 3 with the control watershed for the pre-treatment period. A reasonable *p*-value was obtained, although the pre-treatment period for which data were available was relatively short (four years). Regression results differed from those obtained by Hicks *et al.* (1991), also shown in Table II, and illustrate the contribution of the period of road construction as part of the pre-treatment period.

Figure 10a plots the residuals for Watershed 3 based on predictions of annual outflow from Watershed 2. Road construction begins in 1959 and harvesting in 1963. The residuals should indicate the impact of this disturbance. As expected following harvest, observed annual outflow was greater than predicted from the



Figure 8. Spatial distribution of differences in saturation deficit (mm) and evapotranspiration (mm) below the road due to road construction effects; for 22 July 1959

unlogged watershed. Increases of approximately 25 per cent occurred with some inter-annual variability. Model results also show a significant though small gain in annual outflow following harvest in Figure 10b. Results for the road-only years (1959–1963), however, contradict model results. Residuals show a decrease in observed annual outflow relative to what was predicted from the control watershed. A decrease in outflow associated with road construction is unexpected given the conceptual model discussed above, which predicts increases or negligible changes in annual outflow for all road construction scenarios. Summer outflow residuals were small (<5 per cent) and show no consistent pattern during the road construction period prior to harvest. To assess whether the decrease in relative annual flow for the 1959–1963 period was due to climatic factors, we repeated the regression analysis for Watershed 1. Watershed 1 was harvested in 1963 with no prior road construction. Residuals for Watershed 1 do not show any significant changes during the 1959–1963 period.

Figure 11 illustrates model predictions of annual outflow, using a 0.5 m cut depth and routing all roads to lowest wetness index area below the road. This road construction scenario serves as the lowest outflow endmember of our conceptual model. Even in this end-member case, the model does not capture reduced outflow effects shown in the road construction period using the observed data, but it does reproduce a similar augmentation of outflow due to forest removal after 1963.

# CONCLUSIONS

Results from the modelling study of Watershed 3 illustrate the potentially complex interactions involved in watershed response to road construction as part of forest harvesting. Results from these simulations focus attention on the spatial and temporal persistence of changes in downslope soil moisture due to the rerouting,



Scenario	Regression model	$\mathbb{R}^2$	<i>p</i> -value
Annual water vield (mm)			
From Hicks et al. (1991) for W3 (1953–1962)	$W3 = 0.839^*W2 + 110.53$	0.94	<0.001
W3 (1954–1958)	$W3 = 0.75^*W2 + 275.99$	0.96	0.017
W1 (1954–1958)	$W1 = 1.11^*W2 + 384.5$	0.98	0.007
Summer water yield (mm) (July to September)			
From Hicks <i>et al.</i> (1991) for W3 (1953–1962)	$W3 = 0.861^*W2 + 11.43$	0.63	0.006
W3 (1954–1958)	$W3 = 1.043^*W2 + 5.59$	0.77	0.1216
W1 (1954–1958)	$W1 = 0.47^*W2 + 4.95$	0.62	0.28

Table II. Least-squares linear regression results (with control watershed, Watershed 2)

W1, Watershed 1; W2, Watershed 2; W3, Watershed 3

concentration and potential diffusion of flow intercepted by the road. This persistence means that the rerouting of water that occurs during particular winter storms has effects on the hillslope response to later storms and summer hydrologic response, including low flow and evapotranspiration.

The most significant effects were found for patterns of spatially distributed summer soil moisture. This study suggests that road construction can produce a significant reduction in downslope soil moisture and associated evapotranspiration in local areas. Reduction in evapotranspiration can in turn have ecological effects on forest health and productivity. Reduction in regrowth and/or low flow both have forest management implications. These results offer impetus for a field-based investigation of road construction effects on harvested areas below roads in water-limited environments. In future work, we plan to use a combination of modelling and field survey techniques to assess the potential for reduced recovery in these areas.



Figure 10. Annual outflow difference due to roads for Watershed 3. (a) Residuals (observed –predicted) for empirical relationship based on Watershed 2 and Watershed 3. (b) Simulated differences (simulations with forest harvesting and roads (5 m cut depth; routing to the stream)–baseline unharvested simulation)



Figure 11. Annual outflow difference due to roads for Watershed 3: simulated differences (simulations with forest harvesting and roads (5 m cut depth; routing to lowest wetness index)-baseline unharvested simulation)

The spatial and temporal persistence of road construction effects on downslope soil moisture also has implications for runoff response, although these effects are less significant. In our modelling study, it appears that roads can increase daily flow for some storms, which is consistent with findings from field research (Jones and Grant, 1996; Wright *et al.*, 1990) that show that increases in peak flow may occur only for specific storm events. Empirical comparisons between observed outflow from Watershed 3 and Watershed 2 also offer evidence of a winter recovery effect, where road effects on outflow vary for different winter storm events and during winter inter-storm periods. The compensation by downslope areas distinguishes increased routing efficiency due to road construction from an increase in stream drainage density. Because streams are located at the bottom of hillslope drainage networks, they do not impact a downslope area. Roads, given their relative hillslope position, do have the potential to impact downslope areas. Simulations here suggest that these effects can have significant effects on the redistribution of soil moisture, flowpaths and source areas for runoff. These results also illustrate the importance of the timing of the processes involved in creating the overall effect of road construction.

Simulations also illustrate the degree to which road construction effects are mediated by road cut depth and road routing characteristics. The hydrologic importance of cases where roads are hydrologically connected to the stream, either directly through culverts or through gullies, has been noted by other researchers (Wemple *et al.*, 1996). These simulations suggest that the concentration or diffusion of subsurface flow, as controlled by the road system drainage pattern, may also have effects on soil moisture and runoff production, although the magnitude of effects is much smaller. These results may be more dramatic in drier, more sensitive regions and suggest the need for field research to collaborate simulation findings. Further study will examine soil moisture both immediately below road cuts and further downslope, for both different cut depths and for different road culvert drainage patterns (i.e. diffusion:culvert routing to low wetness index vs. concentration:culvert routing to high wetness index).

Finally, comparisons between the modelled response and observed responses indicate that there are additional controlling processes that are not captured by our conceptual model. Although the statistical significance of the observed relationships was small, the observed relationship between the control watershed and the harvested watershed illustrates an annual reduction in outflow associated with roads. Seasonal comparisons further suggest that this reduction, relative to the pre-harvesting periods, occurred mainly during the late winter and spring. We suggest several possible explanations for this discrepancy between the model and paired catchment relationships. The simulations indicate the complex role played by the combination of increased drainage efficiency during a storm and the delayed effect of a reduction in downslope recharge. Observed results may indicate a greater and disproportionate impact of the downslope reduction in recharge. Hysterisis effects in the downslope area could account for this effect, allowing more water in downslope areas to be lost due to evapotranspiration in the case where water is channelled by the road, particularly during the spring period when soil moisture drawdown from saturation tends to occur. Similarly, reduced saturation levels in downslope areas below the road may have a non-linear effect on outflow response. Alternatively, it may be that roads also act as terraces, holding some of the intercepted flow in surface storage, which is then lost as evaporation. Further field investigation is necessary to examine these hypotheses.

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