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Subsurface Water Flow Rates Over Bedrock on Steep Slopes in the Carnation Creek Experimental Watershed

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Abstract

Subsurface flow rates along the bedrock surface were measured at three steep slope, forest soil sites within the Carnation Creek watershed located on the west coast of Vancouver Island, British Columbia. A salt tracer was used to monitor flow between a buried perforated pipe and the roadcut. Subsurface flow rates were an order of magnitude higher at two obvious seepage sites than at the non-seepage site, although flow pathways were found to be heterogeneous under both conditions. Subsurface flow at the non-seepage site apppears to be laminar whereas some of the flow at the seepage sites is probably turbulent based on an evaluation of the Reynolds number. The subsurface flow rates measured in this study are generally higher than those recorded in several other areas in coastal B.C. and Oregon, but similar in magnitude to measurements in Idaho and New Zealand.

Introduction

A dominant mechanism of hillslope water movement in coastal British Columbia mountain watersheds is rapid subsurface flow. Surface runoff is almost nonexistent on these forested slopes as thick organic forest floors and coarse mineral soils laced with tree roots produce infiltration capacities far in excess of maximum expected rainfall intensities. Slope groundwater tables in the Carnation Creek Experimental Watershed develop and rise rapidly after rain starts and fluctuate with variations in rainfall intensity (Hetherington, 1982). Similar findings have been reported for other areas of coastal western North America (Buchanan et al., 1990; Jackson and Cundy, 1992; Sidle, 1986). Water flows through the soil rapidly via a complex network of preferred pathways which include inter-connected decayed roots which act like pipes, layers or lenses of coarse materials, voids around rocks, along live roots, and worm holes. Some of this water may be existing (old) soil water that has been mobilized by the addition of the (new) rain water (McDonnell, 1990). Whatever the source, the groundwater data plus visual observations during rainfall of a sheltered mid-slope trench soil face, also in the watershed, indicate that rain water moves rapidly down through the soil profile to the impermeable layer (bedrock) and then laterally downslope over this layer. Water arrives at the impermeable layer faster than it can drain downslope, producing a transient rise in water table depth on the slope until rain ceases or an equilibrium is reached.

As part of a broader investigation of slope hydrology in the watershed, the study reported here was conducted to measure directly the downslope rate of stormwater movement over the impermeable bedrock surface. While limited, this study provides a direct measure of the range of velocities for this component of subsurface flow on our steep coastal watershed slopes.

Study Area

The Carnation Creek watershed is located on the west coast of Vancouver Island, British Columbia, 49°N and 125°W. It has been the site of a long-term fish/forestry interaction research program which included monitoring and investigation of various components of the hydrological cycle (Hartman and Scrivener, 1990; Hetherintgton, 1982). The watershed lies within the Coastal Western Hemlock Biogeoclimatic Zone (Krajina,1969). Major tree species are western hemlock (Tsuga heterophylla) and amabilis fir (Abies amabilis) with lesser amounts of western red cedar (Thuja plicata), Sitka spruce (Picea sitchensis) and Douglas fir (Pseudotsuga menziesii). About 40% of the drainage area was clearcut from 1976-1981 and much of the cleared area was replanted with Douglas fir. Basin slopes are steep, up to 80%, elevations range from sea level to 900 m, and bedrock is of volcanic origin. The mainly Orthic Ferro-Humic podzol soils are shallow (< 1 m mean depth), highly permeable, coarse colluvial materials of gravelly loam to loamy sand texture with an organic surface layer. They are laced with live and dead roots, particularly in the top 30-50 cm of the mineral soil.

Annual precipitation (mostly rain) has ranged from 2100 to over 5000 mm, about 75% occurring during the winter period from October to March. Individual storms have produced 300 to 400 mm of rain in 48 to 60 hours. Streamflow is flashy due to intense rainfall and rapid runoff, and about two-thirds of annual precipitation leaves the watershed as runoff.

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Methods

Three mid-slope sites were selected for the study: H1 and H2 on the same road in a clearcut (harvested in 1978) in the upper watershed and FD on a road in a lower watershed clearcut (harvested in 1976). Roadcut sites were chosen because of accessibility and ease of monitoring flow. Vegetation at each site included young western hemlock plus ferns (Blechnum spicant, Pteridium aquilinum, and Polystichum minitum at site FD). Sites H2 and FD were in obvious seepage locations with numerous coarse rock fragments, while site H1 had few rocks and did not appear to have seepage between storms. Other site characteristics are listed in Table 1.

Table 1. Characteristics of subsurface flow study sites

Site	Ground Slope (degrees)	Aspect	Soil Depth (m)	Flow Path Length (m)	Head Difference (m)
H1	28	North	0.75	3.25	1.53
H2	37	East	0.80	2.70	1.62
FD	35	North	0.50	3.50	2.00

At each site, 142 cm long perforated (6 mm diameter holes) 5.5 cm diameter PVC pipes covered with nylon cloth (280 micron mesh) were installed on bedrock in narrow trenches dug about 3 m (Table 1) upslope from, and parallel to vertical roadcut soil faces. These pipes were attached to vertical connector pipes extending above ground level. Care was taken to minimize disturbance of soil in the lowest 10-15 cm of the trenches. The perforated pipes were covered with about 20 cm of sand and the rest of the trench backfilled with soil. Soil in the 10 cm above bedrock was of sandy loam texture at each site.

Water flow rates between the buried pipes and the roadcuts were measured by adding a salt tracer solution to the pipes via the vertical connectors during rain storms and monitoring the outflow at the roadcut with a Horizon Model 1484-10 conductivity meter. To establish the best spots for monitoring, water was pumped into the buried pipes when there was no natural subsurface flow (September 1987) and the outflow points were identified and marked. Water was pumped from a 450 litre tank at a rate sufficient to maintain a head of water in the vertical pipes. This procedure was repeated in September 1988 at site H1 to determine whether water moved laterally cross-slope from the buried pipe as well as directly downslope. To do this, a narrow trench was dug from the roadcut for 3.5 m directly upslope at a location 3.5 m to the side of the buried pipe in the direction that the terrain appeared to slope. This trench was observed for seepage during the pump test.

Tracer applications were conducted during two storms at site H1 and one storm each at sites H2 and FD. A 5N sodium chloride (NaCl) solution was poured into the vertical pipe and flushed with water to ensure injection of the tracer into the subsurface flow. Amounts of tracer added were as follows: at H1 7 litres December 1987 and 2 litres January 1989; at H2 and FD 1 litre January 1990. About 6 to 10 litres of water were used to flush the tracer. Roadcut monitoring was continued at least until the peak conductivity had occurred. Periodic measurements were also taken of flow rates at the sampling points and water levels in the vertical pipes. For ease of comparing the results, the conductivity readings were standardized by dividing each value by the maximum reading and multiplying by 100.

Subsurface flow pore velocities (v_p) (the actual flow through pores and voids in the soil) were determined by dividing the direct flow path by both the time to start of conductivity increase and the time to the peak conductivity. Velocity of flow (v) through a cross-sectional area of soil was derived by adjusting for porosity (α)

$$v = \alpha \; v_p \qquad [1]$$

where a value of 0.70 for α was adopted based on soil measurements from other sites in the watershed.

Hydraulic conductivity (K) was derived from the Darcy equation

$$K = v \; dl/dh \qquad [2]$$

where dl is the flow path from the buried pipe to the roadcut and dh is the elevational difference between the two points. This equation assumes that the flow is laminar, which conceivably might not be the case for rapid subsurface flow at the seepage sites. The Reynolds Number (Re) can be used to check whether flow is laminar or turbulent

$$Re = p \; v \; d/\mu \qquad [3]$$

where p is the fluid density (1000 kg m^{-3}), v the flow velocity (m s^{-1}), d the mean soil grain diameter (0.00 m), and (the viscosity (1.31E-3 N s m^{-2}) (Freeze and Cherry, 1979). Darcy's law is valid as long as Re based on the grain diameter is less than 10 (Bear, 197; Megahan and Clayton, 1983).

Results and Discussion

The tracer applications have revealed a distinct difference in tracer concentractions over time, and hence in rate of water movement, between site H1 and the two seepage sites H2 and FD (Fig. 1). At the seepage sites, tracer reached the road cut within 2 minutes, conductivities rose rapidly to peaks within 5 minutes and then also declined quickly (Table 2, Fig. 1). In contrast, conductivities at site H1 were slower to start rising, increased much more gradually to peak levels and also tapered off more gradually (Fig. 1). These results indicate a rapid, high volume flow at the seepage sites that both moved and diluted the tracer quickly. At site H1, the extended appearance of tracer indicates slower, lower volume flow. Flow rate measurements at the sampling points corroborate this conclusion (Table 2).

The tracer responses at the two seepage sites were remarkably similar as were those for the two storms at the non-seepage site. The soil was thoroughly wetted during all storm events as indicated by the antecedent precipitation amounts and water table depths (Table 2). The shallow water table depth at site FD indicates the presence of sufficient macro-channels and conduits to convey water to the roadcut at a rate equal to the inflow rate to the site. Observed considerable seepage flow and tracer along the roadcut to the right of the buried pipe suggests the occurrence of significant lateral as well as direct downslope flow from the pipe at this site. The earlier occurrence of the conductivity peak during the January 1989 storm at site H1 probably resulted from the higher volume of flow (Table 2) with resulting increased dilution of the tracer.

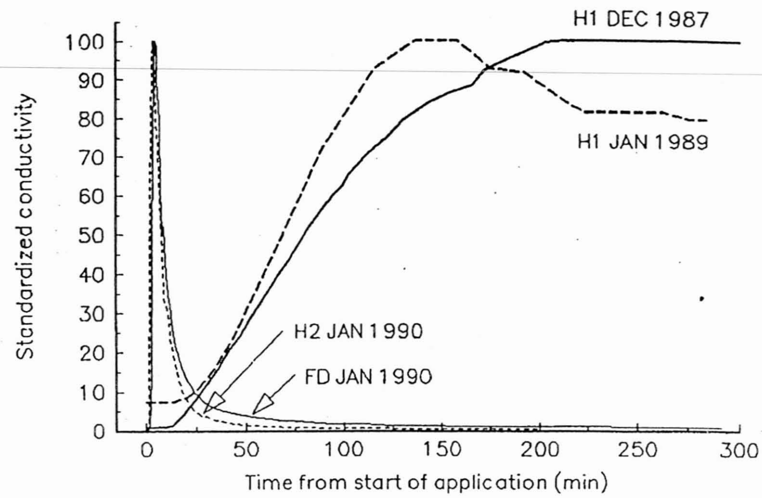

Fig. 1 Variation of conductivity with time from start of tracer application

During the water only applications, water seepage occurred at several distinct spots along the soil-bedrock interface at each site, indicating heterogeneity in the preferred flow paths, as would be expected. Conductivity measurements taken during the tracer tests confirmed this observation.

The water only application at site H1 in September 1988 showed that some flow from the buried pipe did flow laterally across and downslope as well as more directly downslope.

Subsurface flow rates at site H1 for the start of conductivity rise were of the same magnitude as those for the first appearance of flow during the water only

Table 2. Information on water only and tracer applications

Site	Date	Conductivity Rise Start (min)	Conductivity Rise Peak (min)	Antecedent Precip. 10-day (min)	Antecedent Precip. 40-day (min)	Water Table Depth (cm)	Flow Rate (ml/min)
	Water Only:						
H1	Sept. 1987	31.0		16	47	0	
H2	Sept. 1987	3.4		16	47	0	
FD	Sept. 1987	4.3		10	38	0	
H1	Sept. 1988a	9.5		62	136	0	
H1	Sept. 1988b	5.0		62	136	0	
	Tracer:						
H1	Dec. 1987	8.7	211.0	431	802	35	160
H1	Jan. 1989	20.0	136.0	108	401	40	300
H2	Jan. 1990	1.1	3.5	94	312	47	4400
FD	Jan. 1990	1.7	4.5	72	255	5	3200

Note: Site H1 Sept. 1988b refers to second water application 53 minutes after end of first.

Table 3. Computed subsurface flow rates for water applications only.					
Site	Date	v_p (ms^{-1})	v (ms^{-1})	K_s (ms^{-1})	Re
H1	Sept. 1987	1.75E-3	1.23E-3	2.61E-3	0.9
H1	Sept. 1988a	5.70E-3	4.00E-3	8.48E-3	3.0
H1	Sept. 1988b	10.83E-3	7.58E-3	16.07E-3	5.8
H2	Sept. 1987	13.24E-3	9.27E-3	15.48E-3	7.0
FD	Sept. 1987	13.57E-3	9.56E-3	16.73E-3	7.3

Note: Site H1 Sept. 1988b refers to second water application 53 minutes after end of first.

application (Tables 3, 4). This similar result for saturated versus supposedly non-saturated conditions indicates the presence of a clear preferred path for water flow. The second water application in September 1988, added after flow from the first application had ceased, resulted in a doubling of the measured flow rate. One possible explanation for this result is that the added water forced some of the old water ahead of it from saturated pores in the soil. Flow rates for the peak conductivities were only 4-15% of the start of rise values (Table 4) and can be taken to represent average flow conditions through a variety of pathways. The estimated Reynolds values indicate that the flow was laminar in both cases (Table 4).

Subsurface flow rates at sites H2 and FD for the start of conductivity rise were about 3 times higher than for the first appearance of flow during the water only application (Tables 3, 4). The estimated Reynolds numbers indicate that flow may have been turbulent at the time of tracer application but possibly non-turbulent during the water only application (Table 4). In these situations, the high volume of flow during the storm tracer applications probably resulted in the higher flow rates. Flow rates for the peak conductivities were almost identical at the two sites and were 28% and 37% of the start of rise values (Table 4). The peak conductivity flow rates were possibly non-turbulent, based on the estimated Reynolds numbers (Table 4), indicating a mixture of turbulent and laminar but rapid subsurface flow at these two seepage sites.

The subsurface flow rates observed in this study are generally higher than those reported for other coastal areas. In summarizing results of other authors, Cheng (1988) reported subsurface flow velocities for coastal B.C. up to 0.6E-3 ms-1 for the soil profile and 0.03E-3 ms^{-1} for the soil matrix, and saturated hydraulic conductivities up to 0.05E-3 ms^{-1}. Cheng (1988) also reported saturated hydraulic conductivities for western Oregon of 0.03-1.1E-3 ms-1.

Megahan and Clayton (1983) undertook a similar tracer roadcut study in Idaho using piezometers for a 29(slope, loamy coarse sand soils over bedrock, and snowmelt conditions. They reported hydraulic conductivity values of 0.30E-3 ms-1 for start of tracer concentration rise and 0.15E-3 ms-1 for peak tracer concentration. These values are similar to those of this study for the non-seepage site but up to two orders of magnitue smaller that those for the seepage sites. In a study undertaken in New Zealand where water was applied to a line source 1 m above a large number of soil pits in a variety of sites, Mosley (1982) measured subsurface flow velocities averaging 3E-3 ms^{-1} with a maximum of 21E-3 ms^{-1}. These values are similar in magnitude to those found in this study.

Conclusions

The results provide quantified estimates of the differences in subsurface flow rates over the bedrock surface between seepage and non-seepage conditions on steep coastal forested mountain slopes. Flow pathways were found to be heterogeneous under both conditions. Subsurface flow at the non-seepage site apppears to be laminar whereas some of the flow at the seepage sites is probably turbulent. The subsurface flow rates measured in this study are generally higher than those recorded in several other areas in coastal B.C. and Oregon, but similar in magnitude to measurements in Idaho and New Zealand.

Table 4. Computed subsurface flow rates for tracer applications

Site	Date	Start of Conductivity Rise (ms^{-1}) Start	Peak	10-day	40-day	Peak Conductivity (ms^{-1}) Depth	Flow	Rate	Re
H1	Dec. 1987	6.16E-3	4.31E-3	9.14E-3	3.3	0.26E-3	0.18E-3	0.38E-3	0.3
H1	Jan. 1989	2.71E-3	1.90E-3	4.03E-3	1.5	0.28E-3	0.40E-3	0.59E-3	0.2
H2	Jan. 1990	46.6E-3	32.6E-3	54.4E-3	25	12.9E-3	9.00E-3	15.0E-3	7
FD	Jan. 1990	35.0E-3	24.5E-3	42.9E-3	19	13.0E-3	9.07E-3	15.9E-3	7

References

Bear, J. 1972. Dynamics of fluids in porous media. American Elsevier, New York.

Buchanan, P., K.W. Savigny and J. de Vries. 1990. A method for modeling water tables at debris avalanche headscarps. J. Hydrol. 113:61-88.

Cheng, J.D. 1988. Subsurface stormflows in the highly permeable forested watersheds of south-western British Columbia. J. Contam. Hydrol. 3:171-191.

Freeze, R.A. and J.A. Cherry. 1979. Groundwater. Prentice-Hall, Inc. Englewood Cliffs, N.J.

Hartman, G.F. and J.C. Scrivener. 1990. Impacts of forestry practices on a coastal stream ecosystem. Carnation Creek, British Columbia. Can. Bull. Fish. Aquat. Sci. 223: 148 p.

Hetherington, E.D. 1982. Effects of forest harvesting on the hydrologic regime of Carnation Creek Experimental Watershed: a preliminary assessment, p. 247-267. In Canadian Hydrology Symposium: 82. National Research Council of Canada, Ottawa.

Jackson, C.R. and T.W. Cundy. 1992. A model of transient, topographically driven, saturated sub-surface flow. Water Resour. Res. 28(5):1417-1427.

Krajina, V.J. 1969. Ecology of forest trees in Britich Columbia, p. 1-146. In V.J. Krajina and R.C. Brooke (Ed.). Ecology of western North America. Dept. of Botany, Univ. of British Columbia, Vancouver, B.C. 349 p.

McDonnell, J.J. 1990. A rationale for old water discharge through macropores in a steep, humid catchment. Water Resour. Res. 26:2821-2832.

Megahan, W.F. and J.L. Clayton. 1983. Tracing subsurface flow on roadcuts on steep, forested slopes. Soil Sci. Soc. Am. J. 47(6):1063-1067.

Mosley, M.P. 1982. Subsurface flow velocities through selected forest soils, South Island, New Zealand. J. Hydrol., 55:65-92.

Sidle, R.C. 1986. Groundwater accretion in unstable hillslopes of coastal Alaska, p. 335-343. In Conjunctive water use, Proc. of the Budapest Symposium. IAHS Publ. no. 156.