The role of near-stream riparian zones in the hydrology of steep upland catchments

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Abstract Surface and subsurface waters were monitored and sampled at various topographic positions in a 40.5-ha headwater catchment to test several hypotheses of runoff generation and stream chemical and isotopic evolution during snowmelt. Transmissivity feedback was observed on the hillslopes during the melt period. Groundwater levels and stream DOC were highly correlated with stream discharge. Hysteresis in the groundwater–streamflow relation suggests that localized water flux from the riparian areas controlled the rising limb and main peak response of the melt hydrograph, whilst hillslope drainage controlled the timing and volume of the falling limb. Lateral flow from upslope positions was detected in the riparian zone

INTRODUCTION

The effect of headwater–stream riparian zones on streamflow generation and chemical composition remains poorly understood. Research linking hillslope runoff with near-stream hydrological conditions (Peters *et al.*, 1995) and chemistry (Hill, 1990) has shown that the riparian zone may reset hillslope flow paths and signatures (Robson *et al.*, 1992). Hillslope waters may reach the stream by a variety of pathways. The alteration of water chemistry along these flow paths is critical to understanding stream biogeochemistry (Hynes, 1983; Likens, 1984; Hill, 1990). Little information exists on relationships between physical water flow paths and chemistry of water discharging into streams. In this study we linked physical hydrometric data and soil information with observations of water isotopic and chemical composition to address the following questions:

- How does hillslope water make its way to the stream channel during snowmelt?
- What is the relative importance of hillslope till water and soil water contributions to streamflow during melt?
- Do soil water solute concentrations evolve downslope along subsurface flow paths?
- Are hillslope water signatures diluted by greater reservoir volumes in the riparian zone?

- How does the hillslope become coupled and de-coupled from the riparian zone during the melt season?

The data and interpretations presented in this paper are a synthesis of recent works completed ny McGlynn (1997) and Kendall (1997).

STUDY AREA

The W-9 subcatchment of the Sleepers River Research Watershed (SRRW) is located in northeastern Vermont, USA, within the Connecticut River basin (Fig. 1). W-9 is 41 ha and is completely forested. Elevation ranges from 519 to 686 m. W-9 is made up of three subcatchments, W-9A (17 ha), W-9B (14 ha), and W-9C (9 ha). Melt response differs between each subcatchment because of differences in slope and aspect. Mean annual precipitation is approximately 1100 mm; 25–35% falls as snow. The till depth averages 1 to 3 m and has a high silt content. Soils range from well-drained podzolic *Distrochrepts* and *Fragiochrepts* to poorly drained boggy *Fragiaquepts*. Riparian zones consist typically of peat accumulations that range from sapric to fibric and up to 0.9 m in depth. These units overly dense clay-silt till, which in turn overlies gravelly till of variable depth above bedrock.

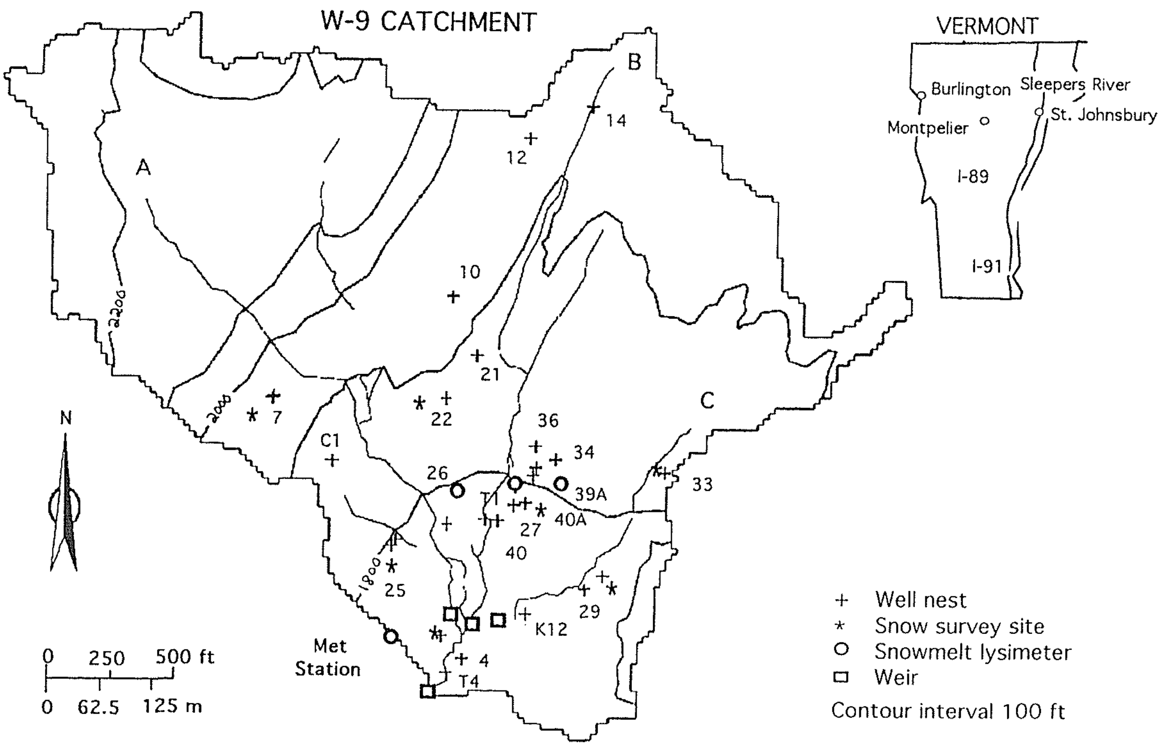

Fig. 1 Map of the W9 catchment showing locations of hillslope wells and near-stream transect.

METHODS

We characterized hillslope waters by measuring hydraulic head daily (three times per day during active melt) with a manual electronic water level indicator at 18 sets of nested wells (Fig. 1). Each well-nest included one well screened within the till, and two or three wells screened at various levels in the mineral and organic soil (Fig. 2). Large increases in penetrability (from dynamic cone-penetrometer tests) signified boundaries between shallow soil, deep soil, till and bedrock or unweathered till. Soil depth averaged 700 mm. Topographic index values $\ln(a/\tan\beta)$ (where a is the upslope contributing area and β is the local slope angle) were computed for the hillslope well-sites from a 7-m resolution DEM using a hybrid single/multiple flow direction algorithm (Wolock & McCabe, 1995). These values were used to explore the links between hillslope water composition and slope position.

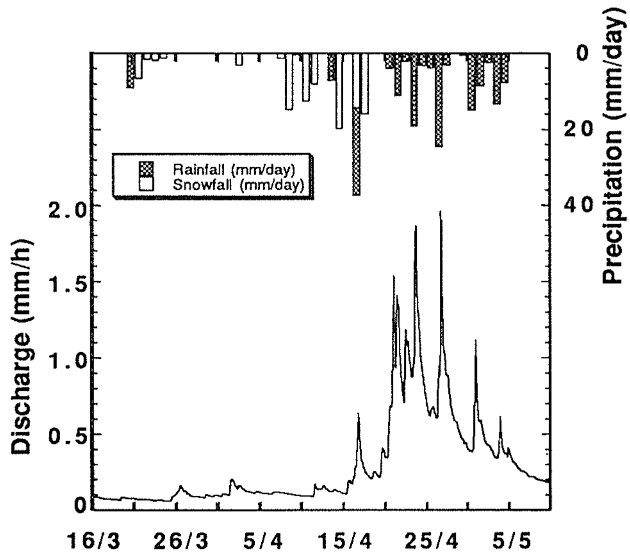

Fig. 2 The 1996 melt period.

The riparian zone was studied at a transect that was instrumented with nested piezometers upstream of the tributary confluence of W-9B near well 21 (Fig. 1). Six nests of piezometers were installed along the transect; each nest had three piezometers (19 mm in diameter), completed at depths of up to 1.6 m depending upon local depth to bedrock. Saturation excess overland flow and shallow subsurface flow in the riparian zone were collected in porous cups. Piezometric head values were measured daily; piezometers were also sampled daily for Ca, Si, DOC, other major cations, and $\delta^{18}O$.

RESULTS AND DISCUSSION

The study period extended from 18 March to 9 May. Small diurnal melts began on 25 March, but stream discharge remained low until the rain-on-snow event of 16–17

April (Fig. 2). The stream reached its snowmelt peak from the rain-on-snow event of 23–24 April. The snowpack averaged 166 mm of water on 18 April, and by 25 April most of the catchment was bare ground.

Depth-to-water-table and magnitude of water-table rise were weakly correlated with ln(a/tanβ). The absolute magnitude of water-table rise for hillslope sites was greater than riparian sites. The highest rise (>1600 mm) was observed at sites with index values less than 7, while levels rose no more than 500 mm at sites with index values greater than 10. There was a weak correlation between specific conductance of subsurface till waters and topographic index. Specific conductance generally increased as topographic index increased.

Streamflow was strongly correlated with groundwater levels. A multiplicative model was fitted to the data; R^2 values were greater than 0.80 at 14 of the 20 well sites; R^2 values were greater than 0.62 at the other six sites. The relation further revealed a threshold water-table level above which streamflow increased at a greater rate. The threshold was closer to ground surface in riparian/discharge areas compared to hillslope/recharge areas. At most sites, the threshold was reached by 21 April when available storage had been filled on the hillslope and water levels intersected the transmissive zone.

Hysteresis was observed in the hillslope groundwater–streamflow relation (Fig. 3). Generally, in riparian zones, groundwater levels were lower on the recession limb of the stream hydrograph. The hysteresis loop reversed higher on the hillslope where groundwater levels were greater on the recession limb. Sites in mid-slope positions showed little hysteresis (Fig. 3). Riparian zone groundwater levels peaked prior to streamflow peak; hillslope groundwater levels peaked after the stream (Fig. 3). This pattern suggested that riparian areas controlled the rising limb and main peak response of the melt hydrograph and that drainage from the hillslope controlled the falling limb. The following paragraphs explore how the riparian zone

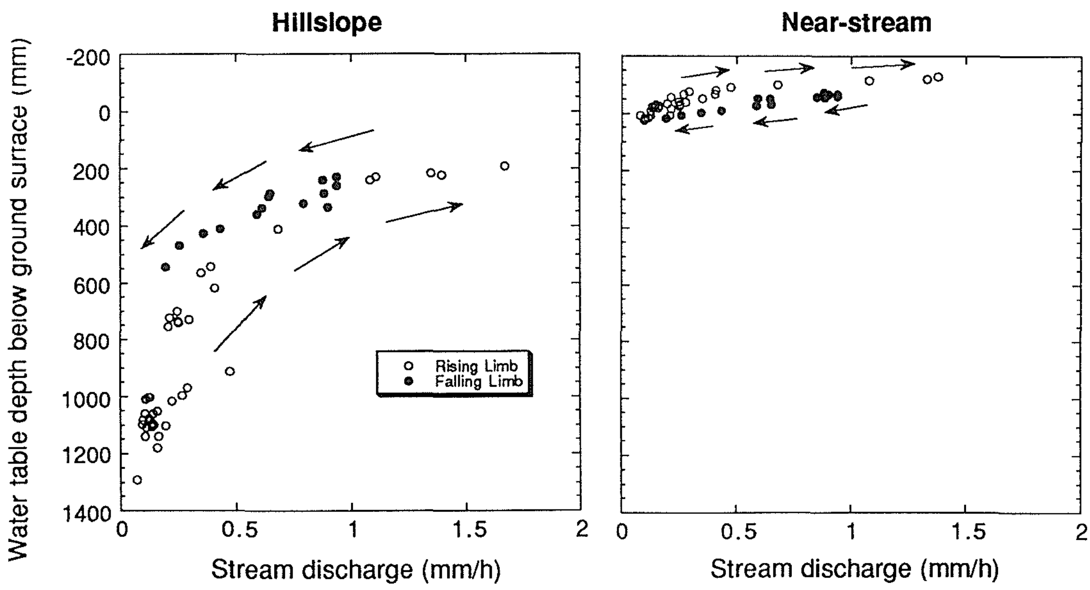

Fig. 3 Hysteresis in the groundwater–streamflow relation.

controlled rising limb streamflow response.

Figure 4(a) shows distinct layering in the riparian zone revealed through dynamic cone-penetrometer tests and soil pit excavations. Peat was layered above the dense

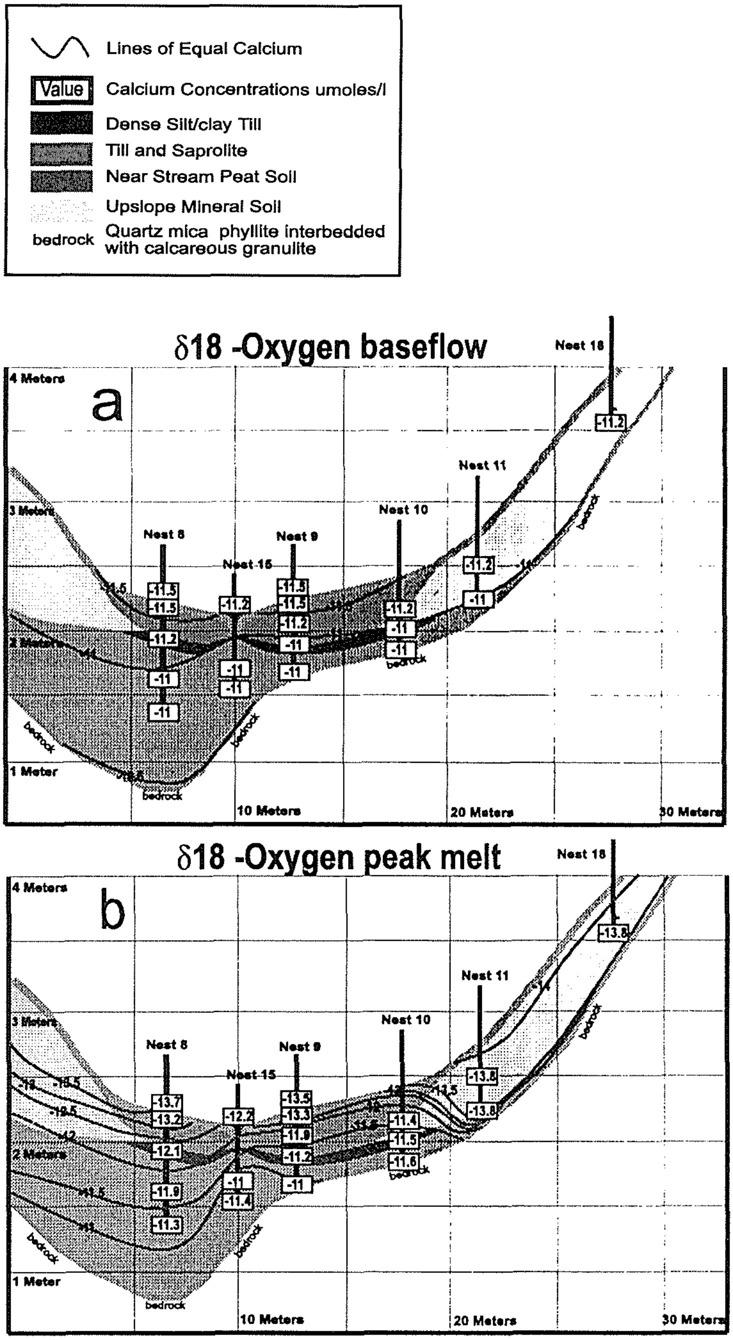

Fig. 4 (part 1) Near-stream cross-sections.

clay/silt-rich till which in turn, graded into a gravelly till above bedrock (Fig. 4(a)). Steep upward hydraulic gradients existed in the riparian zone during melt. Discharge gradients decreased away from the stream; a lateral gradient existed at the break in

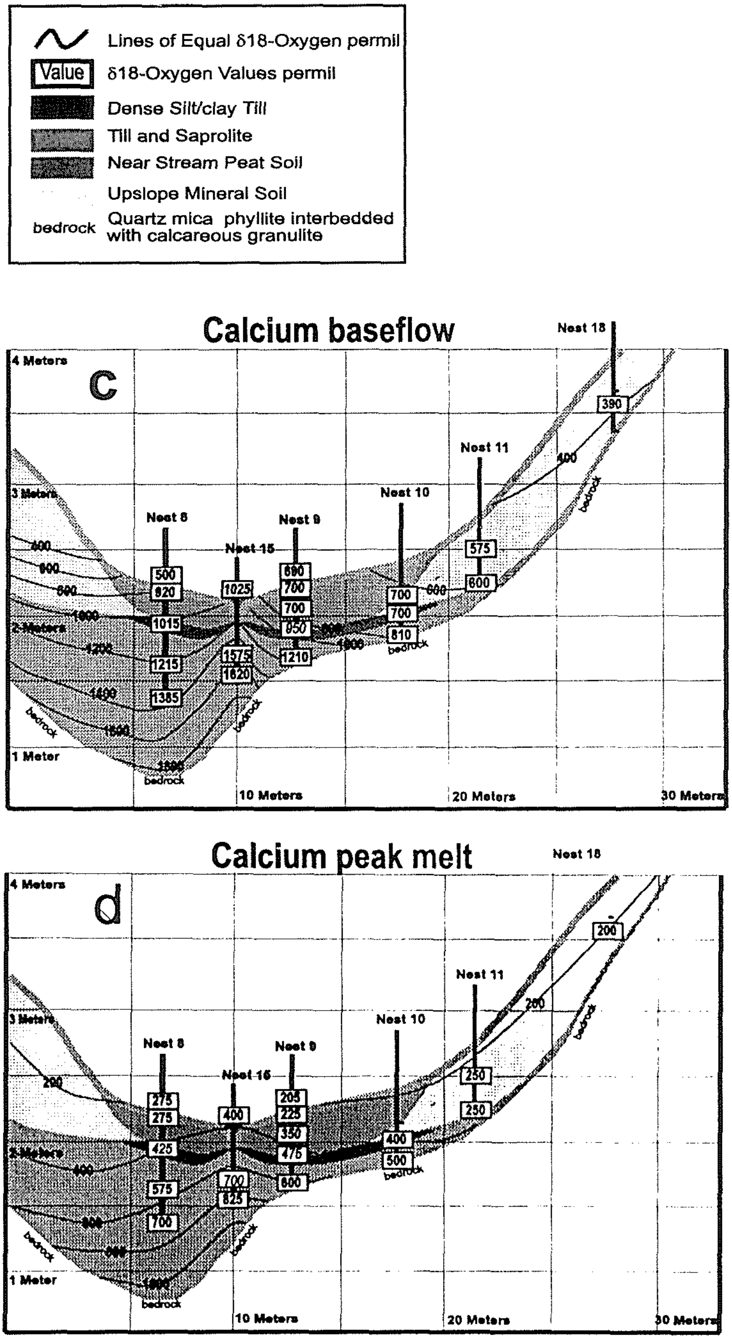

Fig. 4 (part 2) Near-stream cross-sections.

slope and a downward recharge gradient existed on the hillslope. This pattern was preserved throughout the melt and post-melt drainage periods.

Flow paths inferred from hydraulic head gradients suggest downward flow on the slope, lateral flow at the break in slope, and upward flow in the saturated near-stream zone throughout the study period. Water chemistry data collected from the nested piezometers and porous cups showed strong concentration stratification with depth. DOC concentrations were greatest at the surface and decreased down through the profile. DOC varied little within individual piezometers temporally. Silicon concentrations followed DOC patterns. Calcium was also highly stratified with highest concentrations at depth and lower concentrations toward the surface. The stratified Ca pattern was consistent throughout the melt and post-melt drainage periods (Figs 4(c)–(d)). All piezometer nests showed lower concentrations of Ca during snowmelt and elevated concentrations at low flows—concentrations increased toward the stream throughout the study period.

Meltwater $\delta^{18}O$ values became enriched as melt progressed. $\delta^{18}O$ values for piezometers and porous cups ranged from −10‰ to −14‰ over the study period. More enriched $\delta^{18}O$ values were measured in deep near-stream piezometers suggesting a pre-melt "old" water source (Fig. 4). Groundwater sampled during low flow conditions in the deep riparian piezometers had higher Ca than piezometers several metres upslope, although $\delta^{18}O$ composition was comparable. During high flow conditions, however, deep piezometers exhibited Ca and $\delta^{18}O$ compositions comparable to upslope piezometers and indeed similar to soil water sampled from wells in much farther upper hillslope positions. These data suggest a direct coupling between the hillslope and the riparian zone during peak flow.

CONCLUSIONS

Our hydrometric and geochemical data indicate that hillslope flow is affected by transmissivity feedback, as described by Rodhe and co-workers in Sweden. Riparian groundwater levels were higher on the rising limb of the stream hydrograph than at the same point on the falling limb. As groundwater levels increased, two changes occurred: (a) Shallow flow paths increased and flow through the organic horizon in the riparian and lower hillslope zones appeared to dominate streamflow. The stream shifted toward a DOC-rich signature similar to that of organic horizon and overland flow, and (b) Storage in the hillslope was replenished. Reverse hysteresis in the groundwater–streamflow relation is indicative of how storage capacity was filled and suggests that drainage of hillslope till and soil water controlled flow during the falling limb of the hydrograph.

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