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Journal of Hydrology 219 (1999) 188–205

Journal of Hydrology

A hydrometric and geochemical approach to test the transmissivity feedback hypothesis during snowmelt

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Received 28 April 1998; accepted 21 April 1999

Abstract

To test the transmissivity feedback hypothesis of runoff generation, surface and subsurface waters were monitored and sampled during the 1996 snowmelt at various topographic positions in a 41 ha forested headwater catchment at Sleepers River, Vermont. Two conditions that promote transmissivity feedback existed in the catchment during the melt period. First, saturated hydraulic conductivity increased toward land surface, from a geometric mean of 3.6 mm h^{-1} in glacial till to 25.6 mm h^{-1} in deep soil to 54.0 mm h^{-1} in shallow soil. Second, groundwater levels rose to within 0.3 m of land surface at all riparian sites and most hillslope sites at peak melt. The importance of transmissivity feedback to streamflow generation was tested at the catchment scale by examination of physical and chemical patterns of groundwater in near-stream (discharge) and hillslope (recharge/lateral flow) zones, and within a geomorphic hollow (convergent flow).

The presence of transmissivity feedback was supported by the abrupt increase in streamflow as the water table rose into the surficial, transmissive zone; a flattening of the groundwater level vs. streamflow curve occurred at most sites. This relation had a clockwise hysteresis (higher groundwater level for given discharge on rising limb than at same discharge on falling limb) at riparian sites, suggesting that the riparian zone was the dominant source area during the rising limb of the melt hydrograph. Hysteresis was counterclockwise at hillslope sites, suggesting that hillslope drainage controlled the snowmelt recession.

End member mixing analysis using Ca, Mg, Na, dissolved organic carbon (DOC), and Si showed that stream chemistry could be explained as a two-component mixture of groundwater high in base cations and an O-horizon/overland flow water high in DOC. The dominance of shallow flow paths during events was indicated by the high positive correlation of DOC with streamflow ($r^2 = 0.82$). Despite the occurrence of transmissivity feedback, hillslope till and soil water were ruled out as end members primarily because their distinctive high-Si composition had little or no effect on streamwater composition. Till water from the geomorphic hollow had a chemistry very close to streamwater base flow, and may represent the base flow end member better than the more concentrated riparian groundwater. During snowmelt, streamwater composition shifted as this base flow was diluted—not by shallow groundwater from the hillslope, but rather by a more surficial O-horizon/overland flow water.

Keywords: Transmissivity feedback; Hillslope; Snowmelt; Riparian zone; Source areas; End-member mixing; Geochemistry; Topographic index

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PII: S0022-1694(99)00059-1

1. Introduction

In mid-latitude catchments, spring snowmelt is responsible for a large percentage of the annual runoff and stream solute flux. Streamwater chemistry during melt is controlled by initial snowpack elution (Jones, 1987) followed by mixing in the subsurface as water moves to the stream. For the past two decades, researchers have used isotopic tracers to characterize mixing of meltwater with soil water and groundwater (Sklash and Farvolden, 1979; Rodhe, 1981; Maulé and Stein, 1990; Wels et al., 1991; Hinton et al., 1994; Burns and McDonnell, 1998). Isotopic studies are in general agreement that the dominant source of streamflow is premelt water (water stored in the catchment prior to the melt) rather than snow meltwater (Rodhe, 1981). Isotopic hydrograph separations are useful for determining water sources (e.g. snowmelt, groundwater), but they do not provide information on flowpaths and runoff mechanisms. Studies that combine hydrometric, isotopic and chemical approaches have had some success in identifying both water sources and flowpaths (Kennedy et al., 1986; Wels et al., 1991; Bazemore et al., 1994; McGlynn et al., 1999).

Many studies have attempted to identify the mechanism of delivery of pre-event water to the stream (for review, see Buttle, 1994). One proposed explanation is saturated wedge interflow. In this model, a transient perched saturated zone forms above soil layers of low conductivity (Weyman, 1973; Chappell et al., 1990; Dunne and Black, 1970a; Bazemore et al., 1994). In a catchment in Tennessee, Mulholland (1993) used Ca and SO_4 variations to demonstrate that saturated interflow contributed an increasing proportion of stream discharge as streamflow increased during a large storm.

Another possible mechanism of old water delivery during snowmelt invokes transmissivity feedback theory. Transmissivity feedback refers to the condition in which saturated hydraulic conductivity increases toward land surface, as observed in glacial soils in Sweden by Bishop (1991). During snowmelt, water flux increases as the water table rises into surficial soil horizons with high saturated hydraulic conductivity. As a result of the greater transmissivity, the rate of groundwater rise slows; premelt (old) water is mobilized and travels rapidly via shallow flowpaths to the stream (Lundin, 1982).

Antecedent moisture conditions in a catchment are an important factor in the hydrologic response to an event. Hinton et al. (1994) examined the effect of antecedent wetness on contributions of groundwater during wet and dry seasons in a headwater catchment underlain by glacial till. They found greater relative contributions to streamflow from discharging groundwater under higher antecedent moisture conditions. Between events, deep till water discharged to the mineral soils near the stream, and the soil and till water mixture was rapidly flushed to the stream during rain and snowmelt events. Hooper et al. (1990) used end member mixing analysis to demonstrate that different flow paths dominate under different antecedent conditions. They found that macropore flow bypassed the mineral horizon during dry conditions; saturated matrix flow appeared to dominate stormflow when the catchment was wet due to expansion of surface saturated areas upslope and steep near-stream hydraulic gradients.

Sidle et al. (1995) examined hydrologic response at various scales in a steep, humid, headwater catchment and found that different watershed positions began to contribute runoff at different moisture thresholds. During dry conditions flow was controlled by contributions from a narrow riparian zone. During storms, the riparian zone expanded and subsurface flow from a hillslope segment increased. During storms, geomorphic hollows began to contribute to streamflow.

Another important factor in hydrologic response is catchment topography. At the catchment scale, surface topography controls groundwater level patterns and stormflow source areas (Dunne et al., 1975; Anderson and Burt, 1978; Beven and Wood, 1983). Source areas of overland flow are dynamic and vary both seasonally and within events (Dunne and Black, 1970b). The topographic index, $\ln(a/\tan\beta)$, where a is the upslope contributing area per unit contour and β is the local slope (Beven and Kirkby, 1979), is a useful index of the propensity of a given point in the catchment to saturate to land surface. Nyberg (1995) found that the water content of soil and the age of water were correlated to the topographic index.

Anticipating that properties of the glacial till soils

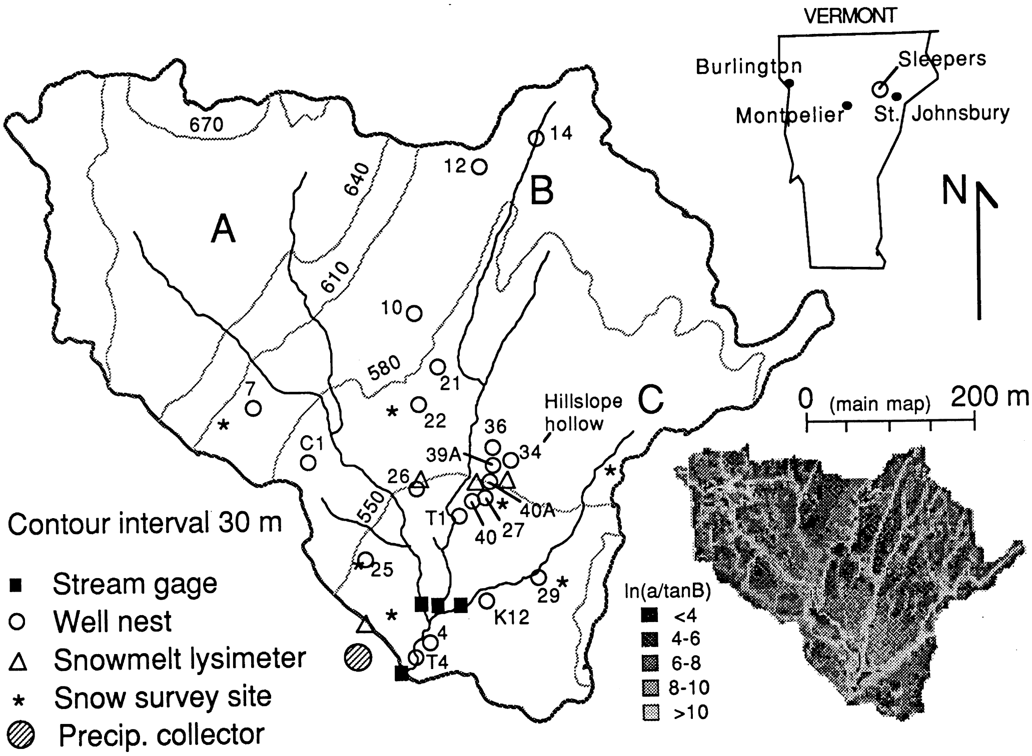

Fig. 1. Map of W-9 catchment at Sleepers River Research Watershed, Danville, Vermont showing topography, sampling sites, and subcatchments A, B, and C. Inset shows ln(a/tan β) distribution.

at Sleepers River Research Watershed in northern Vermont are similar to those at the site of Bishop (1991) in Sweden, we tested the transmissivity feedback theory of streamflow generation during the 1996 snowmelt. Sleepers River appeared to be a favorable site for transmissivity feedback because soils maintain a high moisture content during the winter (Shanley and Kendall, 1995). Thus, even small amounts of rain or meltwater can cause the water table to rise into the surficial soil zone where transmissivities are higher. Recent studies at Sleepers using isotopic and chemical hydrograph separations have shown an increasing proportion of shallow soil water in the stream as snowmelt progresses (Smith and Shanley, 1995; Titus et al., 1995), indicating the importance of a shallow, subsurface flowpath. We examined hydrometric and geochemical patterns on a hillslope transect and at various topographic positions in a forested headwater catchment to address the following questions:

1. Do hydrometric and geochemical evidence support the transmissivity feedback hypothesis of streamflow generation in the catchment during snowmelt?
2. Do hillslope till water and mineral soil water contribute to streamflow during melt?
3. What is the role of geomorphic hollows in streamflow generation?

2. Study area

The study was conducted at W-9, a 40.5 ha forested catchment of the Sleepers River Research Watershed (SRRW). SRRW is in the upper Connecticut River basin in northeastern Vermont (Fig. 1). Elevation at W-9 ranges from 524 to 679 m. The dominant aspect is south and slopes range from 0 to 90% with an average of 13% (Shanley et al., 1995b). W-9 has three subcatchments: W-9A, W-9B, and W-9C. Melt response differs between each subcatchment because

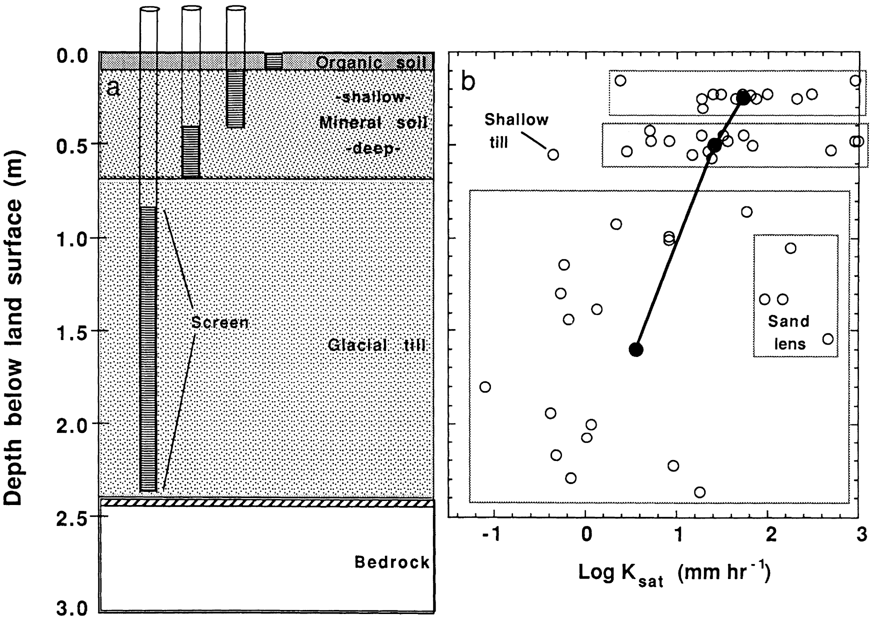

Fig. 2. (a) Schematic of typical monitoring well nest configuration. (b) Logarithm of saturated hydraulic conductivity as a function of depth (midpoint of well screen). Geometric mean of saturated hydraulic conductivity for glacial till, deep and shallow soil layers shown by large solid points.

of differences in slope and aspect. W-9A (16.9 ha) has the steepest slopes and faces southeast, W-9B (12.9 ha) is intermediate in slope and faces south, and W-9C (8.1 ha) has the most gentle slopes and faces southwest.

The mean annual air temperature at Sleepers River is 6°C. January is the coldest month with a mean temperature of −8°C, and July is the warmest month with a mean temperature of 20°C. Mean annual precipitation is approximately 1100 mm, fairly evenly distributed throughout the year; 25–35% falls as snow. The snowpack is typically present from late November to mid-April. The annual runoff peak usually occurs during spring melt, and minimum flows occur between July and October.

The W-9 catchment is underlain primarily by the Waits River formation, a quartz-mica phyllite with beds of calcareous granulite (Shanley et al., 1995b). A silty calcareous glacial till, 1–4 m in thickness, overlies the bedrock. Soils formed in the till are mainly spodosols above approximately 610 m elevation and inceptisols below (DeKett and Long, NRCS, written communication, 1995). They range from well-drained podzolic Distrochrepts and Fragiochrepts to poorly drained boggy Fragiaquepts. Soil depth averages 700 mm. Streamwater chemistry is controlled primarily by calcite dissolution (Shanley et al., 1995b).

Forest cover is mixed northern hardwoods dominated by sugar maple, yellow birch, and white ash. The primary understory species are striped maple, sugar maple, hobblebush, balsam fir, and red spruce. A few stands of balsam fir and red spruce are present near the W-9 weir and in the higher elevations of W-9A and W-9C. Small wetlands occur at these headwater sites and also at other locations within subcatchments W-9A and W-9B.

3. Methods

The study was conducted from 18 March to 9 May 1996, encompassing the main snowmelt period. Precipitation amount, snow water equivalent, groundwater levels, streamflow, and selected chemical parameters in groundwater and streamwater were monitored. Eighteen sets of nested wells were established (Fig. 1): three in W-9A, 11 in W-9B and four in

W-9C. Five of the nests in W-9B were arranged in a downslope transect on an instrumented hillslope. Measurements were made at two additional sites where only till wells were present, giving a total of 20 sites.

Each well nest generally included one well screened within the till and two wells screened within the soil (Fig. 2). Screening intervals were based on changes in soil penetration resistance as indicated by cone penetrometer profiles (Yoshinaga and Ohnuki, 1995). Progressive downward increases in penetration resistance were field correlated with boundaries between shallow soil, deep soil, unweathered till, and bedrock (more detail given in McGlynn et al., 1999). A typical installation had a till well screened in the lowest 1.5 m of till above bedrock, a deep soil well screened from 0.7 to 0.4 m depth, and a shallow soil well screened from 0.4 to 0.1 m depth. At riparian sites where surface saturation occurs, water was collected from the uppermost 0.1 m of soil by 60 mm diameter perforated polyethylene cups. These cups collected O-horizon water as well as overland flow.

Water levels were measured manually with an electronic indicator at all 20 groundwater sites, daily during baseflow and three times per day during melt. All groundwaters were sampled five times under a range of snowmelt hydrologic conditions for major cations, dissolved organic carbon (DOC), Si, and specific conductance; the five sites on the instrumented hillslope in W-9B were sampled three additional times. In this paper, 'till water' refers to groundwater from wells screened in the till, 'soil water' refers to groundwater from wells screened in the mineral soil, and 'overland flow' refers to the saturated overland flow/O-horizon water collected from the perforated cups. Till water was always present at all sites. Soil water was present when mineral soil horizons became saturated (or when a perched water table formed in mineral soil) during snowmelt. Overland flow was present first at riparian sites and later at lower hillslope sites as snowmelt progressed.

Streamflow was monitored in W-9 and its three subcatchments at V-notch weirs. Stage was recorded by datalogger every 5 min using an electronic potentiometer driven by a float in a stilling well. Streamwater was sampled for major cations, DOC, Si, and specific conductance every 3 h during events and daily during baseflow conditions.

Snow water equivalent (SWE) and snow depth were measured weekly prior to snowmelt and daily during the main melt period on a seven-point snowcourse (Fig. 1). Melt water was sampled one or two times per day during active melt from four 1 m^2 snow lysimeters on gentle slopes of various aspects in W-9 (Fig. 1).

Precipitation was measured near the W-9 weir with a weighing bucket rain gage and recorded electronically at 5 min intervals. Precipitation was sampled for each event with a wetfall/dryfall collector at the same site.

Saturated hydraulic conductivity was measured at each of the 49 individual wells using the method of Hvorslev (1951). Latitude and longitude of each well nest were determined with a portable Trimble Pro XL3 global positioning system unit. Topographic index values $\ln(a/\tan\beta)$ were computed for these sites from a 6 m resolution DEM using a hybrid single/multiple flow direction algorithm (Wolock and McCabe, 1995).

Specific conductance was measured on all samples with a Hach Model 44600 Conductivity Meter[3]. A subset of samples was filtered (0.4 μm pore size cellulose acetate membrane), acidified (HNO_3 to pH 1.0), and analyzed for major cations and Si by a direct current plasma emission spectrometer at the Department of Geology, Syracuse University, New York. The subset included till water, soil water, and overland flow from the five-site transect on the instrumented hillslope in W-9B (sites 36, 39A, 40A, 27, 40; Fig. 1), as well as stream samples from the W-9 weir. Aliquots from the same set of samples plus samples from three additional sites (12, 14, and 22) were filtered (0.7 μm pore size glass fiber membrane) and analyzed for DOC by ultraviolet persulfate oxidation with infrared detection at the USGS laboratory in Troy, NY.

Following the method of Christophersen and Hooper (1992), we applied principal components analysis (PCA) to streamwater solute concentrations to estimate how many end members are needed to explain the observed streamwater composition. End

[3] Use of brand names is for informational purposes only and does not imply endorsement by the US Geological Survey.

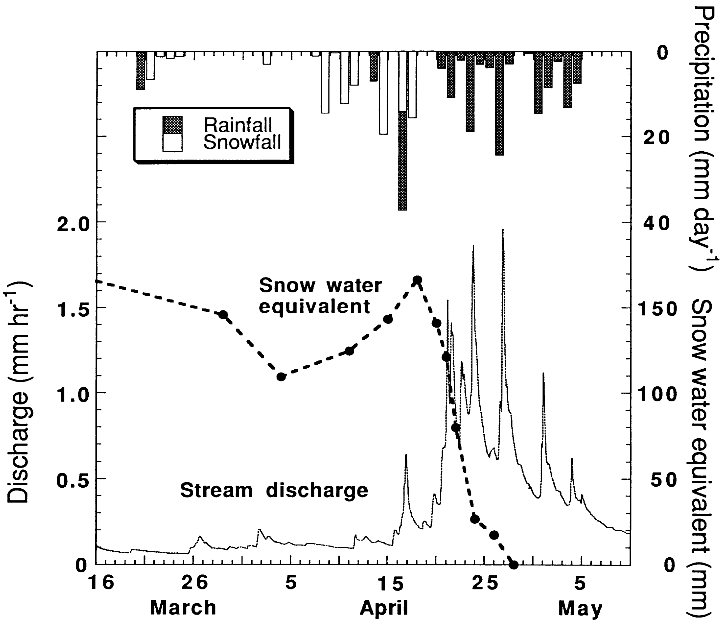

Fig. 3. W-9 stream hydrograph, precipitation, and average remaining snow water equivalent during the study period.

Table 1
Summary of water volume relationships for the 1996 snowmelt period

Date	Input			Output	Storage change (mm)
	Melt (mm)	Rain/snow (mm)	Total (mm)	Stream (mm)	
14–29 March [a]	23	9	32	34	− 2
29 March–4 April	37	0	37	18	19
4–11 April	0	0	0	20	− 20
11–15 April	0	7	7	26	− 19
15–18 April	0	23	23	55	− 32
18–20 April	25	0	25	56	− 31
20–21 April	20	15	35	18	17
21–22 April	41	0	41	16	25
22–24 April	53	24	78	46	32
24–26 April	9	4	13	23	− 10
26–28 April	17	28	45	28	17
29 April	0	1	1	9	− 8
30 April	0	15	15	10	5
1 May	0	9	9	9	0
2 May	0	2	2	7	− 5
3 May	0	13	13	6	7
4 May	0	8	8	5	3

[a] Snow water equivalent on 4 March was 169 mm.

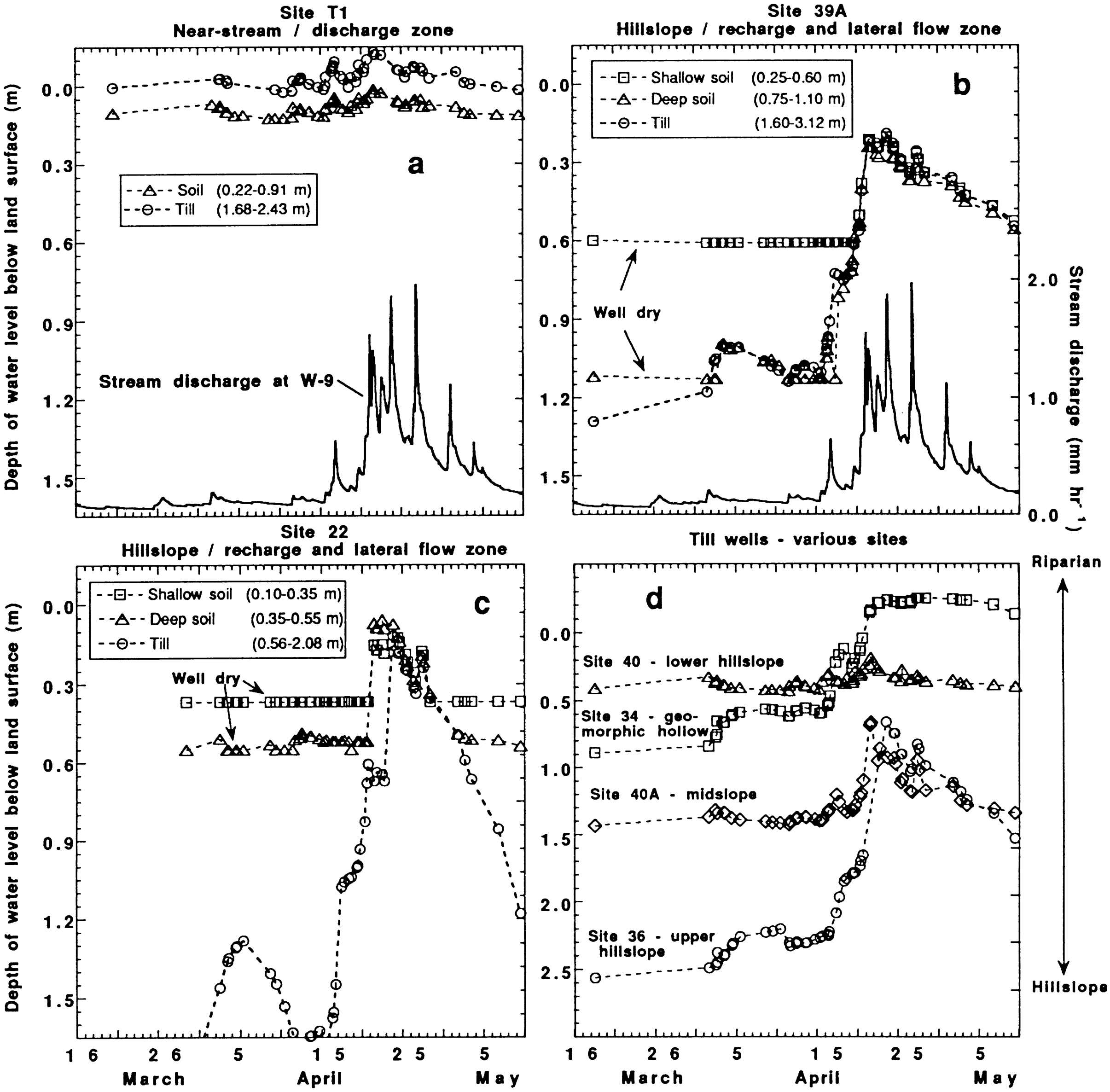

Fig. 4. Groundwater hydrographs for (a) a near-stream soil/till profile in a discharge zone, (b,c) hillslope soil/till profiles in recharge/lateral flow zones, and (d) till wells at various sites. W-9 stream hydrograph shown for comparison.

member mixing analysis (EMMA) (Hooper et al., 1990) was performed to identify actual end members and determine how they mixed to form streamwater. The solutes selected to define the end members were Ca, Mg, Na, Si, and DOC. These solutes were assumed to mix conservatively in the generation of streamwater.

4. Results

4.1. Snowmelt chronology and the stream hydrograph

Precipitation was above average in the winter of 1995–1996. Average SWE was 169 mm in the W-9 catchment by mid-March (Fig. 3), despite a series of midwinter thaws. Small diurnal melts began on 25 March. Although the snowpack SWE decreased to 109 mm by 4 April, stream discharge remained low, indicating that most of the melt replenished subsurface storage (Table 1). The snowpack rebounded to a SWE of 166 mm by mid-April. A rain/snow event on 16–17 April (Fig. 3, Table 1) was followed by 3 days of diurnal melt, then a rain-on-snow event on 21–22 April. The stream reached its snowmelt peak from the rain-on-snow event of 23–24 April, and by 25th April most of the catchment was snow-free. On 26 and 27 April, a large rain event produced an even greater streamflow peak although only subcatchment C had significant snow remaining. The ensuing post-melt recession was interrupted by a few small rainstorms.

4.2. Subsurface hydrology

4.2.1. Saturated Hydraulic Conductivity of Soil and Till

Saturated hydraulic conductivity (K_{sat}) generally increased upward in the soil profile (Fig. 2); K_{sat} was highly correlated with soil depth ($r^2 = 0.27$; $p < 0.0005$). The geometric mean of K_{sat} increased from 3.6 mm h^{-1} in the glacial till to 25.6 mm h^{-1} in deep soil to 54.0 mm h^{-1} in shallow soil. These differences were highly significant ($p < 0.05$) between the till and deep soil, and less significant between deep soil and shallow soil ($p = 0.25$). K_{sat} values of till were most variable and ranged from 0.08 to 460 mm h^{-1}. The higher values reflect the presence of permeable glacial outwash deposits. At a few sites, K_{sat} of the deeper till was greater than that of shallow till. For example, at site 14 in the headwaters of W9-B (Fig. 1), K_{sat} of shallow till was 0.44 mm h^{-1} while K_{sat} deeper in the profile was 179 mm h^{-1}. The higher K_{sat} at depth may reflect deposits of coarse materials at the bedrock/till interface. Such variability is common in heterogeneous glacial deposits (Freeze and Cherry, 1979).

4.2.2. Groundwater hydrograph patterns

Groundwater sites were classified as discharge or recharge zones based on the upward or downward hydraulic head gradient at each nest. (Screened intervals were sufficiently small to use water levels within each well as an approximation of the hydraulic head). Lateral flow zones (negligible head gradient) were also observed. Twelve of the 18 nested well sites were recharge/lateral flow zones, mostly in hillslope settings (e.g sites 22 and 40A) (Fig. 1). The six discharge sites were found either near the stream (sites T1, T4, and 4) or at breaks in slope (sites 7, 12, and C1).

Discharge and recharge zones exhibited contrasting temporal patterns of water level variations (Fig. 4). In discharge zones (e.g. site T1, Fig. 4(a)), the water table was generally close to land surface even before any snowmelt occurred. The water table rose quickly in response to diurnal melt and rain-on-snow inputs. The overall water table rise from baseflow to peak was relatively small; the range for all near-stream sites was 0.03–0.32 m of rise. The rapid rise and fall of the well hydrograph mimicked the stream hydrograph (Fig. 4(a)). However, water tables in discharge zones began to recede before peak melt, and returned to approximately premelt levels within 1–2 weeks after peak melt.

In recharge/lateral flow zones, the water table was well below land surface prior to the onset of snowmelt (Fig. 4(b,c and d)). Water levels began to rise during the first major diurnal-melt input. At some sites, groundwater hydrographs fluctuated up and down in response to diurnal melt and rain-on-snow events (e.g. site 40A, Fig. 4(d)). At other sites the water level rose almost continuously through peak melt (e.g. site 39A, Fig. 4(b); site 36, Fig. 4(d)). The unabated rise in water levels at these sites indicated that storage was filling in the till and soil. The total magnitude of water table rise was considerably greater than that in the discharge zones. By 9 May, well into the snowmelt recession period, the water table at most recharge/lateral flow sites had not receded to its premelt level. For example, the water level at Site 39A on the instrumented hillslope was 0.6 m higher on 9 May than it was on 15 April prior to the main melt (Fig. 4(b)).

At three of the 18 nested well sites, hydraulic head gradients indicated that temporary perched water tables formed during the melt period. The perched water table at site 22 (Fig. 4(c)) persisted only for a few days, until the hydraulic head in the till well rose rapidly to coincide with that in the shallow wells, indicating that the entire profile had saturated. At the midslope site (40A, Fig. 4(d)), water level in the shallow soil wells (not shown) rose to within 0.2 m of

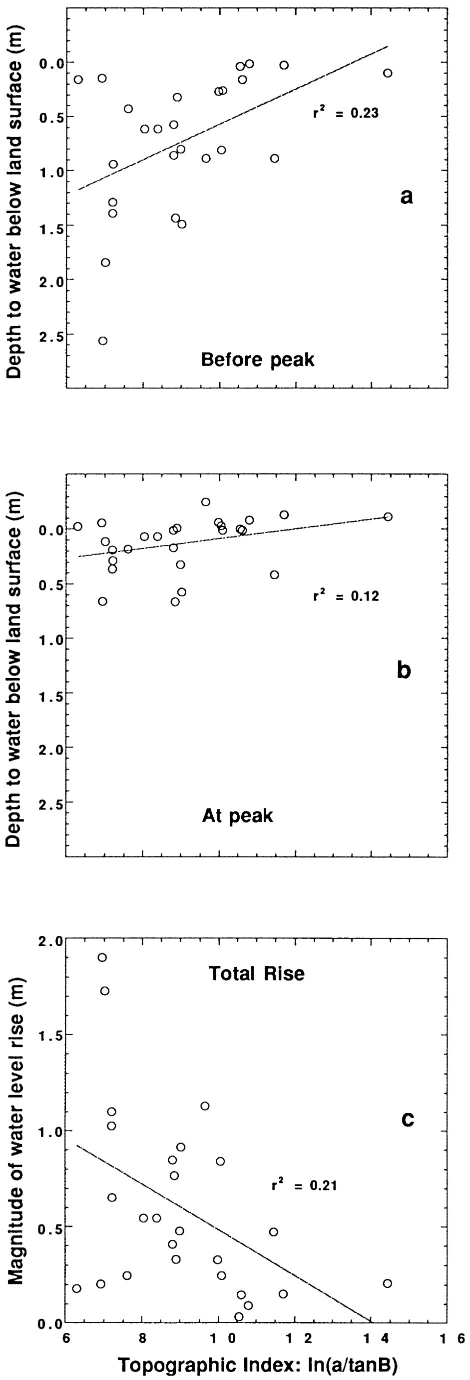

Fig. 5. Relation between depth to water and topographic index ln(a/tan β) for all till wells (a) before peak flow and (b) at peak flow, (c) relation between total water level rise during snowmelt and topographic index.

land surface for three days before peak melt, while water level in the till well remained greater than 0.6 m below land surface.

4.2.3. Groundwater levels and ln(a/tan β)

Premelt depth to water table weakly correlated with the topographic index ln(a/tan β) ($r^2 = 0.23$; $p < 0.05$) (Fig. 5(a)). Riparian sites tended to have high topographic index values, and water tables were near land surface. However, the correlation nearly vanished at peak melt when the water table approached land surface even at hillslope positions ($r^2 = 0.12$; $p < 0.1$) (Fig. 5(b)). The overall snowmelt water table rise had a weak inverse correlation with ln(a/tan β) ($r^2 = 0.21$; $p < 0.05$) (Fig. 5(c)). Hillslope sites had greater magnitude of rise than riparian sites. The greatest magnitude of rise ($>$ 1.60 m) occurred at sites with index values less than 7. No site with an index value greater than 10.5 had a rise greater than 0.50 m. Our results are in general agreement with those of Moore and Thompson (1996), who found a weak but significant correlation between observed water table variations and the topographic index.

4.3. Groundwater level-streamflow hysteresis

At all sites streamflow was strongly correlated with groundwater levels (Fig. 6). A power function ($y = ax^b$) was fitted for each of the 20 till wells; r^2 values were greater than 0.62 at all sites (all significant at $p < 0.0001$), and greater than 0.80 at 14 of the 20 sites. As snowmelt progressed, each site had a threshold water level above which streamflow increased markedly with further small rises in the water table. This threshold was within the soil zone and was closer to land surface in near-stream/discharge areas than in hillslope/recharge areas. At most sites, the threshold was reached on 21 April. By this time storage had been filled on the hillslope and water levels had risen into the transmissive zone in both near-stream and hillslope settings.

At most sites there was a marked hysteresis in the groundwater level—streamflow relation (Fig. 6). In riparian zones, the hysteresis was clockwise; groundwater levels were higher on the rising limb of the stream snowmelt hydrograph than at the same streamflow on the recession limb. At hillslope sites, hysteresis was counterclockwise; groundwater response

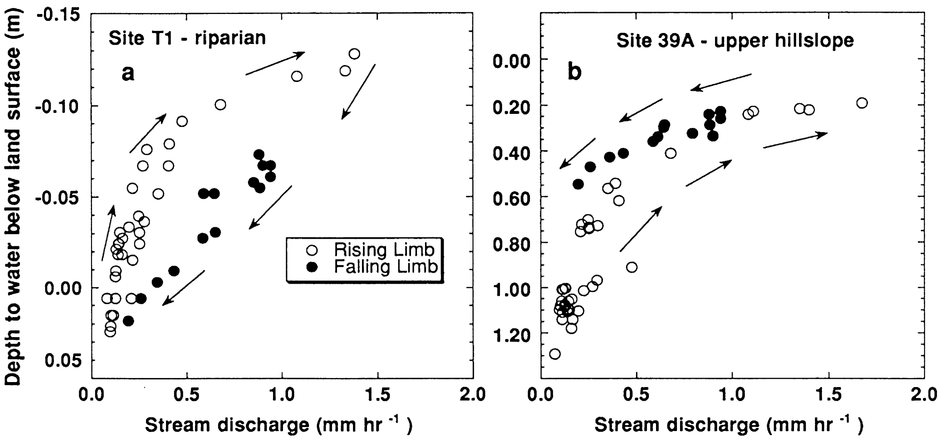

Fig. 6. Relation between groundwater level and stream discharge for (a) near stream, and (b) upper hillslope sites. Arrows denote approximate time sequence, indicating hysteresis. Note difference in *y*-axis scales.

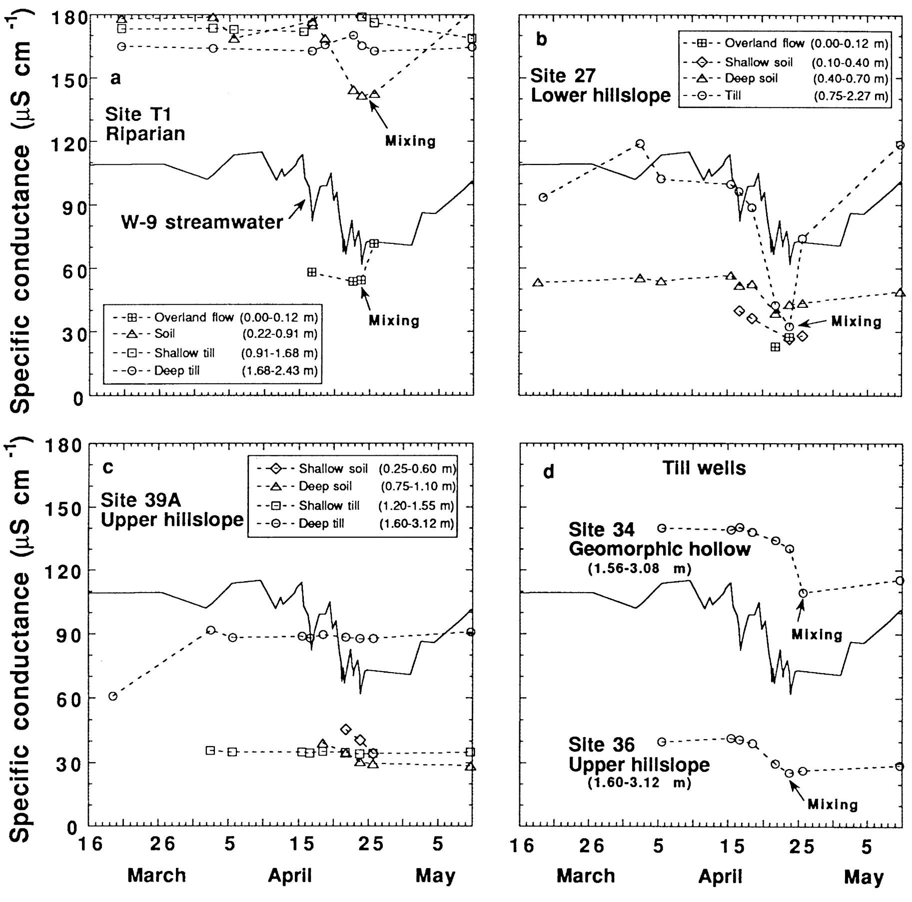

Fig. 7. Temporal trend in specific conductance of W-9 streamwater (all panels), and till water, soil water, and overland flow for (a) near stream, (b) lower hillslope, (c) upper hillslope, and (d) two contrasting hillslope sites (till water only).

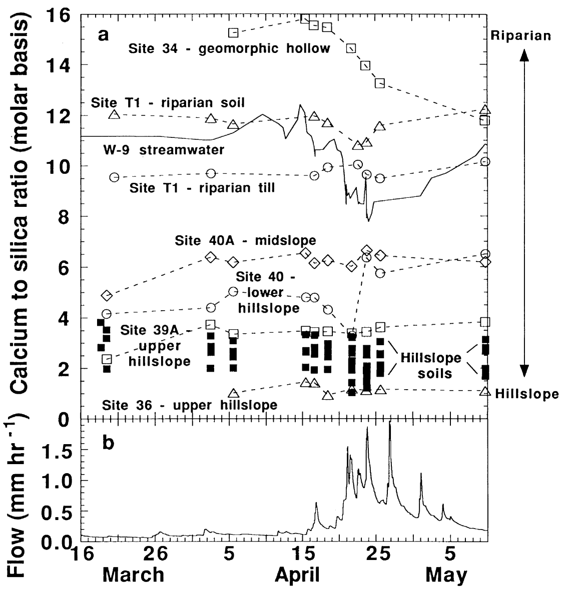

Fig. 8. Temporal trend in (a) calcium/silica ratios for till water at several sites and riparian soil water at one site on the instrumented hillslope (open symbols) and all instrumented hillslope soil waters (solid symbols), and (b) W-9 streamflow.

lagged the streamflow increase, but once recharge occurred, water levels remained high well into the streamflow recession limb. The threshold concept and power function relation between groundwater level and stream discharge were most applicable to the rising limb; hysteresis resulted in a more linear relation on the falling limb (Fig. 6). A power function applied to the whole melt period at the riparian T1 site (Fig. 6(a)) had an r^2 of 0.64, compared to an r^2 of 0.88 for the rising limb only.

4.4. Spatial and temporal patterns in chemistry

4.4.1. Streamwater chemistry

Streamwater chemistry was strongly linked to stream discharge. Of the five solutes analyzed, only DOC increased with increasing flow (log function, $r^2 = 0.82$). From base flow to peak flow, DOC increased by a factor of 2.7. In contrast, base cation and Si concentrations were diluted by increasing flows, with very high r^2 values (log function); 0.98 for Ca and Mg, 0.92 for Na, and 0.84 for Si. From base flow to peak flow, Ca and Mg were diluted by 50%, Na by 40%, and Si by 32%. Specific conductance was also highly correlated with discharge ($r^2 = 0.98$), in keeping with the dominance of Ca in this calcareous catchment. The patterns of specific conductance discussed next are generally representative of the behavior of the base cations and Si.

4.4.2. Specific conductance

Spatial variability of specific conductance in the soil/till profile was greater than temporal variability (Fig. 7). At the near-stream site (T1), specific conductance was high (160–185 μS cm^{-1}), and uniform through the profile (Fig. 7(a)). An upward hydraulic head gradient kept the conductance of soil waters nearly as high as that of till water. This pattern was noted in four of the six discharge sites in this study. Even overland flow at the near-stream site had a higher conductance than soil water at most recharge sites.

The specific conductance of hillslope till water ranged from 60 to 140 μS cm^{-1}, less than that of near-stream till water, but bracketing the range of streamwater (Fig.7 (b and c)). The conductance of hillslope soil water ranged from 20 to 60 μS cm^{-1}, which was two to three times less than till water at most sites. At a given site, shallow soil water and deep soil water tended to have nearly the same conductance. Till water was diluted during snowmelt at nine of the 12 recharge/lateral flow sites, suggesting mixing with meltwater or soil water. The amount of dilution was minor, except for a greater than two-fold dilution at site 27 (Fig. 7(b)).

Specific conductance of till water varied considerably as a function of topographic setting (Fig. 7(d)). At site 36, in a recharge zone where the depth to water table was greater than 3 m during summer and fall, specific conductance ranged only from 25 to 45 μS cm^{-1}. At site 34, 20 m away and 1.5 m lower in land surface elevation, but in a geomorphic hollow where water discharged and flowed overland during high flows, specific conductance ranged from 105 to 140 μS cm^{-1}.

Theoretically, as the topographic index increases, residence time of subsurface water should also increase (Wolock et al., 1997). As increased residence time promotes increased weathering, one would anticipate a positive correlation between the specific conductance of groundwater and the topographic index. For till water in W-9, however, specific conductance was only weakly correlated to the

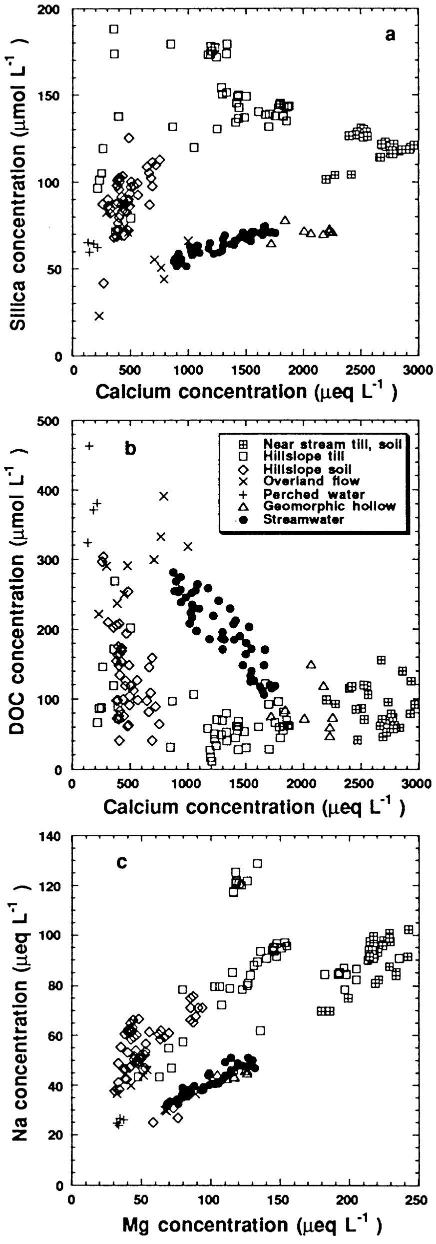

Fig. 9. Bivariate mixing diagrams for (a) silica and calcium, (b) DOC and calcium, and (c) sodium and magnesium. Plots include compositions of W-9 streamwater and potential end members.

topographic index ($r^2 = 0.13$, $p < 0.2$). For soil water and overland flow, there was no significant relation at all, perhaps because residence times of water in these zones was short regardless of topographic position.

4.4.3. Calcium to silica ratios

Calcium-to-silica ratios in subsurface waters ranged widely, from less than 1 to nearly 16 (molar basis) (Fig. 8). As with specific conductance, spatial variability was much greater than temporal variability. The Ca/Si ratio generally increased toward the stream. All soil water Ca/Si ratios were consistently in the range of till water from the upper hillslope, except at the near-stream discharge site (T1), where Ca/Si of soil water was similar to that of the riparian till water at that site. The Ca/Si values at the near-stream site were much higher than those on the hillslope, and were similar to those of streamwater. Till water at the geomorphic hollow (site 34) had Ca/Si that was anomalously high relative to other hillslope sites, and somewhat higher than that of streamwater.

4.5. PCA and EMMA

Stream solute concentrations were used in a principal components analysis (PCA) following Christophersen and Hooper (1992). Nearly 94% of the variability in stream chemistry could be explained by just one principal component, implying that streamwater is primarily a mixture of two end members. To apply end-member mixing analysis (EMMA), candidate end members were selected by identifying the solutions that bound streamwater concentrations for all pairwise combinations of the solutes (Hooper et al., 1990). Potential end members were grouped into 6 water types on 2-component mixing diagrams (Fig. 9) as follows: *near-stream soil/till water* from one well nest located on a stream bank (T1); *hillslope till water* from five sites on the instrumented hillslope transect (36, 39A, 40A, 27, 40); *hillslope soil water* from four of these five sites (no soil water wells existed at site 36); *overland flow* from all O-horizon/overland flow cups; *perched soil water* from one midslope site (40A); and till water from the *geomorphic hollow* site (34) where the water table rose above land surface. Meltwater alone was not evaluated as an end member based on an earlier study at Sleepers River (Titus et al., 1995), wherein the meltwater flowing overland was found to rapidly lose its isotopic signature through mixing with discharging groundwater.

The potential end members differed significantly in chemical composition. With the exception of hillslope till water, each of the potential end members plotted in a fairly small field on the bivariate plots (Fig. 9). This grouping pattern occurred despite the fact that the end member compositions represented a broad range of hydrologic conditions, and in some cases diverse locations. Three examples of the 10 possible bivariate plots are presented.

On the Si–Ca bivariate plot (Fig. 9(a)), streamwater formed a linear pattern bounded by geomorphic hollow water at base flow and overland flow water at high flow. Waters from the near-stream site plotted approximately on the streamwater line but were about two times more concentrated than base flow. All other waters plotted above and well away from the streamwater line (perched water was only slightly above the line). Compared to streamwater, subsurface hillslope water was generally enriched in silica, indicative of a labile source of silica in the mineral soil (Shanley et al., 1995a), and somewhat depleted in calcium, suggesting less contact with unweathered calcareous till. The resulting low Ca/Si ratios (Fig. 8) caused hillslope waters to plot in a field quite distinct from that of streamwater. Si and Ca concentrations increased from soil water to till water. The most concentrated till water samples had Ca similar to the stream at base flow, but had nearly 3 times as much Si. Thus, hillslope till and soil water were not viable end members of stream composition; no low-Si end member was identified with which the hillslope water could mix to form streamwater.

In the DOC–Ca bivariate plot (Fig. 9(b)), candidate end members occupied broader fields but more successfully bounded stream concentrations. Near-stream waters were distinct from hillslope waters; hillslope till waters were variable with some sites resembling soil water. Soil waters varied little in Ca but varied widely in DOC, although only a few soil water samples approached the high peak DOC concentrations in the stream. Overland flow water and perched soil water had DOC concentrations high enough to bound streamwater. As melt progressed streamwater composition shifted toward these high-DOC signatures.

In the Na–Mg bivariate plot (Fig. 9(c)), the hillslope waters (with the exception of a few points) did not adequately bound the streamwater composition. As in the Si–Ca plot, most hillslope waters plotted along a line different from that of streamwater, suggesting a different control on hillslope water composition. The field for the geomorphic hollow water, however, directly coincided with that of the stream.

In summary, on all EMMA bivariate plots, W-9 streamwater composition occupied a linear field, bounded at one end by a deep flow path component–geomorphic hollow water or near-stream till water (high in base cations and silica and low in DOC), and at the other end by a shallow flow path component–overland flow water or perched soil water (low in base cations and silica and high in DOC). Subsurface hillslope waters were not viable end members during snowmelt.

At peak flow, stream chemistry could be explained as a mix of discharging, near-stream groundwater and shallow organic horizon flow. The organic horizon flow, however, was transient. It occurred when groundwater levels rose into the surficial transmissive zone, but this zone drained rapidly following events. Therefore, at baseflow it is unlikely that the organic horizon end member contributed significantly to streamflow. Perched groundwater also drained quickly and was not spatially extensive (observed at only three of the 18 nested well sites). As shallow flow path contributions diminished on the event hydrograph recession, near-stream groundwater in itself was too concentrated to explain stream baseflow. From these considerations, geomorphic hollow water is a more suitable choice than near-stream groundwater as the deep flow path end member.

5. Discussion

Based on the groundwater hydrographs and soil/till hydraulic properties, transmissivity feedback appeared to play a key role in the snowmelt response at Sleepers River. However, the chemical data suggest that the contribution of hillslope water to the stream is minor. The hydrologic and chemical response of subsurface waters was only weakly related to surficial topography, as represented by the topographic index. Perhaps the subsurface bedrock topography dictated subsurface flow paths, as found at Panola Mountain, Georgia by McDonnell et al. (1996). The geomorphic hollow site discussed in this study may be just such a subsurface convergent zone. The following discussion centers on the 3 questions raised in the Introduction.

5.1. Do hydrometric and chemical evidence support transmissivity feedback theory?

Saturated hydraulic conductivity generally increased toward land surface in the soil/till profile in this forested headwater catchment. As infiltrating snowmelt filled storage on the hillslope, groundwater levels rose into the surficial transmissive zone. In transmissivity feedback theory (Bishop, 1991), additional water inputs drain rapidly through the more transmissive upper soil horizons. The rate of water table rise slows as water moves rapidly to the stream via near-surface flowpaths.

The groundwater–streamflow relation provides a key test of the transmissivity feedback hypothesis. Each site had a groundwater level threshold above which the streamflow increased sharply. This threshold, which was most apparent on the rising limb, corresponded in general to the depth in the profile at which measured K_{sat} increased. In other words, when water rose into the more transmissive soil zone, stream discharge increased significantly and further rise in the water table was small. Further, stream DOC concentrations increased during high flows, suggesting that DOC was flushed from shallow soil horizons as groundwater levels rose into those horizons (Boyer et al., 1995; Hornberger et al., 1994). Thus, both the hydrologic patterns and DOC concentration dynamics were consistent with transmissivity feedback theory.

The streamflow–groundwater level relation had a hysteresis which indicated differences in the timing of contributions from near-stream and hillslope zones. At riparian sites, hysteresis was clockwise, i.e. the water table was higher for a given discharge on the rising limb compared to the same discharge on the falling limb. This clockwise hysteresis suggested that the rising limb of the snowmelt hydrograph was controlled by rapid drainage from transmissive near-stream zones. The spatial extent (near-stream only) of this rapid rising limb response of the water table is also consistent with groundwater ridging theory (Novakowski and Gillham, 1988). However, the high transmissivity in the upper soil layers would prevent the formation of a near-surface capillary fringe necessary for flow generation by groundwater ridging. At hillslope sites, hysteresis was counter-clockwise, suggesting a greater hillslope contribution to flow during the post-peak recession limb of the stream hydrograph. At nearly all sites, regardless of landscape position, the time of highest water table was nearly simultaneous with peak stream discharge.

During the rising limb, while the riparian areas were controlling the stream response, meltwater inputs on the hillslope were filling storage in the low-permeability till. Peak flow occurred on 26 April when a 28 mm rainfall on the remaining patchy snowpack caused water tables throughout the catchment to rise into the zone of high transmissivity. After the rapid drainage from the shallow transmissive zone, hillslope groundwater levels declined gradually in parallel with streamflow recession, until stream baseflow returned to premelt levels in June. The opposing senses of hysteresis at riparian and hillslope sites suggest that the falling limb of the stream hydrograph was controlled by contributions integrated from a broad area—i.e. the catchment hillslopes. However, chemical evidence indicates that hillslope till and soil water contributions to streamflow were limited.

5.2. Do hillslope till and soil water contribute to streamflow during the snowmelt period?

In regard to streamflow contributions from the hillslope, the hydrometric and chemical evidence pose a broad paradox. The large water table rise in upper hillslope positions, coupled with the evidence for transmissivity feedback and the rapid downslope movement of water, suggest that the hillslope plays a key role in streamflow generation. However, both till and soil water sampled from various sites on the hillslope consistently had the "wrong" chemistry to explain stream composition. Hooper et al. (1998) likewise found a lack of chemical expression of hillslope water inputs to streamwater at the Panola catchment in Georgia. Hinton et al. (1994), in contrast, used isotopic evidence to show that subsurface flow through soil and glacial till did make a significant contribution to streamflow in a catchment in Ontario.

The lack of participation of the hillslope in the snowmelt runoff event is best illustrated by the failure of streamwater composition to shift toward the subsurface hillslope water field during snowmelt

(Fig. 9). Most notably, hillslope waters had excess silica relative to streamwater. While Si is not an ideal conservative element, it is difficult to forsee a mechanism by which hillslope waters could *lose* Si en route to the stream. Precipitation of Si was ruled out because all waters were highly undersaturated with respect to any Si mineral. Adsorption of Si was ruled out because adsorption would most likely have regulated Si within the soil and till prior to sampling. Uptake of Si by benthic diatoms was deemed unlikely given the cold streamwater temperatures of 1–2°C and the high stream discharges. Valett et al. (1996) found that biological nutrient uptake (in their case, of nitrogen) was relatively constant over a range of temperatures in a New Mexico stream, so that relative uptake was minimal under conditions of high discharge.

To recapitulate, hydrometric evidence suggested that shallow groundwater on the hillslope would be an end member that represents the dilution of streamwater during snowmelt. Instead, chemical evidence suggested that the hillslope was hydrologically decoupled from the riparian/stream system. We offer four possible explanations to reconcile the discrepancy between the hydrometric and chemical findings:

1. Planar hillslopes are hydrologically inactive zones compared to convergent zones or geomorphic hollows. This explanation would appear to be refuted at W-9 by the dynamic water table rise and sustained recession on the hillslope. However, Anderson and Burt (1978) measured groundwater inputs at intervals along a stream reach and found that hollows were the major source of streamwater in terms of input per unit length of channel and input per unit area of hillslope drained. At the geomorphic hollow (site 34), the water table rose markedly and remained elevated for weeks after peak streamflow because of a large upslope contributing area. Although the planar hillslope groundwater behaved similarly, the chemical signature of the hollow site was similar to the stream signature, indicating that hollows may “funnel” a high percentage of subsurface water to the stream.
2. Hillslope till and soil waters may mix with waters lower in silica and contribute to streamflow as a mixture. The mixing zone may be within the geomorphic hollows as discussed above, or there may be an end member low in silica that was not sampled.
3. Till and soil water from the hillslope studied is not representative of the catchment. There may be till and soil water signatures in other areas of the catchment that do explain stream chemistry. However, McGlynn et al. (1999), working in the headwaters of W-9B, found solute concentrations in till and soil water that were similar to those in this study.
4. The volumetric contributions of hillslope till and soil water are small compared to the subsurface riparian zone reservoir. Although the 2–3 m till thickness as determined from the cone penetrometer would seem to limit the potential size of the riparian reservoir, there may be areas of deeper till and/or fractured bedrock that increase its effective size. The possibility of bedrock fracture flow at W-9 has not been investigated.

5.3. What is the role of geomorphic hollows?

Hillslope sites were sampled with the expectation of finding recharge waters that were potential end members of streamflow composition whose contributions to streamflow increased during snowmelt. However, the geomorphic hollow (site 34) proved to be in a discharge zone, and it had the proper composition of an end member for *base flow* (Fig. 8). During snowmelt, the hydraulic head at the geomorphic hollow site rose rapidly from 0.9 m below land surface to nearly 0.3 m above land surface (Fig. 4(d)). From 20 April until beyond the end of the study period (9 May), flow emanated from a point near the sampling well and flowed overland for a few meters before reinfiltrating downslope. Although the general shape of the groundwater hydrograph at the hollow site (rapid rise and gradual recession) was similar to other sites (Fig. 4), the water level remained above land surface for at least 20 days. Because the water table was well within the zone of transmissivity feedback, the sustained high water level suggests that the site was fed by a large reservoir of subsurface water from upslope. We propose that the geomorphic hollows, or depressional areas of convergent flow, might be an important transit zone for groundwater of base flow composition from the hillslope to the stream.

Sidle et al. (1995) found that geomorphic hollows or zero-order basins appear to contribute to stormflow when a threshold of saturation is reached. Until this time geomorphic hollows contribute subsurface flow much like any other part of the hillslope. Woods and Rowe (1996) measured subsurface stormflow at 30 points in a trough across the base of a steep forested catchment. They found that flow varied with surface topography and was greatest at the base of convergent areas. In a similar study, McDonnell et al. (1996) found that subsurface bedrock topography was the main control on subsurface flow. The notion that geomorphic hollows might be important source areas of well-mixed waters is an extension of the variable source area concept (Hewlett and Hibbert, 1967). Storm runoff is generated on only a small part of the catchment. The contributing area varies seasonally and is significantly larger during spring snowmelt than during short, intense summer storms (Dunne and Black, 1970a,b).

Geomorphic hollow water has the appropriate composition for the base flow end member for W-9 streamwater. The riparian till water is the only other candidate end member that plots on the base flow end of the streamwater line, but it is enriched in Si and base cations relative to the hollow water. The composition of the hollow water and its similarity to stream composition suggest a chemical evolution that is common in the catchment, but was largely missed by the sampling scheme, perhaps because this water discharges in a limited number of convergent areas. In this conceptual framework, the geomorphic hollow water represents water of approximately average residence time in the catchment, and the riparian groundwater has above-average residence time.

6. Conclusions

Hydrometric and geochemical evidence support the transmissivity feedback hypothesis of streamflow generation during snowmelt in the W-9 catchment. Saturated hydraulic conductivity increased toward land surface, and groundwater levels rose close to land surface even at hillslope sites during snowmelt. Most sites had a clear threshold water table above which further rise was small, and this point generally coincided with large increases in stream discharge. Streamwater DOC concentration had a strong positive correlation with stream discharge indicating that as flow increased, an increasing proportion of streamflow was generated by flow through the surficial organic horizons. The DOC increase was consistent with the high water tables and further supported the transmissivity feedback hypothesis.

During the 1996 snowmelt, contrasting patterns of groundwater level fluctuations and chemical compositions were observed in the soil/till profile at near-stream (discharge) zones, hillslope (recharge/lateral flow) zones, and a geomorphic hollow site. Near-stream groundwater levels were higher on the rising limb of the stream hydrograph than at the same point on the falling limb. This clockwise hysteresis indicated that near-stream sources to streamflow were most important early in the melt.

As snowmelt progressed, two changes occurred. First, shallow flowpaths increased in importance. The stream shifted toward a DOC-rich composition similar to that of O-horizon/overland flow water. Second, storage in the hillslope was replenished. Counterclockwise hysteresis in the groundwater–streamflow relation at hillslope sites reflects this filling of storage capacity and suggests that drainage of hillslope till and soil water controlled flow during the falling limb of the snowmelt hydrograph.

Despite the hydrometric evidence of a large hillslope contribution to streamflow, hillslope till and soil water did not have the right chemistry to be viable end members of streamwater composition. Both had silica concentrations higher than those in streamwater even at low flows. This apparent decoupling of the hillslope and riparian zone may be a simple reservoir size problem, whereby additions of hillslope water to the near-stream zone are small compared to the size of the riparian subsurface reservoir. Groundwater that discharged from a geomorphic hollow, on the other hand, had a composition very similar to streamwater base flow. Streamwater appears to be a two-component mixture of a groundwater of this composition diluted by a shallow O-horizon/overland flow water during snowmelt.

Acknowledgements

This research was supported by the US Geological Survey Water, Energy, and Biogeochemical Budgets (WEBB) program. We are grateful to Thor Smith, Ann Chalmers, and Jon Denner for their valuable insights and assistance in the field. Thanks are also due to Don Siegel, Geology Department, Syracuse University for providing his laboratory and expertise with the chemical analyses and to David Wolock of the USGS for providing topographic data and interpretation.

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