

Shallow Water Table Fluctuations in Relation to Soil Penetration Resistance

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Abstract

Hydrologic modeling of catchments is frequently hampered by lack of information on subsurface stratigraphy and zones of preferred flow. We evaluated the usefulness of soil penetration resistance, easily measured by a dynamic cone penetrometer, together with measurements of ground water level fluctuations, as a cost-effective means to infer subsurface flow patterns. At our field site at Sleepers River, Vermont, penetration resistance was lowest in the surficial 10 to 30 cm, then typically increased to a local maximum at 60 to 80 cm, which we interpreted as the soil/till interface. Below this depth usually lies a zone of decreased resistance in the till, giving way to either a gradual or abrupt increase in resistance toward the bedrock surface at 1 to 4.5 m depth. Penetration resistance had a weak but significant negative correlation with saturated hydraulic conductivity determined by bail tests ($r^2 = 0.25$, $p < 0.05$). At many wells, monthly ground water levels tended to cluster at or just above the resistant zone near the soil/till interface. Chemical and isotopic dynamics in nested wells finished above and below the resistant zone suggest that the zone may temporarily isolate the deeper ground water reservoir from meltwater inputs, which were clearly identified by low $\delta^{18}\text{O}$ values. In ground water discharge zones, $\delta^{18}\text{O}$ values tended to converge throughout the profile. In contrast, dissolved organic carbon (DOC) maintained a gradient of increasing concentration toward land surface, even in otherwise well-mixed waters, reflecting its rapid release from organic horizons. Understanding the effect of soil penetration resistance on ground water behavior may be useful in future catchment modeling efforts.

Introduction

A common approach in small catchment research is to study fluxes and processes in individual landscape components and determine how they scale up or combine to form the integrated catchment response in streamflow. Ground water is a key component as it usually supplies most of the streamflow, while chemical evolution along the ground water flowpath controls the dominant stream chemical signature of the catchment. Even stormflow and snowmelt runoff are generally dominated by ground water (Buttle 1998), but sufficient recharge may cause formation of shal-

low ground water of contrasting chemical composition (Kendall et al. 1999). This paper looks at the dynamics of the ground water system, including the relative importance of these deep and shallow ground water sources to streamflow and the degree to which they mix.

The dominant stormflow generation process in humid temperate landscapes is saturation overland flow (Dunne and Black 1970). The response of streams to rainfall or snowmelt is largely dependent on the extent of surface saturation (where the water table rises to land surface) and the water needed to achieve this condition at any given point (the saturation deficit). Tracking the saturation deficit and extent of saturated areas (where deficit = 0) is a key feature of the topographically based TOPMODEL (Beven and Kirkby 1979), which is being applied at this catchment.

The other important factor in streamflow generation is the texture and distribution of aquifer materials, which determine the hydraulic conductivity (Masch and Denny 1966; Freeze and Cherry 1979). The saturated hydraulic conductivity (K_{sat}) regulates aquifer yield to stream water at a given water table level and controls how quickly water infiltrates (Bishop 1991). The overlay of local soil-moisture

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conditions on these aquifer properties thus determines the position of the water table—and ultimately, streamflow.

The position of the water table also plays a role in stream water chemistry. Infiltrating rain and snowmelt, modified by passage through the organic-rich surficial soil, recharge the ground water. The chemistry of this newly recharged shallow ground water may be markedly different than that of the deeper pre-existing ground water (Christopherson and Hooper 1992). The latter is generally dominated by solutes derived from weathering of minerals in the soil and bedrock. Freshly recharged ground water is generally dilute in weathering solutes but enriched in surficial soil leachates such as DOC, nitrate, and silica (Kendall et al. 1999). It may take some time for these waters to mix, during which time the shallow ground water system remains chemically stratified. Younger ground water readily discharges to stream water because of higher hydraulic conductivities typically found in surficial soils (Bishop 1991; Kendall et al. 1999). The chemical and isotopic signature of this discharging shallow ground water will reflect its recent origin.

In this study, conducted at Sleepers River, Vermont, we analyzed a 10-year record of monthly water table fluctuations and one snowmelt period of chemical and isotopic variations of ground water, with respect to profiles of soil-penetration resistance determined by a dynamic cone penetrometer. Soil penetrometers have a long history of use for

soil assessments in agriculture (Shaw et al. 1942; Hillel 1982) and construction sites (Bonita 2000). The concept has only recently been applied to hydrological studies at forested sites (Yoshinaga and Ohnuki 1995; Zumbuhl 1998; McGlynn et al. 1999). Hjerdt (2002) investigated fine-resolution ground water dynamics in relation to soil characteristics at the present study site during the 1999 snowmelt.

The analysis was performed at various geomorphic settings within a small forested catchment. The objective was to evaluate the role of resistant zones within the shallow aquifer in controlling the water table and stream water chemistry. The working hypothesis was that soil penetration resistance as determined by the dynamic cone penetrometer is negatively correlated with hydraulic conductivity. If so, the relatively easy-to-acquire data (10 to 20 profiles per day with a two-person team) could provide valuable surrogate information on hydraulic conductivity without the need for well installations.

Study Site

The study area was the forested, 41 ha (hectare) W-9 catchment at the Sleepers River Research Watershed in northeastern Vermont (Shanley et al. 2002; Shanley and Chalmers 1999) (Figure 1). The research watershed was established in 1957 by the U.S. Department of Agriculture

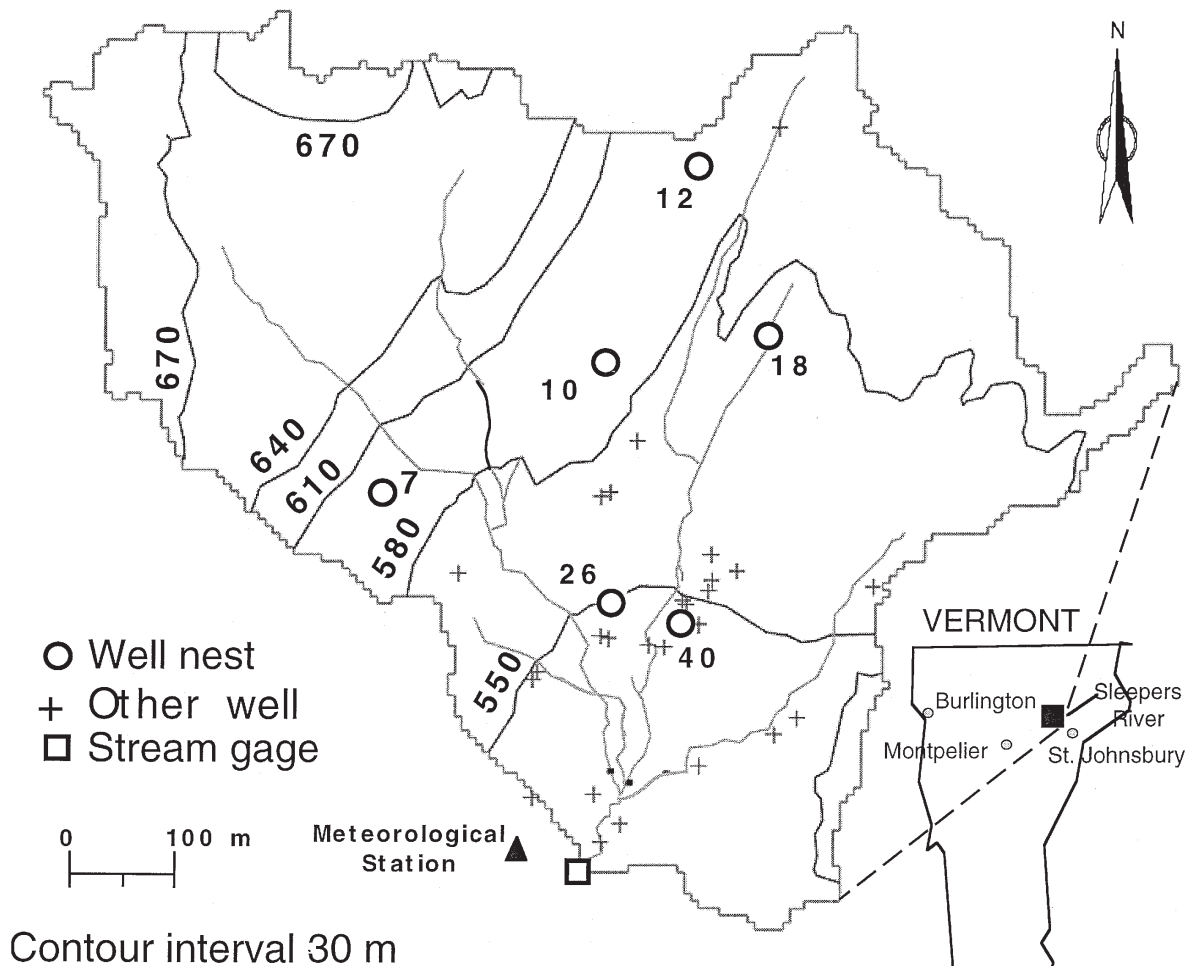


Figure 1. Topographic map of Sleepers River Watershed W-9 showing sampling well locations. One- and two-digit numbers are well nests referenced in the text. Three-digit numbers denote elevation contours in meters.

(USDA), Agricultural Research Service, and has been the site of hydrologic and biogeochemical process research by the U.S. Geological Survey (USGS) and collaborating academic institutions and federal agencies since 1991. Sleepers River is one of five sites of the USGS Water, Energy, and Biogeochemical Budgets (WEBB) research program.

The W-9 watershed ranges in elevation from 520 to 675 m and is entirely forested with northern hardwoods (sugar maple, white ash, yellow birch, American beech) with small pockets of softwoods (red spruce, balsam fir). The forest was partially harvested in 1929 and reharvested for yellow birch in 1960; the watershed may have been cleared for grazing in the 1800s (Thorne et al. 1988). The relatively steep terrain in the catchment is broken up by an upper plateau, headwater swamps, mid-elevation benches, and gentle slopes in the lowest elevations. The area is underlain primarily by the Waits River Formation, a calcite-bearing granulite interlayered with a micaceous phyllite (Hall 1959). About 1 to 4 m of glacial till derived primarily from the Waits River Formation, but also from some granitic sources, mantles the bedrock. The till is a dense, blue-gray to olive basal till dominated by fine silt (Newell 1970; Springston and Haselton 1999).

Approximately 50 to 90 cm of soil is developed on the glacial till (Kendall et al. 1999; McGlynn et al. 1999). The two main soil types present are typic dystocrepts (spodosols and inceptisols) in the uplands and histosols in the lowlands. Histosols also occupy flat, swampy headwater areas and hillslope discharge zones. They have mucky surface horizons and are poorly drained. The dystocrepts are generally well drained. Cobble and boulder content is surprisingly low in much of the catchment, possibly because the original clasts have weathered to the point that they are weaker than the matrix; near-complete saprolitization of cobbles and small boulders was observed in many excavations.

Methods

The dynamic cone penetrometer, known also as the knocking pole (Yoshinaga and Ohnuki 1995), consists of several 0.5 m flights of 15 mm diameter stainless steel rod with etched graduations every 5 cm. A 20 mm long, 24 mm diameter cone attached to the lead flight is driven into the soil with increments of equal force, imparted by repeatedly dropping a 5 kg sliding weight from a 63 cm height onto a strike plate threaded to the topmost flight. Data are recorded as the number of drops, or "knocks," required to drive the pole each 5 cm increment. Bedrock was operationally defined as the point where more than 15 knocks were needed to move the pole 5 cm, although this criterion was relaxed if clear downward progress was still detected. The plate could be inverted and struck from below to extract the pole. The penetrometer had 10 flights, enabling measurement to 5 m depth. A byproduct of this effort is a determination of depth to bedrock if not >5 m. Knocking-pole profiles were acquired at 88 sites on a grid in W-9 and at selected well-installation sites.

Forty 5 cm diameter PVC wells were installed in the W-9 catchment in 1991 (Thomas 1992). Wells were placed in 10 cm holes augured to bedrock at 1.5 to 4 m depth below land surface. Machine-slotted screens made up the

bottom 1.5 m of each well. The holes were backfilled with native materials and a rubber packer was installed above the screen. Water levels have been recorded monthly since installation, with more frequent readings during some snowmelt periods. Knocking-pole profiles were acquired in the winter of 1996 at several existing well sites representing a range of hillslope and riparian settings. The immediate purpose for this knocking-pole work was to guide the depths and screening intervals for sets of nested wells to be installed to monitor the 1996 snowmelt. The new shallow nested wells were screened over 30 cm intervals; either two or three wells were installed as needed to fully represent the zone from the soil/till interface (inferred from a sharp increase in resistance to penetration) to the soil surface. In addition, a small perforated polyethylene cup was set into the uppermost 8 cm of forest floor to collect ground water at land surface when saturated. Bail tests (Hvorslev 1951) were performed at each well of all nested well sites near peak water table level to determine K_{sat} (Kendall et al. 1999).

During the 1996 snowmelt, water level measurements were made at the original and shallow-nested well sets on a daily or subdaily schedule (Kendall et al. 1999). Samples were collected on 10 dates at some of the well nests for major ions and $\delta^{18}\text{O}$. Tracking the chemistry and isotopes over time at different depths within the saturated zone allowed an assessment of stratification and mixing in the subsurface. Major cations and silica (Si) were analyzed on filtered (0.4 μm cellulose acetate membrane) and acidified (HNO_3 to pH 1.0) samples by direct-current plasma-emission spectrometry at the Syracuse University Department of Geology. Major anions were analyzed by ion chromatography at the U.S. Geological Survey laboratory in Atlanta, Georgia. Dissolved organic carbon (DOC) was analyzed by ultraviolet persulfate oxidation with infrared detection at the U.S. Geological Survey laboratory in Troy, New York. Finally, $\delta^{18}\text{O}$ was determined by mass spectrometry at the U.S. Geological Survey laboratory in Menlo Park, California.

Results and Discussion

General Resistance Patterns

In general, resistance to penetration increased with increasing depth in the soil/till profile (Figure 2). In most profiles, resistance increased sharply at some point between 40 and 100 cm depth. Where soil descriptions were available, this discontinuity generally corresponded to the soil/till interface, or the B/C horizon boundary (Figure 3). This relatively resistant zone in the upper till was generally 15 to 25 cm thick and, in many profiles, gave way to a zone of easier penetration below it. From this zone down to the bedrock surface, resistance increased in a gradual though often erratic pattern.

Resistance to penetration may be locally affected (increased) by clasts or roots. Past experience from well installations and observations of soil pits indicated that rock fragments are minimal in many of the watershed soil types. An experienced penetrometer user can usually distinguish clasts from bedrock and move to another site. Roots are

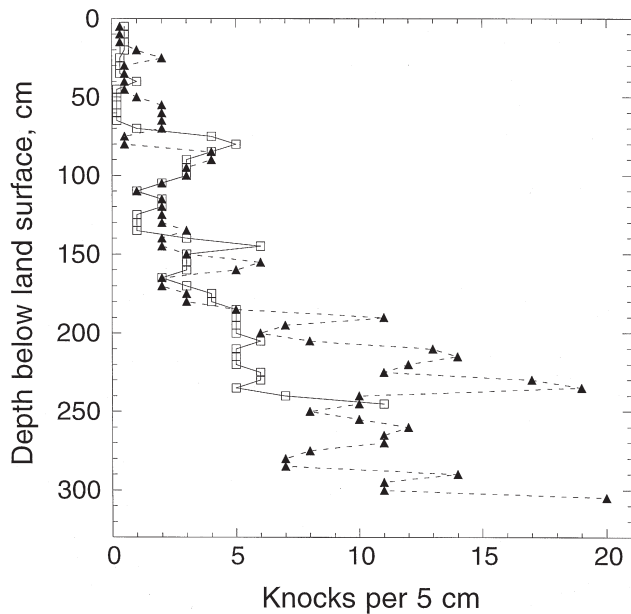


Figure 2. Typical soil/till resistance profiles from penetrometer data. The two symbols represent two sites 1 m apart to show reproducibility.

more easily identified because they are generally shallow in the profile and they cause the penetrometer to bounce. Reproducible depth to bedrock determinations during well installations (Thomas 1992) and consistent depths determined by the knocking pole at a well site compared to the original well-installation depth suggested that refusal was caused by bedrock and not by clasts or boulders within the till.

As a test of reproducibility of the knocking-pole data, we profiled two sites 1 m apart. The resulting resistance profiles agreed in their major features, though resistance

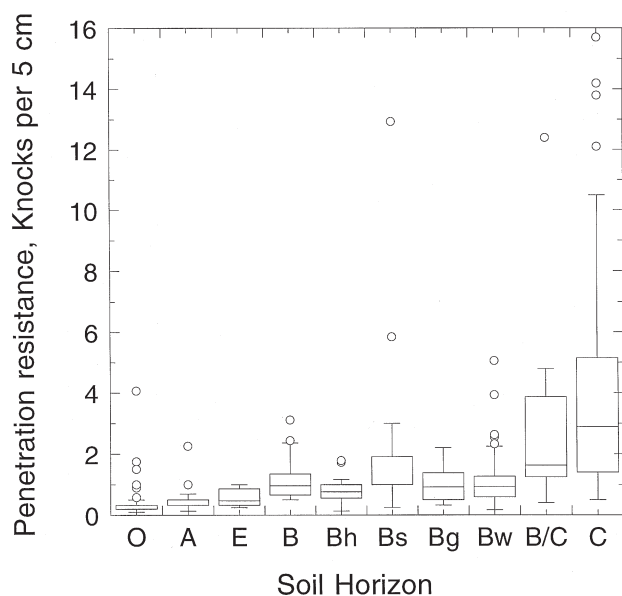


Figure 3. Boxplot of resistance to penetration, by soil horizon, from 88 grid sites. The horizontal line within each box represents the median; the top and bottom of each box represent quartiles; the ticks above and below each box represent the 10th and 90th percentiles; points beyond the ticks represent outliers.

peaks and troughs were offset by ~10 cm depth (Figure 2). Minor resistance peaks appearing in one profile but absent in the other may represent the effect of clasts. This test, and the generally consistent pattern among most of the sites tested, suggests that the resistance profiles capture true physical features of the soil and till.

The pattern of increasing resistance with depth is illustrated by a plot of median values from the 88 profiles on the grid survey (Figure 4). The erratic variations below ~300 cm reflect the limited number of profiles that reached this depth or greater (indicated by histogram, Figure 4). Depth to bedrock in the 88 profiles ranged from 50 to 450 cm, with a median of 140 cm.

Soil Penetration Resistance and Hydraulic Conductivity

At several nested well sites in various geomorphic settings, soil-resistance profiles measured by the knocking pole could be paired with vertical profiles of K_{sat} measured by bail tests. The resolution of the penetrometer measurements was 5 cm, whereas the K_{sat} determination was integrated over the well screen length—30 cm for the soil wells and 150 cm for the till wells. To match the data, we computed arithmetic mean, harmonic mean, and minimum of the knocks per 5 cm over each screened interval. Each of the three sets of calculated knock values was regressed against $\log K_{sat}$. Soil penetration resistance was inversely related to K_{sat} . The arithmetic mean had the best correlation ($r^2 = 0.25$, $p < 0.05$) (Figure 5), followed by the harmonic mean ($r^2 = 0.23$) and the minimum ($r^2 = 0.21$). Note that the K_{sat} gradient generally followed the depth profile, decreasing from shallow soil to deep soil to till. For the remainder of this paper, we will interpret the resistant layers as zones of low K_{sat} .

Many factors contribute to the result that soil penetration resistance explains only 25% of the variance in K_{sat} . Some error is introduced because of the difference in scale of the measurements. Variations in soil moisture among sites may explain much of the variance in K_{sat} (Shaw et al.

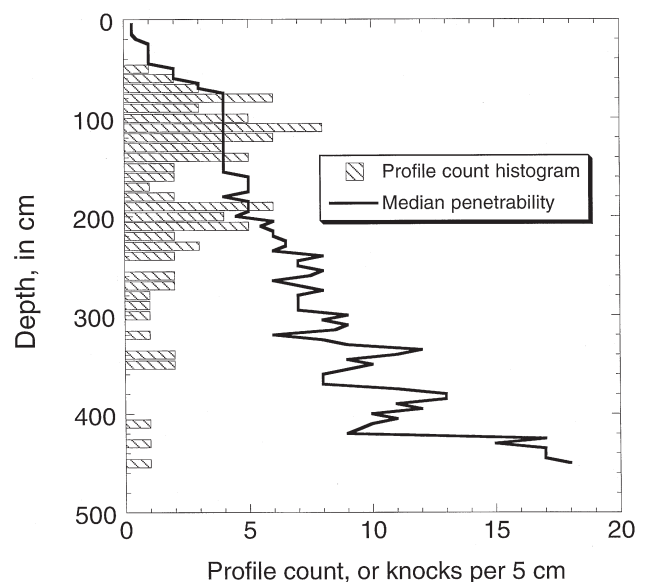


Figure 4. Histogram of depth to bedrock as determined by penetrometer data from 88 sites; median resistance from 88 sites vs. depth.

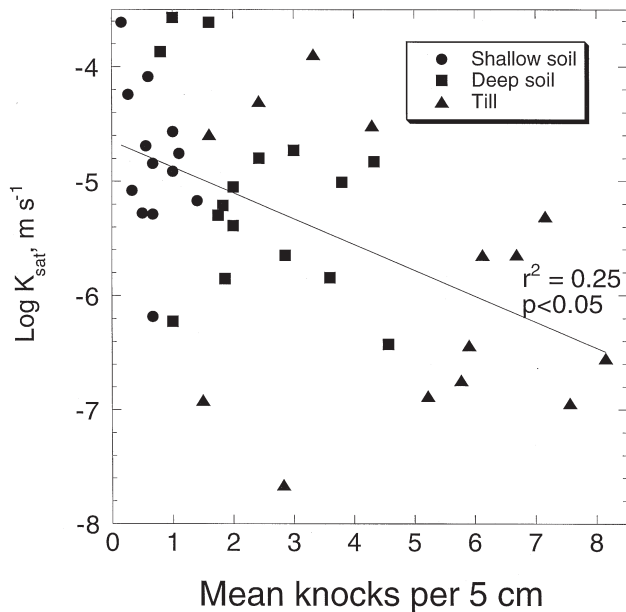


Figure 5. Saturated hydraulic conductivity (K_{sat}) vs. soil resistance. Because K_{sat} was determined over a minimum screened interval of 30 cm, whereas soil resistance was determined at 5 cm intervals, the average resistance value (average knocks/5 cm) within the screened interval was matched to the K_{sat} value for this plot.

1942). However, the generally high water tables at this study site tend to limit this source of variability to the soil zone (not the till). The degree of compaction and type of clay minerals present are other factors influencing penetration resistance (Baver et al. 1972). Probably the most important control on K_{sat} is textural composition, and several methods have been developed to predict K_{sat} from soil texture (Masch and Denny 1966; Freeze and Cherry 1979). Unfortunately, no textural analyses were available from any of the knocking pole sites. Despite the low predictive power for K_{sat} , penetration resistance is easily measured and its patterns help to interpret water and solute movement, as discussed in the following sections.

Resistance Profiles and Ground Water Levels

Water table levels tended to remain at or just above zones of high resistance in the soil/till profile during most of the year at many sites (Figure 6). This pattern occurred to a greater or lesser degree in diverse geomorphic settings. The panels in Figure 6 are arranged in order of topographic position, from upland bench (top pair) to upland channel head (middle pair) to lowland riparian/hillslope transition (bottom pair). The latter pair exhibit the most pronounced effect. The resistant zone appears to form a “base” that supports ground water levels during all times except abnormally dry summers.

What is the physical significance of the resistant layers? Within the till, variations in resistance probably represent variations in till texture and depositional sequences. However, the higher resistance at the soil/till interface relative to zones above and below it likely represents a textural change as the high-porosity loamy soil gives way to the dense, low-porosity unaltered till dominated by fine silt

(Thorne et al. 1988; Newell 1970). The transition may be caused by pedogenic translocation of soil clay particles into the upper till. The co-occurrence of the modal depth of the temporal ground water level distribution at this resistant layer poses a “chicken or egg” question. Do ground water levels cluster at this depth because of the high-resistance layer, or did the high-resistance layer develop in response to the water table dynamic?

The relation of water table level to the soil/till high-resistance zone may be affected by the vertical component of ground water movement. At ground water discharge sites, which include most of the sites discussed here, the highly conductive zone just above the till may be the first zone contacted by the upward moving ground water that can drain the water as rapidly as it is supplied. Upwardly increasing hydraulic conductivity tends to limit ground water rise—this is the transmissivity feedback mechanism documented at this site by Kendall et al. (1999). At ground water recharge (downward gradient) or lateral flow (no vertical gradient) sites, water may “back up” into the high-transmissivity zone because water throughput in the till is too low. The net effect is the same: The high-resistance zone appears to form a base level for the water table. The final possibility is that the high-resistance zone forms a confining unit that supports a perched water table. However, perched water was present at only two of 20 sites monitored during the 1996 snowmelt (Kendall et al. 1999). Furthermore, the ground water levels reported are from wells screened and packed within the till, and thus should represent the piezometric surface of the true saturated zone.

In the preceding scenario, the low-hydraulic conductivity of the till in general causes the water table to remain fairly high in all but the driest summers. Thomas (1992) and Belitz and Dripps (1999) calculated that the hydraulic conductivity of the till matrix was too low even to supply the observed base flow. Comer and Zimmerman (1969) demonstrated that the till in W-3, the next largest basin, which contains W-9, had a remarkable ability to sustain base flow. The sharp drops in water table level during dry summers might be explained by diminishing upslope contributions. The fine-silty till has a high field capacity; from saturation, a lowering of the volumetric water content by as little as 4% is needed to reach field capacity. Thus the water table may decline significantly with minimal drainage.

Ground Water Mixing: Isotopic and Chemical Evidence

Given the tendency for ground water level to fluctuate within a rather narrow zone above the soil/till interface, we questioned the implications for ground water mixing. Theoretically, in a ground water discharge zone, upwelling ground water should prevent stratification; ground water is continually replenished from upgradient, and its travel up through the till represents only the very end of a relatively long flowpath of a well-defined packet of water. However, the dynamic infiltration of large volumes of snowmelt could alter this condition.

During the 1996 snowmelt, we sampled the nested wells for oxygen isotopes of water and for major-ion chemistry and DOC. Snowmelt is an opportune time to use isotopes to evaluate the mixing of ground water and snowmelt because snowmelt has a much lower $\delta^{18}\text{O}$ than ground

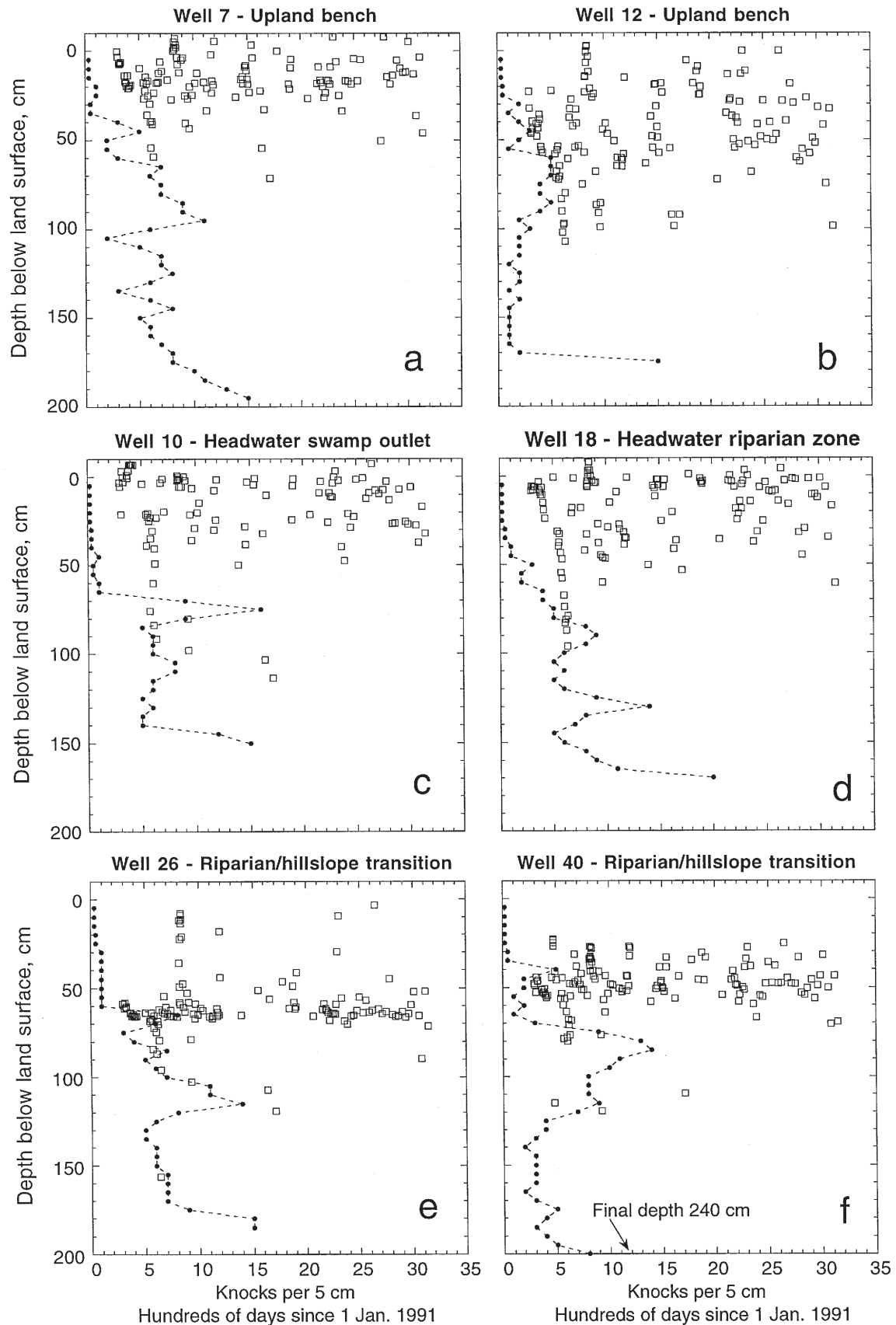
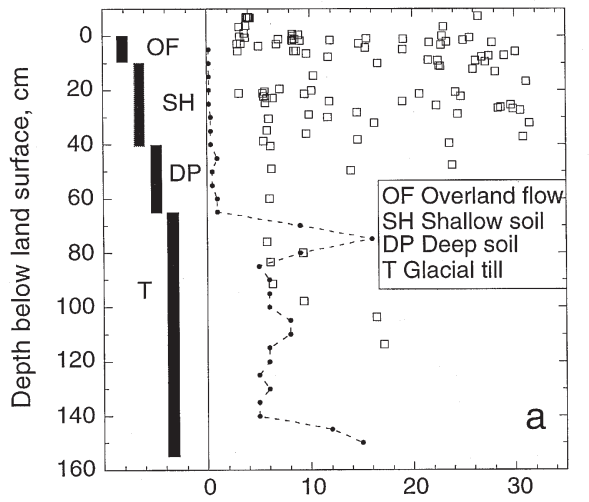


Figure 6. Monthly ground water levels (squares) from 1991 to 1998 plotted on resistance profiles at six sites: (a) Well 7 and (b) Well 12, upland benches; (c) Well 10, headwater swamp outlet; (d) Well 18, headwater riparian zone; (e) Well 26 and (f) Well 40, riparian/hillslope transition zones.

water (Rodhe 1998; Shanley et al. 2002). DOC, on the other hand, is a good indicator of water that has followed

shallow surficial flowpaths, such as snowmelt under wet conditions (Peters et al. 1995; Boyer et al. 1997).

At Well 10, sited in a histosol (peat overlying dense, unweathered till) near the outlet of a swamp, the ground water profile was well mixed throughout snowmelt, as indicated by the isotopic patterns (Figure 7). At all levels, $\delta^{18}\text{O}$ exhibited an excursion of roughly 1.0 permil toward the snowmelt value before returning to the premelt value. At any given sampling time, however, the range of $\delta^{18}\text{O}$ was generally on the order of only 0.2 permil. Thus, a moderate input of meltwater appeared to mix relatively uniformly with the existing ground water throughout the profile.



Knocks per 5 cm; Hundreds of days since 1 Jan. 1991

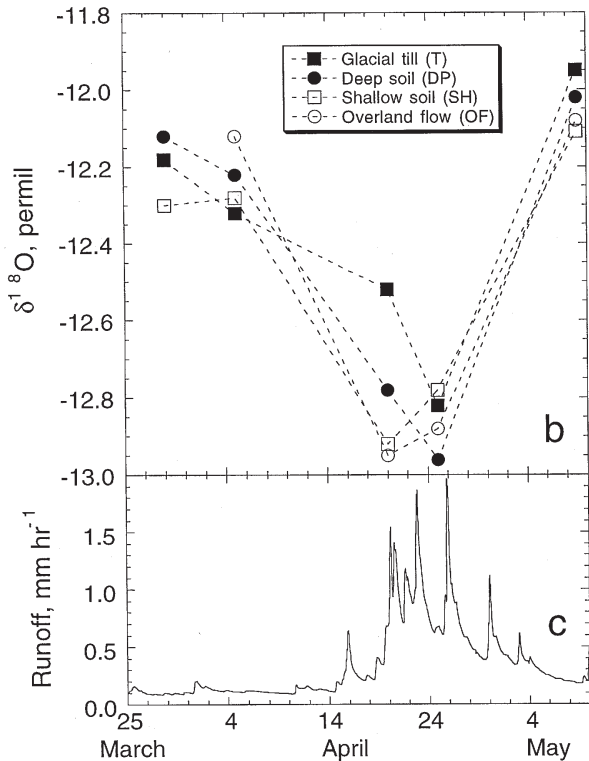
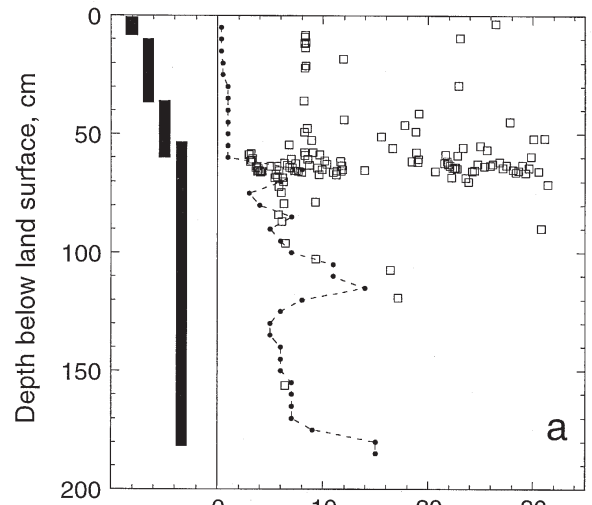


Figure 7. Well 10, headwater swamp outlet: (a) soil penetration resistance profile and long-term ground water-level data showing screened intervals of nested wells; (b) $\delta^{18}\text{O}$ at four levels of the saturated zone during the 1996 snowmelt period; (c) the W-9 stream hydrograph as a general indicator of hydrologic conditions.

At Well 26, the initial saturation of the profile clearly caused stratification (Figure 8). Water was first observed in the overland flow cups on April 18, indicating surface saturation. Although the deeper waters had shifted isotopically toward snowmelt by that date, the overland flow (0 to 10 cm depth) and shallow soil water (10 to 35 cm) clearly had mixed with a greater proportion of infiltrating meltwater. By the next sampling date on April 22, the $\delta^{18}\text{O}$ at all four depths had converged on nearly the identical intermediate value. By this date, near the peak of the melt, stronger



Knocks per 5 cm; Hundreds of days since 1 Jan. 1991

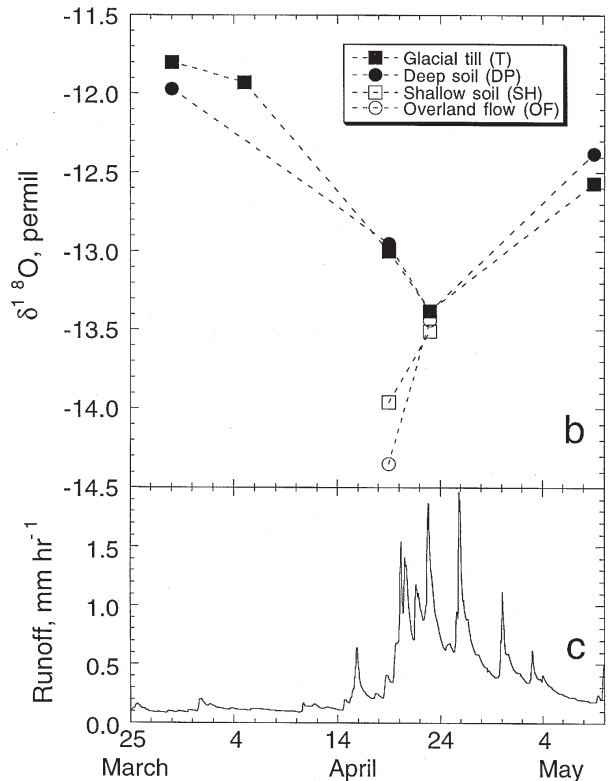


Figure 8. Well 26, riparian/hillslope transition zone: (a) soil penetration resistance profile and long-term ground water-level data showing screened intervals of nested wells; (b) $\delta^{18}\text{O}$ at four levels of the saturated zone during the 1996 snowmelt period; (c) the W-9 stream hydrograph as a general indicator of hydrologic conditions.

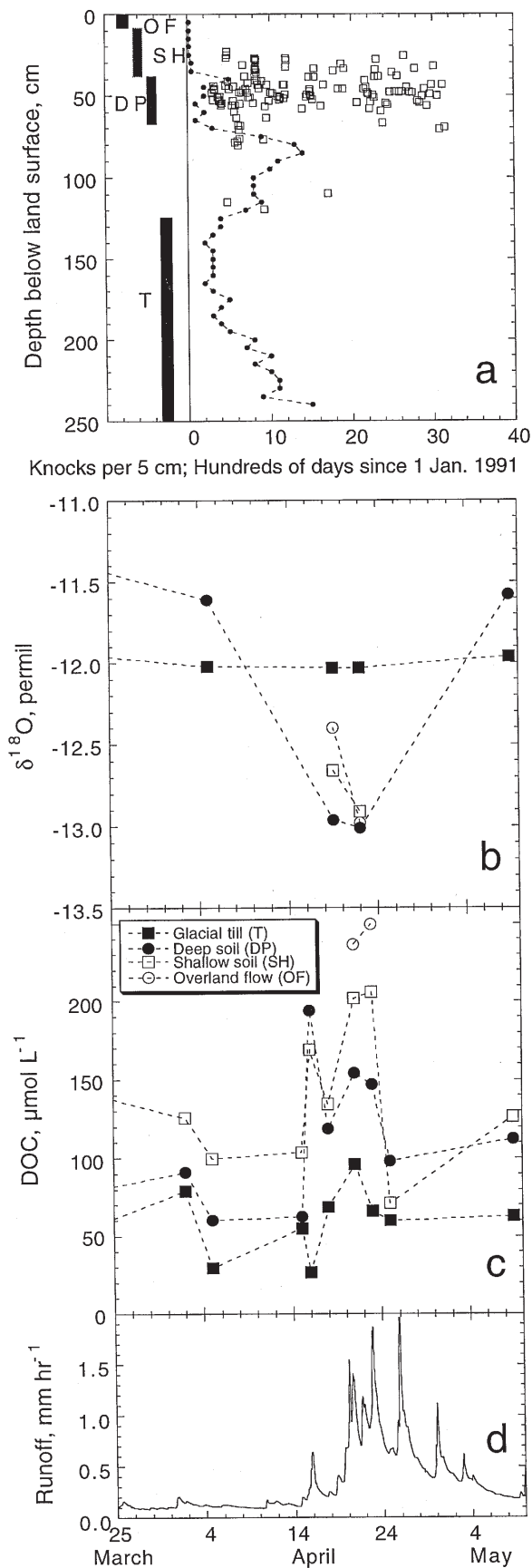


Figure 9. Well 40, riparian/hillslope transition zone: (a) soil penetration resistance profile and long-term ground water-level data showing screened intervals of nested wells; (b) $\delta^{18}\text{O}$ at four levels of the saturated zone during the 1996 snowmelt period; (c) DOC at four levels of the saturated zone during the 1996 snowmelt period; (d) the W-9 stream hydrograph as a general indicator of hydrologic conditions.

hydraulic gradients likely induced greater mixing, but the isotopic data indicate that a considerable amount of meltwater was incorporated in the mix.

Well 40 represents an area where ground water remained stratified (Figure 9). Note that the $\delta^{18}\text{O}$ of ground water in the till remained virtually constant during the melt. At the other three levels, however, the Well 40 site showed similarities to Well 26 in that there was stratification on the initial day of surface saturation (April 18), but mixing had occurred by April 22. The pattern of $\delta^{18}\text{O}$ with depth on April 18 was counterintuitive in that the deep soil water showed more snowmelt influence than the shallower zones. DOC, by contrast, decreased with depth in the typical manner. Interestingly, DOC changed little at any of the sites during the two surface-saturated (water was present in overland flow cups) sampling days, despite the isotopic evidence of a shift from stratified to well-mixed status. This contrast in $\delta^{18}\text{O}$ and DOC behavior likely reflects the rapid equilibration of DOC in soil solution and illustrates the complementary information often provided by isotopic (time source) and chemical (geographic source) tracers.

Conclusions

The dynamic cone penetrometer (knocking pole) is an inexpensive device that can provide information on subsurface hydraulic characteristics. Although it measures resistance to penetration force, we found a significant empirical relation between resistance to penetration and measured hydraulic conductivities. Water table dynamics and isotopic and chemical variations within the subsurface can be readily interpreted if resistance to penetration is assumed to represent resistance to water flow (inverse relation between resistance and K_{sat}). These results will help constrain ground water behavior in ongoing hydrologic modeling efforts in the catchment.

Ground water tended to maintain a level at or just above a resistant zone at the soil/till interface. We surmised that, whether direction of ground water movement was upward or downward, transmission of water in the low-resistance zone above this layer was the primary control on water table level. Even in ground water discharge zones, infiltration of meltwater from the surface can lead to temporary stratification of the ground water profile. Chemical stratification of these zones may persist for labile constituents such as DOC, which appear to equilibrate rapidly with infiltrating waters.

Acknowledgments

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