Honor Paper Award

Environmental Isotope Hydrograph Separation During Snowmelt in a Suburban Catchment

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ABSTRACT

An environmental isotope hydrograph separation was conducted using ^{18}O to assess the sources of storm runoff and to simulate Cl^- export in streamflow during the 1990 spring melt in a small suburban basin. Event water supplied 57% of total runoff from the basin, as well as 69% of peak discharge during a large rain-on-snow event. Results support the hypotheses that (1) event water contributions dominate stormflow as a result of Horton overland flow from modified surfaces, and (2) the fraction of total runoff supplied by event water corresponds to the developed portion of the basin. Groundwater made appreciable contributions to peak stormflow during snowmelt only after substantial recharge had occurred in near-stream areas. Event and pre-event fractions of streamflow were used in conjunction with a two-component mixing model to simulate Cl^- export from the basin. Initial exports were simulated fairly well, particularly when the source of Cl^- in event water was allowed to vary over space and time. The model performed poorly during the later stages of melt, and appears to represent a simplistic view of hydrochemical processes in suburban hydrological systems.

INTRODUCTION

The use of environmental isotopes such as oxygen-18 (^{18}O) and deuterium (^{2}H) as conservative tracers of water movement has reinvigorated research into hydrological processes in drainage basins, particularly as a result of their ability to assist studies of the temporal aspects of runoff generation. These hydrograph separations are often most successful during snowmelt periods, since the pronounced seasonal variations in the ^{2}H and ^{18}O of precipitation in cold climates often result in winter snowfalls with an isotopic content that is significantly lighter than that of summer and autumn rains. Thus, snowmelt water may be readily distinguished from autumn rainwater held in storage (Buttle and Sami 1990). Results have repeatedly demonstrated that streamflow generated during snowmelt is predominantly supplied by water stored in the catchment prior to the event (*pre-event water*), rather than by meltwater and rainfall contributed to the catchment during the event itself (*event water*) (e.g. Rodhe 1987, Moore 1989). However, most isotopic hydrograph separations have been conducted in small forested basins, and the applicability of this technique to the study of runoff generation in developed areas is unclear.

Suburban development induces pronounced changes in the hydrological mechanisms operating in a drainage basin, as a result of increases in the extent of artificial surface cover together with enhanced drainage provided by gutters, storm sewers and floodways. This modification of the hydrologic regime of suburban basins has been found to occur under rainfall, rain-on-snow and snowmelt conditions (Buttle 1990). Whereas streamflow from undisturbed drainage basins may be generated by a variety of processes (cf. Dunne 1978), Horton overland flow from artificial and modified surfaces is the dominant runoff generating mechanism in suburban catchments (Buttle 1990). Suburban hydrological systems exhibit rapid responses to precipitation inputs as well as limited mixing and storage of water, making them especially suited to the application of environmental isotopes as tracers (Lawler 1987). This suggests the following hypotheses: (1) stormflow from suburban drainage basins during spring snowmelt will be dominated by event water contributions; and (2) the proportion of total streamflow supplied by event water corresponds to the fraction of the basin covered by surfaces capable of supplying Horton overland flow to the drainage system.

De-icing salts (e.g. NaCl) are used extensively in many northern communities as a means of road clearance during winter months, and a large proportion of the applied NaCl might be expected to be retained in the pre-melt snowcover of a suburban basin (Vonk et al. 1991). Given that this meltwater will leave suburban areas mainly via Horton overland flow, and assuming that de-icing salt levels in meltwater will exceed concentrations in soil water and groundwater, an additional hypothesis can be formulated: (3) a two-component mixing model, using event and pre-event fractions of total streamflow and associated Cl^- concentrations, provides successful predictions of observed Cl^- export from a suburban basin during spring snowmelt.

These hypotheses were tested using measurements made during the 1990 spring snowmelt period in a suburban basin.

STUDY AREA

The basin (1.066 km^2) is located in the Kawartha Heights subdivision of Peterborough, Ontario (44°N, 78°W). The 30-year (1951-1980) mean annual temperature is 6-7°C and mean annual precipitation is 735 mm, 20% of which falls as snow. The basin has a local relief of 48 m with gentle slopes. Soil cover consists of well-drained Otonabee loams and Bondhead sandy loams, which are underlain by sandy till (Buttle 1990).

Intermittent suburban development since 1974 covered 59.8% of the basin with roads, residences and construction zones by the spring of 1990. Open fields (32.6%) and forest (7.6%) made up the remainder of the catchment. Residential areas are dominated by single family dwellings surrounded by lawns and gardens. These areas are drained by storm sewers which discharge into the stream that flows from the basin.

METHODS

A stratified random snow survey was conducted on 28 February 1990, prior to the main melt period. Snowpack w. e. was measured within suburban, open and wooded areas. Geometries and w.e. of snowbanks along major and minor roads were also measured, and snowpack samples were collected.

Shortwave radiation, net all-wave radiation, wind speed, relative humidity, air temperature, and precipitation were recorded over a suburban lawn (Fig. 1). These measurements were used to determine the snowpack's energy balance, and thus obtain hourly melt rate estimates (cf. Price 1988). Two 1 m^2 snowmelt lysimeters located adjacent to the meteorological site were used to obtain meltwater samples at least once a day during the melt period. Bulk precipitation samples were obtained throughout the melt at this site.

A transect of shallow wells was established across the stream a short distance upstream of the basin outfall (Fig. 1). Water table position was measured daily and groundwater was sampled periodically throughout the melt. Discharge was recorded continuously at the basin outfall. An automatic sampler was used to obtain streamflow samples at 2 h intervals from the start of the main melt on 8 March until the end of melt (20 March). Spot samples of surface flow from fields and roads were also taken during the monitoring period.

All samples were analyzed using an Orion Cl^- electrode (Model 94-17B), which has a detection limit of 0.5 mg L^{-1} and an accuracy of ± 2%. Selected samples were analyzed for ^{18}O at the Earth Sciences Department, University of Waterloo. All ^{18}O are expressed relative to the SMOW standard, and the precision of ^{18}O duplicate analyses averaged ± 0.1‰.

RESULTS AND DISCUSSION

Snowcover, snowmelt, groundwater, runoff and streamflow

Table 1 presents snowcover data for various surface types prior to melt (28 February). The snow-free fraction of the basin was 22.2%, the area-weighted mean snowpack w.e. was 26.2 mm, and snowcover had a mean ^{18}O signature of -16.34‰ (± 1.67‰) on this date (Fig. 2). The spatial pattern of

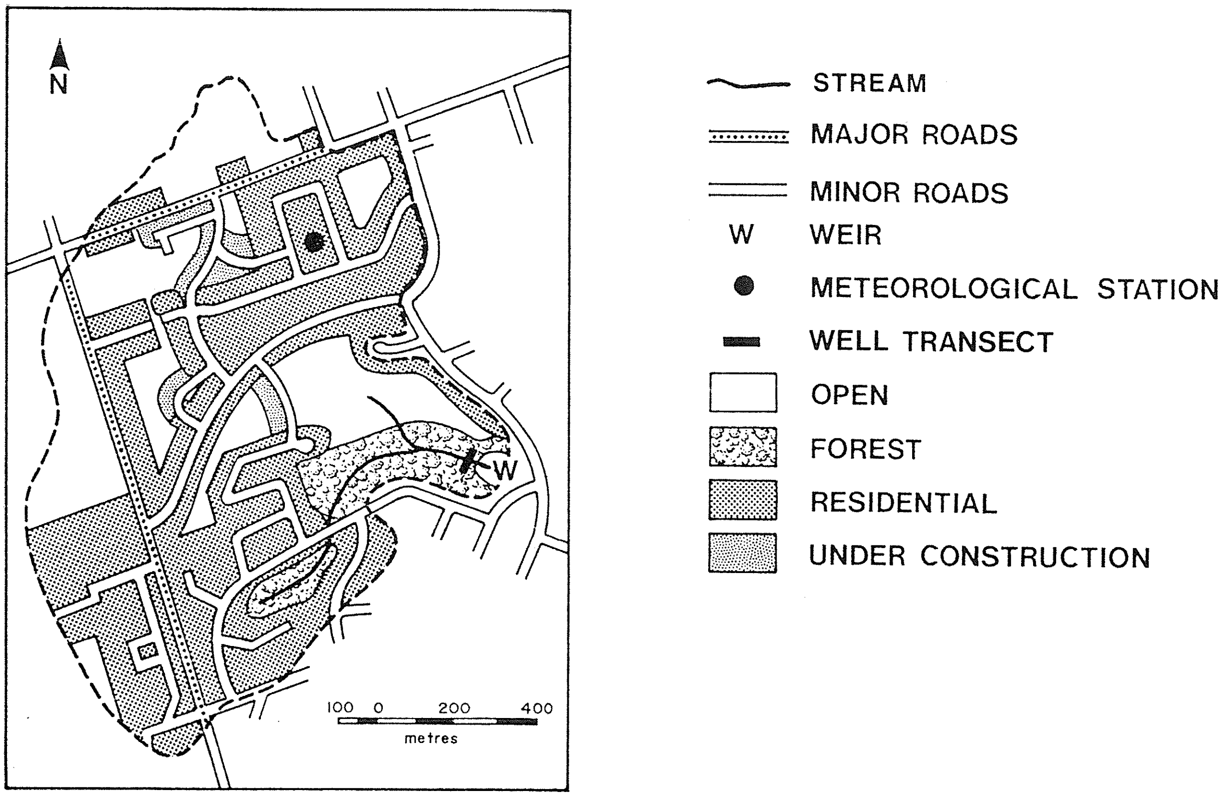

Figure 1 Land use and instrumentation, Kawartha Heights study basin.

TABLE 1. **Percent coverage of total basin area, average snowpack characteristics and Cl^- concentrations for surface types in the basin, 28 February 1990.**

Surface Type	*Percent Cover*	*Depth (m)*	*Density ($kg\ m^{-3}$)*	*W.E.* (m)*	*$[Cl^-]$ ($mg\ L^{-1}$)*
SNOWBANKS					
Major roads	0.5	0.45	334	0.073	304.8
Minor roads	1.1	0.27	377	0.052	48.3
Driveways	1.5	0.24	302	0.044	8.2
FRONT LAWNS	7.8	0.14	266	0.038	2.5
BACK LAWNS	24.6	0.14	207	0.029	3.4
OPEN FIELDS & CONSTRUCTION AREAS	34.7	0.09	301	0.027	1.7
FOREST	7.6	0.27	231	0.062	1.5

* W.E. - water equivalent

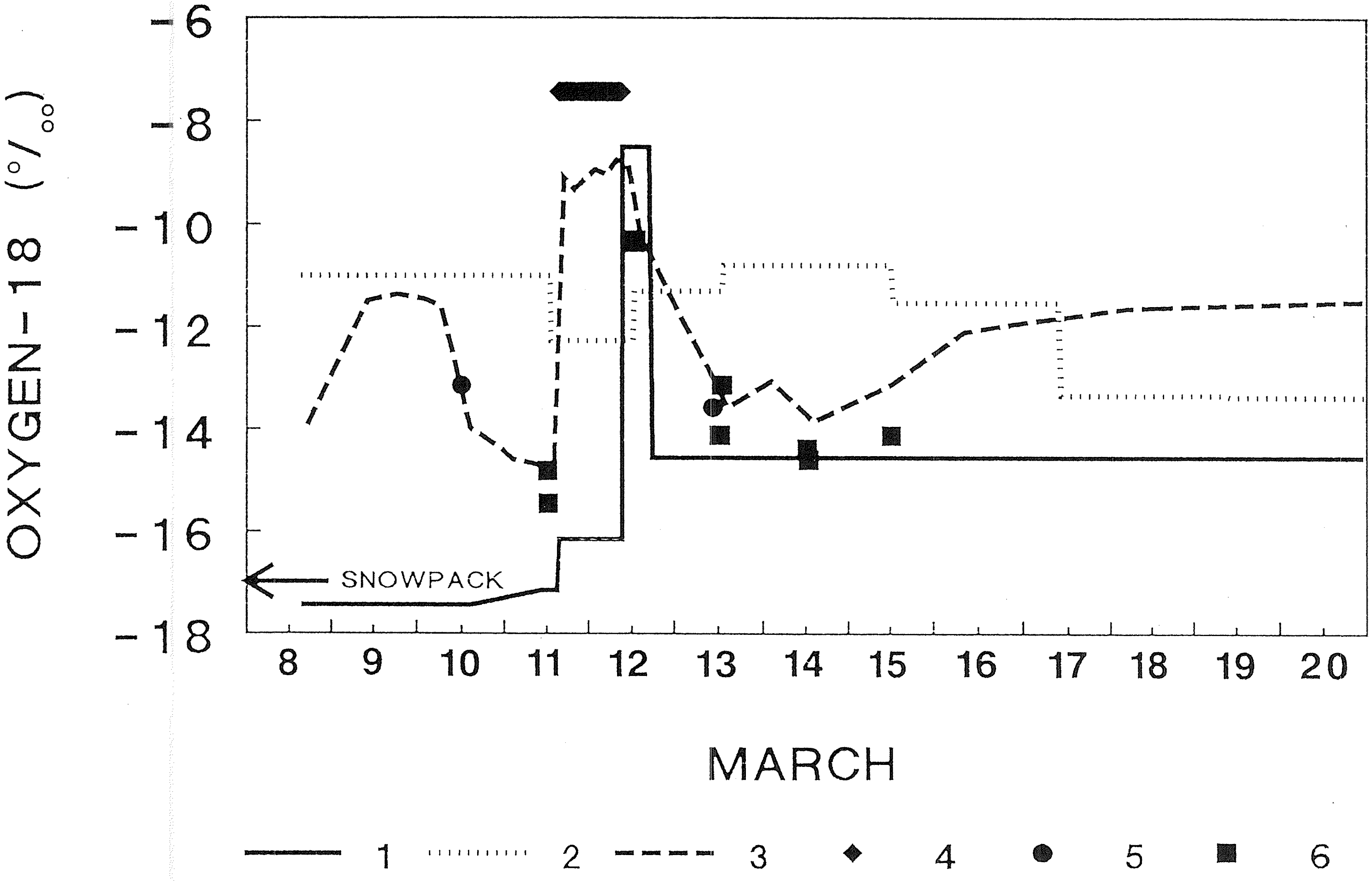

Figure 2 *^{18}O levels in the pre-melt snowpack, in water from the snowmelt lysimeter (1), groundwater (2), streamflow (3), rainfall (4), and runoff samples from roads (5) and fields (6), spring 1990.*

Cl^- levels in the basin's snowpack reflects the fact that de-icing salts are usually applied to roads during the initial phase of a snowfall, with main roads receiving more NaCl during a winter than residential streets (Scott 1976). Most of this Cl^- is transferred to roadside snowbanks during subsequent plowing, while the drift of salt brine from roads to front and back lawns results in higher Cl^- concentrations in snowcover on these surfaces than for open field and forest snowpacks (Vonk et al. 1991).

The main melt began on 8 March, and Fig. 3 presents streamflow, meltwater inputs and daily precipitation depths for the melt period. Melt data became unreliable after 12 March, due to loss of snowcover under the radiometers. Nevertheless, energy balance estimates following this date provide an index of relative changes in snowmelt intensity during the monitoring period. ^{18}O levels in meltwater (Fig. 2) tended to be lower than concentrations in snowcover, suggesting fractionation of ^{18}O during the initial melt; however, there was no statistically significant difference between these levels. A large rain-on-snow event added 35.3 mm to the basin on 11-12 March, with an ^{18}O signature of -7.43‰ (Fig. 2), while the bulk sample obtained for a smaller rainfall on 17 March (1.2 mm) was not sufficient to permit ^{18}O analysis.

The pre-melt water table was more than 0.5 m below the ground surface except for a small zone adjacent to the channel (Fig. 4). Pronounced recharge during the rain-on-snow event of 11-12 March resulted in a steepening of the near-stream hydraulic gradients and an expansion of the seepage face, both of which are consistent with increased groundwater inputs to the channel (Gillham 1984). Groundwater ^{18}O values were heavier than meltwater levels at the commencement of melt (Fig. 2). The isotopic signature of groundwater responded to surficial inputs, with a time lag of two to three days. There was a slight overall decline in groundwater ^{18}O over the course of the melt of approximately 2‰. This change is similar to that observed by Rodhe (1987) in discharge from springs over the snowmelt period, which he attributed to 2 processes:

recharge of isotopically different meltwater and pre-event soil water and subsequent mixing; and

extension of phreatic conditions into the overlying unsaturated zone, with conversion of isotopically different soil water to groundwater.

Of the 62.7 mm of water supplied to the basin from 8 to 20 March, 61.8 mm (99%) left as runoff. Total quickflow determined using the Hewlett and Hibbert (1967) hydrograph separation method was 45.4 mm, giving a quickflow response ratio (quickflow/[snowpack w.e. plus precipitation]) of 0.72 for the entire melt period. This is 1.75 times the maximum quickflow percentage observed for this basin during the 1988 snowmelt period (Buttle 1990), and is consistent with the expansion of developed surface cover from 52% to approximately 60% of the basin area between 1988 and 1990. The time lag between peak melt intensity and peak streamflow was 5 h on 10 March (the first day of increased streamflow), and quickly declined to values ranging from 0 to 2 h for subsequent days. This is similar to temporal changes in time lags observed by Buttle and Xu (1988) for a fully developed subcatchment of the basin. Peak discharge of 1.55 $m^3 s^{-1}$ was observed during the rain-on-snow event on 11-12 March. This represents a runoff rate of 5.2 mm h^{-1}, which is 33% larger than the peak runoff observed in previous years (Buttle 1990).

^{18}O signatures of runoff samples collected from roads and open field areas in the catchment were similar to those observed in streamflow (Fig. 2), suggesting that most of the streamflow was contributed by surface runoff. These runoff samples tended to have ^{18}O somewhat lower than that in streamflow, indicating a slight enrichment of the ^{18}O signature of surface runoff during its passage through the basin. Calculations by Rodhe (1987) suggest that evaporation of runoff can produce enrichment in the order of 0.5‰, which is roughly the difference between runoff and streamflow ^{18}O observed here. Initial streamflow ^{18}O values approximated those in groundwater during the early melt, but responded rapidly to variations in the signature of event water following the higher melt rates observed after 10 March (Fig. 2). Streamflow isotopic levels remained between those of groundwater and melt/precipitation for most of the melt period.

Stormflow components

^{18}O levels in meltwater, precipitation and groundwater were used in a two-component mixing model to estimate the event and pre-event components of streamflow recorded at the weir:

$$Q_t = Q_p + Q_e \qquad (1)$$

$$C_tQ_t = C_pQ_p + C_eQ_e \qquad (2)$$

$$X = (C_t - C_e)/(C_p - C_e) \qquad (3)$$

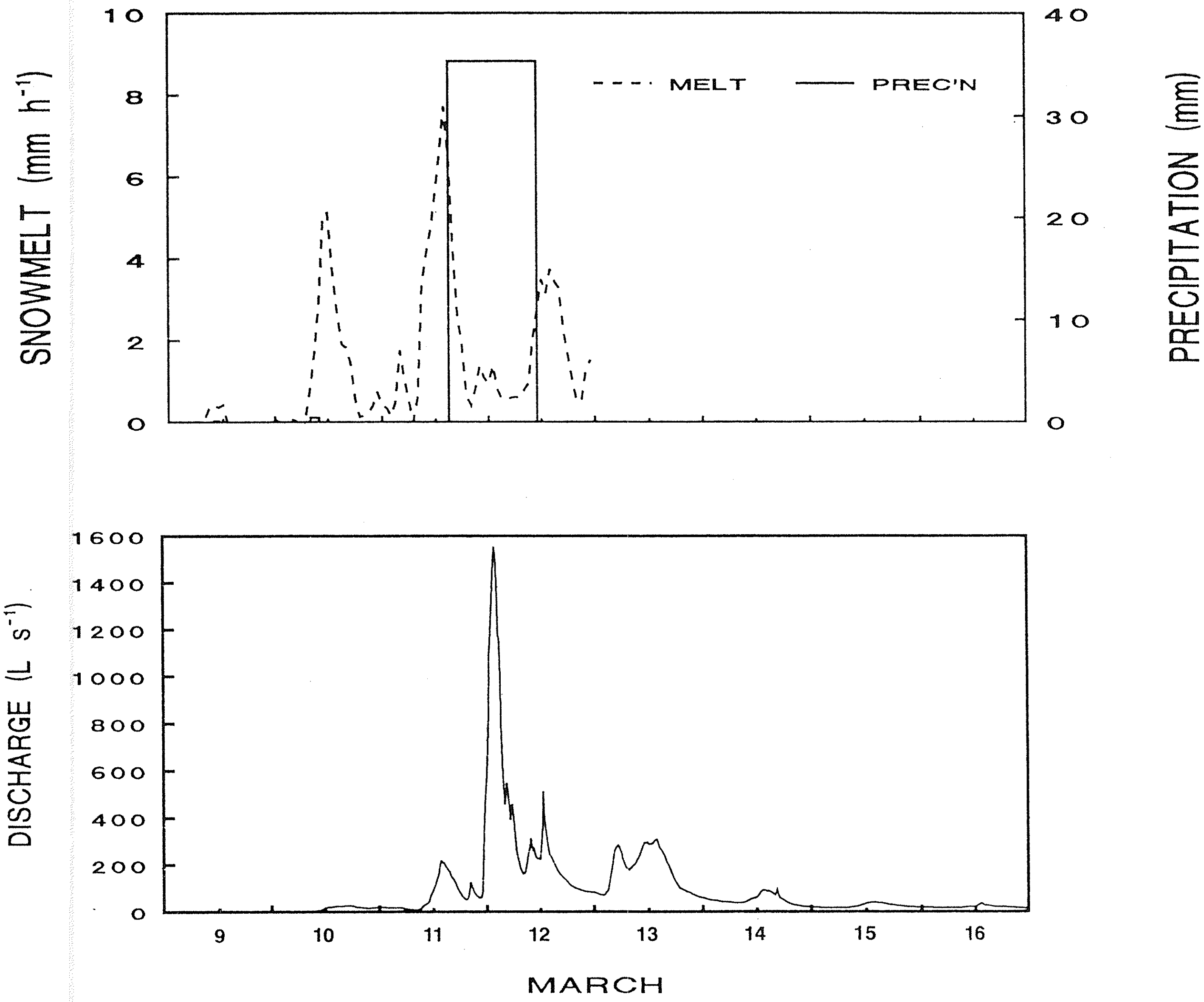

Figure 3 Precipitation, snowmelt rates, and discharge from the study basin during the main melt period.

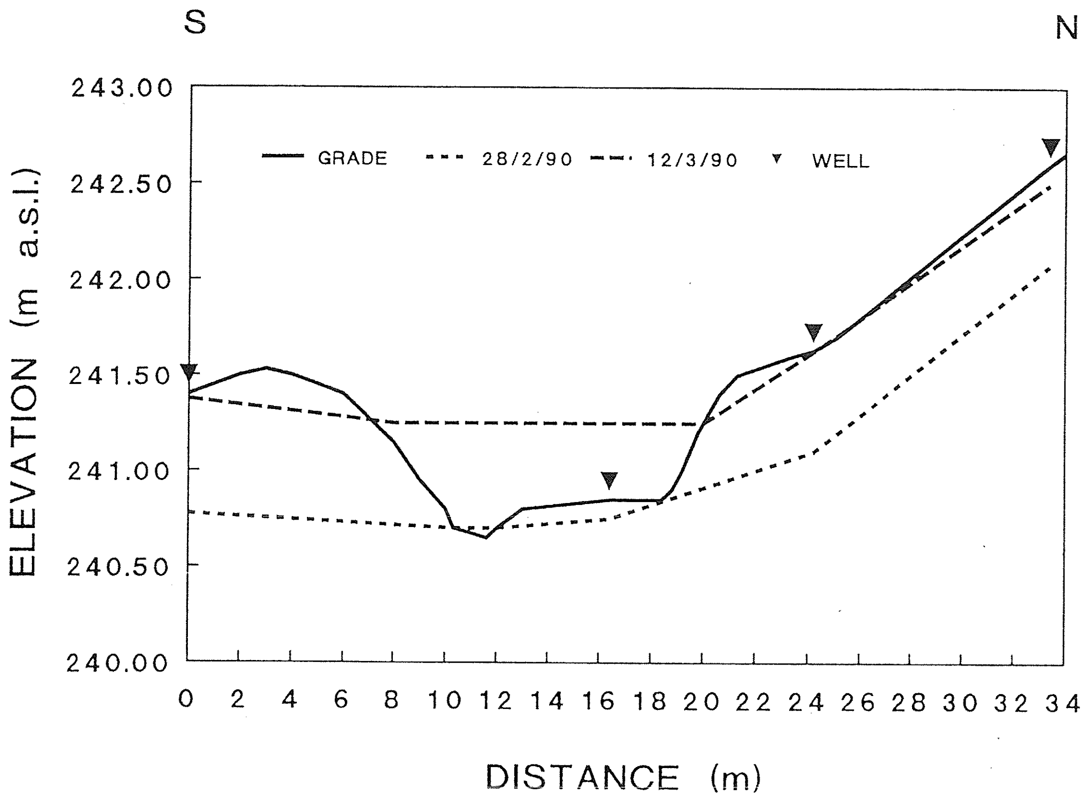

Figure 4 *Water table geometry in the near-stream zone prior to melt and during the 11-12 March rain-on-snow event.*

where Q_t is streamflow; Q_p and Q_e are contributions from pre-event (soil water, groundwater) and event (melt, rainfall) water; C_t, C_p and C_e are ^{18}O levels in streamflow, pre-event and event waters, respectively; and X is the pre-event fraction of total streamflow. Interpretation of X depends to a great extent on the assumptions made regarding C_p. Many studies employ a constant signature for C_p that equals the isotopic content of pre-event stream baseflow (e.g. Moore 1989). Under these conditions X refers to the fraction of total flow supplied by soil water and groundwater present in the basin prior to the event; however, this leads to an underestimate of the actual fraction of groundwater supplied to the channel during the course of the rain or melt event (Rodhe 1987). The hydrograph separation employed here incorporates temporal variations in the ^{18}O signature of discharging groundwater by using the ^{18}O in near-stream wells (Fig. 2) to represent C_p. Thus X is the groundwater fraction of total discharge at the time of streamflow sampling.

This approach rests on several additional assumptions which have been summarized by Sklash and Farvolden (1979): (1) there is a significant difference between the isotopic content of the event and pre-event components; (2) the isotope signature of event water is constant in space and time; (3) contributions of water from the vadose zone must be negligible, or the isotopic content of soil water must be similar to that of groundwater; (4) pre-event water has a spatially-uniform isotopic signature; and (5) contributions to streamflow from surface storage are negligible.

Assumptions (1) and (5) appear to have been satisfied, and data were not available to evaluate the degree to which assumptions (3) and (4) were met. Fig. 2 indicates that the assumption of temporal invariability of C_e was violated. However, these variations can be incorporated into the hydrograph separation by assuming that new water was instantaneously introduced to the stream (Rodhe 1981). This may be justified by the fact that event contributions supplied streamflow via the entry of Horton overland flow from modified surfaces to the storm sewer system, and its rapid delivery to the stream (travel times in the order of 0-2 h). The assumption that the isotope signature of event water is constant in space and time is of particular relevance when applying the environmental isotope hydrograph separation method during rain-on-snow events in suburban areas. Under these conditions, event water consists of two components: rainfall on artificial surfaces and rain/meltwater from snowcovered surfaces. Contributions to streamflow from these two sources may differ greatly, as might their isotopic signatures. This was the case during the rain-on-snow event of 11-12 March, when 35.3 mm, with an ^{18}O signature of -7.43‰, fell on the basin (Fig. 2). Snowmelt lysimeter samples indicated that the isotopic signature of water leaving the snowpack ranged from -17.16 to -8.5‰ during this event. Total water loss from one lysimeter (melt and precipitation) was 20.4 mm over the duration of the storm, suggesting that a substantial amount of the precipitation was stored in the snowpack. Given that the rainfall depth greatly exceeded total water loss from the snowpack (which in turn incorporates some rainwater moving through the snowpack), we have assumed that the event water signature during this storm equalled ^{18}O in the precipitation. This is supported by previous hydrometric observations that rainfall on artificial surfaces dominates storm runoff from this basin (Buttle 1990).

An isotopic hydrograph separation indicates that event water comprised 57% of the 58.5 mm of total runoff for the period shown in Fig. 5, and that it supplied 69% of peak discharge during the rain-on-snow event. These fractions are similar to the proportion of the basin that has undergone suburban development, which was estimated to be 60%. Thus, results from the hydrograph separation support hypotheses (1) and (2). It may be possible to use environmental isotope hydrograph separations in built-up areas to assess the size of the *actual* runoff contributing area. This may differ appreciably from the runoff contributing area inferred on the basis of the size of artificial surfaces in the basin, particularly during spring snowmelt when lawns and gardens may generate overland flow (Buttle 1990).

The dominance of event water contributions during spring melt observed here contrasts with results obtained from undisturbed basins (Rodhe 1987, Moore 1989). Nevertheless, groundwater supplied up to 70% of peak streamflow during individual snowmelt events, such as that of 13 March. The large contribution of groundwater to the stream channel during this event is supported by the increased hydraulic gradients and expanded seepage faces in the near-stream zone following rain-on-snow on 11-12 March (Fig. 4).

A number of studies have examined the timing of event and pre-event hydrographs relative to the total hydrograph in an effort to infer the nature of the hydrological processes responsible for the isotopic results. For example, Sklash et al. (1986) observed that the event water hydrograph preceded that of pre-event water in forested catchments in New Zealand, which they attributed to the generation of event water by saturation overland flow from near-stream areas. Conversely, Nolan and Hill (1990) noted that pre-event water dominated the rising limbs of hydrographs in a 10.6 km^2 basin near San Francisco that had been modified by quarrying activities. They argued this reflected the action of flood waves that displace pre-event water in the stream channel network in advance of the downstream passage of event water. Flood waves can result in a lag between changes in streamflow volume and streamflow composition (Glover and Johnson 1974), and may be accentuated by the impervious surface cover of suburban basins (Nolan and Hill 1990). The hydrograph separation in this study (Fig. 5) indicates that the event water hydrograph preceded or coincided with pre-event contributions. This suggests that event water was rapidly translated to the stream channel from modified surfaces in the basin. The absence of a lag effect may be the result of the small perennial channel network in the Kawartha Heights basin (Fig. 1) relative to that in the basin examined by Nolan and Hill (1990).

Modelling Cl$^-$ export from the catchment

Event and pre-event fractions of total streamflow identified from the hydrograph separation were employed in a two-component mixing model to simulate the observed export of Cl$^-$ from the catchment. C_p and C_e are now the Cl$^-$ concentrations in pre-event and event water, respectively, and eq. 2 is rearranged to solve for the Cl$^-$ concentration in

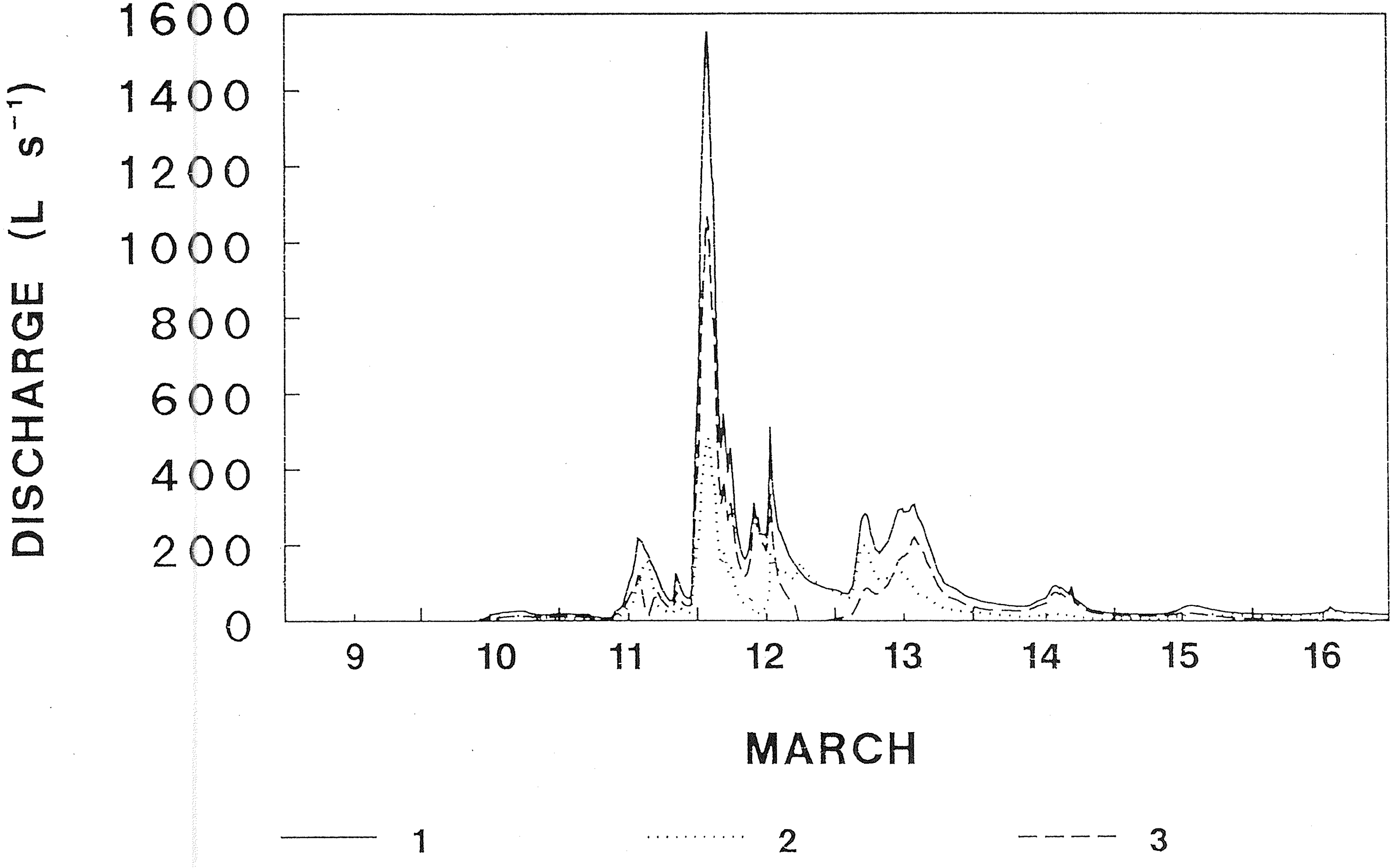

Figure 5 *Total streamflow (1) and pre-event (2) and event (3) components estimated from the isotopic hydrograph separation.*

streamflow, C_t. Cl$^-$ levels in groundwater were assumed to represent pre-event water concentrations. These concentrations quickly rose from pre-melt levels of 15.8 mg L^{-1} to a peak of 27.5 mg L^{-1} on 11 March and declined to 13.5 mg L^{-1} by 16 March, and were used to update C_p in the two-component model.

Attempts to assign a Cl$^-$ level to event water contributions during snowmelt in suburban areas must consider the large spatial variations in Cl$^-$ concentrations in the pre-melt snowpack (Table 1). These variations in turn promote spatial and temporal differences in the source of meltwater carrying Cl$^-$ to the stream, due to the ability of de-icing salts to lower the freezing point of water. Thus roadside snowbanks, which may possess high Cl$^-$ concentrations, often begin to melt prior to areas of snowcover with lower Cl$^-$ levels (Scott 1976). Therefore three alternative conditions were assumed for Cl$^-$ concentrations in event water in order to evaluate the influence of spatio-temporal changes in Cl$^-$ sources upon export from the basin: (1) that meltwater was mainly generated from lawns in the basin, and that output from the snowmelt lysimeters represents the Cl$^-$ concentration in this meltwater; (2) that all Cl$^-$ in meltwater was supplied from snowbanks lining major and minor roads as well as driveways in the basin; and (3) that all Cl$^-$ in meltwater was supplied only from snowbanks lining major and minor roads.

Volume-weighted Cl$^-$ concentrations in the different snowbank types were determined for conditions (2) and (3). For all 3 conditions it was assumed that Cl$^-$ levels in precipitation represent those in event water during the rain-on-snow event on 11-12 March, and that C_e reverted to conditions (1), (2) or (3) at the end of rainfall. Observed and estimated Cl$^-$ concentrations in streamflow were multiplied by the average discharge between sampling periods in order to obtain Cl$^-$ export rates from the basin (Fig. 6).

Results indicate that the model does a reasonable job of simulating observed Cl$^-$ exports when it is assumed that initial melt (10 March) was from roadside snowbanks possessing high Cl$^-$ concentrations (condition 3). Concurrent field observations also indicated that most meltwater was supplied by these snowbanks. Nevertheless, condition (3) underpredicts the Cl$^-$ load, which may reflect use of the mean Cl$^-$ concentration in roadside snowbanks as C_e. Initial meltwater was likely enriched in Cl$^-$ relative to the mean concentration in these snowbanks prior to melt, due to the "concentration effect" produced by the leaching of soluble ions from snow crystal surfaces and grain boundaries by meltwater (Jones and Stein 1990). Observed exports during snowmelt on 11 March were intermediate between those predicted using conditions (1) and (2), suggesting that meltwater contributions from other snow-covered areas (lawns, driveway snowbanks) reached the stream channel on this day. It also appears that the assumption that Cl$^-$ levels in precipitation represent those in event water is justified during rain-on-snow on 11-12 March, and that condition (1) produces a good simulation of the observed Cl$^-$ exports immediately following this event. The latter point suggests that meltwater from lawns in the basin contributed a substantial portion of the event water fraction during this period.

However, use of conditions (2) and (3) in the two-component mixing model produces dramatic overestimates of Cl$^-$ exports on 12 and 13 March. Both days had large event water contributions (Fig. 5), and the overpredictions result from the high Cl$^-$ levels assumed to be in meltwater from snowbanks lining roads and driveways. Much of the pre-melt Cl$^-$ was probably flushed from these sites during the initial melt period, as noted above. In addition, all three conditions underpredict export towards the end of melt, suggesting the temporary storage of Cl$^-$ in the basin's soils during the initial melt and its subsequent transport to the stream. Thus a two-component mixing model may have limited applicability to suburban basins, where the wide range in permeability and drainage efficiency that exists for the component surface types can produce a myriad of differing retention times for water and solutes.

SUMMARY

An environmental isotope hydrograph separation was conducted in a small suburban basin during the 1990 spring melt. The basin has undergone progressive development since 1974, such that 60% of its surface cover consisted of roads, residential areas and construction zones. This was reflected in peak discharges and a seasonal quickflow response ratio in excess of those recorded previously. Event water supplied 57% of total runoff from the basin, as well as 69% of peak discharge during a large rain-on-snow event. Results support the hypotheses that (1) stormflow from suburban basins during spring snowmelt is dominated by event water contributions as a result of Horton overland flow

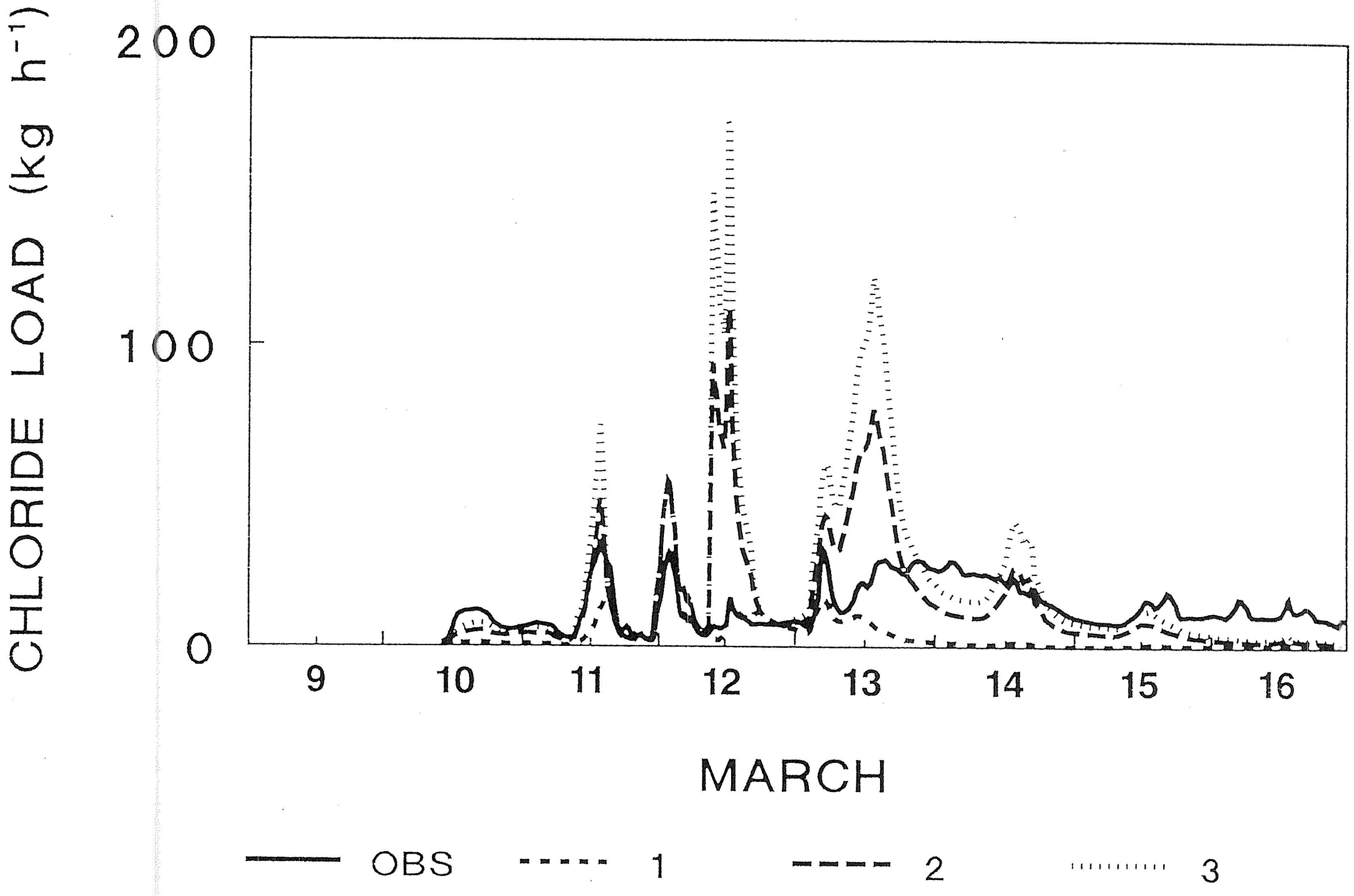

Figure 6 *Observed (OBS) and predicted Cl^- loads in streamflow using the two-component mixing model under conditions (1), (2) and (3). See text for details.*

from modified surfaces, and (2) the fraction of total runoff supplied by event water corresponds closely to the proportion of the basin capable of supplying Horton overland flow to the stream. Therefore it may be possible to use environmental isotope hydrograph separations to estimate the size of runoff contributing areas in suburban basins. Groundwater made appreciable contributions to peak stormflow only after substantial groundwater recharge had occurred in near-stream areas.

A two-component mixing model, based on event and pre-event fractions of total streamflow, was used to simulate Cl^- export from the basin during the melt period. Initial exports were simulated fairly well, provided that the source of Cl^- in event water was allowed to vary over space and time. However, the model produced a poor simulation of Cl^- exports during the later stages of melt. Therefore a two-component representation of the suburban hydrological system appears to be overly simplistic, and fails to incorporate hydrochemical processes that may regulate streamflow chemistry.

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