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Runoff Generating Processes in Boreal Forest Environments with Glacial Tills

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This review describes the processes by which runoff is generated from rain or snowmelt in a boreal forest landscape with a shallow layer of glacial tills overlying a relatively impermeable bedrock. Glacial tills are the main surface deposits in the Nordic countries, and are also of frequent occurrence in other boreal forest environments in the Northern Hemisphere. Soil moisture and groundwater conditions control the partitioning of rain or snowmelt into evapotranspiration, runoff and temporary storage. Groundwater is viewed as the major determinant of runoff generation, both because it is the most important contributor to event flow, and because of its influence on saturation overland flow. A characteristic feature of till deposits is a saturated hydraulic conductivity which decreases rapidly with depth. As a consequence, topography has a significant impact on runoff by controlling movement and storage of water through convergence and divergence of flow. Modeling and field experience point to the idea of a continuum in both spatial and temporal occurrence of saturation overland flow and subsurface flow within individual catchments under different rainfall and snowmelt events and antecedent groundwater and soil moisture conditions. Results from studies using hydrological models with a structure which may be suitable for landscapes with glacial tills are presented.

Introduction

As a result of several Pleistocene glaciations, till deposits mantle the bedrock in large areas in the boreal forest zone, a circumpolar region between 50° and 70° northern latitude covering 11% of the world's land mass (Strahler and Strahler 1978). Vegetation in this region is dominated by coniferous tree species, however, deciduos trees are common. The climate of the boreal forest zone is characterized by a strong seasonal variation with long, cold winters when precipitation accumulates as snow, and brief summers (Bonan and Shugart 1989). Soil water may be frozen for several months each year, and snowmelt represents a major event in the hydrological cycle (Stein *et al.* 1994). Although much of the boreal forest climate is classified as humid, with precipitation totals between 500 mm and 1,000 mm per year, large areas in Canada and Siberia have annual precipitation totals less than 400 mm and are classified as subhumid or semiarid (Strahler and Strahler 1978). Annual precipitation exceeds actual evapotranspiration, leading to a net water excess over the boreal forest landscape (Bonan and Shugart 1989). This water is available for spatial redistribution according to regional topography and the characteristics of the surface materials (Price *et al.* 1997). Hydrological processes in the boreal forest zone have a large impact on global climate since they affect physical, biological and chemical processes controlling exchanges of carbon dioxide, hydrocarbons, energy and water between the land surface and the atmosphere (Arris and Eagleson 1994; Bonan *et al.* 1995; Granger and Pomeroy 1997; Pomeroy and Granger 1997). However, changes in the storage of water, heat and carbon in this region is not well understood (Halldin *et al.* 1999). Knowledge of the spatial and temporal variations in land surface hydrological processes is a requirement for describing water balance dynamics in boreal forest landscapes (Metcalfe and Buttle 1999). Processes occurring during redistribution of water and generation of runoff in environments with till deposits must be considered in this context.

Till is a non-sorted sediment composed of bedrock fragments ranging in size from clay to boulders, which have been deposited by glaciers without transport by water (Strahler and Strahler 1978). The characteristics of tills which have the greatest influence on hydraulic properties are distribution of pores and fractures, porosity, and degree of homogeneity and isotropy. These factors are controlled by grain size distribution, the spatial distribution and orientation of particles, structural properties and the degree of compaction (Haldorsen and Krüger 1990). Freezing and thawing, root and soil fauna activities, chemical processes and supply of humus change the characteristics of till deposits. These processes are most active in superficial layers (Lundin 1982). As a result, porosity and saturated hydraulic conductivity of tills are large near the ground surface, but decrease rapidly with depth (Espeby 1990b; Lind and Lundin 1990; Nordén 1991). Due to the large and systematic vertical variations, hydraulic properties have a higher correlation in the horizontal than in the vertical direction (Jensen and Mantoglou 1992). This was confirmed by Nyberg (1995a) who considered it possible to establish values for porosity and water retention representative of a catchment with till deposits, and Lundin (1982) who observed that porosity values did not show large differences between subareas of a catchment. Furthermore, Nordén (1991) investigated soil water retention at different tensions in several vertical profiles at two study sites. Results showed that the variations were larger within than between the profiles, at each site respectively. The maximum values of soil water retention coincided with the highest values of organic matter. On the other hand, Espeby (1990b) concluded from statistical analysis of soil samples that saturated hydraulic conductivity varied significantly between different parts of a hillslope.

In order to describe the partitioning of rain or snowmelt into evapotranspiration, runoff and temporary storage, it is necessary to consider the ways in which water moves from hillslopes into small streams, and the mechanisms which attenuate and delay the flow of water above and below the ground surface (Freeze 1974; Kirkby 1988). Results from several studies have shown that runoff from undisturbed headwater catchments in humid temperate environments is dominated by subsurface flow, with a contribution from saturation overland flow during runoff events, *i.e.* the increase of streamflow and the subsequent recession caused by a certain period of rainfall or snowmelt (*e.g.* Sklash and Farvolden 1979; Ogunkoya and Jenkins 1991, 1993; Turton *et al.* 1992; Brown *et al.* 1999). Similar results have been obtained from studies in boreal forest environments with till deposits (*e.g.* Rodhe 1981; Hinton *et al.* 1994; Peters *et al.* 1995; Collins *et al.* 2000). Even stormflow, *i.e.* runoff entering the stream channel during or immediately after rainfall or snowmelt events is dominated by pre-event water, *i.e.* liquid water which existed in the catchment previous to the event (Rodhe 1987; Bishop 1991). Furthermore, soil moisture in the root zone plays a key role in a catchment's response to infiltrated water, which is either returned to the atmosphere through evapotranspiration, or percolated to the saturated zone (Anderson and Burt 1990a). Myrabø (1986, 1997) and Nyberg (1995a) showed that catchments in boreal forest environments with till deposits respond to snowmelt or rainfall events in a manner that is closely related to their wetness state. The hydrographs of runoff events in small catchments are controlled by infiltration, vertical percolation through the unsaturated zone to the groundwater table and downslope flow (Kirkby 1988). Describing the processes which influence the spatial distribution of soil moisture and groundwater conditions and the downslope flow of water is therefore a requirement for developing physically based precipitation-runoff models at the scale of hillslopes or small catchments in a landscape with till deposits (Hinton *et al.* 1993). A qualitative description of how water flows through the soil is also essential for understanding the chemical processes encountered during flow of water through a catchment to streams and lakes (Sklash 1990). Christophersen *et al.* (1993) stated that intensive studies of hydrological processes is a requirement for developing and improving models of the mechanisms influencing the chemical composition of runoff.

The objective of this review is to describe the processes by which runoff is generated from rain or snowmelt on hillslopes in a forest dominated landscape with a shallow layer of glacial till deposits overlying a comparatively impermeable bedrock. Although the hydrological responses of catchments and the shape of streamflow hydrographs may be influenced by the spatial and temporal variability of water input from rainfall or snowmelt (Grayson *et al.* 1995; Singh 1997), this aspect is not considered. Neither is streamflow or flow of groundwater in the underlying bedrock. Some precipitation-runoff models that have a structure which may be suitable for landscapes with shallow till deposits are presented, however, several other models with the potential for describing processes in this type of environment exist. Although many of the citations do not refer to studies in landscapes with till deposits, they may still be valid for this environment since the physical laws governing flow of water are universal. The historical development of the understanding of runoff generation dynamics in forests is presented by several authors; *e.g.* Dunne (1978); Kirkby (1988); Anderson and Burt (1990a); Bonell (1993). The literature which is presented in this review is mostly confined to publications from Europe and North-America during the last 20 years.

Saturated Zone

A characteristic feature of till deposits is a saturated hydraulic conductivity which decreases rapidly with depth (Lind and Lundin 1990). As a consequence, the groundwater table largely follows the topography, with a depth of a few metres below the ground surface in elevated areas. In the lower parts of certain hillslopes and in some low areas, the groundwater table may rise above the ground surface (Lundin 1982). Almost the whole vertical depth of the surface deposits overlying the bedrock may be needed to transmit groundwater downslope (Rodhe and Seibert 1999). Accumulation of groundwater which has recharged upslope, topographical convergence, reduced hydraulic conductivity or decreasing sediment thickness in the downslope direction may result in saturation of the entire soil profile (Hinton *et al.* 1993). Depending on whether the water flows into or out of the groundwater zone, a catchment can be divided into recharge and discharge areas for groundwater (Gustafsson 1968). All rainwater and meltwater on recharge areas infiltrate, whereas all such water on discharge areas flows laterally to the stream during the event (Rodhe 1987).

Topography causes groundwater stored in a catchment to move towards the stream due to a downslope gradient in gravitational potential. Where groundwater levels are near or at the ground surface, the slope of the groundwater table equals the surface slope. However, the direction of groundwater flow may differ from the steepest surface gradient (Hinton *et al.* 1993). Nyberg (1995a) showed that the flow of water in a catchment with till deposits to a large extent was governed by topography and soil depth; water was rapidly drained from the steep hillslope flanks with shallow soils to the central valley, where the soil cover was deeper and the storage capacity higher. The saturated zone in the valley bottom was thicker and the velocity of water consequently slower. The large saturated hydraulic conductivity near the soil surface generated high flow rates in superficial layers during short periods of high flow. The age of groundwater in this catchment was found to be positively related to the local upslope subcatchment area (Rodhe *et al.* 1996).

Intermittent water input from rainfall and snowmelt and seasonal variations in the amount of water consumed by evapotranspiration result in temporal fluctuations in the depth to the groundwater table and the storage of water in the unsaturated zone (Nyberg 1995b). Diurnal fluctuations of the groundwater table caused by evapotranspiration were observed in a catchment with till deposits in Sweden by Johansson (1986). Lundin (1982) and Nyberg *et al.* (1993) observed that the saturated zone in small headwater catchments with till deposits was mostly absent at the hillslope flanks and in steep slopes with shallow soil cover, whereas the valley bottom contained permanent groundwater. During wet periods a groundwater zone was present over almost the entire catchment. Based on detailed groundwater level observations and water balance modeling, Nyberg (1995b) concluded that less than 10% of the water stored in a catchment was groundwater during periods of low flow, whereas that proportion increased to 60% at peak flows. On average, 75% of the water in the catchment was stored in the unsaturated zone.

Unsaturated Zone

The soil moisture content in the unsaturated zone depends on the depth to the groundwater table and the heterogeneous nature of soil properties, *e.g.* porosity, hydraulic conductivity and water retention, root concentration and the temporal and spatial variations of water input from snowmelt or throughfall (Bouten *et al.* 1992). The shallow depth to the saturated zone leads to a close relationship between groundwater and soil moisture conditions. This is due to the capillary transport of water and means that the groundwater level determines the possible range of fluctuations of the soil moisture content (Lundin 1982). When the groundwater table is lowered due to downslope flow, water is drained from the unsaturated zone above. After some time the movement of water is reduced, and a state of hydrostatic equilibrium which is determined by the properties of the till deposits and the depth to the groundwater table is established in the unsaturated zone (Nyberg 1995b). The hydraulic head is now constant in a vertical profile and the pressure of the pore water decreases in proportion with the heigth above the groundwater table. The exact form of the soil moisture profile varies with the texture and structure of the soil, specifically with the amount of water that can be held by capillary forces at any elevation above the groundwater table (Dunne 1978; Bear 1979). During episodes of infiltration, the soil moisture content rises above the equilibrium value to allow vertical flow, followed by a rise of the groundwater table and a new equilibrium state. The assumption of vertical hydrostatic equilibrium was used by Lundin (1982) and Nyberg (1995b) for estimating the amount of water stored in the unsaturated zone as a function of depth to the groundwater table. Lundin (1982) applied a linear regression model, while Nyberg (1995b) simulated water storage with a model base on the water retention characteristics of the soil. Beldring *et al.* (1999) modeled the spatial variability of surface soil moisture in catchments with till deposits by combining an assumption of vertical hydrostatic equilibrium with a relationship between water content and soil moisture tension. Soil moisture content in the root zone was allowed to decrease below the equilibrium value due to evapotranspiration. The spatial variability of soil moisture at different scales was described using statistical distribution functions conditioned on the physical characteristics of the soil matrix and the depth to the groundwater table. The model was well suited to describe observed data, confirming that the depth to the groundwater table is the main factor controlling the soil moisture content in the unsaturated zone.

Infiltration and Percolation

As undisturbed forest soils in general have a surface layer which can accept all rain or snowmelt, infiltration is seldom a limiting factor of catchment response, especially in humid temperate latitudes (Bonell 1993). Unless the saturated zone covers the entire soil profile, liquid water from snowmelt or throughfall and stemflow generally infiltrates through the soil surface, and percolation to the saturated zone takes place as soon as the soil moisture deficit which develops in the root zone due to evapotranspiration is filled up (Lundin 1982). Although litter interception may not be of large importance in evergreen coniferous forests, the surface of boreal forests is frequently covered by a thick carpet of lichens and mosses with a large capacity for storing water (Strong and La Roi 1983a, 1983b; Bonan and Shugart 1989).

The vertical transport of water through the unsaturated soil matrix in till deposits is slow, and except for areas with a shallow groundwater table, it will generally take days or months before the percolating water molecules reach the saturated zone (Rodhe 1989). Nevertheless, rainfall or snowmelt is followed by an almost immediate rise of the groundwater table due to an initially high soil moisture content and a rapid transfer of increased soil water pressure through the vadose zone (Lundin 1982; Rodhe 1989; Myrabø 1997). Furthermore, breaking up of the wetting front may induce rapid flow along concentrated zones with higher water content than the surrounding soil matrix (Liu *et al.* 1994; Young *et al.* 1999). In addition, macropores larger than the textural voids may allow preferential flow to bypass the unsaturated soil matrix, thereby reaching the groundwater table rapidly (Beven and Germann 1982; Peters *et al.* 1995). Water entry into macropores at the soil surface occurs when the ability of the soil matrix to infiltrate water is less than the rate of water input. This mechanism is more important when the rate of rainfall or snowmelt is high (Germann 1990).

The temporal variations of depth to the groundwater table in till deposits are characterized by rapid rise during infiltration and percolation and a subsequent slow recession phase between such events, occurring almost simultaneously in different parts of the hillslopes (Myrabø 1986; Espeby 1990a; Nyberg 1995a; Beldring *et al.* 1999). Macropores in till deposits have been shown to play an important water conducting role during percolation, resulting in a rapid rise of the groundwater table (Espeby 1990a). Furthermore, the low storage coefficient of tills results in large vertical variations of the groundwater table. The storage coefficient (of an unconfined aquifer) is defined as the volume of water released per unit surface area per unit decline of groundwater table (Dingman 1994). Lundin (1982) found that the storage coefficient of till deposits in a Swedish catchment increased from 0.001 at 1.5 m depth to 0.1 at 0.1 m depth, while Rodhe (1989) concluded that the storage coefficient of tills varied from 0.07 at the bottom of the soil profile to 0.1 – 0.15 at the top of the mineral soil. In the humus layer the values exceeded 0.5.

Johansson (1987) estimated groundwater recharge in tills by two methods: (i) simulations using a one-dimensional model of water flow in the soil which was verified using observed data; and (ii) transforming observed changes in groundwater levels to equivalent amounts of water using recession curves based on information about the storage coefficient of the soil. The boundary conditions for the soil water flow model were defined using meteorological data and models for snow storage, interception, evapotranspiration and groundwater flow. The first method was able to simulate observed fluctuations of the groundwater table, although the results were rather insensitive to the balance between evapotranspiration and groundwater flow. The second method was unable to provide consistent results for different years, and it was impossible to assess the values of the storage coefficient.

Abstraction of Subsurface Water by Evapotranspiration

Soil evaporation and transpiration from vegetation extract water from the saturated and unsaturated zones through a gradient in hydraulic head which induces movement of water (Dingman 1994). This causes a deficit relative to the soil moisture content at equilibrium to develop in the root zone in the recharge areas. In the discharge areas at the bottom of slopes an upward directed groundwater flow supplies water which is filling up this deficit. The soil moisture deficit relative to the equilibrium value is largest in the upper parts of slopes where the groundwater table is deep (Lundin 1982). The water consumed by soil evaporation and transpiration is raised to the surface from both the unsaturated and the saturated zones, depending on root water uptake and capillarity. As long as the groundwater table is within the root zone, water is extracted from the saturated zone, and the soil moisture deficit is zero. When the groundwater table is below the root zone, the fraction of water consumed from the saturated zone decreases with increasing depth to the groundwater table, while the fraction of water extracted from the unsaturated zone increases (Kovács 1986). Johansson (1986) observed diurnal fluctuations of the groundwater table in a catchment with till deposits in Sweden during summer conditions, and simulations using a one-dimensional model of water flow in the soil showed that evapotranspiration could influence the groundwater table at depths greater than 2 metres. No direct root water uptake from the saturated zone was necessary in the model, capillary transport caused by a shallow root system was able to produce the observed fluctuations of the groundwater table given the proper soil water retention properties.

Soil evaporation and transpiration are dependent on subsurface flows of heat and water, which are controlled by properties such as soil water retention, saturated and unsaturated hydraulic conductivities, heat capacity, latent heat of fusion and thermal conductivity (Jansson 1991). The effect of variability in soil properties on evapotranspiration is most likely to be large during periods with water deficiency, whereas little effect can be expected with frequent wetting and low potential evaporation (Lewan and Jansson 1996). The most important properties of vegetation in terms of transpiration are the development of vertical root distribution, the surface resistance for water flow between the plants and the atmosphere during periods with a non-limiting water storage in the soil, how the plants regulate transpiration and water uptake from the soil when water deficiency occurs, and how the vegetation cover influences the aerodynamic conditions in the atmosphere and the radiation balance of the land surface (Wallace and Oliver 1990; Jansson 1991). Nijssen *et al.* (1997) compared results from a distributed hydrology-soil-vegetation model (Wigmosta *et al.* 1994) with detailed measurements of moisture and energy fluxes in a boreal forest environment. The model simulated spatially distributed water and energy balance and lateral redistribution of water in each computational element using two canopy layers and three soil layers representing the root system. The diurnal cycle of latent heat flux was correctly described, while a lag in simulated sensible heat flux emphazised the importance of a correct representation of ground heat flux and ground heat storage.

Water uptake by fine roots is the most important supply of water to transpiration (Grelle *et al.* 1999). In boreal forest communities nearly the entire root system is confined to the upper layers of the soil profile. Strong and La Roi (1983a, 1983b) found that roots in stands of different tree species were concentrated close to the ground surface, with horizontal spreading within 15 cm of the forest floor generally dominating root development. Results from a study by Tryon and Chapin (1983) showed that the seasonal pattern of root elongation was closely correlated with temperature and reached maximum rates in summer. The majority of roots of different tree species were located within the top 20 cm of the soil. Clemensson-Lindell and Persson (1995) found that the lateral distribution of fine roots was apparently random, and more than two thirds of the roots were located in the humus layer. Cuenca *et al.* (1997) performed detailed measurement of soil moisture in a boreal forest landscape. The results showed that an upward flux of water caused by evapotranspiration existed at small depths, while a downward flux due to vertical drainage occurred below a dynamic zero-flux plane.

Overland Flow

The water delivered to the ground surface by rain or snowmelt events can travel to the first draining stream as subsurface flow or overland flow. There are two mechanisms that produce overland flow: i) saturation overland flow that occurs when the rising groundwater table intersects the ground surface; and ii) Hortonian or infiltration excess overland flow that occurs when the rainfall intensity exceeds the infiltration capacity of the soil (Moore and Foster 1990). Return flow of subsurface water which has infiltrated upslope also contributes to saturation overland flow (Kirkby 1988). Overland flow may also originate from fixed source areas with shallow soils or bare bedrock (Bonell 1993). In forest covered catchments in areas with shallow till deposits, this will often occur at the top of ridges where exposed bedrock may be found. However, overland flow which is generated in this manner will generally infiltrate in bedrock fissures or in the cover of till deposits in lower parts of the hillslopes (Grip and Rodhe 1994). Although infiltration excess overland flow is of little importance, freezing of the ground may reduce the saturated hydraulic conductivity due to the presence of ice, leading to a lower infiltration capacity and increased possibility for surface runoff (Stein *et al.* 1994). Furthermore, the presence of ice rich substrates may hinder deep percolation, producing lateral subsurface flow, primarily in the organic layer (Carey and Woo 1999). Prévost *et al.* (1990) observed frost in superficial layers of a catchment with till deposits. They showed in a model study that reducing the infiltration capacity during snowmelt improved the agreement between simulated and observed hydrographs. Nyberg *et al.* (2001) investigated the effects of frost on flowpaths along a hillslope in an area with till deposits in Sweden. In spite of obvious frost effects in several vertical profiles, there were no indications that the amount or timing of runoff were influenced. If parts of the pore space remain air-filled, rain or snowmelt can infiltrate frozen till deposits (Stähli *et al.* 2001).

Tracer Experiments

Dunne (1978) concluded that subsurface stormflow, return flow and direct precipitation on saturated areas were the three major runoff generating mechanisms in forest environments with soils of high infiltration capacity. Saturation overland flow was considered to be the most important source of stormflow, except in the case where steep hillslopes with deep and permeable soils border a narrow valley floor. Ward (1984) argued that saturation overland flow and saturated and unsaturated subsurface flow dominated the hydrograph peak. The importance of preferential flow paths was emphasized. However, several studies performing hydrograph separation based on conservative tracers have indicated that subsurface water present in the catchment previous to rain or snowmelt events constitutes the major component of stormflow (*e.g.* Sklash and Farvolden 1979; Pearce *et al.* 1986; Sklash *et al.* 1986). The purpose of hydrograph separation techniques using chemical or isotopic tracers is to partition the runoff hydrograph into its component sources and calculate the relative contribution from each source (Sklash 1990). Lundin (1982) concluded from tracer experiments and observed groundwater levels that saturated subsurface flow near the ground surface was the most important source of stormflow in a catchment with till deposits in Sweden. Myrabø (1986) mapped saturated areas and performed hydrograph separation based on the electrical conductivity of snow, rainfall and runoff in order to determine the contributions to streamflow from different flow paths in a catchment with till deposits in Norway. Groundwater fractions during snowmelt exceeded 50%. Using hydrograph separation by means of the oxygen isotope ^{18}O in ten different till catchments, Rodhe (1987) found that between 42% and 86% of stream discharge during snowmelt consisted of groundwater, while the groundwater fractions during rainfall exceeded 68%. The groundwater fractions estimated by ^{18}O refer to the proportions of water that existed in the catchment previous to the event. The actual groundwater fractions are therefore even larger than shown by hydrograph separation, since also some new rain- or meltwater flowed to the streams as groundwater. Bishop *et al.* (1990) investigated flow paths in a till catchment by sampling water chemistry and hydraulic head along a hillslope. They concluded that the major fraction of flow from the hillslope was confined to the upper 40 cm of the soil. Hinton *et al.* (1994) examined the contributions to stormflow from till a till catchment using hydrograph separation. The results showed that groundwater which exists in the catchment prior to runoff events can provide large contributions. Lange *et al.* (1996) concluded from tracer experiments during steady state flow conditions that stormflow is caused by water flowing in the upper layer of tills, whereas water flowing in deeper layers has long transit time. Tracer experiments performed by Nyberg *et al.* (1999) showed that the major transport of water in a till catchment occurred as fast saturated flow in superficial layers of high hydraulic conductivity, while a portion of the tracer had transit times of the order of weeks or months, which was interpreted as an effect of flow in the unsaturated zone. Collins *et al.* (2000) found that pre-event water contributed significantly to runoff, despite the rapid response of a catchment with till deposits. Progressively decreasing fractions of pre-event water suggested that displacement and mixing of water occurred simultaneously. Hangen *et al.* (2001) combined hydrograph separation, hydrometric measurements and baseflow recession analysis in a headwater catchment. The process of runoff generation could be divided into three temporal stages: i) displacement of water in near stream areas supplemented by saturation overland flow; ii) fast depletion of a near-channel reservoir comprising soil moisture and groundwater; and iii) delayed reaction of the hillslope aquifer.

Saturated Subsurface Flow

Subsurface flow that contributes significantly to streamflow during rain or snowmelt events must arise from mechanisms that quickly produce steep hydraulic gradients in materials of high saturated hydraulic conductivity near the stream (Rodhe 1987). As the hydraulic conductivity of a soil in general is much larger under saturated than unsaturated conditions (Hillel 1980), the existence of saturated zones is important for the flow of water. Highly conductive flow pathways in the superficial layers of the soil play a key role in this process (Lundin 1982). Nyberg *et al.* (1993) inferred from the high particle velocities observed during tracer experiments in a catchment with till deposits that much of the stormflow was concentrated in a small fraction of the pore space. It is clear from the signatures of conservative tracers in streamflow that substantial proportions of stormflow consist of water that existed in the catchments prior to the rainfall or snowmelt events, showing the importance of processes mobilizing pre-event water (Bishop 1991; Nyberg 1995b).

Sklash and Farvolden (1979), Pearce *et al.* (1986) and Sklash *et al.* (1986) proposed that infiltration and percolation of water in areas with a shallow depth to the saturated zone leads to a ridge in the groundwater table and an increased streamward hydraulic gradient. Gillham (1984) showed that small volumes of infiltrated water may generate rapid and large head increments in areas where the depth to the groundwater table is less than the air entry tension head of the soil water retention curve, transforming the tension-saturated zone into a ridge of groundwater with pressures exceeding atmospheric pressure. The hydraulic head of groundwater and consequently the hydraulic gradient near the stream increases. Furthermore, the cross-sectional area available for flow of water becomes larger (Rodhe 1989). The physical mechanisms responsible for the active role of groundwater during generation of runoff are therefore controlled by the transient discharge areas. Along the edges of these areas, the groundwater table and the capillary fringe above is close to the surface. As the size of the discharge area is extended, more subsurface water can participate during generation of runoff. The groundwater may discharge directly into the stream, or return to the surface as a part of the saturation overland flow. The response of upslope groundwater becomes important later in the runoff event. Groundwater flow from upslope locations is also important for supplying baseflow during dry periods (Hinton *et al.* 1993).

A discharge area may be saturated or unsaturated, depending on whether the groundwater table reaches the ground surface or not. Water input to saturated discharge areas generates overland flow, while in unsaturated discharge areas infiltrating water and upflowing groundwater is diverted laterally through superficial layers of high saturated hydraulic conductivity. Unsaturated discharge areas are probably common in till deposits (Rodhe 1987). Owing to the large saturated hydraulic conductivity near the ground surface, the outflow of groundwater from both saturated and unsaturated discharge areas may respond rapidly to rainfall or snowmelt in the recharge areas, causing a substantial groundwater component in stream stormflow (Lundin 1982; Nyberg *et al.* 1993). The existence of highly conductive flow paths in superficial soil layers is important for generating stormflow (Rodhe 1989). Bishop (1991) concluded that before a storm begins the difference in water content between unsaturated and saturated conditions within these highly conductive pathways is often just a small fraction of the total volume of water in the soil horizon. Newly added water from rainfall or snowmelt changes the pressure state in the unsaturated zone close to the groundwater table from negative to positive, initializing flow of water already present in the soil matrix. Furthermore, Bishop (1991) argued that concentrated flow paths may occur at different depths, *e.g.* at the soil-bedrock interface, along lenses with high saturated hydraulic conductivity or dispersed throughout the soil profile as macropores.

The areal extent of discharge areas for a catchment is highly variable, expanding with a rising groundwater table and thus with groundwater flow (Rodhe 1987). Myrabø (1986, 1997) showed that in a till environment, the basin fraction of discharge area and the mean total discharge have a high correlation. This was supported by Nyberg *et al.* (1993) who found that the runoff from a small headwater catchment in till deposits increased drastically when the depth to the groundwater table diminished.

Unsaturated Subsurface Flow

Kirkby (1988) argued that the direction of flow in the unsaturated zone is normally close to vertical, and that lateral hydraulic conductivities must be many times larger than vertical to produce significant lateral flow. Roberge and Plamondon (1987) concluded from experiments in a catchment with shallow till deposits that unsaturated matrix flow was a negligible component of downslope flow. Unsaturated flow is therefore first of all important during percolation of infiltrating water particles to the groundwater table. However, several studies have shown that lateral diversions of unsaturated flow may occur. McCord *et al.* (1991) used tracer experiments and model studies to show that unsaturated flow has a downslope component due to the dependence of hydraulic conductivity on water content. Although the relative importance of this flow component decreases with increasing soil water content, this flow will occur soon after infiltration begins and may therefore contribute to runoff events, in particular when the vertical extent of the unsaturated zone is large. Nyberg *et al.* (1999) concluded from the long tail of the transit time distribution of a tracer injected in a small till catchment that slow lateral transport in the unsaturated zone occurred. Johansson (1985) and Nyberg (1996) concluded from field studies and model experiments that although downslope unsaturated flow between rainfall or snowmelt events cannot be excluded in shallow till deposits, it is negligible compared to saturated flow, and vertical unsaturated flow dominates during water input from rain or snowmelt. Furthermore, in order for a hillslope to supply water to a stream, a saturated zone must exist adjacent to the stream to provide a streamward hydraulic gradient. Thus water cannot travel to a stream entirely as unsaturated flow (Dingman 1994).

Preferential Flow Paths

Many soils contain a secondary pore structure with a characteristic length several orders of magnitude greater than that between individual pores (Beven and Germann 1982). These voids are created by freezing and thawing, swelling and shrinking, root and soil fauna activity and chemical processes. Systems of such macropores connected in networks parallel to the slope can produce saturated hydraulic conductivities much higher than those associated with the soil texture. A criterion for distinguishing between matrix flow through the textural pores and macropore flow is that matrix flow may be described as potential flow using Darcy's law, whereas flow in macropore systems does not comply with the requirements for potential flow (Dingman 1984). Another characteristic feature of macropores is that they exert insignificant capillarity on the water running in them (Germann 1990). Lateral abstraction of water from macropores into the surrounding soil matrix occurs in unsaturated soils, however, this effect is reduced with increasing wetness conditions (Beven and Germann 1982). Horizontal and vertical macropore structures are common in tills (Espeby 1990a; Haldorsen and Krüger 1990; Jenssen 1990), and macropore flow is probably taking place at the same time as flow through the textural pores of the soil matrix. Bishop (1991) and Nyberg *et al.* (1993) concluded that although the exact nature of downslope flow processes was not known, the majority of flow in till catchments during periods of high stream discharge was localized in highly conductive superficial layers, including saturation overland flow during peak runoff. Macropore flow and matrix flow are therefore both important contributors to stormflow.

Roberge and Plamondon (1987) investigated flow paths during snowmelt in a catchment with shallow till deposits in Canada. They argued that saturated matrix flow accounted for 80% or more of the hillslope flow. Preferential flow in highly conductive pathways was generated when the groundwater table reached the top of the mineral soil, and during short periods it dominated downslope flow. Peters *et al.* (1995) performed hydrometric observations and isotopic hydrograph separation in a catchment with a shallow layer of till deposits in Canada. They concluded that a significant proportion of event water from rain or snowmelt at the sideslopes percolated to the impermeable bedrock via vertical flow in macropores, where mixing with unsaturated pre-event water occurred. This was followed by rapid downslope saturated flow in a weathered zone at the soil-bedrock interface, with pre-event water constituting the major fraction of stormflow. Matrix flow of groundwater occurred in near-stream areas, but was less important than envisaged by the groundwater ridging mechanism. Buttle and House (1997) investigated the effect of macropores on infiltration capacity in a catchment with shallow till deposit using ring infiltrometers and constant head permeameters. The bulk infiltration capacity of the macroporous deposit was significantly larger than the saturated hydraulic conductivity of the soil matrix. Buttle and Turcotte (1999) found a strong association between throughfall intensity and hillslope runoff, suggesting that coupled vertical and lateral macropore flows controlled runoff generation during small and medium events in a till catchment. Overland flow also increased with throughfall intensity.

Although preferential flow occurring through macropores can conduct water downslope in otherwise unsaturated soils (Bonell 1993), this phenomenon probably has little significance for contribution to streamflow, since water will be lost from the macropore system due to sorption from the surrounding unsaturated soil matrix (Germann 1990). The most important role of macropores in the unsaturated zone is probably by providing a means for rapid vertical bypassing of the soil matrix during vertical flow so that some water reaches the groundwater table quickly, thereby producing lateral flow in the saturated zone (Espeby 1990a).

Source Areas of Runoff

Source areas of runoff may be defined as areas in which rainfall or snowmelt in some way generates streamflow during the event. Pearce *et al.* (1986) put forward a source area concept in which Hortonian overland flow, saturation overland flow and subsurface flow are the three runoff generating mechanisms. Subsurface stormflow may occur as matrix flow or as preferential flow through systems of highly conductive pathways (Sklash 1990). The generation of subsurface stormflow is connected with the occurence of saturation excess overland flow. Subsurface flow maintains soil saturation during dry periods and accounts for the expansion of variable source areas during storms. Thus the source areas for these two types of stormflow are more or less the same (Anderson and Burt 1990b). The term partial area should be reserved for the area where Hortonian overland flow is generated, while the terms variable source area or contributing area are used to designate the proportion of the catchment which contributes to stormflow as subsurface flow, return flow or saturation excess overland flow. The stormflow yielding proportion of the watershed shrinks and expands depending on topography, soils, the amount of rainfall or snowmelt and the antecedent wetness of the soil(Anderson and Burt 1990a).

In boreal forest environments with glacial tills event flow may be either caused by infiltration, raising the groundwater level and thus increasing the subsurface flow, or direct runoff due to saturation overland flow (Nyberg 1995a). The source areas of runoff are found in concave terrain or at the bottom of hillslopes where the groundwater table is shallow or the entire soil profile is saturated. Within a given watershed, the extent of these source areas vary widely with time, reflecting the overall catchment wetness.

Topography

The three-dimensional role of topography in controlling movement and storage of water through convergence and divergence of flow has a significant impact on subsurface flow, which in turn is a major determinant of saturated areas and streamflow (Bonell 1993). The downslope flow of groundwater is an important means of redistributing the water in a catchment, leading to significant spatial variability of water supply to roots and evapotranspiration rates (Franks *et al.* 1997). Saturation overland flow prevails on concave slopes in contrast to subsurface stormflow on convex slopes (Dingman 1994). If water arrives in hillslope hollows faster than it can be transmitted downslope, saturation overland flow may also develop in areas relatively far from the stream (Ward 1984). Topography can therefore be used to distinguish between areas with different wetness conditions and influences on hydrological responses (Beven and Kirkby 1979; Beven and Wood 1983; O'Loughlin 1986; Thompson and Moore 1996). Indices which combine topographical attributes are often used to estimate the spatial distribution of moisture states in a catchment (Anderson and Burt 1990b).

Attributes derived from digital elevation models have been used for describing the influence of topography on soil moisture or groundwater conditions in regions with till deposits. In a study which showed that spatial response units in a landscape dominated by tills can be identified with the help of geomorphology, Krasovskaia (1985) used a classification based on Hack and Goodlett (1960) to differentiate between three types of topographical units in a catchment: i) nose, the driest part, including the ridge crest and the nearby slopes where the contours are convex outward; ii) hollow, the central part of the basin along the stream with favourable moisture conditions, an area in which the contours are concave outward; iii) slope, the zone between nose and hollow with transitional moisture conditions where the contours are straight or nearly so. Results from this study showed that groundwater and soil moisture conditions differed significantly between topographical units within catchments with till deposits, but not between the same type of units in different catchments. These results were confirmed by Beldring *et al.* (1999) who investigated the spatial distributions of depth to the groundwater table and soil moisture content in the unsaturated zone at different scales in a boreal forest landscape with till deposits in Sweden. Hinton *et al.* (1993) presented results from investigations in a forested till catchment. Topographical convergence in plan and decreasing sediment thickness resulted in surface saturation and groundwater discharge. Hillslope gradients adjacent to discharge areas determined how fluctuating groundwater levels influenced the spatial extent of saturated areas. Furthermore, this study showed that the assumption that groundwater flow is perpedicular to the topographical contours is not always correct. Therefore, they concluded that digital elevation models to be used in hydrological modeling should be based on groundwater equipotentials rather than surface topography, although they did not suggest how this information should be obtained.

Several studies have attempted to relate spatially distributed wetness conditions in catchments with till deposits to the topographical index presented by Beven and Kirkby (1979). This index describes the distribution of wetness states in a catchment as a function of upslope area draining through a point and the tendency for downslope flow by gravitational forces. Thompson and Moore (1996) studied relations between topographical characteristics derived from digital elevation models and spatially distributed groundwater levels observed in a small forested catchment. The topographical index (Beven and Kirkby 1979) was unable to predict observations for most of the piezometers. Phenomena not related to surface topography, such as soil properties, the existence of macropores and the topography of the base of the soil profile, were believed to be the most probable cause of deviations between observations and predictions. Nyberg (1996) and Sulebak *et al.* (2000) applied linear regression models for relating observed patterns of soil moisture in the unsaturated zone to this index. Both these studies concluded that the topographical index was able to explain observed patterns of wetness to a certain degree, however, linear regression models based on other topographical attributes were equally good. Rodhe and Seibert (1999) compared the frequency distribution of this index to the spatial distribution of bogs, assuming that the latter represented the extreme end of wetness states in the landscape. The topographical index failed to represent bogs in a flat region, while it performed better in a hilly region. One explanation of the failure of the index in the flat region was that the horizontal spatial resolution of the digital elevation model was coarser than the typical lenght scales of the topographic features, which was only a few tenths of metres.

Precipitation-Runoff Models

The HBV model (Bergström 1995; Lindström *et al.* 1997) has been used in boreal forest landscapes with shallow till deposits in Scandinavia for several decades. It is a distributed conceptual precipitation-runoff model which uses sub-basins as the primary hydrological units, and within these an area-elevation distribution and a crude classification of land use (forest, open, lakes) are applied. Bergström and Sandberg

(1983) used the HBV model to simulate the response of groundwater reservoirs in different geological environments, including tills, to climatological input. Lindström and Rodhe (1986) applied the PULSE model, a modified verson of the HBV model adapted for hydrochemical applications, for modeling exchange of water and ^{18}O in till environments. Vehviläinen and Motovilov (1989) included the effect of soil frost on runoff in the HBV model. Vehviläinen and Lohvansuu (1991) ivestigated the impacts of climate change on runoff and snow cover in Finland. Seibert (1999) applied the HBV model to catchments in a boreal forest landscape in Sweden with the purpose of relating regional parameter sets to physically measurable catchment characterics using two-parameter regression functions. Good results were achieved during runoff simulations and several of the relationships between model parameters and landscape characteristics supported the physical basis of the model.

Johansson (1985) modeled saturated and unsaturated flow processes in a hillslope covered by shallow till deposits using numerical solutions to Darcy's law and the continuity equation. The saturated hydraulic conductivity decreased with depth below the surface according to the study by Lundin (1982). Results showed that outflow from the saturated zone was mainly due to infiltration close to the stream, resulting in a rise of the groundwater table into layers of high saturated hydraulic conductivity and an increased hydraulic gradient. Zones of surface saturation developed in case of a concave slope, but not in the case of a straight slope. Subsurface flow simulated by the model produced streamflow hydrographs corresponding to observations in catchments with till deposits.

Espeby (1992) applied a cascade of one-dimensional soil columns based on the SOIL model (Jansson 1991) to simulate the generation of runoff from a hillslope in a till environment. The SOIL model describes flow of water and heat in a vertical soil profile using the Richards equation and the Fourier equation. Boundary conditions for each soil column were defined using meterorological data and models for snow storage, interception, evapotranspiration and groundwater flow. The hydraulic gradient driving groundwater flow from one soil column to the next was equal to the hillslope angle. Vertical bypass flow in macropores was described by a conceptual approach which routed water in excess of the sorption capacity of the soil downwards. Macropore flow allowed a rapid response of the groundwater table during rainfall or snowmelt events, which was necessary to simulate the peaks of observed runoff hydrographs from the hillslope. With only potential flow taking place, a substantial amount of water was stored in the soil matrix and did not contribute to runoff peaks. Stähli *et al.* (2001) applied a similar SOIL model cascade in order to quantify the effects of frost on snowmelt and runoff in a boreal forest environment with till deposits. Subsurface flow was the dominant runoff component in the model simulations. However, local overland flow was identified when deep soil frost combined with high initial saturation led to formation of ice which blocked the water conducting pores.

Beldring *et al.* (2000) and Beldring(2002) applied kinematic wave approximations to saturated subsurface and overland flows for describing the spatial distribution of soil moisture and groundwater conditions and their significance for runoff and evapotranspiration fluxes in catchments with shallow till deposits. The precipitation-runoff model was able to simulate the interactions between snow storage, subsurface moisture conditions, runoff and evapotranspiration in catchments in the boreal forest zone in Norway and Sweden. The results confirmed the important role of soil moisture and groundwater in controlling the dynamic nature of hydrological processes in this environment.

Motovilov *et al.* (1999) applied the distributed, physically based ECOMAG model in a boreal forest region of approximately 8000 km^2 in Sweden with a global set of parameters based on land surface characteristics. This model describes state variables and flow of water in three dimensions using realistic, process-based equations. Distributed observations of runoff, soil moisture and groundwater levels were used during calibration, and subsequently model-simulated values were compared with spatially distributed observations of runoff and evapotranspiration.

The TOPMODEL concept (Beven and Kirkby 1979; Beven *et al.* 1995) calculates the dynamic distribution of wetness states and runoff producing areas in a catchment through the use of an index representing topographical characteristics which are fundamental for flow processes (Moore *et al.* 1991; Grayson *et al.* 1992a, 1992b). Local groundwater table depths are related to catchment average groundwater storage. Runoff production is described by infiltration excess overland flow, saturation overland flow and saturated subsurface flow through a succession of steady state representations. Percolation to the saturated zone from a surface infiltration store occurs at a constant rate. An exponential decrease in saturated hydraulic conductivity or transmissivity with depth is assumed. Moore and Thompson (1996) evaluated whether groundwater levels predicted by TOPMODEL agreed with observed data in a forested till catchment in Canada. Observed data were fitted well by a linear regression model including time and location effects predicted by TOPMODEL. Seibert *et al.* (1997) applied a version of TOPMODEL which included an exponential increase in storage in the saturated zone with a rising groundwater table. They were able to reproduce observed runoff from a small watershed (0.63 ha) in an area with shallow till deposits in Sweden, but failed to match simulated and observed groundwater data. Lamb *et al.* (1997) simulated runoff and spatially distributed groundwater levels with a hydrological model based on the TOPMODEL concept, using data from a small watershed (0.75 ha) in an area with till deposits in Norway. A modified storage function of the saturated zone was determined from observed stream flow recessions, and a topographical index including soil properties through the use of a power law was suggested. The accuracy of simulated groundwater leves was only approximate. Lamb *et al.* (1998) investigated how distributed groundwater table observations modified simulation and parameter uncertainty of TOPMODEL, using data from the same watershed as Lamb *et al.* (1997). Parameter uncertainty was reduced when simulations were conditioned on observed runoff and groundwater levels instead of only runoff. However, the uncertainty of catchment runoff predictions increased and simulation uncertainty bounds failed to enclose many of the observed groundwater levels.

Conclusions

Groundwater is viewed as the major determinant of runoff generation in forest environments with shallow till deposits, both because it is the most important contributor to event flow, and because of its influence on saturation overland flow. Newly added water from rainfall or snowmelt changes the pressure state in the unsaturated zone close to the groundwater table from negative to positive, initializing flow of water already present in the soil matrix. Mobilizing of water in highly conductive flow pathways near the ground surface and the increase in hydraulic gradient and cross-sectional area available for flow result in stormflow being dominated by subsurface flow. Depending on whether the water flows into or out of the groundwater zone, a catchment can be divided into recharge and discharge areas for groundwater. All rainwater and meltwater on recharge areas infiltrate, whereas all such water on discharge areas flows laterally to the stream during the event. Source areas of runoff may be defined as areas in which rainfall or snowmelt in some way generates streamflow during the event. These areas are found in concave terrain or at the bottom of hillslopes where the groundwater table is shallow or the entire soil profile is saturated. Within a given watershed, the spatial extent of the source areas vary widely with time, reflecting the overall catchment wetness. The response of upslope groundwater becomes important later in the event. Groundwater flow from upslope locations is also important for supplying baseflow during dry periods. Modeling and field experience point to the idea of a continuum in both spatial and temporal occurrence of saturation overland flow and subsurface flow within individual catchments under different rainfall and snowmelt events and antecedent groundwater and soil moisture conditions.

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