Nordic Hydrology, 20, 1989, 1-8

On the Generation of Stream Runoff in Till Soils

Paper presented at the Nordic Hydrological Conference
(Rovaniemi, Finland, August – 1988)

Allan Rodhe
Division of Hydrology, Uppsala University, Sweden

Isotope studies in Swedish till basins indicate that stream stormflow is normally dominated by pre-event water. The rapid response of the groundwater outflow to infiltration may be explained by a large increase in the hydraulic conductivity of the soil towards the ground surface. In homogeneous soils the effect of the capillary fringe may be important in building up large total head gradients towards the stream. In generating runoff peaks in the streams, the saturated discharge area contributes 100 %, by saturation overland flow. Various parts of the recharge area contribute less than 100 %, and less effectively the longer the distance to the recharge area is. The areal extent of the contributing recharge area is considerably larger than the discharge area.

Introduction

The mechanism by which rainfall or snowmelt in a basin is transformed into streamflow, *i.e.,* the runoff process or the process of streamflow generation, is not yet fully understood. Basic questions which need to be answered, related to climate and physiography, are: What paths do water particles take through the basin, what are the magnitudes of flows and residence times of the water on the surface and in different soil layers, and how can the flow processes involved be formulated mathematically? A better knowledge of the runoff process is needed for a further development of mathematical runoff models and, particularly, for an understanding of the chemical changes taking place in water during its flow through the basin to the draining stream.

In this paper, some aspects of the runoff process are discussed from the results obtained by isotopic hydrograph separation in several Swedish basins using oxygen-18 as a tracer (Rodhe 1987).

The Oxygen-18 Study

The investigation was performed in 10 basins with areas ranging from 0.03 to 6.6 km^2 in 6 localities in Sweden. The basins represent characteristic types of landscapes encountered in Sweden, with gneiss or granite rock covered by glacial till soils, vegetated by coniferous forest.

Streamflow was separated into flows of event water (fresh rain- or meltwater) and pre-event water (groundwater) using a simple two-component model for the flows of water and tracer from two reservoirs to the stream. The tracer used was the environmental stable isotope oxygen-18. The separations showed that storm runoff from the investigated basins was usually dominated by pre-event water (Fig. 1). The dominance was univocal for all rainfall events and most of the snowmelt events. Since some of the discharged event water may be groundwater, recharged during the event, the groundwater fraction of streamflow is larger than, or equal to, the fraction of pre-event water.

The accuracy of the method was discussed in detail by Rodhe (1987), who concluded that the most reliable results are those obtained from fairly large rainfall events in small steep basins. For the total volume fraction of groundwater discharged during an event, the accuracy was estimated to 10-15 percentage points.

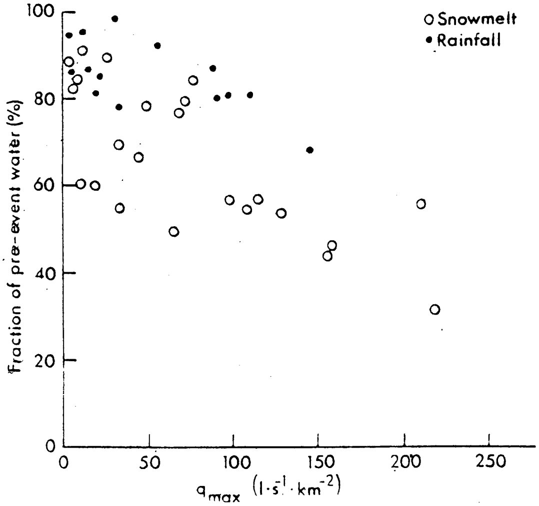

Fig. 1.
Total volume fraction of pre-event water, as estimated by oxygen-18, versus maximum streamflow. Snowmelt and rainfall events in 10 Swedish basins. (From Rodhe 1987).

Discussion

A large number of isotope studies on streamflow generation have been performed during the last 20 years (see Rodhe 1987). Most of the study basins are within the temperate climate zone, but physiographic and geologic factors vary largely, from steep Alpine catchments to agricultural land of low relief. There are also large differences in the rates of water flow in the investigated events. Nevertheless, the results are similar in practically all these studies, indicating that runoff events in small streams in temperate areas are normally dominated by pre-event water. Even if exceptions do occur, the phenomenon seems to be general.

Mechanisms for the Response of Groundwater Discharge to Water Input

The view formulated by Horton (1933), that overland flow due to rainfall excess is the dominating component of stormflow in streams, has had a very powerful impact on the concept of streamflow generation in hydrology and water engineering. When chemical and isotope studies in the late 1960s showed that stormflow was often dominated by pre-event water, researchers were perplexed. How can groundwater flow, known as a "slow" process, react so quickly to rain or meltwater input? Various processes have been suggested: lateral unsaturated flow with a saturated zone at the base of the slopes acting as a "conduit" (Hewlett and Hibbert 1967), groundwater wave propagation (Martinec 1975), macropore flow (Mosley 1979) and rapid head increase close to the stream due to the effect of the capillary fringe (Sklash and Farvolden 1979; Gillham 1984).

While discussing the response of the groundwater discharge to water input it is important to distinguish between the particle velocity of water and the rate of pressure propagation. The particle velocities determine the transit times of water, whereas the rate of pressure propagation determines the time of response of the outflow. In a till basin of first order, the former time is of the order of days to years (*e.g.*, Lindström and Rodhe 1986), whereas the latter is of the order of minutes to hours.

In a runoff event, the groundwater outflow may increase by 5 to 50 times the pre-event value within a few hours or a day after the onset of infiltration. Let us look at some necessary conditions for such an increase.

When the water table in a hillslope rises as a result of a water input, the groundwater flow increases for two reasons: increased total head gradient due to increased slope of the water table and increased transmissivity due to contribution by additional soil horizons. In areas where the water table largely follows the topography, the relative increase of the slope of the water table is unlikely to exceed some 10 percents. The increase in the cross-sectional area for lateral groundwater flow may be of similar magnitude. Thus, in a homogeneous soil the relative flow increase due to a rise of a shallow water table is too small to explain the manyfold increase in groundwater outflow observed indirectly in the isotope studies. In many soils,

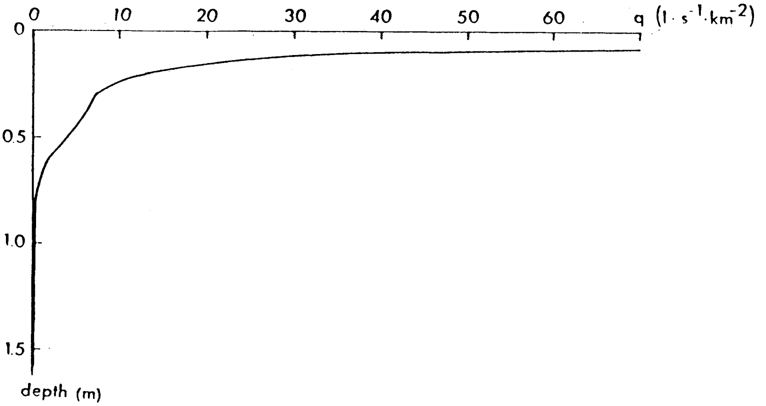

Fig. 2. Total lateral groundwater flow as a function of the depth to the water table calculated from a hydraulic conductivity profile. The hillslope is assumed to be 50 m long and the slope of the water table 0.1 m/m at the base. (Data from Lundin 1982).

however, the saturated hydraulic conductivity increases towards the ground surface. With the large increase in hydraulic conductivity towards the ground surface reported for a till soil by Lundin (1982), the groundwater flow may increase manyfold by a small rise of a shallow water table, even if the slope of the water table remains essentially constant (Fig. 2).

In a homogeneous soil the water table will show quickest response close to the discharge area. There, the rate of pressure propagation in the unsaturated zone is high, since the water content is comparatively high due to the moderate tensions prevailing. This, in combination with a short distance to the water table, gives a rapid response. The high water content in the whole unsaturated zone further causes a small amount of added water to produce a large rise of the water table, *i.e.*, the storage coefficient is small.

The above effect is the basis of the capillary fringe concept, advocated as an explanation for the rapid response of groundwater discharge observed from ^{18}O by Sklash and Farvolden (1979). In areas where the depth to the water table is less than the air entry pressure of the water retention curve (the so-called capillary fringe), small volumes of infiltrated water may generate very rapid and large head increments, as shown theoretically with some field support by Gillham (1984). With suitable geometry of the stream channel banks, the head gradient towards the stream, and thus the groundwater outflow, may increase manyfold.

The capillary fringe concept may thus offer an explanation for the observed increase of groundwater outflow, also in soils with little or no increase in the hydraulic conductivity towards the ground surface. It may also explain the occurrence of deep groundwater stormflow, the existence of which was indicated from hydrochemical observations by Calles (1982). Large rises in the water table close to the stream or close to a low-lying area are a necessary condition for a substantial

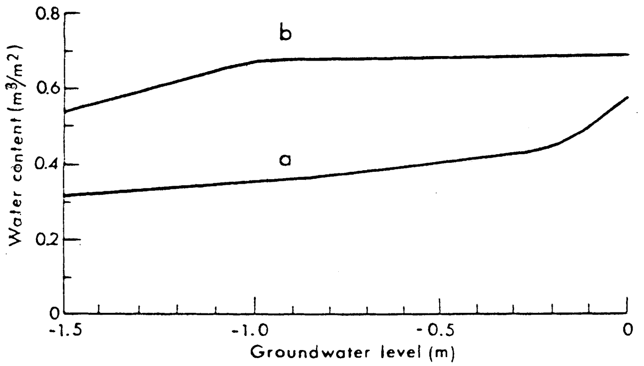

Fig. 3. Water content of the topmost 1.5 m of the soil with the water table at various levels (groundwater level 0 m ≡ ground surface). Curve a) is calculated from water retention curves at different depths in a till soil reported by Lundin (1982, profile U2). Curve b) is calculated for a hypothetical homogeneous soil, characterized by a water retention curve for fine sand reported by Anderson and Wiklert (1972).

increase in the vertical outflow of deep groundwater. Large rises in the water table higher up in the recharge area can give only small relative changes in the vertical head gradient towards the stream or its surrounding discharge area.

In a till soil, having pores of very different sizes, the pores empty gradually as the pressure potential becomes more negative. The air entry pressure has often a small negative value (a few centimetres), particularly in the shallow layers, where there may be large structural pores due to various soil processes (Lundin 1982 and Johansson 1986). By combining the water retention curves of the soil at different depths reported by Lundin (1982), the water content of a soil profile in equilibrium with a water table at various depths was calculated. From these curves the total water content in the profile as a function of the groundwater level was obtained (Fig. 3). The storage coefficient, equalling the slope of the curve in Fig. 3, increased from about 7 % at depth, to 10-15 % in the top of the mineral soil and up to more than 50 % in the organic layer. (These values are considerably larger than those reported by Lundin for the same area, obtained from comparisons between precipitation and water table fluctuations, which varied from about 1 % through 4 % to 15 %). The increase in the storage coefficient towards the ground surface counteracts rapid and large head increments by small water inputs to the surface. But since the hydraulic conductivity increases with height, a large increment in the head gradient is not necessary for a large increase in the groundwater flow to take place.

For comparison, a curve for a homogeneous soil of well-sorted fine sand (water retention data from Anderson and Wiklert 1972) is also shown in Fig. 4. Here the storage coefficient becomes very small when the water table rises and the capillary fringe reaches the ground surface.

The Origin of Stormflow

Isotope studies have shown that only a minor part of the water particles discharged during a runoff event consists of new rain- or meltwater. Rodhe (1987) assumed that the discharged volume of new water equalled the rain or melting on saturated discharge areas, whose areal extent thereby could be estimated. The estimated extents agreed reasonably well with the results of field surveys during some of the snowmelt runoff events. In doing such estimates it was assumed that all new rain- or meltwater on saturated discharge areas ran off in the stream during the events. The assumption agrees with the expected velocity of overland flow, a few centimetres per second, implying that overland-flowing water from the whole discharge area reaches the stream within minutes of hours.

The particle velocity for flow in the soil is smaller than that for overland flow by several orders of magnitude. The vertical velocity in the unsaturated zone seldom exceeds a few cm/h, and this velocity remains only during and shortly after the event of infiltration (*cf.* the mean particle velocities around 1 m/year observed by Saxena 1987). It is thus only in areas with very shallow groundwater that rainwater particles reach the groundwater during the runoff event. Rough estimates, based on observed hydraulic conductivities and porosities in till soils, show that the groundwater particles discharged during an event were probably located within or in close vicinity of the discharge area at the onset of the event.

The above comments concern the origin of the water particles. Finally, the origin of stormflow will be discussed from a different angle: Where in the basin are the impulses for stormflow given? In these discussions, a sub-area is said to contribute if rainfall or snowmelt in the sub-area during a runoff event in some way affects the streamflow during the event, *i.e.*, if the water input to the sub-area gives impulses for stream stormflow.

Saturated discharge areas (see Grip and Rodhe 1988) can be said to contribute 100 %. If evapotranspiration during the flow event is disregarded, the flow impulse from these areas equals the rainfall or snowmelt they receive. Here the impulses are propagated by saturation overland flow.

Due to storage in the soil and evapotranspiration, the volume discharged to the stream as a result of infiltration in the recharge areas is smaller than the total infiltrated volume. Thus recharge areas do not contribute 100 %. In the vicinity of the discharge area, the contribution to streamflow can be close to 100 %, but upslope it gradually decreases with increasing distance to the discharge area. In areas where the water flow is concentrated by the topography, *i.e.*, in topographic hollows and other concave landforms, the impulses to stormflow are particularly large, by saturation overland flow as well as by rapid groundwater discharge response to infiltration.

The fraction of saturated discharge areas of a basin, Y, was estimated by Rodhe (1987) as

$$Y = \frac{V_p}{V_{wi}}$$

where V_p is the discharged volume of new rain- or meltwater and V_{wi} the volume of the water input to the basin. The extent of areas giving impulses for groundwater discharge cannot be estimated in a corresponding way, however, since these areas do not contribute 100 %. But we know that these areas are larger than the area needed if the contribution were 100 %, *i.e.*, their fraction of the basin area is larger than V_g/V_{wi}, where V_g is the discharged volume of groundwater. Since the runoff events are generally dominated by groundwater ($V_g > V_p$), the impulses must come from an area considerably larger than the saturated discharge area. The fraction of the basin area needed to generate a runoff event is larger than the discharged fraction of the water input, $(V_p + V_g)/V_{wi}$, which is the area fraction needed with a 100 % contribution (the so-called minimum contributing area discussed by Dickinson and Whiteley 1970). In the study by Rodhe (1987), this fraction varied from 10 % in small summer events to more than 90 % in large autumn or spring floods.

Conclusion

Isotope studies in humid temperate areas show that runoff events in such areas are normally dominated by pre-event water. For the rapid and large response of the groundwater outflow to rain- or meltwater input, observed indirectly in the isotope studies, two conditions must be fulfilled in the discharge area: a sufficiently large gradient in total head must build up rapidly enough, and the hydraulic conductivity and the cross section for flow must be large enough. A few observations in Swedish till soils show a large increase in the hydraulic conductivity towards the ground surface. With such an increase, the groundwater outflow may increase manyfold, even by a moderate rise of a shallow water table. In homogeneous soils, rapid and large head increments close to the stream, due to the effect of the capillary fringe, may be important. This effect may also generate rapid increments of deep groundwater outflow to the streams.

Estimates based on expected particle velocities for the water flow in till soils show that the bulk of the groundwater particles discharged during a runoff event were situated within or close to the discharge area at the onset of the event. The area contributing to stream stormflow is defined as the area in which rainfall or snowmelt in some way contributes to the stream response during an event. The area contributing to fresh rain- or meltwater flow is mainly the saturated discharge area. The area contributing to groundwater flow is considerably larger, with the contribution decreasing in effectiveness from the vicinity of the discharge area towards more distant parts of the basin.

References

Andersson, S., and Wiklert, P. (1972) Markfysikaliska undersökningar i odlad jord. XXIII. Om de vattenhållande egenskaperna hos svenska jordarter, *Grundförbättring* (Journal of Agricultural Land Improvement), *Vol. 25 (2-3)*, pp 53-143 (in Swedish with English summary).

Calles, U.M. (1985) Deep groundwater contribution to a small stream, *Nordic Hydrology, Vol. 16 (1),* pp 45-54.

Dickinson, W.T., and Whiteley, H. (1970) Watershed areas contributing to runoff, IAHS Publ. 96:1.12-1.26.

Gillham, R.W. (1984) The capillary fringe and its effect on water-table response, *J. Hydrol., Vol. 67,* pp. 307-324.

Grip, H., and Rodhe, A. (1988) *Vattnets väg från regn till bäck,* Hallgren och Fallgren, Uppsala, 156 pp.

Hewlett, J.D., and Hibbert, A.R. (1967) Factors affecting the response of small watersheds to precipitation in humid areas. In: Sopper, W.E. and Lull, H.W. (eds), *Int. Symp. on Forest Hydrology 1965,* Penn. State Univ., Pergamon press, New York, pp. 275-290.

Horton, R.E. (1933) The rôle of infiltration in the hydrological cycle, *Trans. Am. Geophys. Union, Vol. 14,* pp. 446-460.

Johansson, P.O. (1986) Diurnal groundwater level fluctuations in sandy till – A model analysis, *J. Hydrol., Vol. 87,* pp. 125-134.

Lindström, G., and Rodhe, A. (1986) Modelling water exchange and transit times in till basins using oxygen-18, *Nordic Hydrology, Vol. 17(4/5),* pp. 325-334.

Lundin, L. (1982) Mark- och grundvatten i moränmark och marktypens betydelse för avrinningen. *UNGI Report* 56, Uppsala Univ., Dept Phys. Geogr., 216 pp. (In Swedish with English summary and figure legends. English title: Soil moisture and ground water in till soil and the significance of soil type for runoff).

Martinec, J. (1975) Subsurface flow from snowmelt traced by tritium, *Water Resour. Res., Vol. 11,* pp. 496-498.

Mosley, M.P. (1979) Streamflow generation in a forested watershed, New Zealand, *Water Resour. Res., Vol. 15(4),* pp. 795-806.

Rodhe, A. (1987) The origin of streamwater traced by oxygen-18, Uppsala Univ., Dept Phys. Geogr., Div. Hydrol., Report Series A 41, 260 pp. Appendix 73 pp.

Saxena, R.K. (1987) Oxygen-18 fractionation in nature and estimation of groundwater recharge, Uppsala Univ., Dept Phys. Geogr., Div. Hydrol., Report Series A 40, 152 pp.

Sklash, M.G., and Farvolden, R.N. (1979) The role of groundwater in storm runoff, *J. Hydrol., Vol. 43,* pp. 45-65.

Received: 19 December, 1988

Address:
Division of Hydrology,
Uppsala University,
Västra Ågatan 24,
S-752 20 Uppsala,
Sweden.