556.16

THE TRUE ORIGIN OF RUNOFF?

by

ESKO KUUSISTO

Hydrological Office
National Board of Waters, Helsinki

Abstract

One of the basic questions of hydrology – the origin of runoff – is still unsolvable. The traditional concepts of Hortonian overland flow, intermediate flow and baseflow do not explain all the peculiarities of runoff formation.

The use of isotope techniques has made it possible to detect the origin of flood water. It has turned out that a large proportion of spring flood volume is actually 'pre-event water'. This would suggest that the true origin of runoff is far from the traditional theory.

1. *Introduction*

In 1684 Edmé Mariotte carried out measurements in the Seine river basin. These measurements provided the first experimental proof that rainfall is sufficient to sustain river flow. Today, almost 300 years later, we can but confirm that very little more is known about the formation of runoff.

The traditional 'trinity theory' of runoff formation is based on three components: baseflow, interflow and overland flow. The baseflow component is the groundwater accretion into the streams, and it is characterized by very slow variations. Interflow or subsurface flow is generated by water which has infiltrated into the upper soil layers. It moves laterally and reaches the stream within the time span of a few hours to days after the rainfall or snowmelt event. Overland flow is the water which travels over ground surface to the channel. The classic concept of HORTON (1933) states that this flow component is generated wherever the rainfall or snowmelt rate exceeds the rate of infiltration.

In recent years, interest in understanding the mechanisms of runoff formation has been growing. The main impetus to this interest has been the possibility to study the 'age' of water entering a stream during and after a rainfall or snowmelt event. This possibility is offered by environmental isotope techniques, especially the methods based on tritium or ^{18}O-isotopes.

The results of these studies have been startling. Some hydrologists involved have ever stated that the separation of hydrographs into three components is irrational, 'nothing more than a convenient fiction' (FREEZE 1972). Especially the concept of interflow has been questioned.

2. *The age of water*

About 0.2 per cent of the water molecules in natural streams contain the stable oxygen isotope ^{18}O (ROHDE 1981). The concentration of ^{18}O in precipitation has a considerable seasonal variation in higher latitudes. To some extent this variation is caused by variations in temperature when water vapor is condensed in the atmosphere. Another reason to the variation is different origin of the air masses. During winter the concentration of ^{18}O is low as compared to the summer values. In groundwater the concentration is comparatively constant throughout the year, due to fairly effective intermixing of water molecules in the underground water storages.

If runoff is assumed to originate from two sources, 'event water' and 'pre-event water', the following mass-balance equation should be valid:

$$c_f Q_f = c_e Q_e + c_p Q_p \qquad (1)$$

where Q_f is total discharge
Q_e is discharge of event water
Q_p is discharge of pre-event water
c_f, c_e, c_p are corresponding isotopic concentrations

The term 'event water' refers to the water entering the surface of the river basin as a consequence of rain or melt event. The 'pre-event water' consists of previous underground water reserves of the drainage basin. If the isotopic concentrations of these two components are significantly different and if they remain constant during the event, equation (1) may be applied.

3. *What happens to the meltwater?*

The ^{18}O-method was applied in Sweden to two small catchments in spring 1979 (ROHDE 1981). The characteristics of the catchments were as follows:

	Nåsten	Stormyra
Area (km^2)	6.8	4.0
Percentage of		
– forest or clearcutting	83	89
– agricultural land	13	8
– bogs	4	3
Percentage of		
– outcrops	25	67
– moraine	55	13
– clay	16	12
– peat	4	8
Altitude range (m)	37	67

The Nåsten catchment is located 5 km SW of Uppsala, the Stormyra catchment 20 km SE of Stockholm. There are no lakes in these catchments.

At the beginning of snowmelt, the areal mean water equivalent of snow was 90 mm in Nåsten and 125 mm in Stormyra. Soil frost depth was not measured.

Fig. 1 shows total discharge and the contributions from groundwater and meltwater (including rain during snowmelt) in the two catchments. During the two parts of the snowmelt season, groundwater fraction of the total flow volume was 0.67 and 0.78 in the Nåsten catchment, and 0.88 and 0.78 in the Stormyra catchment, respectively. The volume of event water corresponded only 10–15 per cent of the total volume of snowmelt and precipitation.

4. *Conceptual implications*

Results comparable to those by Rohde have been obtained in several studies. HERRMANN & *al.* (1979) studied a mountaineous Lainbach catchment, with an area of 19 km^2, in Switzerland. The percentage of pre-event water during snowmelt period was 78. In a study in the basin Modry Due (CSSR), the pre-event water amounted to 63 per cent, and in the basin Dischma (Switzerland) it amounted to 64 per cent of total runoff during snowmelt period (MARTINEC 1975). Similar results have been obtained for rainfall events, too (SKLASH & FARVOLDEN 1979).

These results clearly indicate that the traditional concepts of runoff formation (Fig. 2a) should be revised. The physically 'sound' separation of hydrograph com-

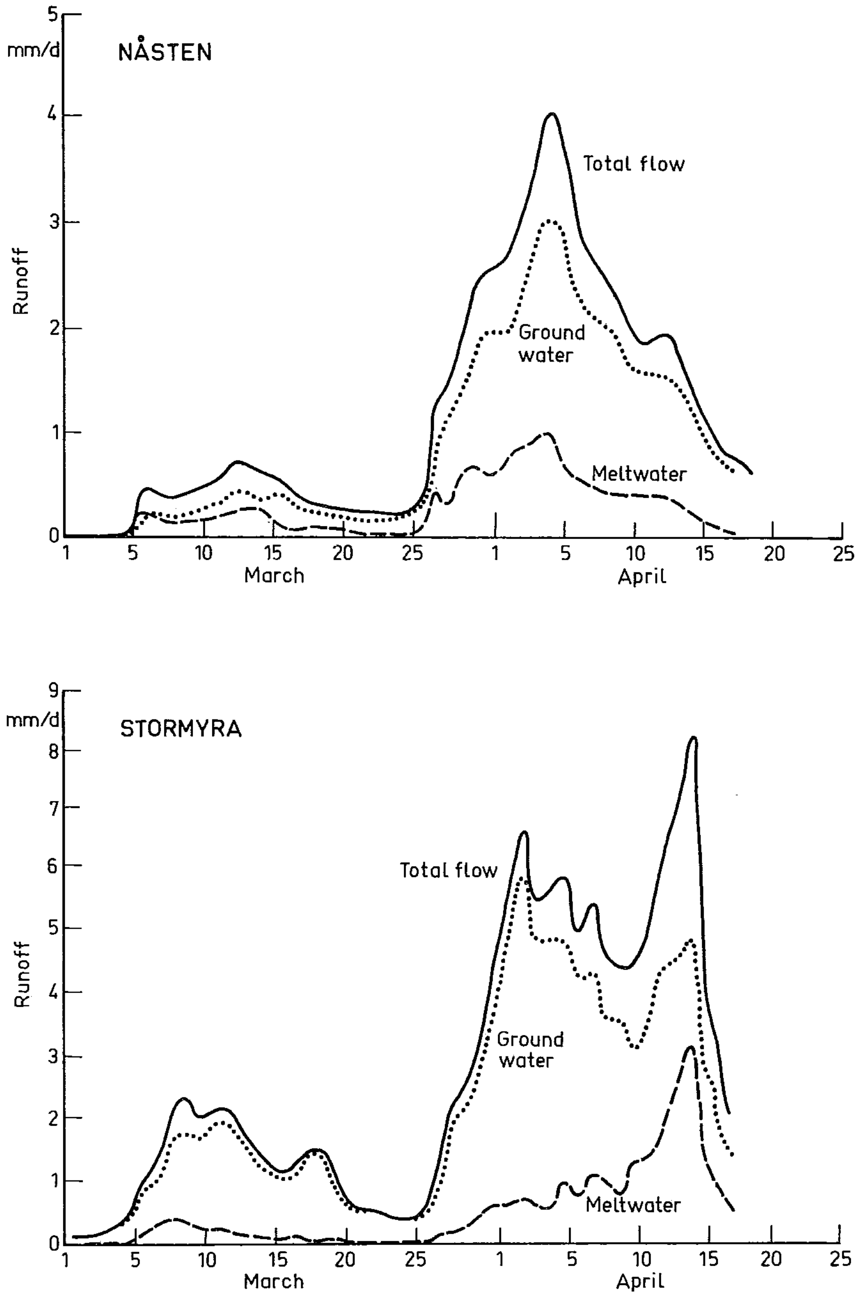

Fig. 1. Total runoff and the fractions of groundwater and meltwater in two small catchments in Sweden in spring 1979 (ROHDE 1981).

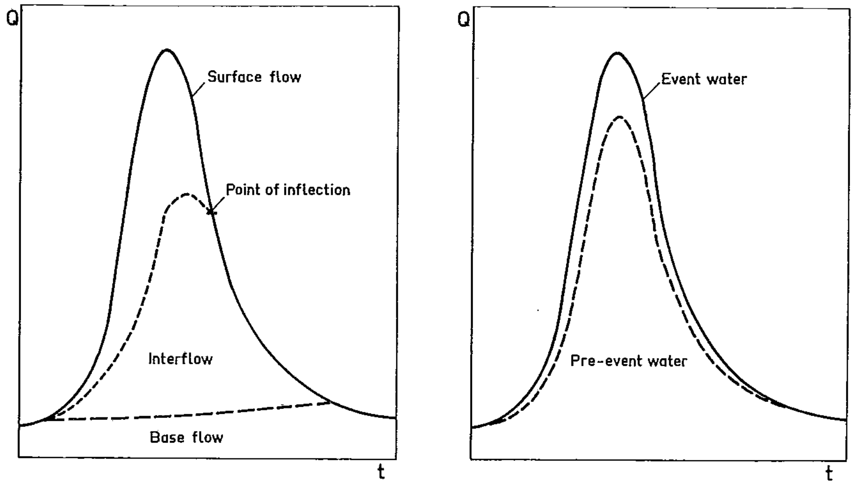

Fig. 2. Traditional and new concepts of runoff formation.

ponents is presented in Fig. 2b. Thus groundwater has a much more active role in the formation of snowmelt and rainfall runoff than the traditional concepts suggest. However, it is difficult to conceptualize how slow-moving groundwater can respond rapidly enough to contribute so significantly to runoff peak.

If seems obvious that the interaction of event water and pre-event water is much more active than it has been understood previously. The greater part of the melt- or rainwater infiltrates and replaces the old subsurface water causing an immediate increase of groundwater flow. Thus the quantitative balance between the input and output of the catchment system is maintained. It still has to be explained how the response of groundwater reservoir can be so quick.

A theory known as 'the variable source area concept' can be used to explain the formation of immediate groundwater flow. The main hypotheses of this theory are as follows:

1. Surface flow originates from an expansion of the channel system. This expansion extends into areas of rapid saturation or low storage capacity.
2. As the channel network extends, it reaches out to intercept subsurface drainage while being fed by rainfall or meltwater from above. In some cases this subsurface component may be responsible for the volume of the runoff.

Fig. 3 illustrates the concept of variable source areas. During a flood event, the low-lying areas near the perennial channels become saturated and surface flow is generated. At the same time, the subsurface flow component from these areas increases rapidly. The channel network also extends to swamps and other areas, where

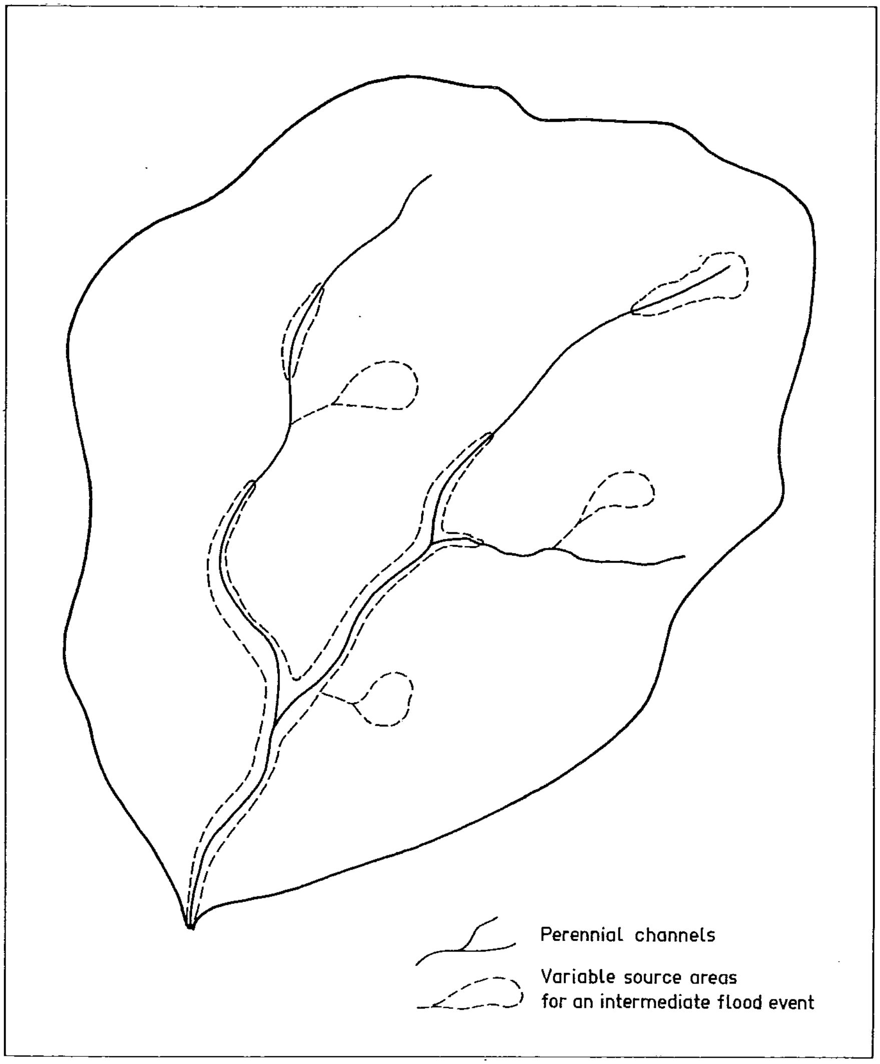

Fig. 3. Variable source areas of a hypothetical catchment.

groundwater table lies close to the ground surface or which have a low permeability (f.i. due to soil frost).

5. *Implications*

The new conceptualization of runoff formation has several important implications. In hydrological modelling it offers new challenges and possibilities. Most existing hydrologic models are based more or less directly on the old concepts of hydrograph separation. However, because the fitting of a hydrological model is dependent on both statistical and physical aspects, a sounder physical structure does not necessarily guarantee a better model performance.

Identification of hydrologically active source areas is also important due to the following reasons (ISHAG & HUFF, 1979):

1. Zones of high runoff generation tend to loose rapidly fertilizers or pesticides to streams draining the area. Thus identifying these areas is a key to regulating stream contaminants.
2. Erosion is most effective in areas of surface runoff. Thus the land use of the source areas should be planned very carefully.

The problem of runoff formation is still far from a complete solution but several clues have been gathered in the recent years. Some variations of stream water chemistry, which have been inadequately explained by old theories, may be understood on the basis of these new concepts. From the point of view of scientific hydrology, these new concepts can lead to entirely new approaches. Are we to be able in the future to have the complete 'age spectrum' of water flowing in our streams? Can we utilize it to understand perfectly how a catchment behaves?

REFERENCES

1. FREEZE, R.A., 1972: Role of subsurface flow in generating surface runoff. *Water Resources Research* 8, 609–623.
2. HERRMANN, A., MARTINEC, J. and W. STICKLER, 1979: Study of snowmelt-runoff components using isotope measurements. *Symposium on the Modelling of Snowcover*, Hannover, New Hampshire, 288–296.
3. ISHAG, A. and D. HUFF, 1979: Hydrologic source areas A: Technique for identifying. *Modelling Hydrologic Processes, Water Resources Publications.* Fort Collins, Colorado, 495–510.
4. MARTINEC, J., 1975: New methods in snowmelt-runoff studies in representative basins. *IAHS Publication 117*, 99–107.
5. ROHDE, A., 1981: Spring flood – meltwater or groundwater? *Nordic Hydrology*, 12, 21–30.
6. SKLASH, M. and R. FARVOLDEN, 1979: The role of groundwater in storm runoff. *Journal of Hydrology*, 43, 45–65.