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Runoff Models – Do They Tell What Actually Happens!

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Bredo Erichsen and Kjell Nordseth

Department of Geography, University of Oslo,
Oslo, Norway

All scientific work performed so far to find the causality of the acidification of many Norwegian open waters, have – considerably – increased our knowledge about precipitation and soil water chemistry. But has it improved our understanding of what happens to the water itself – from being rain – or meltwater – to reappearing into the nearest stream channel? Most hydrochemical models so far have been based on too generalized and too simplified concepts of hillslope runoff genesis. It won't mend matters, however, that the last 20-30 years' of investigation within international hillslope hydrology has rendered conflicting results. Most analytical hydrologists today are, thus, anxious to have at least one conceptural model with a correct description of the runoff processes within a natural hillslope. This article tries to open up for a discussion of the relevance of the most adequate conceptual models in hillslope hydrology. Snowmelt runoff is emphasized and based upon our own experience from small forested watersheds in SE-Norway.

Introduction

Analytical hillslope hydrology is one of two major trends in modern surface water hydrology (Kirkby 1978). The first is the development of complex simulation models due to the access of increasingly powerful computers. The second is the analytical approach to investigate the physical processes involved in a hillslope hydrological cycle, i.e. the huge amount of experience gained from densely instrumented field catchment studies. Analytical field studies – in particular – are emphasized in order to get:

- an understanding of the runoff processes itself,
- a basis for understanding/modelling hydrochemical processes,
- a basis for understanding/modelling erosion,
- a better basis for modelling a catchment's hydrological response.

So far, field studies have shown that former runoff models are not valid in any analytical approach – particularly for forest catchments. Fundamental concepts are questioned, and it is a strong need for re-examining the physical processes involved in transporting/transforming a water input through a natural hillslope/channel system.

Runoff Models

The classical model of Robert E. Horton (1933) deserves particular notice. It is the first model attempt in hillslope runoff analyses what so ever. The model concepts are simple and have evolved through his infiltration theory (1931). Rain and meltwater are routed along two separate courses to the nearest stream channel. The output – or flood hydrograph – may, thus, be separated into two basic components. If precipitation (or melting) intensity does not exceed the infiltration capacity of the soil surface, the entire net water input infiltrates into the ground, percolates through the soil and re-appears into the stream as groundwater – or "base flow". If, on the other hand, the intensity exceeds the capacity, excess water runs off as "overland flow" on the ground surface. The Horton theory conveniently fitted Sherman's (1932) unit-hydrograph theory of basin runoff the coincidence of which has implied a strong persistence of Horton's ideas also in computer-based runoff models (Amorocho and Hart 1964).

Hursh (1936) was one of those hydrologists who would not accept an overall validity of a Horton model. Two main arguments had to be considered. Overland flow was rarely if ever observed on forested hillslopes in humid climates. If that's so, what runoff process is quick enough to explain the short lag between a precipitation and a runoff peak?

One possible procedure is still to keep a two-component model. That is true even if the infiltration capacity is not exceeded, and all the net water input infiltrates. The permeability through a natural soil profile is rarely constant. It most often decreases – even discontinuously, and a local saturation of water may occur above a soil horizon which is sufficiently impermeable to impede the vertical water flux (Weyman 1973) or permeable to initiate a water flow in the most fine-grained layer due to capillary tension (Hillel 1971). A downslope flow of water

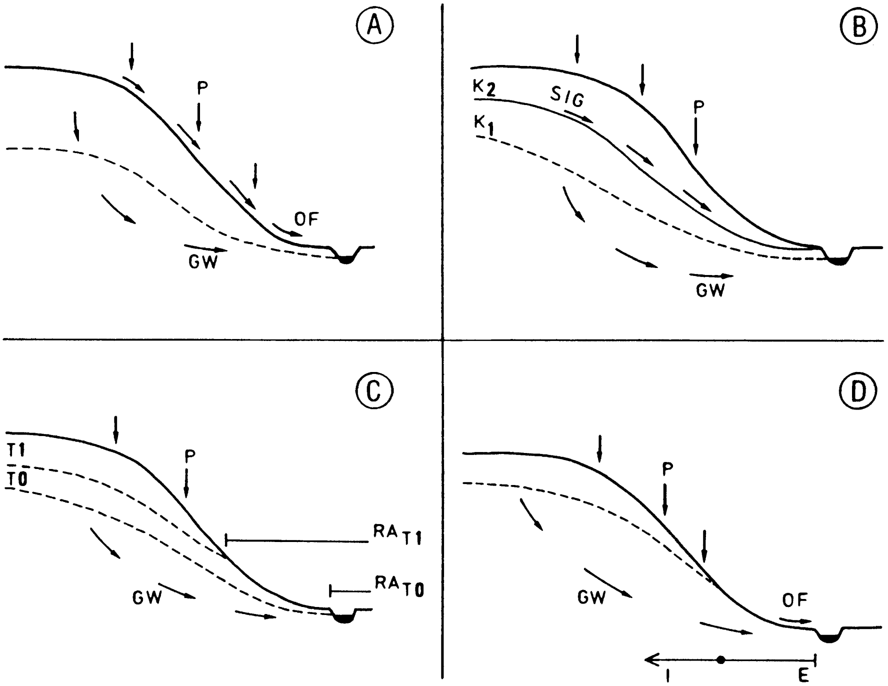


Fig. 1. Conceptual hillslope runoff models.

A: A Horton two-component model,
B: A subsurface flow model,
C: A response area model,
D: A piston-flow model with effluent areas.

(OF: overland flow, SIG: subsurface flow, GW: groundwater flow, RA: response area, I: influent area, E: effluent area, P: precipitation, T_0/T_1 time before and after a storm, K_1/K_2: hydraulic transmissitivity).

may, thus, be initiated along the slope (Fig. 1b) as what Hursh (1936) called "subsurface flow" and other "interflow" or "throughflow". This kind of runoff genesis has been reported from several watersheds particularly those with a cover of strongly stratified loose deposits (Whipkey 1965, Weyman 1973, Anderson and Burt 1982).

Unfortunately – the lag between a precipitation and a runoff peak is, however, much longer than is the case with a Horton flow (Whipkey and Kirkby 1978). The subsurface flow is slow so much so that many will claim it to be important only for regulating recession runoff and the soil moisture state before the next storm (Weyman 1973).

An alternative procedure implies not to reject overland flow. Overland flow may in fact occur particularly on slope segments which are already saturated by water. These "contributing areas" to the overall storm flow from the watershed are concavities where the flow lines converge, and slope segments near the slope base along the streams where lateral soil water drainage produces high moisture conditions. The extent of these areas does, however, change both in space and time (Fig. 1c) and explains the invalidity of linearity in a hydrological response and also the mis-applicance of a lumped model. The runoff process is a non-Hortonian flow even though the local infiltration capacity has not been exceeded. It is therefore termed "saturation overland flow" (Kirkby and Chorley 1967) and the principle, as applied on modelling, "dynamic watershed concept" (TVA 1964) or "partial area concept" (Betson 1964). The theory has been found valid in several case studies and seems to agree with observed quick storm flow volumes and observed lag time (Anderson and Burt 1978, Betson and Marius 1969, Dunne and Black 1970a,b, Taylor 1982).

A third group of hydrologists has emphasized the role of groundwater in runoff genesis even during the first phase of a storm flow response. The modelling concept implies that the input of precipitation (or meltwater) on the upper parts of a hillslope (i.e. "influent areas") raises the groundwater table and thereby causes an increased outflow of groundwater from the lower parts and from the river banks (i.e. "effluent areas") (Gustafsson 1946, 1970). According to this theory a main part of the quick storm flow has the same characteristics as groundwater. The process is a piston-flow, and saturated overland flow may occur only on the effluent areas (Fig. 1d) (Herrmann 1980, Dincer et al. 1970, Sklash and Farvolden 1979, Martinec 1975, Rodhe 1981).

Finally, "piping" or "pipe-flow" is a very quick sub-surface runoff process particularly effective in generating runoff in forested watersheds with silty loose deposits. The runoff occurs as concentrated flows in interconnected natural pipes, i.e. root cavities, fissures or large natural non-capillary pipes (ref. Beven and Germann 1982). Pipe-flow may account for a substantial volume of total flood flow. But it has also been reported to contribute more to the shape of the flood hydrograph than being of any primary importance to the overall runoff (Jones 1971).

Methods

The first analytical attempts to identify the different components of the stormwater hydrograph relied on a simple graphical separation technique according to the Hortonian two-component model. That model has no serious premises of conflicting spatial variability. The watershed may, thus, be looked upon more or less as one structureless unit – a black-box. The practical separation procedure on each hydrograph was and still is highly empirical despite several sophisticated theories and suggestions. We still do not know what is the actual genetical difference between runoff on each side of a separation line. According to Hewlett and Hibbert (1967) "Hydrograph separation is one of the most desparate analysis techniques in use in hydrology."!

As we cannot strictly measure each component, one possible solution is to try to separate the runoff water hydrochemically. Each water unit gains different chemical characteristics depending on what course it follows to the stream and for how long time it stays within the soil. The chemical parameter to be selected must have good diagnostic properties. If we agree with a two component model ($Q_a + Q_b = Q_{\text{tot}}$), each component has its own characteristical concentration (C_x). The relationship between each runoff component may, thus, be expressed in the form of a mass-balance equation

$$c_{\text{tot}} Q_{\text{tot}} = c_a A_a + c_b Q_b$$

The parameter most frequently applied is specific conductance (Nakamura 1971) as well as dissolved ions which occur in different concentrations in groundwater on the one hand and precipitation or snow on the other, i.e. iron, silicon, nitrate, sulfate, chloride, magnesium, calsium, potassium and sodium (Pinder and Jones 1969). Particular attention has been paid to the chloride constituent because of its negative charge. It should therefore be repelled from soil colloids and, thence, follow the water through the macro-pore system. Our own investigations and experience highly doubt the validity of such a statement. Moreover, to equalize precipitation water and quick surface runoff apparently causes an over-estimation of the groundwater component. That is because the chemical characteristics of precipitation water change immediately in contact with vegetation and soil (Pilgrim et al. 1979, Rosenqvist 1977, Rueslåtten and Jørgensen 1976). The change in chemistry also heavily depends on the moisture state of the watershed (Walling and Foster 1975) and the decaying state of lower vegetation. The last point should be particularly important to the water's access to dissolved ions during snowmelting.

Neither hydrologists nor soil chemists or biologists do actually understand all those geochemical and biochemical processes involved within the soil cover. That is perhaps the one reason for utmost precaution in applying non-conservative constituents in hydrologic routing. In that sense; tracers – natural or artifical – have favourable properties in order to route water units through such a "closed" system as a soil-covered hillslope.

The isotope oxygen-18 is such a natural tracer because its seasonal variation in concentration implies a distinct difference between fresh meltwater and old groundwater. According to Rodhe (1981) groundwater alone may account for more than 85% of the total water volume drawn by a streamflow hydrograph and, thence, verify a piston-type model. In addition to oxygen-18, Herrmann (1980) also applied tritium and deuterium. The results are more or less the same, i.e. a groundwater share of about 70-80% even during separate maximum floods (ref. Dincer et al. 1970, Sklash and Farvolden 1979, Martinec 1975). The advantage of applying natural isotopes is that their concentrations do not change by infiltrating the soil. They may thus be considered as conservative tracers, and it is hoped that the results of a mass budget equation should be more reliable.

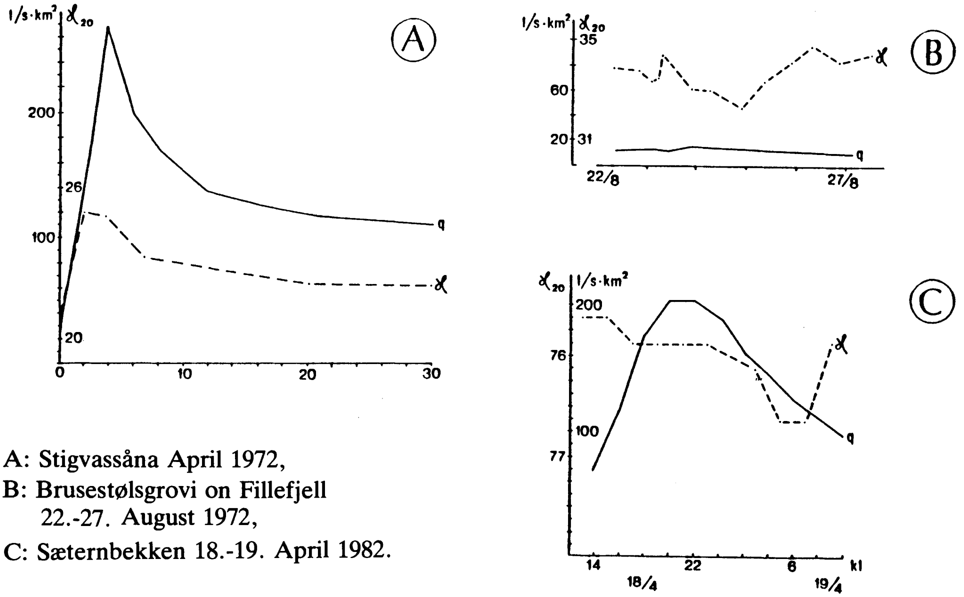
Discussion

As an introduction to a discussion, three different but typical meltwater hydrographs, more or less selected by chance, are presented in Fig. 2a-c together with their corresponding "chemographs". A simple dilution model is obviously not correct. Nor do the studies show any unique relationship between dissolved load and water discharge. In one example the ionic concentration increases during a flood rise. In another it decreases. The same concentration may also change systematically even if the water discharge is stable.

A simple Hortonian model concept must be rejected – first of all by physical reasons. No observations do verify overland flow even below the snow cover. Nor do the hydrochemical surveys reveal any obvious dilution effect during the flood peak. Most reports on quick subsurface flow suggest on the other hand far longer lags on the hydrographs than what is our experience. Subsurface flow is important to the recession runoff, but it evidently cannot be responsible alone for the entire quick runoff response. If the water stays that long time within the pore system of the soil, are we then able to separate it properly from groundwater or return flow by chemical means? According to Pilgrim et al. (1979) a change in chemistry progresses vary rapidly. In some studies it takes only minutes to reach a half-way stage to old groundwater characteristics!

In fact, subsurface flow in combination with the dynamic response area concept may explain a much shorter lag and lesser flood volumes. But this model too relies on a dilution effect during maximum runoff intensities. Therefore, a piston-flow model within effluent areas seems so far to be the best approach towards an explanation of the runoff genesis. But it has unfortunately a "bad habit" of excluding other runoff processes which actually have been observed.

What about a combination of accepted components of several models? First, there is an obvious agreement between the concepts of dynamic response areas resp. effluent areas. Either the water input on upper hillslopes flows slowly downslope as subsurface flow supplying water to the steadily increasing response area, – or it rises the local groundwater table and induces a quick-response piston-flow (return flow) of older groundwater. What is the same is that direct meltwater or precipitation on the saturated areas flows quickly as saturated overland flow to the stream. The piston-type theory is still a two-component model separating



A: Stigvassåna April 1972,
B: Brusestølsgrovi on Fillefjell
22.-27. August 1972,
C: Sæternbekken 18.-19. April 1982.

Fig. 2. Runoff hydrographs and corresponding "chemographs" for specific conductance.

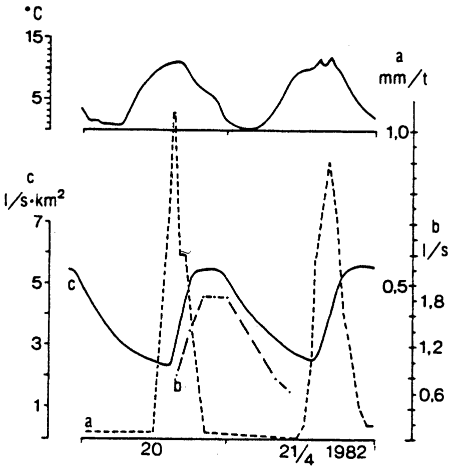


Fig. 3. Snowmelt graphs in Sæternbekken Exp. Basin 20.-21. April 1982. Upper graph shows air temperature.

Graph A: snowmelt intensity (mm/h) as recorded in a snowmelt lysimeter.

Graph B: subsurface flow (l/sec) within the upper 40 cm of the soil cover as recorded by throughflow gutters within a natural till-covered slope.

Graph C: Stream runoff (30 da).

between two rather different types of runoff processes. What is a disadvantage is that the theory makes it difficult also to have some lateral subsurface flow and even pipe-flow within the upper soil cover. Subsurface flow is a natural runoff process in most watersheds, and it may contribute effectively to the dynamics of the response or effluent areas. Is, however, the development of a small "perched aquifer" due to temporary saturation above a particular soil horizon, able to set up also a piston-type response not only within that horizon, but also through the groundwater flow? If it is only a piston-flow contributing streamflow to the river, this process most likely is induced uniformly throughout the watershed. To account for a substantially less quick floodflow volume than expected by an areally uniform response, is the outflow of return flow of old water proportional to the area of effluent slope segments?

It is obvious from this discussion that we do not have any generally accepted concept of hillslope runoff neither for a proper model structure for runoff alone nor for its corresponding hydrochemical processes. So far the results of more than 20-30 years' of investigations do not favour any unique conclusion. In addition, they still depend too much on what methods and procedures have been applied. It seems therefore reasonable to address a warning against procedures which reject types of processes because it is impossible – or difficult – to measure and quantify their importance. Rather it is worth remembering Dunne's statement (1978) that "The various models of storm runoff, therefore, are complementary rather than contradictory".

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Address:
Department of Geography,
University of Oslo,
Box 1042-Blindern,
N-Oslo 3,
Norway.