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Nordic Hydrology, 17, 1986, 335-346

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Runoff Studies in a Small Catchment

Paper presented at the Nordic Hydrological Conference
(Reykjavik, Iceland, August – 1986)

Steinar Myrabø

Institute for Geophysics, University of Oslo,
Norway

This paper discusses results from a field study in a small East-Norwegian catchment. The main object of the study was to separate the different runoff processes in a small catchment. Direct measurements of precipitation, snowmelt, runoff and the saturated basin area were undertaken in the field together with chemical hydrograph separation.

A functional relation between saturated area and runoff was established, showing that the initial runoff being a good moisture indicator for a basin. Further the hydrograph of pure saturated overlandflow (produced from rain on the saturated area) may be separated from the rest of the runoff at any moment of time.

This paper also discusses the results in view of existing methods to estimate soil moisture and to forecast runoff.

One of the main conclusions is that the dynamic response area should be taken into consideration both in field investigations and in hydrological models, – specially in humid climate.

Introduction

The traditional understanding of the runoff processes, where the storm runoff only consists of the overlandflow from the entire catchment, was first put forward by the American engineer Robert A. Horton about 1933. This type of overlandflow occurs when the intensity of rain or water from melting snow/ice becomes larger than the infiltration capacity of the soil, resulting in the soil being saturated from above.

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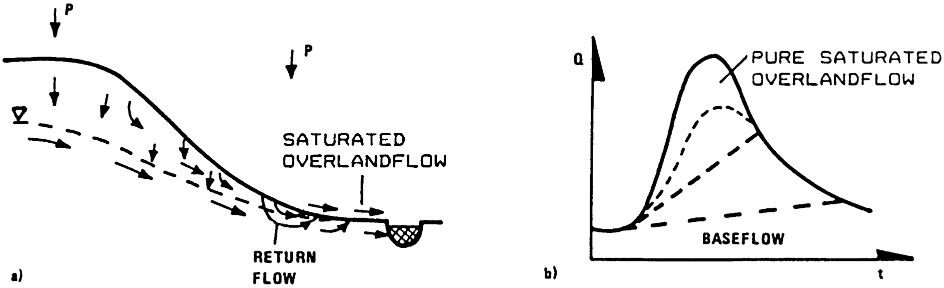

Fig. 1. Illustration of the dynamic response area model. a) Slope profile showing runoff processes. b) Typical hydrogram with different separation lines.

Lateral subsurface flow was not included in Hortons' model. However, between 1934 and 1944 important contributions to the understanding of subsurface stormflow appeared. During the next decades throughflow/interflow models were developed.

The concept of partial area appeared as the research on throughflow processes was intensified during the last two decades. The concept partial contributing area / dynamic source area was developed early in the sixties in the U.S. According to this view overlandflow only exists over a small part of the catchment where the soil is saturated from below up to the surface. This saturated overlandflow consists partly of rainfall together with water from melting snow which has precipitated on the saturated area (pure overlandflow) and partly of return flow (see Fig. 1).

In some models other runoff processes such as piping (i.e. runoff in root cavities and animal burrows) or piston flow (forcing out the old rainfall as a result of a new rainfall) are also accounted for. In other approaches, the catchment has been divided into homogeneous areas to be modelled separately.

Anyhow, in most of the latest published studies of runoff drainage in humid areas, – according to Kirkby (1980), some type of dynamic response area model has been used. The dynamic role in hillslope/basin hydrology played by this type of models under certain soil and slope conditions is therefore now forming a basis for a spectrum of models lying between the extremes represented by the Horton and the pure throughflow models.

In this study one of the main objects was to look at the processes generating precipitation to runoff in streams which direct the water through the runoff area and define the amount of runoff and the residence time at the different horizons. The runoff processes existing in a small catchment was to be thoroughly investigated. It was essential to find out how the variation in the area of soil moisture could be included in models.

This is of importance in the development of mathematical runoff models and for the understanding of hydrochemical processes. To know and to be able to separate the runoff processes is also fundamental within different professions as hydrology,

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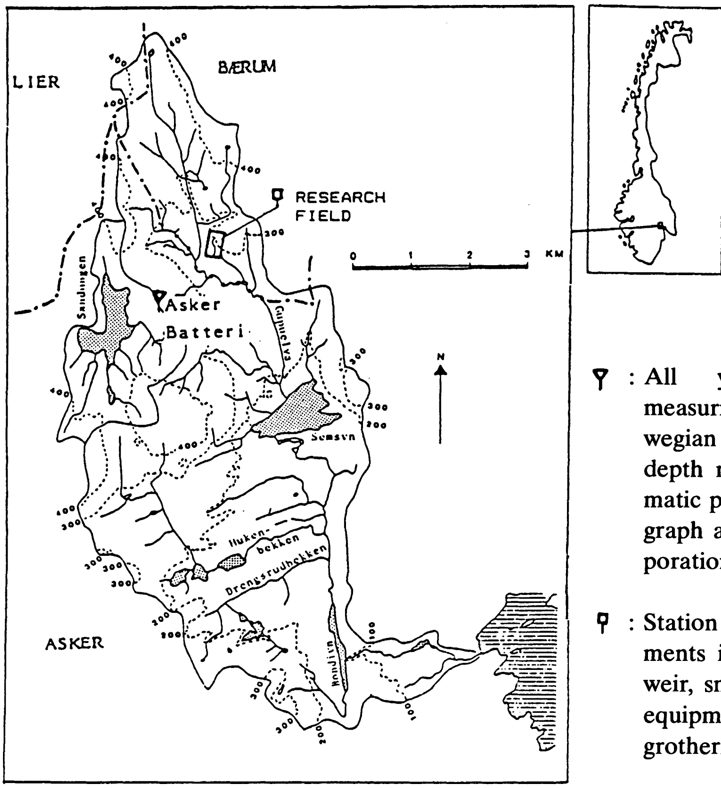

: All year precipitation measuring equipment (Norwegian standard), snow depth measuring rod, plumatic pluviograph, thermograph and a Thorsrud evaporation pan.

: Station for runoff measurements including a V-notch weir, snow/rain registration equipment, thermo- and hygrothermograph.

Fig. 2. Topographic map showing the catchment of the Asker river including the research field (marked rectangle). A map of Norway giving the geographical location of the Asker river is also included in the upper right corner of the figure. (Adapted from Wingård et al. 1981).

agriculture, forestry, conservation of the environment and for controlling water quality.

In the work described here we have particularly used the dynamic response area model to explain the results from the field measurements. It was therefore important to measure the saturated area in the catchment according to the runoff. The research work was concentrated about the upper part of the Asker river basin (see Fig. 2) in the period from august 1981 throughout the fall 1983.

To test the different models, hydrograph separation by specific conductivity and mapping of saturated area according to the runoff together with other techniques was used for separation of the different runoff processes. Direct measurements of rainfall, melting of snow and ice, evaporation and runoff, which all are contributing variables in the water budget in a basin, were also undertaken.

For detailed description of the methods for the measurements see Myrabø (1985 a).

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Experimental Area

The catchment in which the study was conducted is situated in the community of Bærum (see Figs. 2 and 3). The area is about 0.085 km^2 and is a part of the Asker river basin of totally 37.2 km^2. This is a typical East-Norwegian forest basin. Almost the entire research field is covered by forest, generally pine forest, but also some foliage forest. The catchment contains some bogs, is mainly covered with deposits and with some elements of bare rock scattered around. The minerals in the area is Permic rombporfyr of the Kolsås type. The deposits consist mainly of a thin incoherent moraine with a fraction of glaciofluvial deposits, specially in the boggy land and along the lower part of the stream.

The climate of the area is strongly variable. Even through the winter a significant part of the precipitation occurs as rainfall. The lowest and highest temperatures measured in the period of registration were – 19 and 31 °C, respectively. The stream which drains the catchment can be almost dry in the middle of the summer, but can also produce a stormflow in the outlet of more than 800 $l/s \cdot km^2$.

Other characteristic data of the catchment are; median level above sea 307 m, maximum height difference 44 m, maximum length 500 m, and maximum width 180 m.

Results and Discussion

The research area showed to be very inhomogeneous with respect to soil moisture. Samples showed large variations, i.e. from completely saturated to almost dry soils within distances of only centimeters. The saturated area also varied strongly with time. In a field having such large temporal and spatial variations in the soil moisture, the area variation of the soil moisture had to be obtained indirectly by a parameter easier to measure. Indications that the saturated area and its dynamical behaviour may be used as a good estimate of the variation in the soil moisture in the field is outlined below.

The water apparently only gathers in certain areas and from here runs off either above or below the surface. According to Dunne, Moore and Taylor (1975), saturated area appears where transport mechanisms below the surface are not sufficient to get rid of all of the water. Giving time, the accumulated amount of water in the ground rises the water level to the surface. According to Dunne and Black (1970) zones of saturation may go down to the bare rock or may build up from a relative impermeable soil layer.

Areas particularly suitable for producing saturated overlandflow are therefore given by local topography and soil characteristics together with the local soil moisture conditions. It is most probable that it is the lowermost part of the field that contains the largest area of saturation, because it is feeded from above by a large drainage area.

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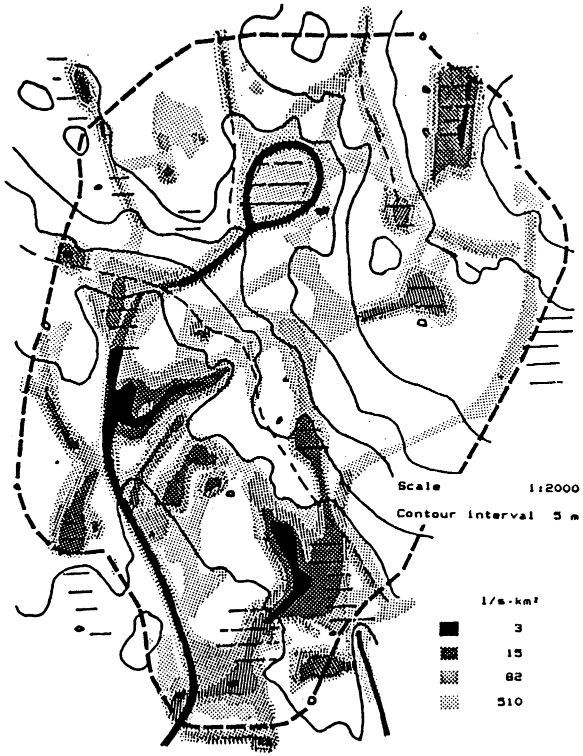

Fig. 3. Topographic map of the research area showing the saturated area during different stream discharge.

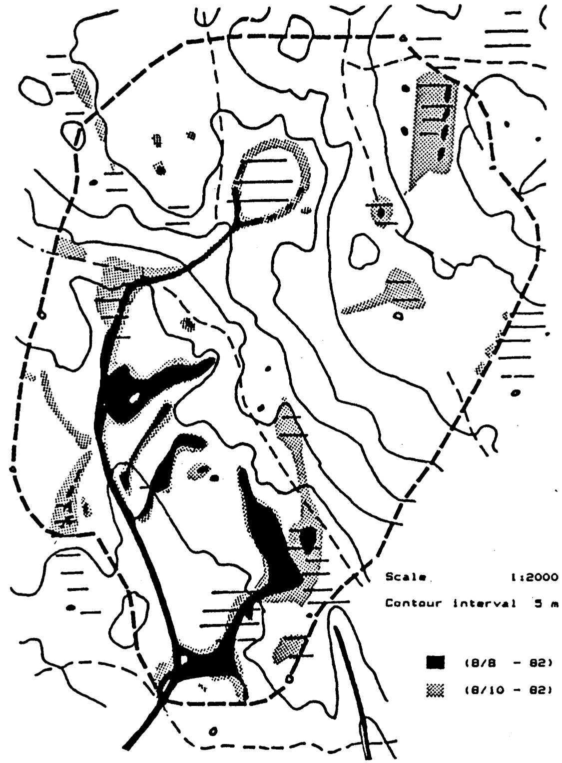

Fig. 4. Topographic map of the research area showing examples of saturated area during equal discharge (30 l/s·km^2), but with different levels of soil moisture in the catchment before the last precipitation.(After a dry summer and two months later).

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The saturated area varied according to season, during and between the events of precipitation. Large variations appeared at different discharge. But for most cases a consistent correlation between saturated area and discharge seemed to exist. During flood conditions, the saturated area expanded to the sides and along hillslopes until it reached a maximum area, mainly defined by the particular precipitation event (dependent of the intensity and duration), the soil characteristics and the initial soil moisture conditions. In addition, new areas of saturation appeared. However, repeated registrations showed the saturated area to be almost the same during equal discharge for cases of recession. Maps of saturated area were thus produced for cases from minimum stream level to about 50% of maximum measured discharge (see Fig. 3).

Measurements show a functional relationship between discharge and saturated area. This is probably the case during all four seasons except when the stream dries out. After a period when the stream has been dried out, the storages maintaining the saturated area between the precipitation events, have to be filled first. When precipitation then occurs, the lowermost deposits in the catchment are first filled (see Fig. 4). This is because these deposits also receive water from areas above in addition to the precipitation on the area.

In periods of dry weather, the stream and the saturated areas receive water from the groundwater and the throughflow. In between the rainfalls this results in the saturated area decreasing in correspondence with the different storages of water in the catchment. The total extent of the saturated area therefore seems to be controlled by the different groundwater –, soil water – and surface storages in the field. Surface storage is here defined as the saturated area contributing water to other saturated areas further down in the catchment. This indicates that saturated area reflects the extension of the storages and gives a good estimate of the content of soil moisture in the catchment. If the saturated area is thoroughly mapped with respect to discharge, this indicates that the discharge may be used as a good indicator of the total soil moisture in the catchment.

The equation best fitted to describe the relation between saturated area and discharge was (found by curve fitting method)

$$A = -1.95 + 3.48\,Q^{0.3} \qquad Q > 0.145\ \mathrm{l/s} \qquad (1)$$

where A is the fraction of saturated area with respect to maximum saturated area (maximum saturated area is taken to be 50% of the total area of the catchment). It is seen from Fig. 5 that Eq. (1) gives a good description of the relation between the discharge and the saturated area in cases between relatively low discharge to normal stormflow events in the catchment. Discrepancies between measured and calculated values (from Eq. (1)) are less than the uncertainties given by the measuring method.

Eq. (1) is thus found to be adequate to estimate the saturated area from the discharge alone both during and after a rainfall. The rain falling directly on the

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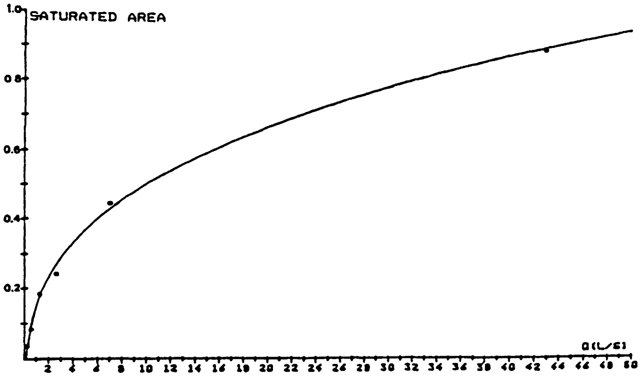

• : indicates the measured values.

Fig. 5.
Graph showing the func tional relation between saturated area (in parts of total saturated area) and stream discharge (Q) in l/s.

saturated area may also be estimated. This precipitation is directed to overlandflow only. To estimate the extent of the saturated area, at a particular time, the discharge at that time is used in Eq. (1). Net rainfall is found by correcting for the storage and for evaporation. The estimated saturated area (given in fraction of the total area of the catchment) may then at each given time be multiplied with the net rainfall. It gives an estimate of the rapid stormflow that is produced as pure overlandflow. A delay, due to among other things storage effects, must also be taken into account. The precipitation is thus distributed over a certain period of time before it is transformed to the outlet of the catchment. This method of hydrograph separation clearly distinguishes pure overlandflow from the rest of the runoff.

Example of a simple use of this method is illustrated in Fig. 6. Smoother curves and a more correct result may even be obtained, if for each particular moment, net rainfall on the saturated areas is calculated and correction for loss by interception storage, storage on the saturated area and evaporation are accounted for. Further correction may be undertaken to improve the result, i.e. if the net rainfall is given a better distribution within the time interval before it reaches the measuring pond as runoff. There are different sources of uncertainties and systematic errors in the measurements and the assumptions made.

Probably the largest systematic error is to be linked to the definition of saturated area (water level down to 5 cm below the surface). This definition causes the extent of the saturated area estimated to contribute directly to the pure overlandflow to be too large. Probably there is also some hysteresis effects in the estimated satura ted area, i.e. in the relation to the discharge.

The measurements of saturated areas were performed during times of recession, as simultaneous measurements during increasing discharge were unpractical and difficult to undertake for such a large basin. Both discharge and saturated area would have changed considerably before the total catchment had been checked. This may cause Eq. (1) not to be completely representative for cases of increasing discharge. This could probably be corrected by introducing a time delay of i.e. one

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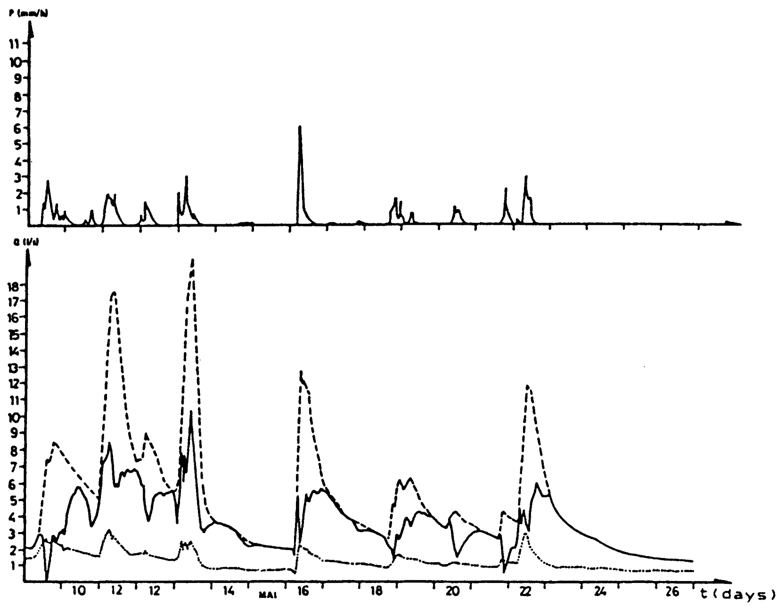

Fig. 6. Examples of hydrograph separation using two different methods, i.e. Eq. (1) and chemical conductivity. Precipitation and stream discharge data during the spring 1983 were used.

The area below the lowermost curve (...) shows "old" groundwater and the area between (---) and (—) pure saturated overland flow, resulting in the area between (—) and (...) representing the throughflow, "new" groundwater and possible pipeflow. The curve (—) above shows the direct precipitation.

or two time elements. The results showed in Fig. 6 would then probably improve. The importance of saturated overlandflow increases with the amount of the stormflow, because the saturated area increases with the discharge (see Fig. 3).

The surface water on the saturated area (inclusive the stream) mixes with the rainfall on the area in the first part of a precipitation event. The surface water consists mainly of throughflow and groundwater that have arrived at the surface as return flow. This water mixes with the pure overlandflow, increases in speed and contributes to the stormflow just in the start of the flood case. After this puls, the return flow contributes with a larger part of total runoff as the rainfall decreases. The return flow may consist of throughflow and new groundwater (eventually also pipeflow) that return to the surface after having moved a relatively short distance in the upper soil levels. In a catchment as inhomogeneous as this, with moraine, stratification and rootsystems, it is likely that some watermovements exist below the surface representing the scale from throughflow to piping. During the field observations, water disappearing in the ground and then reappearing on the surface a few metres down the slope was seen. An example of this may be seen from Fig. 3, where the upstream part of the stream disappears below the path crossing

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the catchment. The water from this part of the stream is seen to reappear further down the slope, – how far down depends on the discharge. Pipeflow may also cause that saturated areas which have no surface connection with the stream contribute to the storm runoff, supposing there is an underground connection to the stream along pipes (McCaig 1983, Jones 1979). As the saturated area decreases and the contribution from the throughflow to the return flow diminishes, the fraction of the runoff due to the groundwater increases. By using the specific conductivity to separate the fraction of groundwater in the hydrograph (see Fig. 6), one probably gets a too high uncertainty, thus obtaining an unreliable result (see Myrabø 1985). The reason for this is partly that the specific conductivity might be affected by other causes. Also the conductivity of the groundwater shows large variations within the same basin.

Consequently, the same catchment may respond differently on equal amounts of precipitation, dependent on the current moisture conditions. If the field is dried out before the precipitation, then the rainfall mainly goes to storage and only a small fraction, possibly nothing, tranforms to runoff. The initial soil moisture in the catchment, indicated by the saturated area or the stream discharge is therefore important in predicting how the catchment responds to a precipitation event.

If the saturated overlandflow is the dominating drainage process during stormflow (Taylor 1982), then the initial discharge together with Eq. (1) is decisive i.e. of how significant the stormflow is going to be, the fraction of rainfall involved and the shape of the hydrograph. If further the same type of rainfall event is giving the same response, i.e. equal runoff, when the initial discharge and other conditions are equal in the catchment (i.e. evaporation and season), this could open new possibilities. Constructing an empirical model based on experience from the particular catchment in consideration could be used to predict how the runoff will develop after different cases of rainfall, – and also possibly how much rainfall would be needed during different discharges to produce a certain stormflow. The above results may also be connected with existing methods to forecast soil moisture and runoff. To estimate the soil moisture content in an area (catchment) the API-index and/or the estimated soil moisture deficit may be used (Wilson 1974).

Estimated soil moisture deficit may be calculated from the observed rainfall and estimated evaporation. The runoff in the area is not accounted for when using this method, and as the evaporation may be difficult to estimate, this method is uncertain. According to Wilson (1974) it is also best suited for larger areas and then gives only an average over a longer period of time.

The API-index gives a daily value and is based on a formula of a depletion curve. The recession constant changes with the evaporation, which is related to the season (Wilson 1974). As the evaporation is different from one year to another, both with respect to amount and seasonal distribution, the API-index only gives a rough measure of the soil moisture condition in an area. The total rainfall during one period also adds to the soil moisture storage (as in a throughflow model). The

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amount of water going directly to overlandflow is therefore not accounted for, which further increases the uncertainty of the method.

In view of the results obtained in this work it may therefore be concluded that the stream discharge used as an estimate for the soil moisture in a catchment results in a more reliable, easier and better method. This is in correspondence with an earlier statistical analysis for small basins by Ruud, Tjomsland and Nordseth (1978). In humid periods good estimates of hourly decomposition may be obtained, if the functional relation between saturated area and stream discharge is found for the catchment. For purposes of forecasting the runoff, both the unit hydrograph and the API- index method may be used.

The unit hydrograph model is based on net precipitation as input parameter. The excess of rain may be separated from the total rainfall by using infiltration curves (Wingård 1980). The initial infiltration rate is dependent on the soil moisture state of the basin. As previously mentioned, the initial soil moisture content is rather roughly estimated, i.e. by using the soil moisture deficit. The excess of rainfall is then averaged over the total basin, – thus also including Hortons' overlandflow (which is believed to contribute insignificantly in humid forest basins). The method therefore initially contains an uncertain value.

The API-index model is based on observed field conditions and rainfall cases where a coaxial correlation analysis is undertaken (Wingård 1980). The input value, the API-index, is as earlier mentioned a rather rough estimate. To arrive at forecasted runoff, processes described by a quadrant has to be considered (Wilson 1974). The evaporation, the duration of the rainfall and the amount of precipitation has to be taken into account. The evaporation is also in this case, as when using the API-index, to be estimated according to season. This amplifies the uncertainty involved in this method. In 1969 the unit hydrograph was also included in the API-index model. Further the model was improved by introducing a retention index, having the purpose of accounting for the interception and depression storage (Wingård 1980). As this model also was based on Hortons' overlandflow, the uncertainty involved in using the model even grew larger.

The main difference between the two methods described above and the method resulting from the project described here is the use of different estimates for the initial soil moisture in the catchment together with the type of runoff model used. Both these methods may be improved by introducing the dynamic response area model together with the initial discharge used as an indicator of the soil moisture in the catchment previous to a rainfall case. A functional relation between saturated area and stream discharge is however to be found in advance for the catchment in consideration.

Hydrograph separation of pure overlandflow may be undertaken by first estimating the net rainfall on the saturated area (as described earlier). Then to transform the net rainfall into runoff, this precipitation may be used as input to the unit hydrograph model. As described here, the unit hydrograph method may be used

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for hydrograph separation of pure overlandflow.

In estimating runoff (stormflow), throughflow and groundwater runoff should also be accounted for, as return flow is important for the hydrograph. To forecast the total runoff, an empirical model (as described earlier) may be constructed. The structure of this model is very similar to the API-index model. However, in the former case the stream discharge is used instead of the API-index. A better estimate for the evaporation than using the season of the year should be found. One possibility could be in addition to use the soil moisture (indicated by the stream discharge) in connection with actual air temperature. Parameters describing the duration and amount of the rainfall may thus be used as in the API-index method. Finally, to forecast the entire runoff hydrograph, the unit hydrograph method may be used.

This should give a more precise method with a better time resolution, as the stream discharge can be measured with a rather high precision on an hourly basis.

Concluding Remarks

The results from this study support the theory that a dynamic response area model is adequate for the type of forest catchment described here.

Overlandflow as described by Horton was never actually observed in the field. Overlandflow from only the mapped saturated area was seen. Piston flow or throughflow probably also contributes only a small fraction to the stormflow – this mainly because of the rapid response and the relatively large difference in delay time between cases of snowless field and periods of snowmelting.

Possible processes generating rainfall to runoff are saturated overlandflow (consisting of pure overlandflow and return flow), piston flow, pipeflow together with throughflow and groundwater runoff directly to the stream. The relative importance of the different processes may change from one field to another with topographic and soil characteristics. Within a particular catchment the contributing fraction from each process also depends on the rainfall case (intensity and duration) together with the initial soil moisture in the catchment.

A main conclusion from this study is that the variation in the stormflow from one flood to the next is mainly controlled by the particular rainfall and the extent of the saturated area (corrected for loss by storage and evaporation). It therefore becomes important to obtain an overview of the saturated areas.

Mapping in the field is probably the best method to localize and estimate extent and variation of the saturated area. Field mapping may however be very time consuming and cumbersome in the long run. It can also only be undertaken now and then. To describe the extent of the saturated area it is therefore necessary with a hydrological technique measuring one or a few parameters on a routine basis. Field mapping of saturated area should therefore be correlated with other field characteristics which are easy to measure. In this work it is indicated that the

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stream discharge within a particular catchment may be such a parameter, as a functional relation between saturated area and stream discharge was found. Another result is that pure overlandflow may be separated from the rest of the runoff.

The extent of the saturated area varied with time. The initial soil moisture in the catchment (indicated by saturated area) showed to be important to predict how the catchment responded during a particular rainfall.

In catchments where the saturated overlandflow is the dominating runoff process during stormflow, an empirical model based on field experience and the functional relationship between saturated area and stream discharge may be constructed. The runoff may then, among other things, be predicted according to different precipitation cases.

In the type of catchment described in this work the dynamical behaviour of the saturated area is therefore important, and thus has to be accounted for in future models.

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Received: 1 October, 1986

Address: Inst. for Geophysics University of Oslo
P.B. 1022, Blindern,
N-0315 Oslo 3, Norway.

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