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Characteristics of Snowmelt Induced Peak Flows in a Small Northern Basin

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Six years' runoff data from Bensbyn Research Watershed (BRW) in northern Sweden is discussed. BRW is 1.6 km^2, out of which 0.5 km^2 is a large meadow and the remaining area consists of a dense coniferous forest. In the runoff analysis, runoff contribution from the meadow is separated from that from the forest. Peak flows are related to snowmelt from each separate area, and to rain events. The snowmelt generated runoff hydrographs are compared to those from rain events. The diurnal fluctuations of the snowmelt-induced runoff are analyzed in order to determine to what extent the stream flow originates from overland flow or subsurface flow. The highest flow recorded, 1.25 mm/h, was the result of a major rain storm of 60 mm occurring two weeks after all snow had disappeared. The peak runoff generated by snowmelt only was 0.78 mm/h. Overland flow is shown to take place from the meadow, but the runoff contribution from the forest is mainly due to subsurface flow. The peak flows from BRW are compared with observations reported in the recent literature.

Introduction

The present paper is a general description on snowmelt induced runoff from Bensbyn Research Watershed (BRW). From this study more specialized papers have been generated, including mathematical models applied to Bensbyn and infiltration during snowmelt periods.

BRW is a small watershed, only 1.6 km^2. Even in a humid climate streams from such small watersheds may be dry for several months, but for short periods the stream flow can be very high. Storms or snowmelt may cause flooding problems.

However, from small watersheds peak flow information is scarce. Designers of roadway drainage structures often have to estimate a design flood discharge from records for gauged watersheds, which are much larger than the actual watershed, or they have to use empirical formulae. Gray and Wigham (1970) present several examples of such formulae. The formulae relate peak discharge to rain precipitation. Where an appreciable snow cover exists, a peak discharge will likely occur during snowmelt. In large river basins, snowmelt-induced runoff usually produces higher peaks than those of rain events. On the other hand, in small watersheds with short lag time, intense rain storms may produce runoff peaks higher than snowmelt. However, snowmelt continues over several days or weeks. The area contributing to runoff increases. Also, the ground is frozen, which at least to some extent should hinder infiltration. In northern Sweden, flooding problems around culverts and high flows from small watershed are usually attributed to snowmelt. This is to some extent also due to culvert obstructions from snow and ice. While in regions with hydrology influenced by snow, high flows almost always occur during and after snowmelt, rainfall-induced floods result from rare precipitation events. Nemanishen (1977) found that only rainfall with a return period of 10-25 years generates any significant runoff from typical prairie watersheds in Canada. Rainfall during snowmelt has often been observed to cause the larger peak flows (Harr 1981). However, rain on snow event can cause anything from no runoff at all, to severe floods. If the snow is dry, all of the rain may be retained by the snowpack. If the snow is ripe and the soil is impermeable, the runoff is intense.

The larger peak flows from a small watershed may be caused by snowmelt, rainfall, or rain on snow events. Task number one should be to determine the water input to the ground surface. Account must be taken of the liquid-holding capacity of the snowpack, and the transport of water through the snowpack. The characteristics of runoff of water reaching the ground surface when snowmelt takes place, may be different from summer conditions. The soil may be less permeable when frozen, thereby increasing the overland flow. On the other hand, the overland flow in the snowpack along the ground or the flow among the roots just below the ground surface and above a concrete frost in the soil is a slow Darcian flow. Overland flow in the presence of snow is therefore a much slower process than overland flow on bare ground. If the soil is well-drained and remains so during snowmelt, the presence of snow cover should not change the runoff characteristics very much compared to non-snow conditions. However, snowmelt takes place over perhaps some weeks. Therefore, a shallow water table may rise to increase the area contributing to "quick" runoff.

BRW is situated in Luleå at the Baltic in northern Sweden. Metorological and runoff observations have been made since 1976. The stream which constitutes the outfall from the small watershed is dry most of the year. Observed flows are related to snowmelt, rain during snowmelt, or rainfall only. The snowmelt-induced runoff is separated into that from a large meadow and that from a coniferous forest. The runoff hydrographs are analyzed and attempts are made to separate stream flow contribution from overland flow and from groundwater flow.

Peak Flow Observations

To state the art of peak flows one would benefit from some comparisons between BRW and results from other small watersheds having minor slopes. At Knob Lake, Quebec, Price et al. (1976) collected data from four plots, about 2,000 m^2 each, in boreal forest. Average crown cover was 15 %. The surface has a high clay content. The runoff during snowmelt 1972 and 1973 was entirely Hortonian overland flow, and the total volume corresponded closely with the total snow water equivalents on the plots. The melt rate was estimated to peak 3-4 mm/h, around 13 hrs. The runoff reached attenuated peak values around 16 hrs, although much longer lag times were also observed.

At Perch Lake, Ontario, Hendrie and Price (1978) made a similar study, also presented by Price et al. (1979). Two runoff plots of 25 m^2 were constructed of which one was lined with polythene sheets in order to intercept all melt. The soil is a deep, permeable, well-sorted sand. The area of study is within an extensive forest mainly of aspen, birch and maple. The most intense water flux reaching the ground surface was 6 mm/h from rain on snow, and 4 mm/h from snowmelt only. The maximum daily melt was only 20 mm/d as compared to almost 60 mm/d at Knob Lake. When the snow was saturated, there was hardly any lag between water input to the snow surface and to the base of the snowpack, and no attenuation of the peak intensity. Practically no runoff, as overland flow, was observed from the uncovered plot during the entire melt season of 1978.

Doyle (1979) presented discharge measurements for five years in creeks on the Canadian Prairie. Out of 43 basins, only three were less than 250 km^2.. It was possible to correlate the peak discharge to the snow cover of late winter, but the correlation to rainfall was always low. The drainage area had only a small influence on the peak discharge. This suggests that a large portion of a flat watershed may not contribute to runoff. The snowmelt peak was found to be the annual peak.

In the two research watersheds near Fairbanks, Alaska, Caribou Creek and Poker Creek, the highest recorded mean daily flow is 10 and 8 mm/day, respectively (Haugen et al. 1982). The areas of the watersheds are 24 and 60 km^2.. At least in the smaller of the two watersheds a snowmelt-induced peak value is not produced every year. In this watershed, rain events have caused runoff peaks very close to the highest peaks from snowmelt events.

Whitely and Yaeger (1979) reported on storm runoff from agriculatural watersheds in southern Ontario. Two of the watersheds ranging in area from 2-23 km^2 are considered here. For the smaller one the lag times from the peak of combined rain and snowmelt to the streamflow peak at the watershed outlet was rather consistent 6-8 h. Range of lag time with no snow cover was 1.5 to 6 h. For the larger watershed estimated lag time doubled with the presence of a snow cover. For this watershed the highest peak was 2.6 mm/h caused by light rain during intense melting. The estimated contributions from overland flow and subsurface flow were approximately equal.

In Sweden, Grip (1982) and Rodhe (1981) found that stream flow from forested areas has mainly a groundwater origin, even during snowmelt. The study by Grip on watersheds smaller than 1 km^2 shows that rain events can produce as much daily runoff as snow melt. However, the hydrographs shown do not have peak flows higher than 10 mm/d.

Martinec (1975) and Hermann et al. (1979) have carried out extensive research on the characteristics of snowmelt-induced runoff. By using isotope techniques "direct flow" is separated from base flow. The estimated groundwater contribution to stream flow for two catchments was 60-80 % during snowmelt. The highest peaks were caused by rain on snow. However, the work was carried out in the Swiss and German Alps, where the conditions are very different from the Swedish lowlands and from the Canadian prairies.

At the Glenn Creek watershed in Alaska, Kane et al. (1981) conducted snowmelt runoff studies. Glenn Creek drains a watershed of 2.25 km^2 containing one part of birch-aspen-white spruce stands, and another part of black spruce stands. Soils in the birch-aspen-white spruce stands consist of a 10-15 cm thick organic mat of forest litter overlying a well-drained silt loam. Permafrost is not present. The black spruce stands, however, are primarily underlain by permafrost. Kane and his co-workers found that the birch-aspen-white spruce stands contributed little to the runoff. The percolation of meltwater through the soil was found to be too slow to generate runoff via subsurface flow. Minor flow in gullies was not observed until 9 days after initial stream flow. Moss-covered slopes of the permafrost area and valley bottoms were the primary contributors to runoff. The observed snowmelt-induced peak flow in 1979 corresponded to about 0.4 mm/h.

At Truelove Lowland, Devon Island, N.W.T., Canada hydrolocial studies were carried out by Holecek and Vosahlo (1974) and by Rydén (1977). The area is situated in the High Arctic. Most of the annual runoff takes place over a period of 2-3 weeks in late June or early July. The ground is frozen with thawing in only the very top layer as summer progresses. Small ponds occur on this flat coastal plain. Their detention storage influences the runoff. Rydén compared the runoff of 1972, 1973 and 1974 of three drainage basins connected to Truelove Lowland (0.12, 0.4, and 22.4 km^2, respectively). The annual peak flow of the small basins, situated on the coastal plain, was in 1972 and 1974 caused by snowmelt and was 0.4 mm/h. In 1973 the annual maximum flow of 0.3 mm/h was caused by rain. The largest basin drains part of a plateau. It is composed of a branched system of ravines; the hydrologic regime is similar to that of a mountain river. The runoff may reach much higher peaks, more than 1 mm/h, than was observed in the two small basins. The flow rate shows a high response to rain.

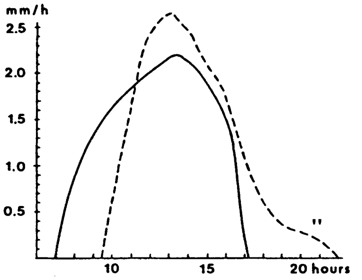

Fig. 1.
Surface melt (solid line) determined from energy balance measurements, and measured runoff (dashed line) from a 25 m long impermeable study plot at WREL.
(Water Resources Engineering, Luleå).

Theoretical Aspects of Runoff in the Presence of Snow Cover

There are several subprocesses involved in the generation of runoff in the presence of a snow cover. Firstly, of course, there is the input of precipitation to the snow surface and the surface melt. The surface melt is usually unevenly distributed over the day with a very pronounced peak. An example is shown in Fig. 1 (Bengtsson 1982c). Meltwater travels through the snowpack, but no water is released until the liquid content is above the irreducible liquid content of the snowpack. Since, as discussed by Colbeck (1972), large melt flux travels faster than small melt flux, melt from the time of peak melt of the day may catch up the early morning melt, and meltwater may reach the base of the pack as a shock wave. The understanding of the process of percolation through snow is much due to the work of Colbeck (1972, 1974, 1978). A snowpack is seldom homogeneous, but there are ice layers or impending horizons. Fingering takes place or vertical drains develop. When the flow of meltwater is concentrated to these drains, the transport rate is much faster than in homogeneous snow. Also the problem of layered snow has been treated by Colbeck (1975). However, information about the structure of a snowpack rarely exists, and the conditions within a snowpack may change during the melt season. Price et al. (1979) found, as mentioned previously, that the effect of the snowpack in attenuating large surface water input when reaching the ground was minor at a site in Ontario. This observation is very different to what Price et al. (1976) found from a site in northern Quebec, where the runoff was well determined using Colbeck's theories of percolation through homogeneous snow. The measured meltwater flux to the base of the snowpack at an open site in Luleå is shown in Fig. 1, where the surface melt flux is also shown. The flux to the ground followed the surface melt flux more closely than is found form a theoretical approach.

The last phase of the runoff process from a snow-covered watershed is the runoff itself. Meltwater that reaches the ground may infiltrate or run off as overland flow. The flow may also enter cracks in the root zone above an almost impermeable concrete frost zone. The groundwater table may rise, so that the area contributing to runoff increases in the course of a melt period. From a theoretical point of view Wankiewicz (1979) reviewed the aspects of storm flow when a snow cover is present. He calculated the lag effect of snow cover on runoff for a slope of 3 percent to be 13 h, for 100 m flow along the ground, independent of rain or melt intensity. Lag time of vertical flow through the snowpack depends on the flux at the surface. For a 1 m deep snowpack and surface flux of 3.5 mm/h, the lag in dry homogeneous snow was calculated to be 12 h, in wet homogeneous snow 3.8 h, and in wet snow with vertical drains 0.6 h. Of course, these numbers depend on snowpack characteristics. However, it is clear that percolation of meltwater through the snowpack is of prime importance when the snow is dry and, for small catchments, when the snow is wet and vertical drains have not developed. Except for steep slopes, overland flow introduces considerable lag between melt and runoff.

Stream flow which originates from groundwater should react directly to changes in meltwater input, as discussed by Martinec (1975) and Bengtsson (1982b). However, as shown by Bengtsson, a separate event within 24 h, such as melt during daytime only, should produce only minor runoff peaks.

Bensbyn Research Watershed

The Bensbyn Research Watershed is 1.63 km^2 of which 70 % is forested area and 30 % is open area, essentially a large meadow. The forest has coniferous stands, mainly spruce with a high canopy density. There are two small creeks, which confluence at the meadow 200 m upstream the outfall of the watershed. The watershed is sketched in Fig. 2. The elevation varies between 4 and 43 m with an average elevation of 15 m above mean sea level. The slope of the meadow towards the creeks is 0.03-0.06. The ground slope in the forest is 0.03-0.10, and the soil is primarily glacial till. There is a small open swampy area in the northwest with organic soils, cf. Fig. 2. The soils of the large meadow are silt on clay or silt on glacial till. The depth of silty soils is more than 1 m. The groundwater table at the meadow has never been observed to be below 1 m. During snowmelt, the groundwater stage in the clay area has been observed to rise above ground level.

The runoff from BRW is monitored through continuous stage-recording at a 90°V-notched weir. To keep the weir ice-free, heat is supplied. There is a manually operated climatological station, where air temperature, relative humidity, pan evaporation, wind speed, precipitation, snow depth and frost depth are registered. In 1977 and 1978 also an automatic meteorological station was used at BRW giving continuous recordings of net radiation, incoming and outgoing solar radiation, temperature profiles in air, snow and soil, humidity and wind profiles. The automatic station was later moved 5 km to the laboratories of Water Resources Engineering, Luleå (WREL). Soil moisture content is measured using the neutron scattering method at 4 stations and the groundwater table is observed at 6 stations. During snowmelt, snow surveys are carried out about every second day. Energy balance computations are made on a daily basis and adjusted to the accumulated snowmelt determined from snow surveys.

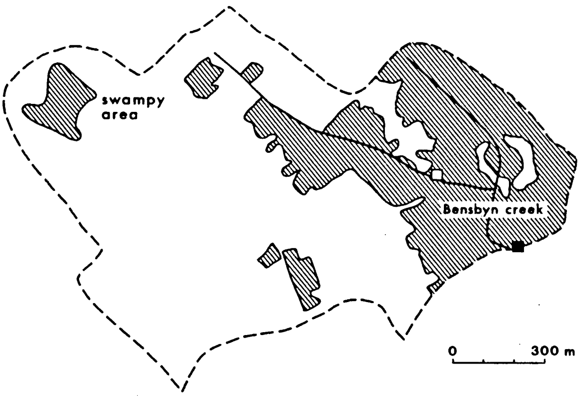

Fig. 2. Map of Bensbyn Research Watershed (BRW).

For most of the year there is hardly any runoff from BRW. Annual runoff is 200-300 mm, of which about half occurs in late April and May. The daily mean temperature is above freezing from May through October. When snowmelt occurs in April and early May, the air temperature during daytime varies from some few degrees up to 10°C, but usually drops below freezing during nights. Rainfall is not common during snowmelt. The snow usually melts over a period of 2-3 weeks of rather sunny weather. Very often the snow on the meadow is gone before the snowpack in the forest starts to release any water. Repeated rain events in late summer or early autumn may also produce runoff.

Melt-Induced Hydrographs from BRW

Snowmelt-induced runoff was observed during the melting periods of 1977 to 1982. The hydrograph of the melt period of 1980, cf. Fig. 3, illustrates some general characteristics of the snowmelt induced stream flow. Runoff was first observed on April 10. By then 40-45 mm of water was released from the meadow snowpack and 20 mm from the forest snowpack. During the second week of runoff, when practically no reduction was observed of the water equivalents of the snowpack in the forest, daily peak flows occurred at about 17 hrs. The runoff originating in the meadow area fluctuated over single days between 0.4 and almost 1.0 mm/h. The daily snowmelt was about 11 mm as determined from energy budget computations and snow surveys. Daily runoff was greater, 14 mm. The runoff may also have been attributed to previous melt in the forest.

When the open field was snow-free by April 26-28, the amount of water released from the snow cover of the forest was about 60 mm. Soon after this time the more intense melt from the forest began, although the melt rate was only 7-10 mm/d. The runoff fluctuated above a fairly steady minimum value. Relative to the area of the forest the flow varied over the day in the range of 0.2 mm/h to 0.35 mm/h, which corresponds to 0.15 to 0.25 mm/h relative to the total area of the cachment.

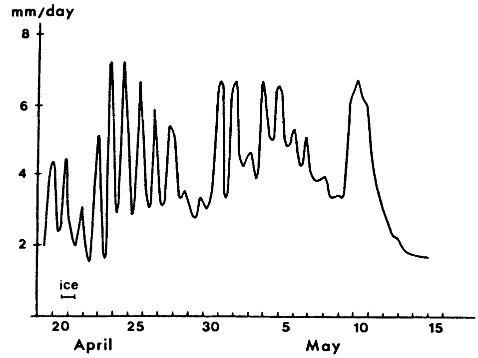

Fig. 3. Hydrograph of BRW, melt runoff 1980.

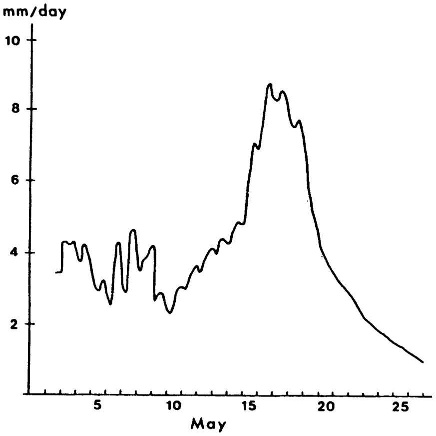

Fig. 4. Hydrograph of BRW, melt runoff 1978.

The maximum diurnal flow always occurred shortly before midnight and the minimum flow some hours before noon. There were bare patches in the forest from May 7. The peak of the hydrograph on May 10 was attributed to rainfall. By June 1, the runoff had decreased to 0.5 mm/d and by mid-June almost ceased. One week after the forest was free from snow, 130 mm of runoff (relative the area of the entire watershed) had been recorded. The total melt and rainfall during the melt period was 160 mm.

The melt period of 1980 can be divided into a) a period of no runoff (April 1-10), b) a period of runoff primarily from the meadow (April 10-27, especially 19-27), c) a period of runoff from the forest (April 28-May 7), and d) a short period of rain contribution (May 9-10). It was attempted to separate the runoff contribution from the meadow from that of the forest for all observed melt periods, as shown below.

Snowmelt Runoff from the Meadow

Most of the open area of BRW is a large meadow, its area being about 0.5 km^2. The meadow is often almost snow-free before any meltwater is released from the snowpack in the forest. Although the southern creek is the longer one of the two creeks of BRW and has the largest catchment, more flow is usually observed in the northern creek. The southern creek is more like an open ditch.

For part of the melt periods of 1978, 1980, 1981 and to a less extent also for that of 1977, the runoff from the meadow can be fairly well separated from that from the forest. In 1978, the water equivalent of the snowpack in the meadow was gradually reduced through April, but the snowmelt was not accelerated until the first week of May. The meadow was snow-free by May 7, when snowmelt runoff from the forest had not yet begun. When, very late in April, runoff was first observed in the Bensbyn creek, the snowpack of the meadow had released 95 mm of water. During the week of the most intense runoff from the meadow, six daily peak values of 0.6 mm/h were observed, usually at 17-18 hrs. The minimum flows in the mornings were between 0.4 and 0.5 mm/h. When the diurnal hydrographs were plotted on lin-log paper, a hydrograph recession time constant was estimated to be 30-40 h. (The recession constant, *k*, used here has unit time so that $Q = Q_o e^{-t/k}$). However, the daily melt hydrographs did not strictly follow an exponential decay; the recession was closer to linear. In early June, the flow almost ceased. The stream hydrograph for the whole melt period of 1978 is shown in Fig. 4. The daily melt runoff hydrographs can often be separated from each other by extrapolating the recession curves, e.g. Davar (1970). However, this did not give a clear picture of the diurnal melt contribution from the meadow.

The groundwater level rose steadily from April 1 until mid-May, in the central part of the open field by 50 cm and very close to the outfall from the catchment by 40 cm. The frost depth on the meadow was more than 30 cm. The hydraulic gradient was less than 0.01. Except for a sandy layer of about 10 cm, the soil is almost impermeable. The contribution of groundwater from the meadow to the streamflow from a direct Darcian approach can be estimated to be less than 1 1/sec. However, there might be some subsurface flow in cracks in the upper part of the frozen soil. Although no water was visible on the ground surface, groundwater level up to 25 cm above the ground was recorded near the outlet. This stage probably represents the groundwater level in the sandy layer. Details about the runoff hydrographs from the meadow for 1978 are shown in Table 1.

The stream flow hydrograph of the melt period of 1980 was shown in Fig. 3 and discussed above. Again, the daily recession was more linear than exponential. Peak flows were recorded at about 17 hrs, and minimum flows at about 7 hrs. The observations are summarized in Table 1.

In 1981 the runoff started April 17, except for some seepage which was observed earlier. By that day, almost 100 mm of water had been released from the snowpack in the meadow and almost as much from the snowpack in the forest. However, from April 17 until May 5 the water equivalent of the snowpack in the forest was not reduced. The runoff in the two last weeks of April and in early May should therefore be due to snowmelt from the meadow. During these 18 days the snowmelt rate was low, only 2-3 mm/d. The highest flow during this period corresponded to about 0.1 mm/h. Typically, the runoff fluctuated over the day between 0.05-0.08 mm/h.

Also for 1977 it was to some extent possible to separate the runoff contribution from snowmelt on the meadow from snowmelt in the forest. Runoff was first observed to take place in the Bensbyn creek on April 28. By then almost no reduction of water equivalents in the forest had been observed, but the accumulated released snowmelt and rain precipitation from the meadow was 70 mm. The

Table 1 – Characteristics of Snowmelt-Induced Runoff from the Meadow of BRW – 0.5 km^2

Year	T mm	W mm	R mm	W_f mm	m mm	r mm
1977	270	70	280	100	–	–
1978	170	95	100	30	8	12
1979	180	40	170	90	–	–
1980	180	45	170	60	11	14
1981	220	100	200	100	2-3	3-4
1982	120	15	70	60	17*	18*

Year	$r_{\min}$ mm/h	a mm/h	$t_{\max}$ hrs	$t_{\min}$ hrs	k h	r_p mm/h
1977	–	–	–	–	–	–
1978	0.45	0.15	1800	700	30-40	0.67
1979	–	–	–	–	–	–
1980	0.04	0.50	1700	700	20	10
1981	0.15	0.10	1700	700	30	0.37
1982	0.60*	0.02*	1900	800	30	–

* some contribution from the forest

T – total amount of water released from snowpack including rain precipitation
W – amount of water released from snow-pack prior to runoff
R – accumulated runoff until snow-free conditions on the meadow
W_f – accumulated amount of water released from the forest by the time the meadow was snowfree
m – daily melt during quasi steady state
r – daily runoff during quasi steady state
$r_{\min}$ – minimum flow during quasi steady-state
a – amplitude of diurnal fluctuations
$t_{\max}$ – time of daily peak flow
$t_{\min}$ – time of daily minimum flow
k – diurnal recession time constant
r_p – peak runoff

flow in the creek increased over the first week of runoff and peaked at about 2.5 mm/h (with reference to the area of the meadow) on May 5. However, already from the first day of observed runoff, water was released not only from the meadow but also from the snowpack in the forest. Higher peak flows were observed later in May in conjunction with rain storms.

The water balance of BRW for the melt period of 1977 is shown in Fig. 5. The variation of soil water content was almost exclusively attributed to the soils of the meadow. When, around May 10, the meadow was free from snow, the soil water content started to decrease.

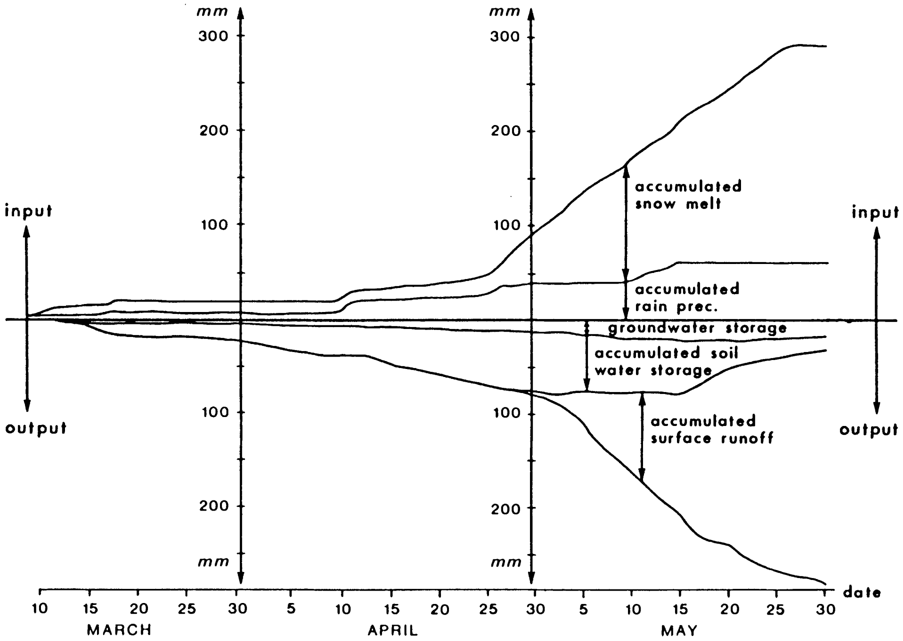

Fig. 5. Accumulated components of water balance of BRW, melt period 1977.

Table 1 summarizes snowmelt runoff from the meadow from 1977 through 1982. It can be noted that the highest flow with no significant contribution from the forest is 1.0 mm/h. During periods of quasi steady-state conditions with similar diurnal fluctuations from day to day, peak flows were usually observed at about five o'clock in the afternoon, the flow started to increase again at about seven o'clock the next morning. The exponential recession time constant, if applicable, was about 30 h. Usually, much water is released from the snowpack before any water starts to flow in the creek. An exception was 1982. Note that the precipitation of the summer and autumn of 1981 was very high, so the soil was very wet when the ground froze.

The runoff hydrograph is first of all determined by the rate at which water reaches the ground. The flux to the bottom of a snowpack should be determined from energy balance computations of the surface melt and routing of the surface melt through the snowpack as described by Colbeck (1974). As discussed above, the conditions within the snowpack influences the percolation rate. It is not possible to determine the distribution of ice layers and vertical drains. It is also difficult to determine the surface melt with a resolution close to an hour, which is needed for computing diurnal stream flow fluctuations. At WREL, 5 km from BRW, runoff is measured form an impermeable 25 m long surface plot. Since the study plot is short, the observed runoff should very much correspond to the liquid flux to the base of the snow cover. Flow peaks usually occur between 13-15 hrs, unless the preceeding night has been very cold, when the peak may occur later in the day. These diurnal peaks are in the range of 0.15-0.25 mm/h, cf. Fig. 1. The surface plot has been described by Westerström (1981).

In order to analyze the snowmelt-induced runoff from the meadow, it seems logical to use data from the study plot. However, the snowmelt usually starts earlier in the season and proceeds faster on the study plots than on the meadow at BRW. Therefore, only the typical diurnal runoff distribution from the impermeable study plot can be used. From snow surveys and energy balance measurements on a daily basis, the daily melt on the meadow at BRW was determined. The depth to which refreezing occurred was determined as suggested by Bengtsson (1982a) and also the amount of water and the time needed to saturate the snowpack to its irreducible liquid content. The amount of melt water reaching the bottom of the snow cover was then determined, and distributed with hourly resolution as observed for similar situations on the study plot.

The melt flux reaches the bottom of the snowpack at a peak rate shortly after noon, but peak runoff from the meadow does not occur until 17-18 hrs. Accordingly, the horizontal transport must be considered, although this part of the watershed is only 0.5 km^2. This is also found from the fact that the melt flux to the base of the snowpack may well exceed 2 mm/h, but the snowmelt induced runoff from the meadow has never been found to exceed 1 mm/h. As shown by Bengtsson (1982b), the daily fluctuations are so large and the recession so fast that it can not be explained by groundwater contribution to the stream flow.

Snowmelt Runoff from the Forest

Every year snowmelt proceeds in the forest after the snow has disappeared from the meadow. Often, the runoff from the forest hardly starts until the meadow is snow-free. In 1977, the runoff from BRW must essentially have been due to snowmelt in the forest over the period May 13-20, since the meadow was free from snow. Peaks, although attenuated, occurred shortly before midnight. The recession of the diurnal hydrographs corresponded to an exponential recession time constant of about 50-60 h. Some data of this melt period is summarized in Table 2, as are data from periods when forest melt was found to be the main contributor to stream flow.

In 1978, the snow had disappeared from the meadow by May 8, but meltwater was not observed to be released, at a significant rate, from the snowpack in the forest until May 10. The discharge increased in a sawtoothed way as was shown in Fig. 4. Daily fluctuations were minor. The highest instantaneous peak flow corresponded to 0.38 mm/h with reference to the whole area of BRW and 0.55 m/h with

Table 2 – Characteristics of Snowmelt-Induced Runoff from the Forest of BRW – 1.1 km^2

Year	T mm	W mm	W_c mm	m mm	r mm
1977	300	–	120	10	10
1978	140	–	30	20	–
1979	170	30	50	9	10
1980	150	20	70	8	7
1981	220	100	110	11	16
1982	160	–	60	7	8

Year	$r_{\min}$ mm/h	a mm/h	$t_{\max}$ hrs	$t_{\min}$ hrs	k h	r_p mm/h
1977	–	–	2400	1100	50-60	0.49
1978	–	–	2400	1100	–	0.55
1979	0.33	0.15	21-2200	7-1200	20-30	0.51
1980	0.21	0.10	2200	1000	40	0.35
1981	0.62	0.20	2200	1000	40	0.84
1982	0.30	0.05	2100	900	–	0.39

for notation cf. Table 1, and

W_c – amount of water released prior to changed streamflow hydrograph characteristics

reference to the area of the forest only. The recession time constant of the falling limb of the hydrograph, when the melt period was completely over, was about 5 days. The small diurnal peaks occurred shortly before midnight. The melt rate was about 20 mm/d during the 3-4 days, when the flow was very high. As explained in a previous study from BRW (Bengtsson 1982b), a steadily rising sawtoothed hydrograph at least indicates that the streamflow originates from a groundwater basin with intermittent recharge.

In 1979, meltwater was released from the snowpack in the forest from about April 26. The daily peaks occurred at about 19 hrs. The meadow was snow-free by May 5 or 6. When snowmelt from the meadow no longer directly contributed to the streamflow in the creek, the daily peaks were registered at about 21 hrs and minimum flows at about 8 hrs. The stream flow fluctuated over the day between 0.35 and 0.45 mm/h with reference to the area of the forest. The recession limb of the diurnal peaks had a reasonable exponential shape with a recession time constant of about 20-30 h.

In 1980, the meadow was snow-free by April 26-28. As shown in Fig. 3 and previously discussed, pronounced runoff fluctuations around a fairly steady mean flow were observed for about a week.

In 1981, most of the snowmelt from the forest occurred after the meadow was snow-free. The hydrograph was similar to that of 1979, but there were larger diurnal fluctuations and the peak flows were higher. During the days of maximum runoff the flow varied over the day between 0.6-0.8 mm/h. This was one week after

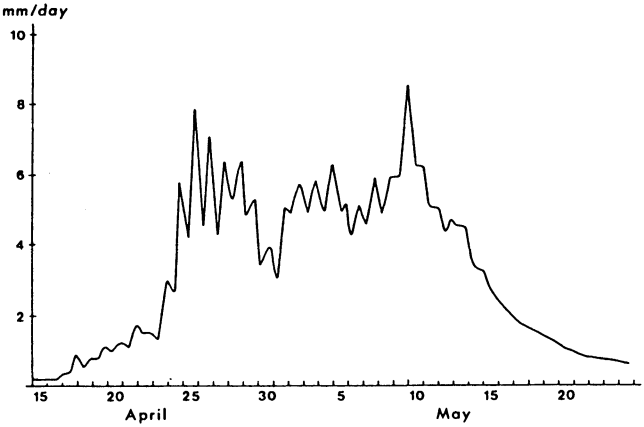

Fig. 6. Hydrograph of BRW, melt runoff 1982.

the meadow was snow-free, so there should hardly have been any stream flow contribution from the meadow. Some snow patches contributed to runoff until May 20. Assuming an exponential decay of the stream flow, the recession time constant for the period directly after the snowmelt was about 5 days.

In 1982, meltwater was continuously released from the snow cover in the forest from April 15 until May 15. The open field was snow-free by April 26-27. The hydrograph of 1982 is shown in Fig. 6. Although it very much had the same character throughout the melt period, the low flow on April 29-30, when there was no snow on the meadow and the intense melt from the forest had not yet started, is clearly noticeable. Some rain fell during the melt period and affected the peaks. When only snowmelt from the forest contributed to runoff, the stream flow fluctuated between 0.30-0.35 mm/h over the day. The recession time constant as determined from the hydrograph, when there was no snow left in the forest, was about 6 days.

In Table 2, the observations from melt periods of essentially runoff contribution from the snow in the forest are summarized. The annual peak flow is about 0.4-0.5 mm/h with respect to the area of the forest except for 1981, when a peak flow of 0.84 mm/h was recorded. In that year, almost identical peak flows and diurnal fluctuations were recorded for four consecutive days just after the snow disappeared from the large open field. The daily runoff for these days exceeded the melt contribution from the forest. It is therefore likely that there was also a contribution from the meadow. For other years, quasi steady-state runoff conditions with very similar peaks and diurnal fluctuations were observed to prevail for some days and even up to a week, when the daily runoff almost equaled the daily melt from the forest. Significant diurnal fluctuations of amplitudes about 50 % of the daily minimum flow were observed for 3 of the 6 melt periods. The diurnal stream flow recession did not show a consistent value but is about 40 h. The final stream flow recession, when the forest is snow-free, has an exponential recession time constant of about 5 days.

Table 3 – Characteristics of Snowmelt-Induced Runoff From BRW – 1.6 km^2 – Meltwater Contribution from Both the Forest and The Meadow–for notation cf. Table 1

Year	m mm	r mm	$r_{\min}$ mm	a mm	k h	r_p mm/h
1977	11	9	0.45	0.2	30-40	0.78
1981	7	7	0.3	0.05	–	0.36
1982	8	6	0.2	0.1	30-40	0.33

Periods of Snowmelt Contribution from the Whole Catchment

At periods meltwater is released simultanously from the forest and the meadow. This was most obvious during some periods in 1977 and 1982. During May 7-11, 1977, the daily stream flow was almost 9 mm/h, with reference to the total area of the catchment, fluctuating with diurnal peak flows of 0.65 mm/h observed to occur at 18-19 hrs and minimum values of 0.45 mm/h at about 7 hrs. These days the daily melt in the forest was about 7 mm, and 20 mm on the meadow. The exponential recession time constant was 30-40 h.

Also in 1981 and 1982, there were periods of melt in the forest when there was still snow on the meadow. Data from periods of "combined" runoff contribution is given in Table 3.

Rainfall When Snow Cover Exists

Rain on snow is treated separately to see if generated hydrographs are different from snowmelt generated hydrographs. Depending on the conditions of the snow, rain on snow may generate runoff of very different magnitudes. Also, the snow distribution over the watershed is of importance for the runoff generation of a storm event. In Luleå, rainfall is not common during snowmelt. When it occurs, it is usually in May after the snow has disappeared from the meadow.

Only once in six years has rain produced runoff from a snowcovered meadow. This was around May 1, 1979. Part of 30 mm precipitation fell as snow. Meltwater was released from the meadow as well as the forest. The peak flow observed was 0.8 mm/h with reference to the entire catchment.

Rainfall has occurred while snow was still present in the forest, but the meadow was free from snow. The highest stream flow in 1977 (May 16) was caused by such an occasion. A light rainfall of 12 mm, mostly during the night and 10 mm daily melt in the forest caused the flow to increase from 150 to 350 l/sec (350 l/sec = 0.8 mm/h with reference to the whole catchment). The recession rate after this and a similar rain event three days earlier corresponded to an exponential time constant of 36 h. Although the melt from the snowpack in the forest continued at 10-15 mm/

d over the days following the rain event, the stream flow decreased steadily.

Also in 1982, the highest peak, although only 0.4 mm/h, was caused by rain on snow in the forest, when the meadow was snow-free. The rain was light (9 mm) and occurred during the night. The daily melt was 7 mm. Almost as high stream flow was, however, recorded due to pure snowmelt just prior to the meadow was snow-free. The recession time constant of the rain event was about 40 h.

In 1979, a light rainfall of 6 mm, which fell on the night of May 12 during a melt period, when the snowmelt rate in the forest was about 8 mm/d, caused a peak flow of 300 l/s (0.7 mm/h). This rain significantly affected the stream flow and interrupted its diurnal rhythm. The volume under the rainfall-induced hydrograph, if the melt component is separated, is 3 mm.

A rain event of 7 mm, just after the entire BRW was snow-free, caused a stream flow peak in mid-May 1980 corresponding to about 0.3 mm/h, which was about the same value as observed when the melt from the forest was at its most intense stage. The recession took place at a rate corresponding to an exponential time constant of about 40 h. If the recession of minimum diurnal flow, i.e. base flow, is extended, runoff due to rain may be separated from base flow of previous melt. The runoff volume from the rain event is found to be very close to the 7 mm measured precipitation.

The number of rain events on snow during the reported six years is very small. Although the rainfall always has been light, 6-9 mm with a duration of about 12 h, flows very close to the annual peak have been recorded during these events. The stream flow recession rate is similar to that of pure snowmelt.

Water Balance for the Melt Period

The water balance of BRW over the melt period was previously discussed for 1977 and a summarizing figure showing accumulated values of runoff, melt, rain precipitation and ground- and soil water storages was shown as Fig. 5. From the figure it can be seen that from May 10, when the open field was snow-free, the accumulated "error" term increases. This term is due to evaporation and measurement errors. Evaporation should increase when the meadow becomes snow-free.

The water balance of BRW for the six melt periods 1977-82 is summarized in Table 4. For every year 1977-80, the accumulated runoff from the first melt of the year until one week after the entire catchment was free from snow almost equals the sum of total melt and total rain precipitation, when the amount of meltwater released from the snow prior to runoff is subtracted. In 1981, a large amount of meltwater was released also from the snowpack of the forest prior to runoff. Much of this meltwater seems to have contributed to stream flow late in the melt period. In 1982 following a wet autumn, stream flow was observed soon after the snowpack started to release any water. More water than other years was retained as storage in the soil during the period stream flow was recorded to occur.

Table 4 – Water Balance and Overall Characteristics of Snowmelt-Induced Runoff from BRW – 1.6 km^2 – With Reference to the Total Area – for notation cf. Table 1

Year	T mm	W mm	R mm	R_f mm	R_3 mm	r_{pm} mm/h	k_o h
1977	290	20	85	245	250	0.8	5
1978	150	30	30	90	105	0.4	5
1979	180	40	60	140	150	0.3	6
1980	160	30	50	100	130	0.3	–
1981	220	100	60	145	155	0.6	5
1982	160	5	20	100	110	0.3	6

R_f – accumulated runoff prior to bare patches in the forest
R_3 – accumulated runoff 3 days after BRW was completely free from snow
r_{pm} – peak runoff from snowmelt
k_o – recession time constant after snow-free conditions.

Rainfall when No Snow Cover

The highest stream flow ever recorded in the Bensbyn creek was caused by a storm on May 29-30, 1982. The whole catchment had been free from snow for 2 weeks. During 15 hours, 63 mm of rain fell. Over 18 hours, from 2 hours after beginning of rainfall, the stream flow increased from less than 20 l/s to more than 550 l/s (0.04 ≃ 1.25 mm/h). Within 48 hours after the rainfall had ceased, 21 mm of accumulated runoff was recorded. When the base flow was separated, the accumulated storm flow was determined to about 23 mm. The storm flow recession showed an exponential decay corresponding to a time constant of about 20 h.

The Bensbyn creek is often dry except during snowmelt. Rainfall causes stream flow only if the soil is very wet from previous rain or snowmelt. Summer peaks as high as 0.25 mm/h occurred only in 1977 and 1978. However, the stream flow gauge was not operated during the wet summer of 1981. The highest flow recorded in the autumn is 0.34 mm/h (early September 1978). The number of rain events producing peak flows exceeding 0.05 mm/h (20 l/s) is only 10. For these 10 storms it was found that the time for the flow to rise to its peak was 18-24 h. The falling stage showed an exponential time constant of 40-60 h, except for the major storm event in late May 1982, when the recession was much faster.

Summarizing Peak Flow Events

Peak flows are given in Table 5 and separated into different categories. The very maximum was recorded for a major storm 2 weeks after the whole BRW was snow-free. For light rainfall during snowmelt, peaks of about 7 mm/h have been observed. Only in one year (1981) out of six snowmelt alone caused a higher peak flow than 0.4 mm/h. That year, significant runoff was observed from the forest before the meadow was free from snow.

Table 5 – Observed Annual Peak Flows (mm/h) and their origin 1977/82 from BRW (area 1.6 km^2)

Year	Absolute Annual Maximum	Meltwater from Meadow	Meltwater from Forest	Meltwater from Meadow and Forest	Rain on Snowpack in Forest and Meadow	Rain on Snowpack in Forest	Rain just after Snow-Free Conditions	Summer and Autumn Rain
1977	0.80	–	–	0.78	–	0.80	–	0.25
1978	0.38	0.21	–	0.38	–	–	0.34	0.34
1979	0.72	–	0.35	–	0.72	0.70	–	0.12
1980	0.32	0.32	0.28	–	–	–	0.30	–
1981	0.60	0.10	0.60	0.36	–	–	–	y
1982	1.25	–	0.27	0.33	–	0.40	1.25	–

y) high stream flow may have occurred, but no data exists.

Comparison of Different Events

Snowmelt and rainfall generated runoff were separated with respect to snow distribution at BRW. When the diurnal recessions of the melt induced runoff from the meadow and the forest are compared (Tables 1 and 2), it is seen that the recession constant generally is less than 30 h for the meadow and about 40 h for the forest. The recession constant for rain events is also about 40 h. However, for the only recorded rainfall of very large volume the recession constant was about 20 h.

Water balance and soil moisture measurements carried out at Värpinge Research Watershed, Lund, Sweden by Falk and coworkers (personal communication J. Falk, TVRL, Techn. Univ. Lund) showed that runoff is rarely generated from rain on flat farmland with clayey soils. Runoff from the meadow of BRW should also be rare and has for the six reported years probably only occurred during snowmelt and on the major storm event (63 mm) of May 1982. However, while melt of about 10 mm/d in the forest, when the meadow is snow-free, only causes rather small stream flow peaks, corresponding rainfall causes higher peaks and much larger volumes of runoff, cf. Fig. 3. Rain events during these periods produces input of water also to the snow-free meadow, while the snowmelt takes place only in the forest. It seems as if the water input to the meadow produces rather fast runoff.

Conclusions

The annual maximum flow for Bensbyn Research Watershed often occurs in conjunction with rain events during the snowmelt period or just after the snow has disappeared. The highest peak flow recorded over six years corresponds to 1.25 mm/h. The largest flow attributed to melt is only 0.78 mm/h. However, the contribution from the meadow of BRW has been 1.0 mm/h relative to that area. Usually, a large amount of water is released from the snowpack before any runoff is observed. This amount can be correlated to the rain precipitation in the preceeding autumn.

Meltwater is usually released from the snowpack at the meadow before the snowpack in the forest releases any water. Diurnal stream flow fluctuations are frequent during melt periods. They are much larger as long as the runoff originates in the meadow. Maximum flow during a day may be twice the minimum flow, but fluctuations may also be very minor. The large diurnal runoff fluctuations can only be attributed to flow along the ground in the snowpack or just beneath the ground surface. Runoff from the forest can be explained to be mainly due to subsurface flow. When there are relatively large diurnal runoff fluctuations, it is estimated that some part of the forested area may contribute to direct runoff. Once runoff has started, the accumulated runoff corresponds closely to the accumulated melt. Rain events during summer and autumn produce hydrographs of similar shape as single days of snowmelt in the forest.

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