
Modelling the Effects of Clearcutting on Runoff: Examples from Central Sweden
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Modelling the Effects of Clearcutting on Runoff—Examples from Central Sweden

Report

By Maja Brandt, Sten Bergström and Marie Gardelin

In order to study the effects of forest management on hydrology in central Sweden a hydrological model (PULSE model) was used both as a reference and as a forecasting tool. Three small basins were monitored before and after clearcutting. Increased total runoff and more pronounced peak flows were observed. The model was recalibrated to post-harvest conditions, and the two sets of model parameters were used to simulate the hydrological effects of hypothetical partial cutting in a large basin. During spring, the location of the cuttings affected peak flows because of nonsynchronous snowmelt and time delays in the basin. In autumn, the location of cuttings had very little effect on the peak flow. The total effect on peak flow of a 10 percent clearcut in a large basin was considered small compared to the effects of extreme weather conditions.

Two years after clearcutting at Aspåsen, Central Sweden. Photo: M. Brandt.

INTRODUCTION

The extreme autumn floods that occurred in Sweden during 1985–1987 have focused interest on the hydrological effects of clearcutting. In particular the flood that occurred in September 1985, which caused several dam failures in central Sweden, roused interest among the hydroelectric power companies. Local authorities in Sweden have also expressed concern about the possible connection between forest-management practices and flooding problems. Forest cover is of particular interest when designing structures susceptible to peak flows, such as dams and spillways and for river-valley development.

Worldwide interest in the hydrological effects of forest management is illustrated by the vast number of research projects in different countries. The problems involved, for example, are discussed in the works of Křeček and Zelený (Czechoslovakia) (1), Gupta (India) (2), Miţă (Romania) (3), Pearce et al. (New Zealand) (4), Plamondon and Ouellet (Canada) (5), and Ponce (USA) (6). Peak flows are particularly interesting for dam builders and have recently been discussed by, among others, Liu (China) (7).

Reviews of studies on changes in runoff are presented by Hibbert (8) and Bosch and Hewlett (9). Most studies use reference areas and regression analysis to calculate the changes. By reanalyzing the data from previous studies on clearcutting Harr (10) pointed to the difficulties involved in using regression analysis. His analysis showed that peak flows during snowmelt increased. This finding contradicts the findings of previous analyses.

The first study in Sweden was initiated in the 1920s (11). Later studies by Grip (12) and Rosén (13) used a forested reference area to determine changes in runoff. Runoff from both the reference and the study area was recorded before and after clearcutting, and the effect was calculated using regression analysis.

In general, studies indicate an increasing water yield following clearcutting of forest areas. This is commonly explained by reduced transpiration and evaporation of the water and/or snow that is normally intercepted by the trees. In addition, more intense snowmelts are generally reported and this agrees well with what is known about the difference between energy balance in open areas and in forests. The problem lies in quantifying the effects. The regression method requires that the basins are of similar type and that the changes in one basin do not affect the untouched reference basin. For example, clearcutting a forest in one area can affect snowdrift, and thus water balance, in an adjacent basin. Furthermore, regression analysis requires a relatively stable climate. A regression equation derived from a period of relatively dry years may produce uncertain results, if the change in one basin is followed by wet years with higher runoff values.

The above problems may be overcome, at least to some extent, if a hydrological model is used. Instead of a gauged reference basin the modelled runoff is then used as a reference. Hydrological-model analysis is more capable of coping with climatological fluctuations, but it is also more susceptible to inconsistencies in climatological records. The regression analysis approach relies on reference basin data, the hydrological model approach relies on climatological records.

METHODS

The Hydrological Model

In this study the hydrological PULSE model for runoff simulation was used to study the effects of clearcutting on runoff.

The PULSE model (14) is a modification of the HBV runoff model (15, 16), which is being used in several countries for hydrological forecasting. The HBV model has been compared to other models of this type by the World Meteorological Organization (WMO) (17) with encouraging results, in spite of its relatively simple structure and limited data demands. The basic structure of the PULSE model is shown in Figure 1. The model takes into account daily totals of precipitation and mean air temperature together with monthly standard values of potential evapotranspiration. Runoff simulation involves three steps:

- snow accumulation and ablation;
- soil moisture accounting;
- generation of runoff and transformation of the hydrograph.

Precipitation is accumulated as snow if the air temperature is lower than a threshold value. A snowfall correction factor accounts for winter evaporation, gauge representativeness, and aerodynamic losses at the precipitation gauge. The melt routine of the model is essentially a degree-day approach according to the following equation:

$$m = C\,(T - T_0)$$

where : m = snowmelt (mm/24 h),
C = degree-day melt factor,
T = mean daily air temperature (°C),
T_0 = threshold temperature.

A 10 percent liquid water-holding capacity of the snow has to be exceeded before any meltwater can leave the snowpack.

Although very simple, the degree-day approach has proved very efficient in basinwide modelling. The well controlled WMO intercomparison of snowmelt models (17) failed to identify any significant improvements when using more complex models in intermediate and large size basins.

Figure 1. Basic structure of the PULSE model.

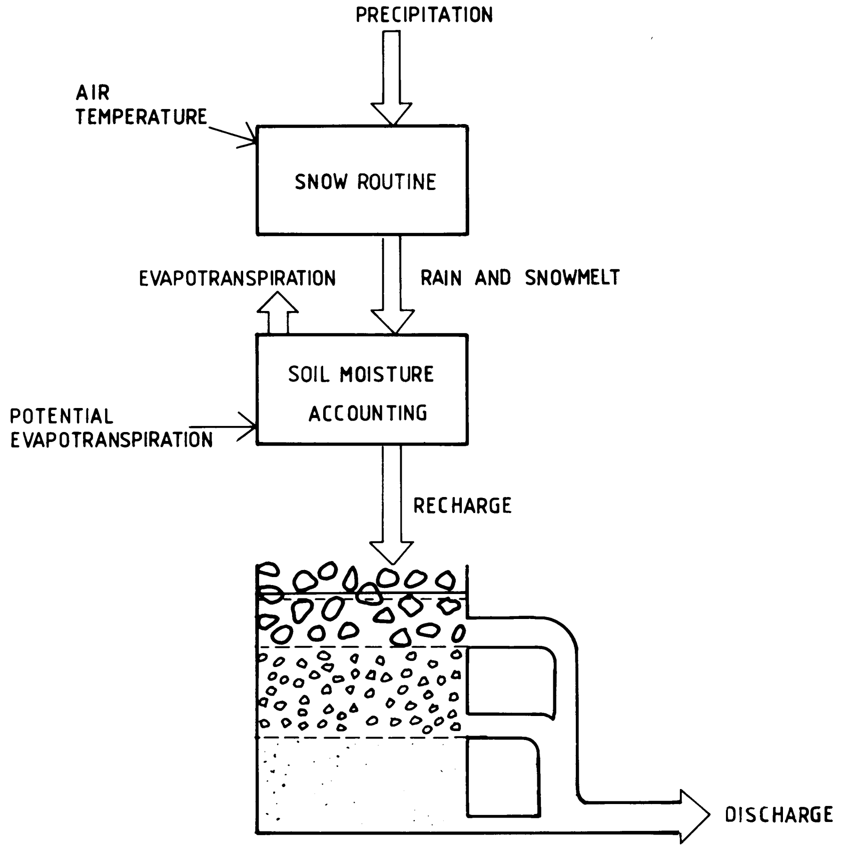


Figure 2. Principal components of the soil-moisture accounting procedure of the PULSE model.

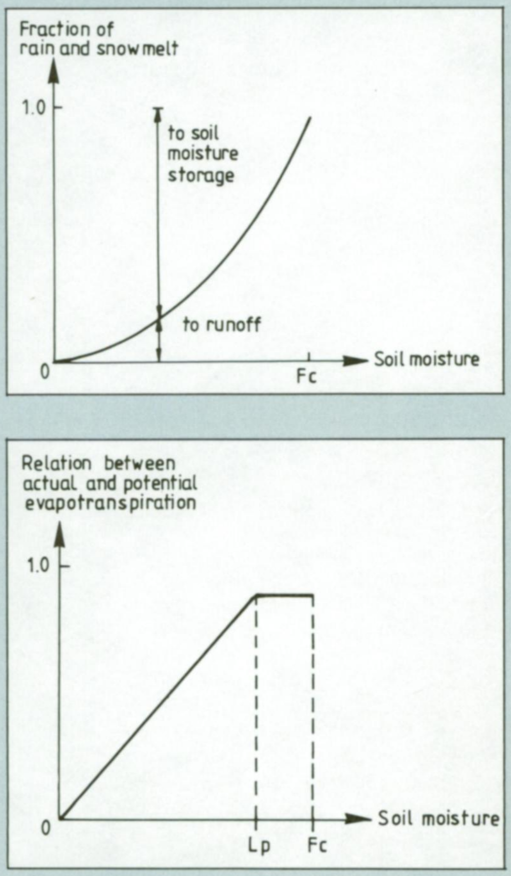
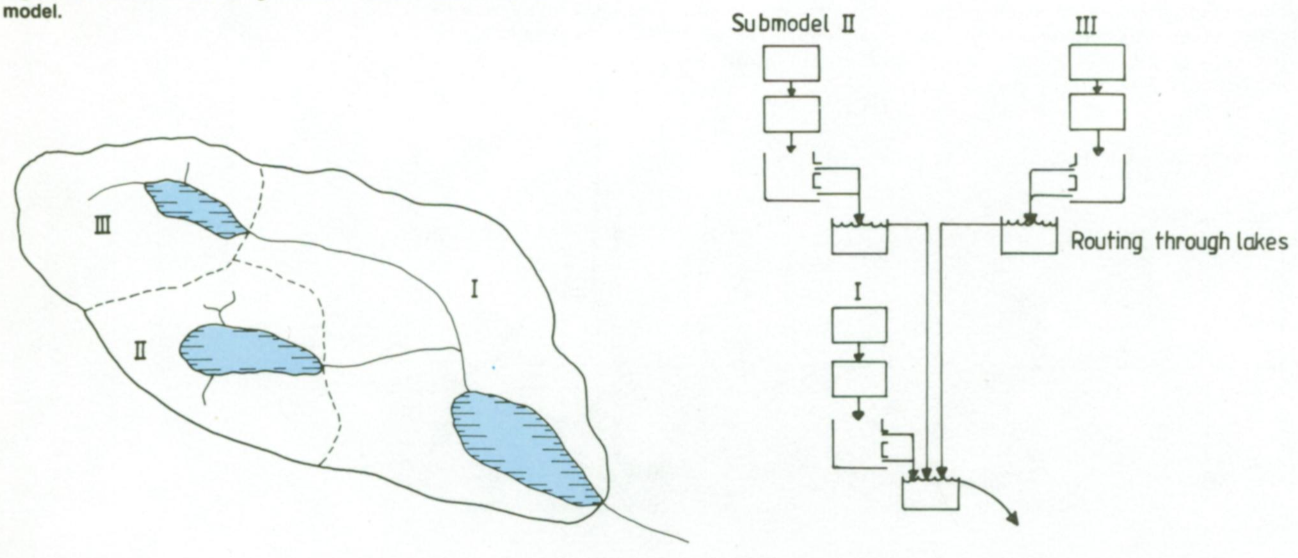


Figure 3. Substructure configuration of the distributed PULSE model.



The soil-moisture accounting routine is summarized in Figure 2. This routine implies that the contribution to runoff from rain or snowmelt is small when the soil is dry and larger under wet conditions. Actual evaporation decreases as the soil dries out. A key parameter of the model is the Fc. The value of Fc represents the maximum amplitude of soil moisture storage in the model. If the model is run with low Fc-values, the actual evapotranspiration levels will drop more rapidly as the soil-moisture storage is emptied. Consequently, the overall soil-moisture deficit of the model will be less pronounced and simulated runoff will increase.

All excess water from the soil moisture zone is collected in the saturated zone. Water is drained at different levels with different recession coefficients, which account for rapid superficial runoff and deeper groundwater with slow drainage.

The routine implies that overland flow is not considered, unless the groundwater table is close to the surface. Among Swedish hydrologists this concept is generally accepted for till soils, see for example Rodhe (18).

When applying the PULSE model to larger basins a division into submodels is recommended. The variation of input variables, precipitation, and air temperature, with elevation above sea level, can thus be taken into account. The use of submodels is particularly important in basins with lakes.

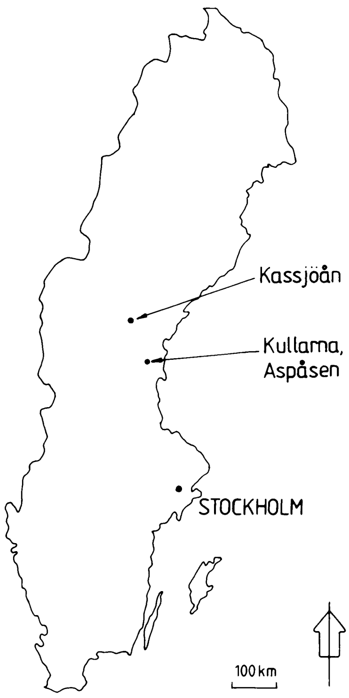
If the model is structured into submodels, defined by the outlet points of the lake (Figure 3), the effects of the lakes on the shape of the hydrograph can be considered in a more physically correct way. This is not possible when a lumped structure is applied. This substructure of the PULSE model limits the demand on model calibration (19) and provides the model with a realistic time distribution of the flow contributions from different parts of the basin. The latter is a very important feature when analyzing the various consequences of forest-management practices.

DATA BASE

The location of the basins studied is shown in Figure 4. Runoff from the basins Kullarna ($1.5\ km^2$) and Sniptjärn ($0.4\ km^2$) has been gauged since 1977. In 1980, 70 percent (Kullarna) and 100 percent (Sniptjärn) of the areas were clearcut. The basins were drained in 1982 and 1983. At Aspåsen ($0.16\ km^2$), runoff measurements were initiated in 1979, and in the winter of 1982/83 85 percent of the area was clearcut.

Precipitation data for these three adjacent basins were collected from two meteorological stations situated 30 kilometers south and 15 kilometers north of the basins. The data series were tested with double-mass analysis. No notable inconsistencies were observed, and the data were found fully acceptable for this study, although the stations were not situated close to the basins or at equivalent heights above sea level. Temperature data were collected from a station 30 kilometers south of the basins. In all cases monthly estimates of the potential evapotranspiration according to Eriksson (20) were applied.

Figure 4. Geographical location of the studied basins.



Partial deforestation in large basins was studied using the representative basin Kassjöån ($164\ km^2$). Runoff data for the period 1975–1984, were chosen. Precipitation and temperature data were collected from a station 20 kilometers north of the basin.

RESULTS

Model Application to Small Basins

In the application of the model to the small basins Kullarna, Sniptjärn, and Aspåsen, the empirical model parameters were set by calibrating against observed runoff for the time period prior to clearcutting (three years). The effect of clearcutting could then be determined as the difference between simulated and recorded runoff when the model was run with the meteorological data measured after clearcutting.

Figure 5 illustrates the increase in runoff from the time of the clearcutting. The obvious effect is a quick drop in the accumulated difference curve (computed minus recorded runoff). The increase varied between 165 and 200 mm per year in the different basins. The greatest effects were observed in spring, when the increase was 50 to 120 mm during the spring flood. During the summer and autumn period, the increase varied between 75 and 95 mm.

When recalibrating the model to post-harvest conditions it was found to be

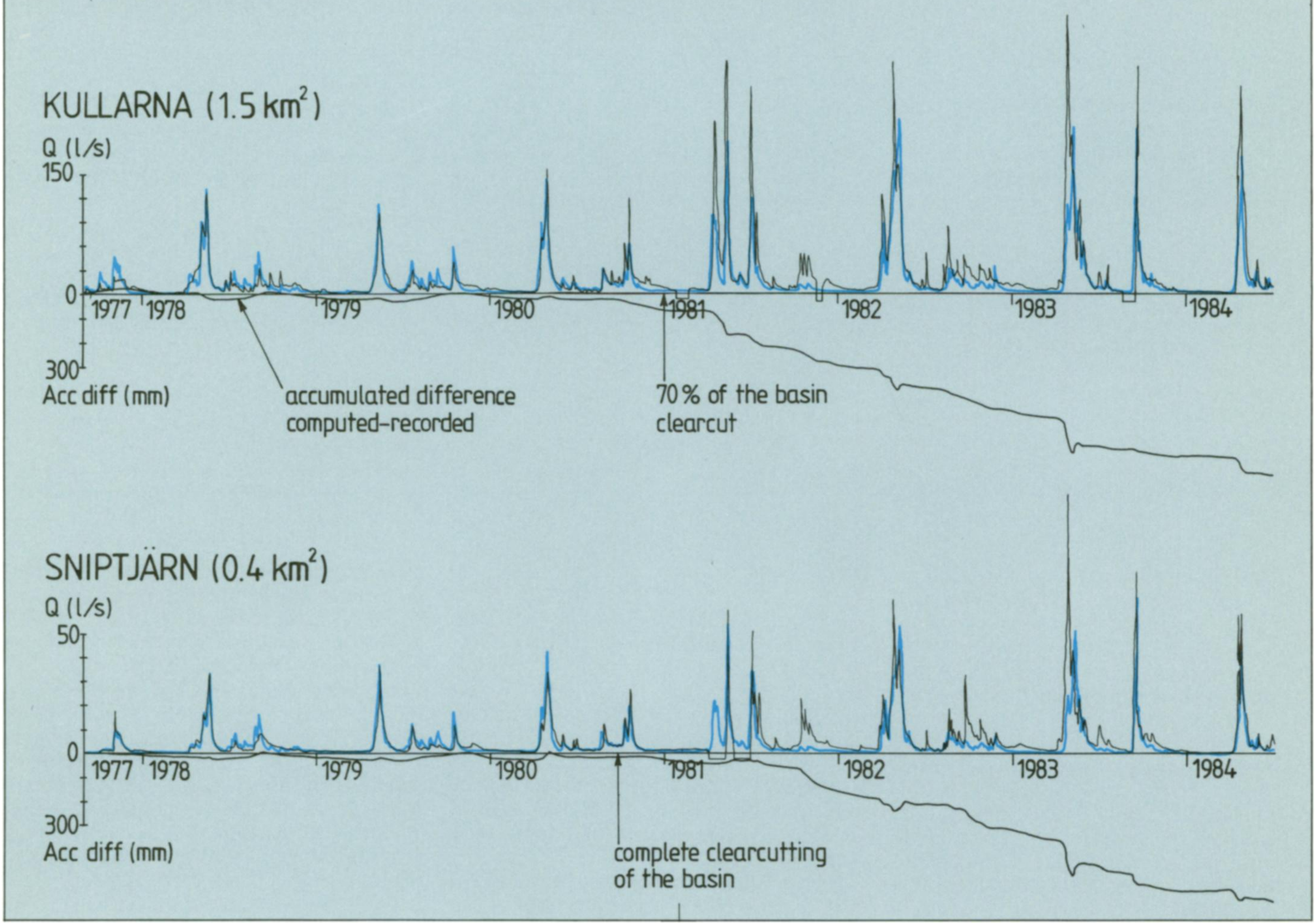


Figure 5. Runoff (Q) simulations for two small basins, illustrating the effect of clearcutting. Recorded hydrograph = thin line. Computed hydrograph = blue line Acc. diff. represents the cumulative difference between computations and observations.

Table 1. Pre-harvest (I) and post-harvest (II) optimum-model parameters (calibrated).

	KULLARNA I	KULLARNA II	SNIPTJÄRN I	SNIPTJÄRN II	ASPÅSEN I	ASPÅSEN II
Snowfall correction	0.85	1.15	0.8	1.10	1.00	1.30
Degree-day melt factor mm · (day · °C)$^{-1}$	2.25	3.50	2.25	3.50	3.00	5.50
Threshold air temperature (T_0) (°C)	0	−0.3	0.5	0	1.4	0.5
Soil-moisture amplitude (Fc) (mm)	200	50	150	40	200	50

necessary to change the values of parameters for the snow routine and for the soil-moisture routine. The correction factor for snow accumulation was increased to account for increasing spring-flood runoff volumes. The degree-day factor was increased to account for a more intense snowmelt, and the threshold temperature was decreased to obtain an earlier start of the melting.

When trees are felled, transpiration and evaporation decrease. In the hydrological model this was accounted for by a decrease in the empirical parameter, Fc, in the soil-moisture routine. A summary of the most significant model parameters for conditions before and after harvest is given in Table 1.

The effects on the snowmelt parameters are in agreement with general experience from forested and open areas (21).

It is noticeable that the reduction in the amplitude of the soil-moisture storage, controlled by Fc, implies that the soil will become less important as a flood controlling factor after clearcutting.

The difference between pre-harvest and post-harvest conditions in the model simulations is shown in Figure 6. Runoff from

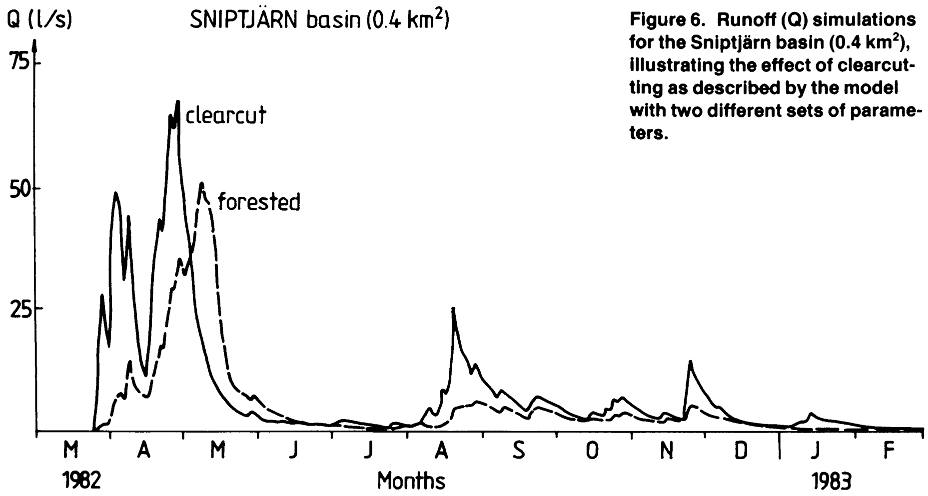


Figure 6. Runoff (Q) simulations for the Sniptjärn basin (0.4 km²), illustrating the effect of clearcutting as described by the model with two different sets of parameters.

Figure 7. The Kassjöån drainage basin. Hypsographic curve and two alternative locations of a hypothetical clearcut covering 10 percent of the drainage basin are indicated.

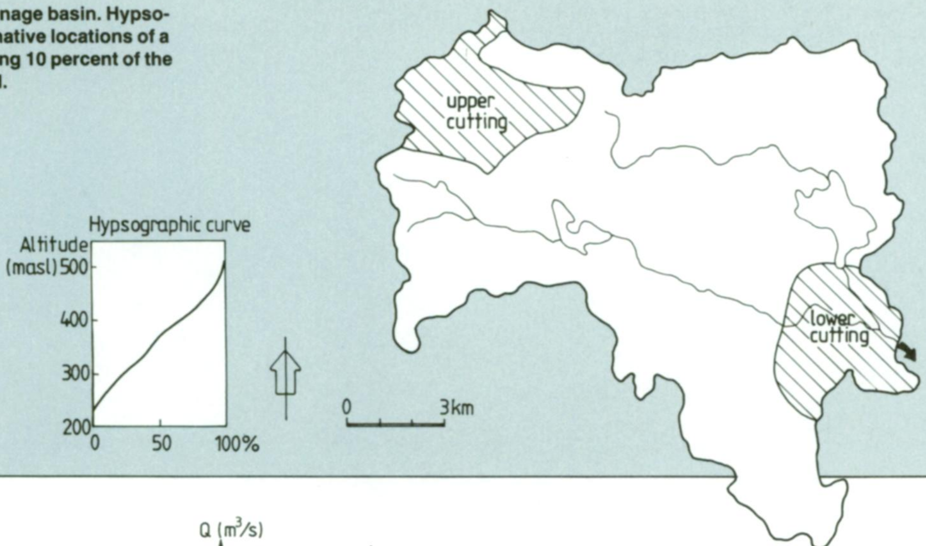
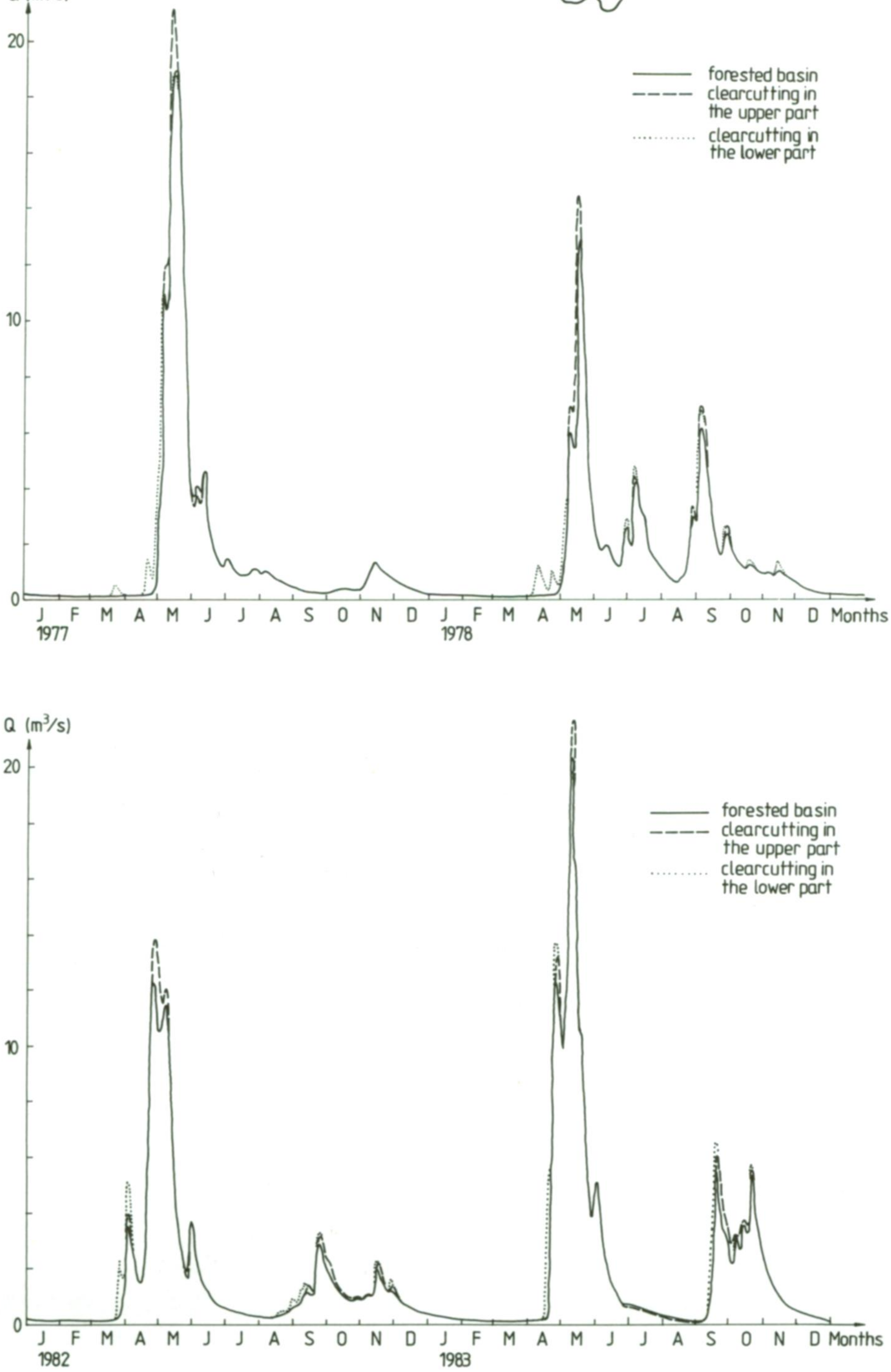


Figure 8. Examples of runoff (Q) simulations for the Kassjöån basin (164 km²), illustrating the effect of different locations of a clearcut covering 10 percent of the basin.



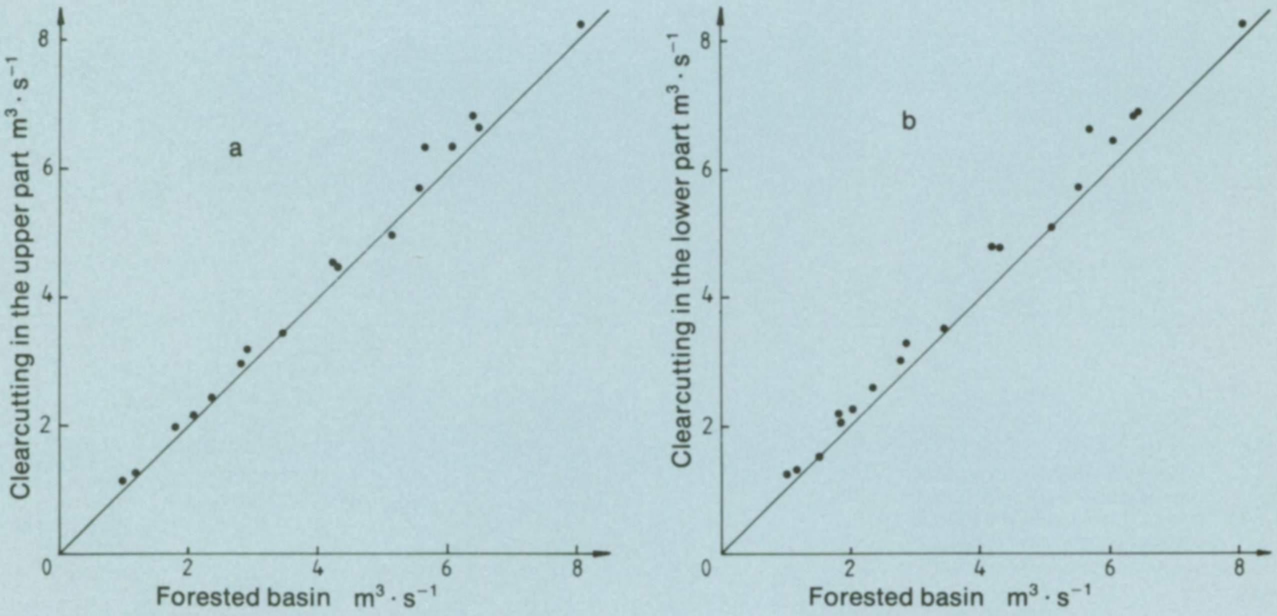
the clearcut basin is generally larger. Snowmelt starts earlier and is more intense, and summer and autumn conditions are significantly wetter due to a smaller soil-moisture deficit.

Model Applications to a Large Basin with Hypothetical Partial Clearcutting

The difference between the two parameter sets, one for forested and one for deforested conditions, formed the basis for the study on partial cuttings in large basins. For this study the drainage basin Kassjöån was used. The basin was divided into sub-basins making it possible to simulate the effect of hypothetical cuttings in different parts of the basin. Simulations were made for two different locations of a clearcut covering 10 percent of the basin area (Figure 7).

Examples of simulations of runoff with partial clearcuts are shown in Figure 8. The results indicate that the effect on runoff is relatively small and, for the spring, related to the location of the cuttings in the basin. The effect on peak flows during summer/autumn and spring is

Figure 9. Simulated peak flows during summer and autumn in the Kassjöån basin (164 km^2). Effects of a hypothetical clearcut covering 10 percent of the basin, located in the upper part (a) or in the lower part (b) of the basin (period: 1975–1984).



summarized in Figures 9 and 10, respectively.

Peak flows during summer and autumn increased by up to five percent as a result of clearcuts in both the studied locations. The importance of the location of the clearcut was considerable for spring flood. In the forested basin, spring flood normally starts in the lower parts. Clearcutting in the upper part of the basin will lead to a more intense snowmelt and an earlier spring flood in this part of the basin. Combined with melting in the lower part this resulted in a nine percent increase of peak flows during spring floods. On the other hand, clearcutting near the outlet of the basin resulted in a more evenly distributed spring flood, due to nonsynchronous snowmelt and the time delays caused by routing of water through the lakes. Peak flows were unchanged or even lower.

DISCUSSION

The conclusion that complete clearcutting of a drainage basin will result in a considerable increase in runoff confirms a well-known fact. However, using a model as a reference base instead of a basin is new. The model avoids the problems of climatic fluctuations that occur during the study period. Instead, the homogeneity of climatological records becomes a very crucial factor, which has to be controlled. The model approach also constitutes a considerably less expensive method than maintaining a reference basin.

It is important to bear in mind that the study of the effects in the large basin is based on comparisons between simulations with hypothetical differences in forest cover. The manipulated small basins were only used to identify suitable model parameters for pre- and post-harvest conditions. In other words, the model is used

Extreme autumn floods in Central Sweden 1985 started a discussion on the hydrological effects of clearcutting. Photo: H. Sanner.

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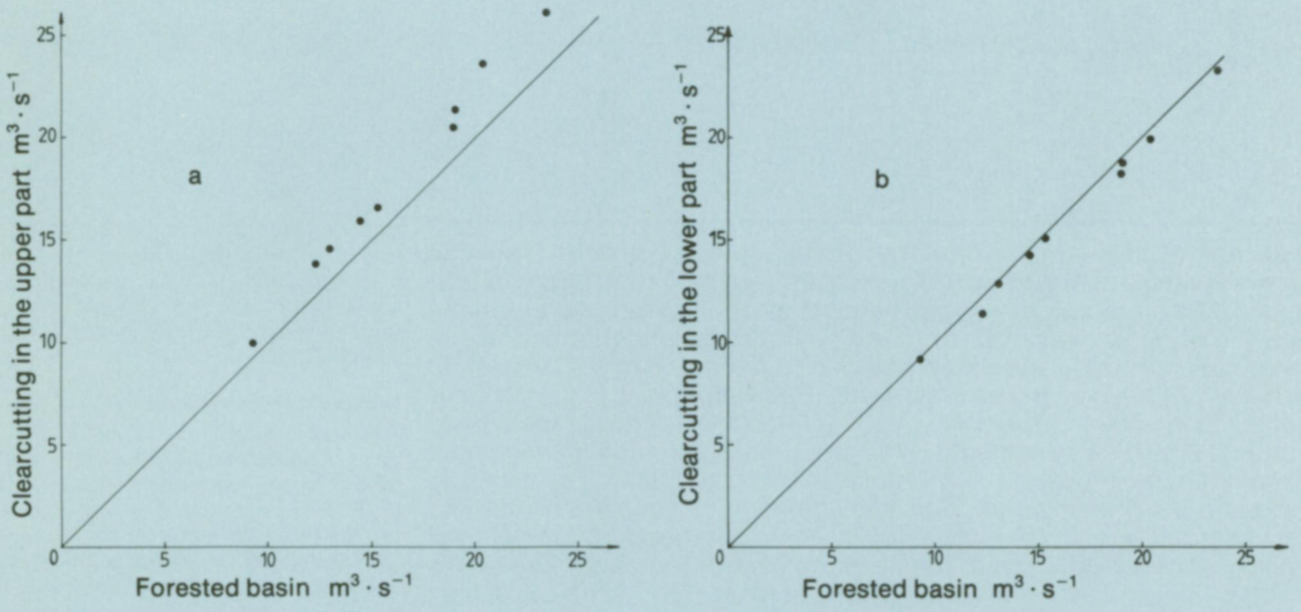

Figure 10. Simulated peak flows during spring in the Kassjöån basin (164 km²). Effects of a hypothetical clearcut covering 10 percent of the basin, located in the upper part (a) or in the lower part (b) of the basin (period: 1975–1984).

as an instrument to spatially and temporally extrapolate known results from a small research site to an integral part of a large basin. Of particular importance is the distribution of snowmelt and damping of contributions from sub-basins by the routing through lakes.

The relatively minor effects of forest management practices are mainly due to the fact that 10 percent is a relatively small, but probably realistic, fraction of a basin of this size. If the full heterogeneity of the system is taken into account, the results may be in agreement with intuition, but the model helps us to quantify the integral effects of different geographical locations of clearcut areas.

The study is based on a relatively crude distinction between forested and clearcut areas, which limits its generality. In any basin there is, of course, a range of tree sizes and a water demand relative to tree age. Forest density may also be changing due to more efficient forest management practices. Another factor, which can disturb the analysis, is that clearcutting is often followed by increased drainage to protect the area and increase production.

Nevertheless, we feel that the model approach to the analysis of hydrological effects of partial clearcutting provides useful data on the order of magnitude of these effects. The results show that forest management practices can have a strong local influence on flood risks, especially in small streams in areas where the percentage of deforestation is high. Considering the relatively small total fraction of clearcuttings in large river basins, it is not realistic to assume that forest management practices are the main cause of high floods in Sweden's main river systems during recent years. These floods can be satisfactorily explained by extreme climate and antecedent soil moisture conditions.

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