Spillway design floods in Sweden: I. New guidelines

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Abstract The new Swedish guidelines for the estimation of design floods for dams and spillways are presented, with emphasis on high-hazard dams. The method is based on a set of regional design precipitation sequences, rescaled for basin area, season and elevation above sea level, and a full hydrological model. A reservoir operation strategy is also a fundamental component of the guidelines. The most critical combination of flood generating factors is searched by systematically inserting the design precipitation sequence into a ten year climatological record, where the initial snowpack has been replaced by a statistical 30-year snowpack. The new guidelines are applicable to single reservoir systems as well as more complex hydroelectric schemes, and cover snowmelt floods, rain floods and combinations of the two. In order to study the probabilities of the computed floods and to avoid regional inconsistencies, extensive comparisons with observed floods and frequency analyses have been carried out.

Débits de crue de projet pour les déversoirs en Suède: I. Description des nouvelles directives

Résumé Les nouvelles directives suèdoises pour le calcul des débits de crue de projet pour les barrages et les déversoirs sont présentées en insistant sur ce qui concerne les barrages à haut-risques. La méthode est basée sur un ensemble de séries de données de précipitations pour une région, mises à l'échelle pour l'aire du bassin, la saison, l'altitude et sur un modèle hydrologique complet. Une stratégie d'exploitation du réservoir est également une composante fondamentale des instructions. La combinaison la plus critique des facteurs générants le débit est recherchée en insérant systématiquement une série de précipitation de projet dans un enregistrement climatologique de 10 années, où la couche de neige initiale a été remplacé par une couche de neige statistique sur 30 ans. Les nouvelles instructions sont applicables pour les systèmes à réservoir unique ainsi que pour des projets hydroélectriques plus complexes, et ce pour les débits provenant de la fonte des neiges, pour les débits de pluies ou pour la combinaison des deux. Afin d'étudier la probabilité de débits calculés et d'éviter les irrégularités régionales, des comparaisons extensives avec des débits observés et des analyses de fréquence ont été effectuées.

INTRODUCTION

Hydroelectric power covers some 50% of the Swedish demand for electricity.

Open for discussion until 1 April 1993

Most of this power is generated in the large rivers of the north where the climate is characterized by long winters with substantial snow accumulation. A complex system of reservoirs is therefore needed to store water from snowmelt in spring and rain in summer and autumn. The design floods for the spillways of the reservoir dams are in focus since a flood in late 1983 in the Rivers Indalsälven and Ångermanälven. A preliminary investigation indicated problems with the existing practice for the estimation of the design flood and resulted in the establishment of The Swedish Committee for Design Flood Determination (Flödeskommittén), which started its work early in 1985. The members of the committee represented both the hydroelectric power industry and governmental agencies (the Swedish Meteorological and Hydrological Institute). In September of the same year the problem was underlined once again when an extreme rain flood in combination with a jammed gate caused the failure of the Noppikoski dam in a tributary of the River Dalälven in Central Sweden.

It was the ambition of the committee to present new guidelines for the estimation of design floods for dams and spillways that meet the following requirements:

(a) they shall result in a safety that is considered satisfactory and reasonable by the responsible authorities and the dam owners;
(b) they shall be clear and consistent and leave as little as possible to subjective considerations;
(c) they shall result in the same degree of safety in all climatological and hydrological regions of the country;
(d) they shall cover rain floods, snowmelt floods and combinations of the two; and
(e) they shall be applicable to single reservoirs as well as to larger systems with several regulation reservoirs.

The committee worked openly to take advantage of available national and international experience within the hydropower industry and elsewhere. Progress reports were presented on several occasions (Bergström & Ohlsson, 1988; Bergström, 1988; Bergström *et al.*, 1989). The final guidelines, which were presented in the summer of 1990 (Flödeskommittén, 1990), differ somewhat from what was presented in those progress reports. The most important amendment is that a full hydrological model is now required both for snowmelt and rain flood conditions in contrast to a simplified model and a separation of these two conditions as was earlier suggested.

The Swedish guidelines for design flood determination should be regarded as recommendations. They have, however, gained acceptance by the hydroelectric industry and the Swedish Meteorological and Hydrological Institute, which is the national agency responsible for the supervision of hydrological conditions in the country, and they will therefore have great impact on design studies for years to come.

The guidelines suggest a classification of dams into two classes, depending on the consequences of a failure. High-hazard dams are dams that in the event of failure would cause large risk for human life, extensive damage on infrastructure or nature and considerable economical damage. Low-hazard dams are classified as potentially dangerous for property and natural values only. Before application of the guidelines, a risk class evaluation has to be performed. For some dams flood wave simulations to judge the potential damage to the downstream area may be needed. Domino effects are also taken into consideration in the risk classification of the dams in a developed hydropower system. This means that a small dam that, in the event of failure, would cause failure of a large downstream dam, will be classified as a high-hazard dam.

Low-hazard dams, as opposed to high-hazard dams, may be designed by flood frequency analysis. For such dams, the guidelines suggest that a return period of at least 100 years should be used, or half of the most critical flood for a high-hazard dam simulation. The following presentation is limited to a description of the design flood guidelines for high-hazard dams. In a companion paper (Lindström & Harlin, 1992) applications and sensitivity analyses of the guidelines to some factors and assumptions are given.

METHODOLOGY

The committee recognized that there are no internationally accepted standards for design flood estimation. A number of methods has been developed in different countries and sometimes there is even a variety of methods within a single country. It is also clear that the record of dam incidents related to inadequate spillways is a matter of major concern for engineers and hydrologists all over the world (ICOLD, 1988; 1992).

There seem to be two main contrasting principles in estimating design floods. One is the statistical approach based on frequency analysis (USWRC, 1982); the other is the calculation of the probable maximum flood by climatological and hydrological considerations and models (NERC, 1975; NRC, 1985; NVE, 1986). The committee considered those two approaches and found that the latter is the more feasible for Swedish hydrological conditions and the configuration of the Swedish hydroelectric power production system as concerns high-hazard dams. The uncertainty introduced when extrapolating short records to low annual probabilities of exceedence and the inability to use the method in a complex system of reservoirs were the main arguments against the use of frequency analysis.

A closer look at international practice left the impression that much effort has been spent on the assessment of the probable maximum precipitation, whereas less attention has been paid to other flood generating factors, such as snowmelt, soil moisture deficits and reservoir operation. The new Swedish guidelines differ in this respect. They are characterized by the use of a full hydrological model including a reservoir operation strategy and a critical timing of flood generating factors, which have all been experienced although not at the same time or place. The result is that very low probabilities can be reached without extrapolation of any single flood generating factor. In order to meet the requirement of objectivity ((b) above) those factors had to be very clearly specified in the guidelines.

Climatological considerations

The work of the committee started with a nationwide investigation of extreme areal precipitation in Sweden (Vedin & Eriksson, 1988; Fig. 1). Emphasis was put on the analysis of extreme areal precipitation to avoid the vague interpretation of areal reduction factors in combination with rainstorms of different origin. Thus the influence of local convective precipitation with high intensity but small areal coverage was minimized. The analysis was very labour-intensive and covered every single observation of precipitation in Swedish official records between 1881 and 1988, with emphasis on areas of 1000 km^2 and 10 000 km^2 respectively. The highest observation on record was a rainstorm of 150 mm per

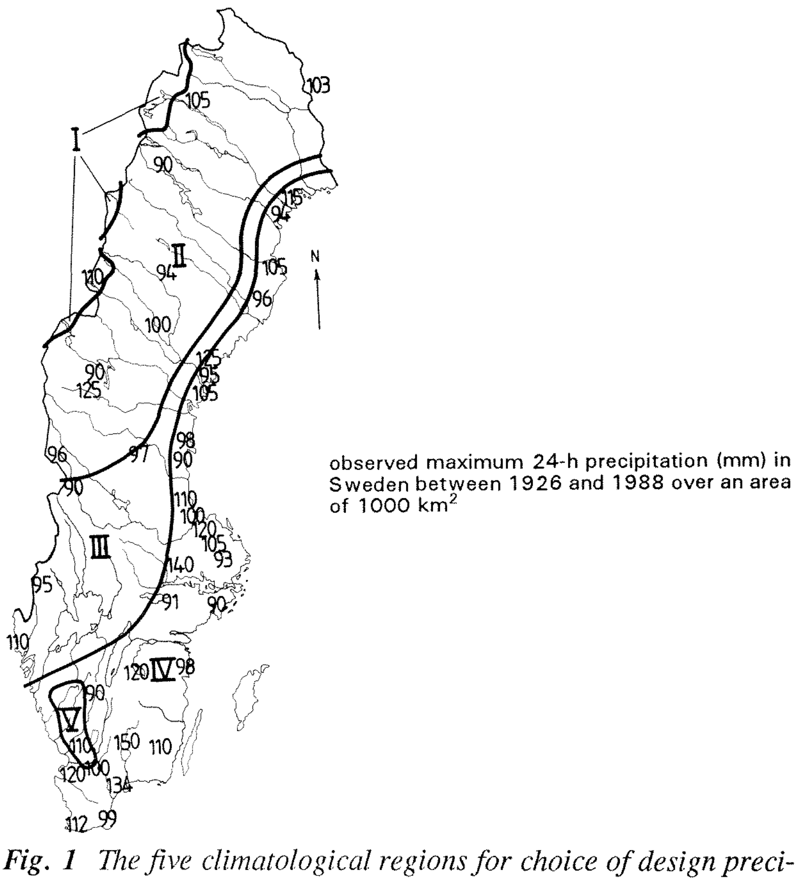
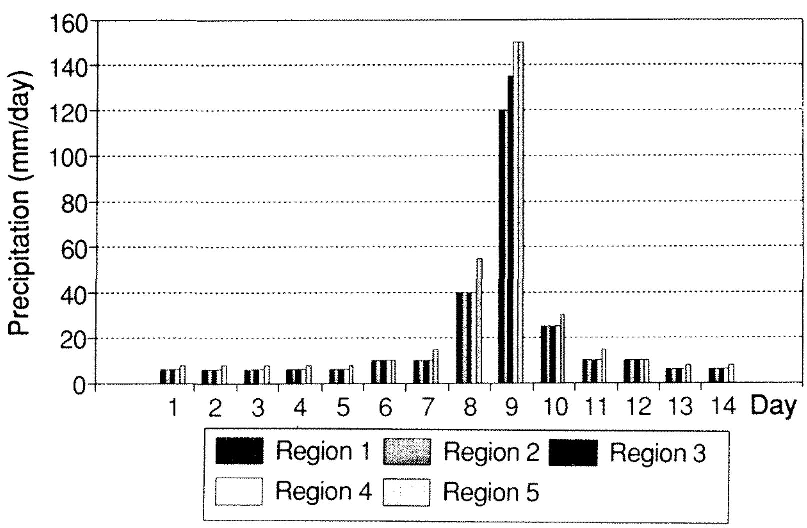


Fig. 1 *The five climatological regions for choice of design precipitation sequence (after Flödeskommittén, 1990; Vedin & Eriksson, 1988).*

24 h over an area of 1000 km² in southern Sweden in August 1945.

The study was restricted to observations with a resolution in time of 24 h. Those are the data normally available, and because of the size of the basins which feed the reservoirs, a higher resolution in time was not considered necessary. Developed Swedish hydropower basins are in general of the order of hundreds to several thousands square kilometres in size. However, for applications to small, quickly responding basins or small basins with low reservoir storage capacity, convective precipitation could be more severe than frontal precipitation and a finer time step in the design flood simulation may be used (Flödeskommittén, 1990).

The nationwide analysis of areal precipitation included a study of intensity-duration-frequency relationships and is the foundation for five basic 14-days design precipitation sequences each of which is specific for each one of five climatological regions (Vedin, 1990; Brandt *et al.*, 1987; Fig. 2). Those sequences were constructed so that they roughly contain the largest amounts experienced over 1-14 day periods of the 100 years of observations available in Sweden. The precipitation sequences were arranged so that they generated the most critical flood development, which led to the location of the highest 24-h value to day nine (Fig. 2). The regional precipitation sequences are subject to corrections for season (Fig. 3), basin area (Fig. 4) and basin elevation (Table 1) before being entered into the hydrological model. It was found that the rescaling of precipitation according to elevation had to be specific for each one of the main rivers due to local effects. One argument for this differentiation is differences in proximity to the precipitation maximum close to the Norwegian coast.



values valid for a 1000 km² area below reference level for altitude corrections, without seasonal corrections

Fig. 2 *14-days design precipitation sequences for the five climatological regions in Sweden.*

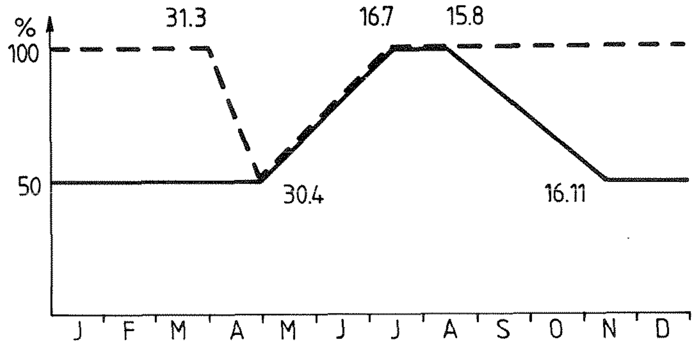


Fig. 3 Examples of seasonal correction of the design precipitation (region 1: dashed line; regions 2-4: continuous line).

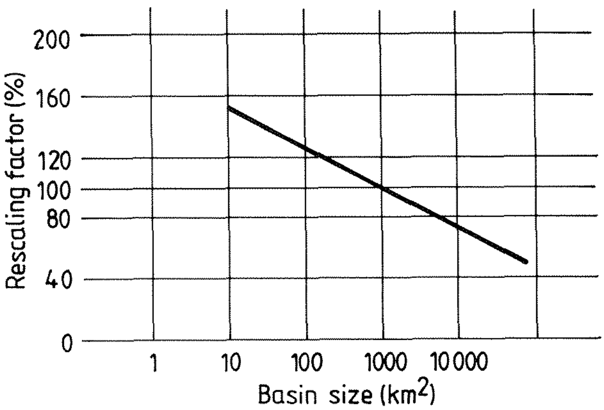


Fig. 4 Rescaling of the initial design precipitation sequences according to the size of the basin.

Hydrological considerations

The committee initiated hydrological research on the main flood generating factors and their interaction in Sweden. Those studies shed light on the importance of critical timing of snowmelt, soil moisture deficits and precipitation (Brandt *et al.*, 1987; Lindström, 1990). An example from the Trängslet

Table 1 Rescaling of the initial design precipitation sequence according to mean basin elevation above a reference altitude

River basin from north to south	Rescaling % per 100 m	Reference altitude (m a.m.s.l.)
Torneälven to Indalsälven	+10	500
Ljungan and Ljusnan	+10	600
Dalälven	+5	600
Klarälven	+5	700

drainage basin in the River Dalälven is shown in Fig. 5.

The committee first investigated the possibility of using a rather simplified hydrological model approach. This worked quite well for smaller systems in northern Sweden (Bergström *et al.*, 1989). It was, however, found that the method would be inappropriate when applied to southern Sweden, where soil moisture deficits are substantial in summer. It was also found inadequate for the modelling of snowmelt floods and for application to the large river basins of north Sweden where spring or even summer conditions may prevail in the lowlands while it is still winter in the mountains. This means that one event may result in snow accumulation in the upper parts of the basin and flood generation in the middle parts, gradually reduced by the increasing soil moisture deficits in the lower parts.

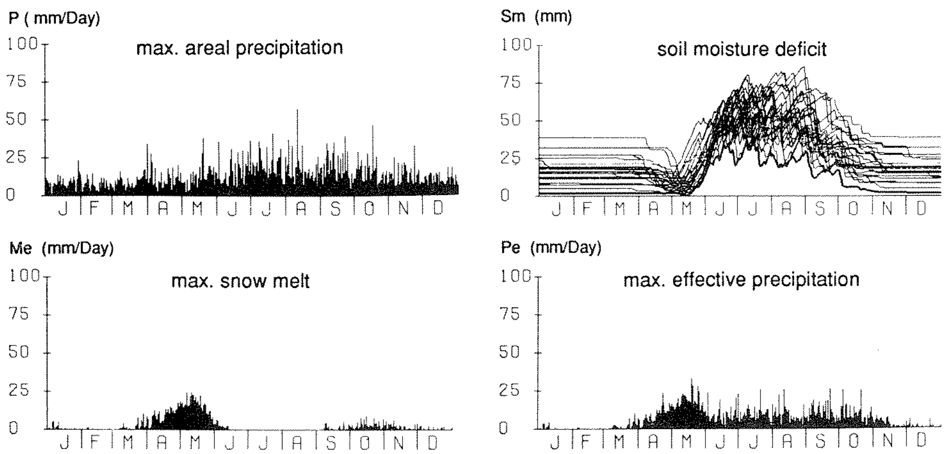


Fig. 5 *Maximum daily areal precipitation and simulations of maximum snowmelt, soil moisture deficit and effective precipitation for Trängslet basin, River Dalälven, 1962-1985.*

According to the guidelines, the simulation of design floods should be based on a relatively complete hydrological model. This means that the model must include routines for snow accumulation and melt, soil moisture accounting, and response of the basin to effective precipitation. Routines are also required for reservoir operation and the distribution of the processes according to the elevation above sea level. Finally, the model must have documented performance in order to yield credible results. The established model in Sweden that meets those requirements is the HBV model (Bergström & Forsman, 1973; Bergström, 1975; Bergström, 1976), but other models of equal (or better) performance are also accepted.

The committee decided that the design simulation should start with a snowpack with an estimated return period of 30 years. This means that extrapolation to return periods far beyond the period of record is avoided. The frequency analysis is based on snowpacks that are generated by the hydrological model. The areal distribution of the design snowpack within the basin is the same as the one found during the most extreme of the years included in the model simulation, and the starting date is the last date of accumulation of any snowpack in the same record. The technique means that the hydrological model has to be calibrated before the snowpack can be extracted for the statistical analysis. The calibration period is approximately ten to fifteen years.

The HBV hydrological model

The HBV model has been applied in nearly 30 countries all over the world and has, for more than a decade, been used for operational forecasting in a large number of basins in Sweden. Its performance has been verified in several papers and reports (Bergström & Forsman, 1973; Aam *et al.*, 1977; Renner & Braun, 1990; Häggström *et al.*, 1990; Hinzman & Kane, 1991; Harlin, 1991). Despite its relatively simple structure it performs as well as the best known models in the world (WMO, 1986). Since the release of the new design flood guidelines it is also being used for design flood simulation in Sweden. The model has routines for snowmelt, soil moisture accounting and evapotranspiration, runoff response and a transformation function (Fig. 6). It can be distributed into sub-basins and it is usually run with daily means of air temperature and precipitation, and with monthly standard estimates of potential evapotranspiration. If the air temperature, T, exceeds the threshold temperature, TT, snowmelt is calculated by the degree-day method:

$$Melt = CFMAX \times (T - TT) \tag{1}$$

where $Melt$ = snowmelt (mm day^{-1}) and $CFMAX$ = degree-day factor (mm °C^{-1} day^{-1}).

The snowpack is assumed to retain liquid meltwater until the unfrozen water content reaches 10% of the total snowpack water equivalent. If the air temperature is below the threshold temperature, unfrozen water in the snowpack refreezes according to:

$$Refreeze = CFR \times CFMAX \times (TT - T) \tag{2}$$

where $Refreeze$ = refreezing meltwater (mm day^{-1}) and CFR = refreezing factor.

Water from precipitation or snowmelt enters the soil routine (Fig. 7). The precipitation (dP) is portioned into a contribution to runoff (dQ) or an increase in soil moisture (S_{sm}). The soil routine gives a small contribution to runoff from rain or snowmelt when the soil is dry and a large contribution for wet conditions. The actual evapotranspiration (E_a) is a function of the soil moisture conditions. The evapotranspiration increases with increasing soil moisture storage, until it reaches its potential value, E_p.

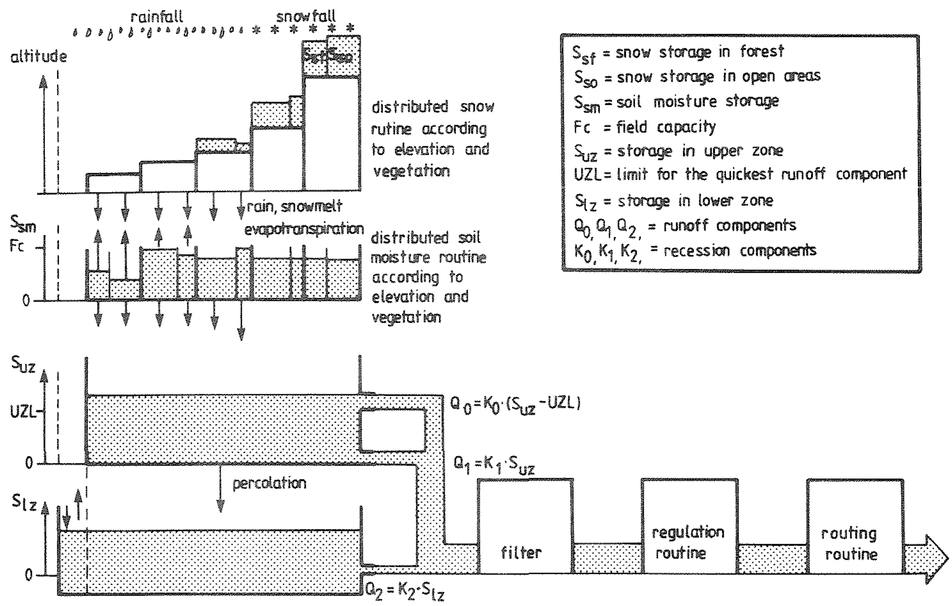


Fig. 6 The basic structure of the HBV model within one sub-basin (from Häggström et al., 1990).

Runoff is modelled by two linked response tanks (Fig. 6). The yield of water from the soil routine, the effective precipitation, is added to the storage (S_{uz}) in the upper tank which is drained under the control of two recession coefficients (K_0 and K_1), separated by a storage threshold (*UZL*). Water percolates from the upper tank and adds to the storage in the lower tank (S_{lz}) by the rate *PERC*. The lower tank also includes evaporation from and precipitation on lakes and it is drained via the recession coefficient K_2. The runoff is computed independently for each sub-basin by adding the contributions from the upper and lower tanks. To account for the flood damping in the river, a simple routing transformation is made, having a triangular distribution of weights with

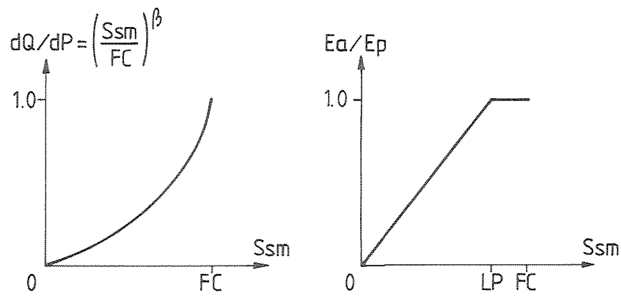


Fig. 7 The soil moisture and evapotranspiration routines in the HBV model (FC is maximum soil moisture storage and LP is the soil moisture limit for potential evapotranspiration).

the base length *MAXBAS* days.

Reservoir operation

The Swedish hydroelectric system is complex with a large number of interacting reservoirs. Their operation has to be considered when modelling the response of the system. Generally the reservoirs are emptied before the onset of snowmelt and refilled during summer and autumn to a degree that depends on the climatological conditions during that specific year. When analysing reservoir response to design floods one may consequently assume that the reservoirs are emptied to a degree that is realistic when a large snowpack is experienced. A reservoir operation strategy that is specific for each dam is worked out in cooperation with the river regulation enterprise of the specific river. This strategy is followed when routing an inflow hydrograph through the reservoir during a flood event. The reservoirs are assumed full before the floods in late summer or in autumn (after August 1).

Experience has shown that a rainstorm of the order of magnitude of the design precipitation sequence causes a more or less chaotic situation, which affects the transmission of electricity. It is therefore not realistic to assume that the water can be evacuated through the turbines of the power station which are assumed to be shut down from the day of highest 24-h value of the precipitation sequence (day no. 9) and over the remaining days of the event.

Simulation technique

The computation of design floods starts in spring with the specified design snowpack, with reservoirs and lake water levels set at mean lowest levels for the time of the year and without soil moisture deficit. The most critical timing of the design precipitation is then found by a trial and error technique. This means that the corrected 14-day sequence is successively inserted, replacing the observed data, at all possible dates of a climatological record of at least ten years. The corresponding floods and water stage developments are simulated by the hydrological model and the reservoir operation strategies (Fig. 8). This methodology means that design snowmelt floods in spring and rain floods at other times of the year, or combinations of the two, are computed by one procedure.

One detail in the guidelines is that the air temperature in spring is lowered by 3°C on day no. 9 and on the remaining days of the design precipitation sequence in order to avoid unrealistic combinations of snowmelt and rainstorms. Another detail is that precipitation adjacent to the inserted design sequence may be adjusted so that no floating 14-day totals will exceed the value of the total design sequence.

The scaling of the design precipitation according to basin area may make local precipitation over a relatively small area more critical than precipitation

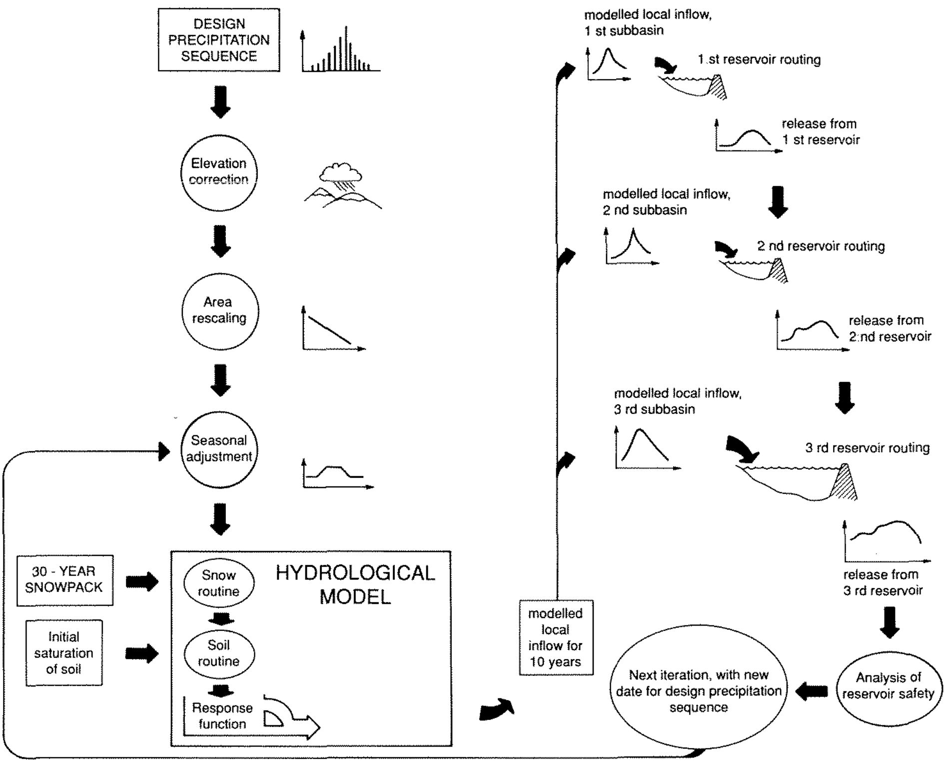


Fig. 8 Schematic presentation of flood simulation and routing through a system of reservoirs according to the Swedish guidelines for design flood determination.

over the entire river system. The committee therefore recommends that both the total inflow and the local inflow generated below an upstream dam or large natural lake should be analysed.

The systematic search for the most severe flood situation within 10 years of climate observations means that, theoretically, 3650 simulations have to be carried out. Thanks to the relative simplicity of the hydrological model, this is not an unsurmountable effort for modern desk top computers. Some of the simulations can also easily be identified as unnecessary and can therefore be omitted. The dam safety criterion is that all dams of the system must be able to withstand the most severe of the simulated inflows. Figure 9 shows how the simulated inflow peaks are distributed in time for a single reservoir, Torrön, on the River Indalsälven. An example of the routing of one of the simulated inflow hydrographs through the same reservoir is shown in Fig. 10.

PROBABILITY AND CONSISTENCY

It is an urgent but difficult task to assess, or at least to try to get an idea of, the

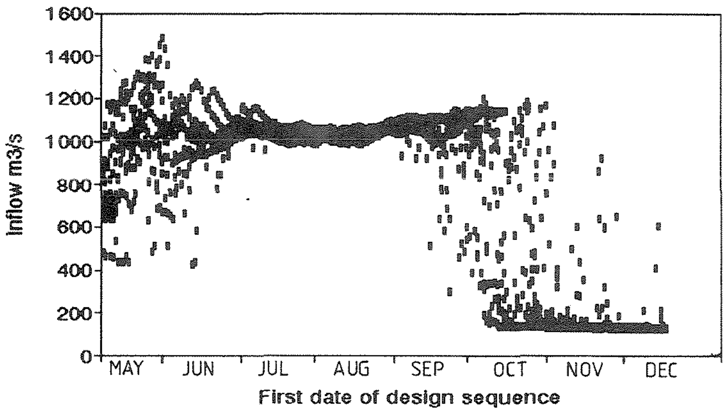


Fig. 9 *Distribution in time of the peak inflow to the Torrön reservoir (1978-1987) according to the iterative design simulation procedure.*

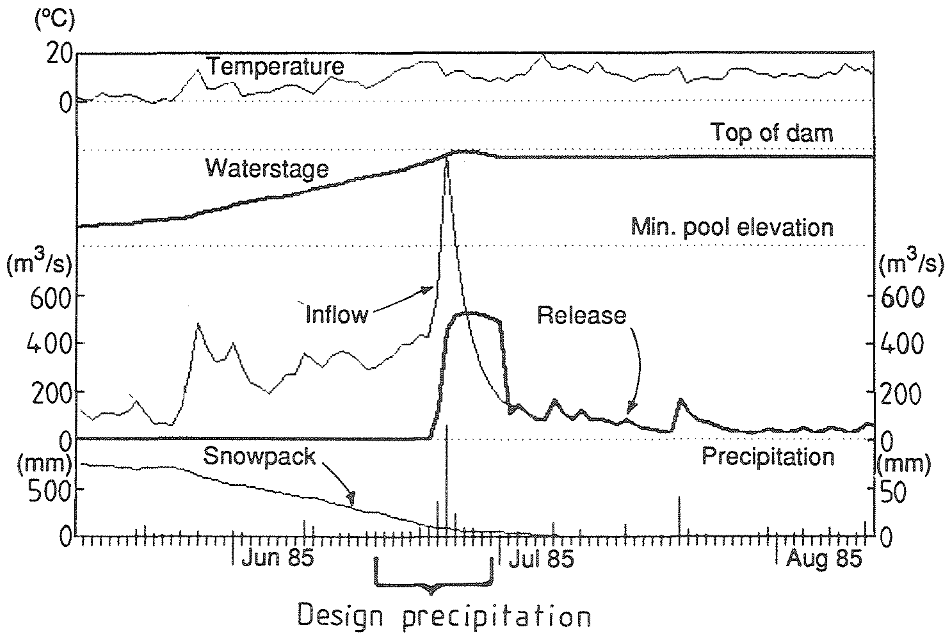


Fig. 10 *Example of the most critical inflow simulation and reservoir response in the single reservoir system of Torrön, Upper Indalsälven, in Northern Sweden.*

probabilities of floods computed according to the above type of guidelines. A lot of effort was spent on verification and control. First of all, computed design floods were compared to actual observations in Swedish rivers, and secondly, comparisons were made with estimated 10 000-year floods according to standard procedures for flood frequency analysis. The results can be found in the work by Bergström (1988) and Bergström *et al.* (1989) but also in an enclosure to the final report by the committee. Historical observations were used in a study by Harlin (1989).

The highest observed floods in Swedish records, on average, stay below 45% of the design flood for spring conditions whereas the corresponding number for summer and autumn is 40%. Single extreme values did not exceed 65% of the design flood after the investigation of some 2800 station-years. The results from the frequency analyses vary greatly between distribution functions and have to be interpreted with great care. Nevertheless, the conclusion of the committee was that the design floods according to the suggested procedures have return periods that exceed 10 000 years, but probabilities cannot be assessed closer than this. The extensive control computations show no sign of regional inconsistencies.

Climate variability and climate change are issues debated at present. The Swedish design flood guidelines are, as all guidelines of this type, based on historical climate periods and therefore influenced by non-stationary climate problems. This was recognized by the Swedish Committee for Design Flood Determination, which concluded that existing scenarios of climate change, and regional interpretation thereof, are too uncertain to justify any additional safety margin (Flödeskommittén, 1990). In the companion paper by Lindström & Harlin (1992), the effect of climatic variability on applications of the guidelines is studied and discussed.

DISCUSSION

The combination of a hydrological model and reservoir operation strategies has many advantages. The most important is that the significant flood generating factors can be combined in a realistic way and that extreme conditions with low probabilities can be reached without too much extrapolation of any one of these factors. Emphasis is put on critical timing rather than maximization of the flood generating factors. The variability of the seasonal patterns over a large basin is accounted for both as concerns the hydrological processes and the reservoir operation.

The most important disadvantage is that a close specification of probabilities is difficult. One can, however, question whether this is possible with any of the existing methods for design flood determination in use today (US Department of Commerce, 1986).

The use of reservoir operation strategies opens the possibility of mastering the design floods in a flexible way for the whole system. This means that problems in a river system can be solved by a combined strategy, based on flood damping by temporary storage in some reservoirs and increased spillway capacities in others. It also means that the design flood analysis must be integrated for the entire river system and carried out in close cooperation with the river regulation enterprises.

The guidelines strictly prescribe most of the climatological and hydrological conditions. This is, of course, a compromise, as many local effects cannot be considered. In the companion paper (Lindström & Harlin, 1992) the sensitivity of the results to those assumptions is analysed further.

The handling of the hydrological model also introduces a main source of uncertainty. First of all, the results depend on the choice of model, and this is why a model with documented performance is required. Secondly, the results depend on how a specific model is calibrated. The sensitivity of the design floods to such uncertainty is also analysed in the companion paper.

The conclusion by the Swedish Committee for Design Flood Determination, after five years of work, is that the suggested method meets the requirements specified in the Introduction. There is also a general consensus among the owners of the most important dams that the guidelines are realistic and will result in an acceptable and reasonable level of safety for the dams of the Swedish hydroelectric power system. The industry has now initiated a comprehensive control program where the safety of all major dams, with respect to design floods, is analysed.

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