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Proposed Swedish Spillway Design Guidelines Compared with Historical Flood Marks at Lake Siljan

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A comparison between the proposed Swedish spillway design floods and historic flood marks made at lake Siljan in central Sweden, is shown. Frequency analysis is performed incorporating pregauge information on water levels together with a sensitivity analysis of modelling assumptions.

A water level of 0.42 to 0.75 metres above the highest historic flood mark (166.10 m.a.sl., 1659) was obtained when routing the design spring flood through lake Siljan. The design autumn flood lifted the lake to 1.56 to 1.52 metres below the highest flood mark. Return period for the design spring and autumn flood was estimated to about 1,000 years. The uncertainty in frequency analysis proved to have larger impact than modelling assumptions on estimating the risk of the design flood.

Introduction

New spillway design guidelines for Swedish dams have been proposed, Swedish Committee on Spillway Design (1989). The method suggested is based on a probable maximum flood (PMF) concept, employing a conceptual rainfall-runoff model in computing the design flood. This method has the advantage of combining experienced hydrological extreme events and giving not only the flood peak, but the whole design flood hydrograph. Hydrological modelling will introduce uncertainty, though in the model itself and in design assumptions. Because of the deterministic methodology, no probabilistic interpretation of the result is given. The classical problem of estimating the design flood return period has thus come in focus again.

One way to tackle this problem is by frequency analysis at a gauged site given a systematic flow record. However, only limited information about the flood frequency distribution at the site is obtained because of the limited experience the flow record reflects. Bergström, Lindström and Sanner (1989), found that the proposed Swedish spillway design guidelines represented floods with a return period beyond 10,000 years, on average over Sweden. To obtain more precise estimates of such extreme floods, one must bring additional information to bear on the problem.

Historic flood data such as high water marks occurring before the period of continuous data is one example of additional information. Although the number of recorded floods only increases marginally, there is also knowledge about the intervening years when no systematic record is available. Maximum annual floods during these periods were less than the historic floods whose values are known. Such a record can be considered as a censored sample from a frequency distribution and because of the historic longer period, improve the accuracy of the frequency analysis.

Benson (1950), was early to discuss the use of historic flood data. He studied a 72-year systematic record from the Susquehanna River at Harrisburg, USA, and a 88-year period prior to gauging with 7 historic floods. His work resulted in new plotting position formulas for the systematic and historical floods so as to remove the discontinuity in the frequency curve at the joint between the two sets of data. USWRC (1982), presents a method of moments technique for estimating distribution parameters with historic data. Also maximum likelihood estimators have been developed for several distribution functions, for example by Leese (1973), Stedinger and Chon (1986) and Clondie and Lee (1982). A comparison of the efficiency between different estimating techniques is presented by Chon and Stedinger (1987).

These papers all show that historic data give valuable information in describing the tail of the frequency distribution and increase the accuracy of the parameter estimates. Although this technique will not enable calculation of the probability of PMF-scale floods, U.S. Department of Commerce (1986), it will perform better than traditional frequency analysis and decrease the error bounds.

This paper addresses the question of how the proposed Swedish design floods compare with the extreme historical flood marks made at lake Siljan in central Sweden. It also attempts to estimate the return period of the design flood and analyze the sensitivity of different modelling assumptions.

Frequency Analysis

The frequency analysis is based on annual maximum water levels for lake Siljan. A continuous series of measured values from the unregulated period starting in 1887

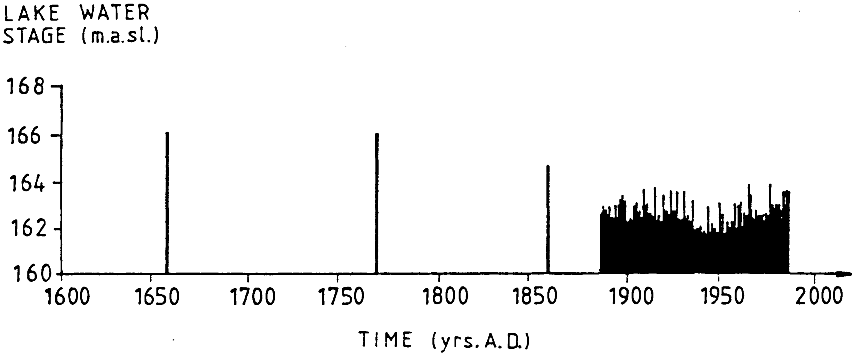

Fig. 1. Historical and systematically recorded annual maximum water levels of lake Siljan.

to 1926 is utilized. From 1927 to 1986 natural conditions have been reconstructed. In this way a continous series of 100 years is obtained.

Three historic floods are also incorporated in the analysis. These are the spring floods of 1659, 1764 and 1860. Fig. 1 shows the water stage data available for the frequency analysis.

The 1659 Year Flood

May the 8th 1659 the large flood caused the river to force a 1.3 kilometer long new channel close to the inlet to lake Siljan and destroyed Säbbenbo farm. This event has been documented by a number of authors in the 18th century and also in the church diary (Lannerbro 1953).

It is not exactly clear what water level the 1659 year flood caused. In a document concerning the regulation of lake Siljan, from 1915, the water level 166.10 m.a.sl. is given, which corresponds to the level given by some of the 18th century authors Lannerbro (1953). Wenner and Lannerbro (1952), who studied the meander field, geology and history of the Siljan basin question that the water could have risen that high, because a parish meeting report from May 19th 1661, describes the 1661 year flood as the lagest flood since 1598, and that larger erosion damage should have occurred.

A mark made at the steamboat pier in Mora, a town on the northen Siljan shoreline, gives the water level to 166.10 m.a.sl. and this is the level used in the analysis.

The 1764 Year Flood

Axel Wallén (1930) dates the flood to about the 20th of May. From church diaries at Hedemora, about 100 km downstream of Siljan, we know that large damage was caused by the flood which was considered as the worst since 1544 in this part of the river. The flood is also recognised by Wenner and Lannerbro (1952), and Lannerbro (1953) as an extreme flood, but no details are given.

A flood mark at the pier in Mora gives the maximum water level to 166.04 m.a.sl. and the flood is also marked as the highest historic flood on a rock foundation of the Kopparvågen house in Falun, some 50 km downstream. The 166.04 level is used in the analysis.

The 1860 Year Flood

This is the best documented of the historic floods. Wallén (1930) gives it the level of 164.70 m.a.sl. and places the flood as the highest in modern time and shows a photograph from 1909 of a flood mark carved on a house in Mora. Wenner and Lannerbro (1952), and Lannerbro (1953) also describe the flood, and flood marks are made both at the pier in Mora and on the Kopparvågen house in Falun. The Swedish Meteorological and Hydrological Institute SMHI (1966) give the maximum water level to between 164.90 and 165.00 m.a.sl. A level of 164.95 m.a.sl. is used in the frequency analysis.

To select an adequate distribution function five different frequency distributions were tried, namely the normal, lognormal 2, lognormal 3, Weibull and the Gumbel distributions. These were plotted in a frequency diagram together with probability plotting of the data set. The Chi-square goodness of fit test was performed. For spring water stage data, all but the Gumbel distribution were rejected at the 95 per cent confidence level. For autumn data the test could not reject any distribution.

Such tests are insensitive to distribution tail behaviour, which are the most important in this study. They also suffer from the weakness that the sample is used twice, once to fit the distribution and once to test the fitness. Cunnane (1985) concludes that »distribution choice cannot be based on theoretical arguments alone«. The Gumbel distribution was selected because of the better correspondence to the historical floods and its theoretical base as an extreme value distribution.

The equations for adjusting statistics for historic data defined in USWRC (1982) were used to estimate the distribution parameters. Plotting positions for the partially censored water stage record from the Bayesian plotting position formula derived by Hirsch and Stedinger (1987) were used.

Design Flood Modelling

The Swedish Committee on Spillway Design (1989) describes the method used in detail. A summery of the proposed Swedish spillway design guidelines is found in Bergström *et. al.* (1989). To apply it to the Siljan basin the HBV model, Bergström (1976), was calibrated for five separate subcatchments and linked together. The subcatchment outlets were at the outlets of lake Idre and lake Skattungen, furthermore at Trängslet and Bössbo, Fig. 2. The catchment area at the main outlet in

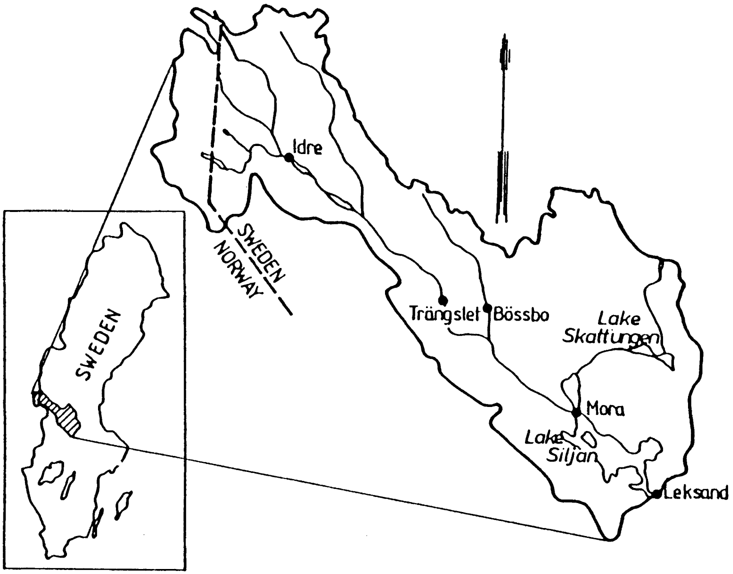

Fig. 2. The lake Siljan basin.

Leksand is 11,973 km^2 of which the lake Siljan constitutes 289 km^2 at average filling.

The Idre and Skattungen lakes were modelled separately with original stage discharge relations. A critical part in the simulation was to describe the outflow from lake Siljan, in particular at high water levels.

The Stage-Discharge Relation of Lake Siljan

The outflow of the lake Siljan is controlled by a natural section control, caused by a gradually increasing slope and constricting width of the outlet channel. This was described by the simple stage-discharge curve. Twentyfive discharge measurements, between the years 1903 and 1916 at different discharge rates have been made at the outlet. These were used to compute the constants in the stage-discharge equation. According to Cook (1987), the theoretically correct rating curve will have a slope less than 2.0, usually between 1.3 and 2.0. The found slope of 1.576 conforms to these theoretical considerations.

The stage-discharge relation should be more accurate than any of the individual gaugings. To get an estimate of the uncertainty of the spread or dispersion of the gaugings about the stage-discharge relation the standard error of estimate *Se* according to WMO (1980), was calculated. Provided that there is no change in the control or the hydraulic conditions, 19 out of 20 of all current meter observations should be included within these limits. At the Siljan outlet 23 of 25 current meter observations were well within the *Se* limits and two were right on the limit boundary.

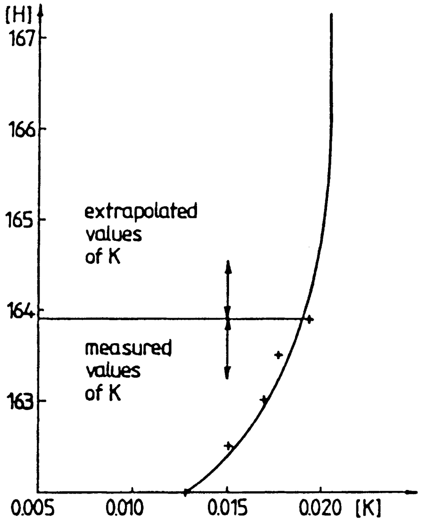

Fig. 3.
Extrapolation of the conveyance coefficient K at high water levels of lake Siljan.

Uncertainty in the stage discharge relation, expressed as a percentage, given by the standard error of the mean *Smr* (WMO 1980), was computed. *Smr* values varied between ± 2 % at intermediate water levels to ± 3 % at high levels of lake Siljan.

Extrapolation of the Rating Curve

The highest historical flood mark at lake Siljan is at an elevation of 166.10 m.a.sl. This should be compared to 163.90, which is the level at the highest current meter observation. An extrapolation of 2.2 metres has thus to be made to be able to estimate the magnitude of the historical floods. The design flood is in this order of size which is the reason for extrapolating the rating curve.

Assuming that the channel cross section and roughness has not changed with time and that the effective control during the historical flood events were the same as the effective control at the upper range of the current meter measurements, an extrapolation can be made. The method chosen was the slope conveyance method (Dalrymple 1948), which is based on application of the Manning equation.

At the lake Siljan outlet the cross section is fairly regular and no overbank flow occurs within the extrapolation range. A plot with stage as the ordinate and the mean velocity as the abscissa gave a curve which tended to become asymptotic to the vertical at higher stages. Because the rate of increase in the velocity at the higher stages diminishes rapidly, this curve could be extended without much error.

For high water stages, the Manning equation can be rewritten as

$$Q \equiv KAR^{2/9} \qquad (1)$$

$$\nu = KR^{2/9} \qquad (2)$$

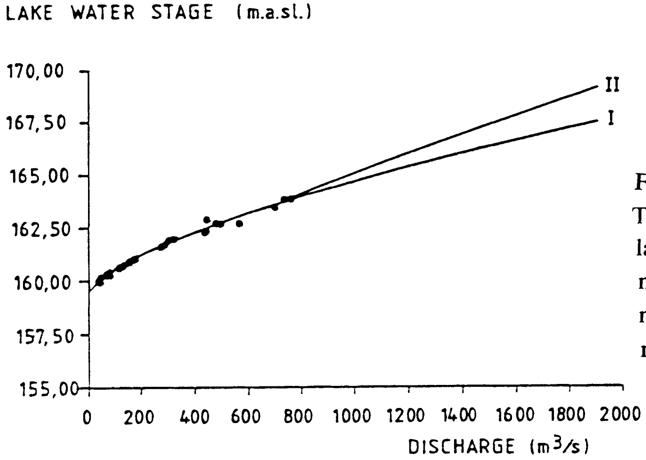

Fig. 4.
The stage discharge relation of lake Siljan. Extrapolation II is made by the slope conveyance method, curve I is the extended rating curve.

Values of the conveyance *K* were computed by using various values of υ from the known upper portion of the rating curve and the corresponding values of *R*. These values of *K* were plotted against gauge height, Fig. 3. This curve was extrapolated and high stage values were combined with their respective values of *A* and *R* to give the discharge.

The resulting stage discharge curve extrapolated by slope conveyance and by extending the original rating curve to higher levels is shown in Fig. 4.

Results

Spring Flood

The spillway design spring flood caused lake Siljan to rise to an elevation of 166.52 or 166.85 m.a.sl. depending on which extrapolation method of the rating curve used. The higher level corresponds to the slope conveyance extrapolated rating curve.

In terms of frequency this corresponds to 3,450 and 6,495 year return periods if the analysis is based on the systematic period of annual maximum water level observations, Fig. 5.

When the three historic floods are incorporated in the frequency analysis the return periods drop to 590 and 965 years respectively, Fig. 6.

The Swedish spillway design guidelines prescribe a snowpack with a return period of 30 years according to the Gumbel distribution. Resulting water levels and return periods, at different snowpacks were simulated. Rating curve extrapolation by the slope conveyance method was chosen and the frequency analysis incorporated the historical flood marks. A straight line in semi-logarithmic scale fitted by least squares was drawn, Fig. 7.

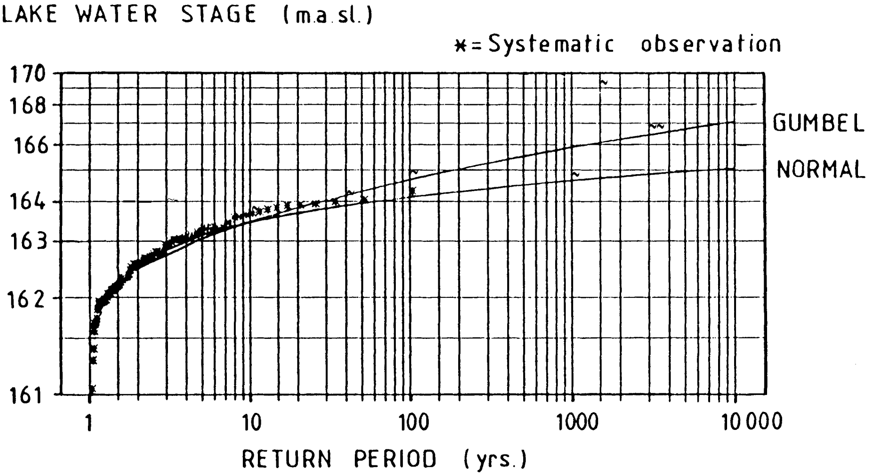

Fig. 5. Frequency analysis based on systematic recordings of annual maximum water levels. The Gumbel distribution was used and for reference the normal distribution is depicted.

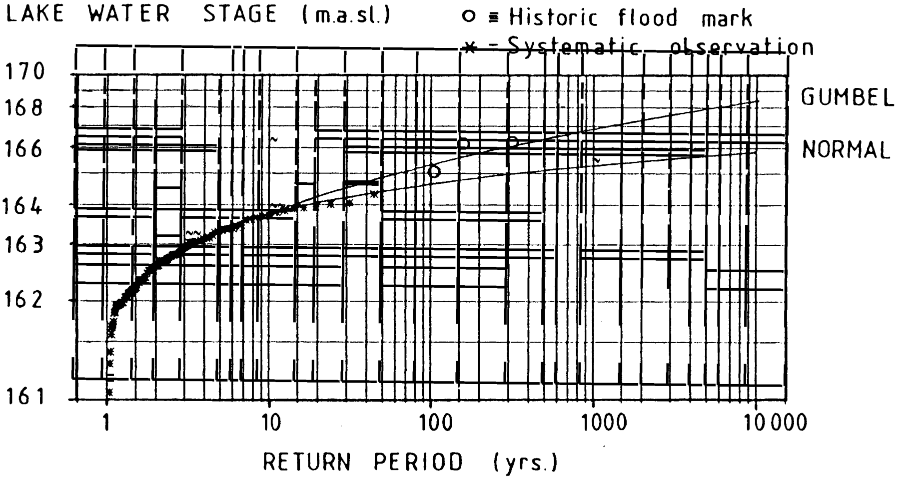

Fig. 6. Frequency analysis based on systematic recordings of annual maximum water levels and historical flood marks. The Gumbel distribution was used and for reference the normal distribution is depicted.

Autumn Flood

Elevations of 164.54 or 164.58 m.a.sl. were the results of routing the design autumn flood through lake Siljan. As initial water stage the prescribed mean maximum autumn water level was employed.

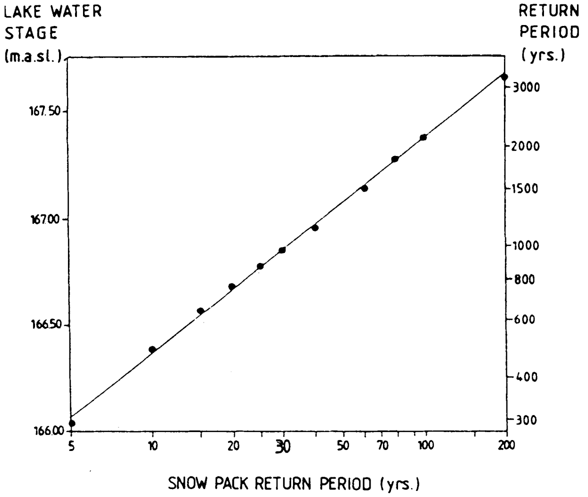

Fig. 7. Lake Siljan water stage and corresponding return period at different snowpacks.

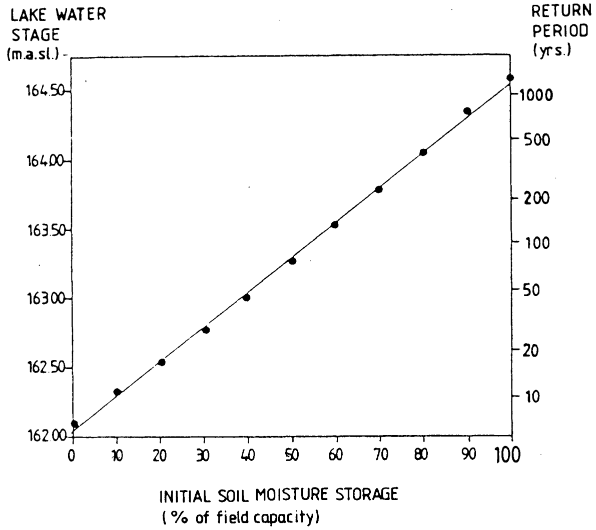

Fig. 8. Lake Siljan water stage and corresponding return period at different initial soil moisture storage.

No historic flood marks for autumn floods have been made. Frequency analysis using the Gumbel distribution, 50 years of observed and 37 years of reconstructed maximum autumn water levels, resulted in return periods for the design autumn flood at 1,180 and 1,280 years respectively.

Initial soil moisture storage is prescribed to 100 % of field capacity. The sensitivity of this prescription was tested and a least squares regression fitted, Fig. 8.

Discussion

The proposed Swedish design spring flood proves to yield water levels of about half a metre above the extreme historic flood marks. If such a climatic and hydrologic situation would occur it would give rise to an increase of the lake Siljan water level, disregarding the effects of regulation, of about 6 m. In a normal year the spring flood would lift the lake about 2 m. Today much of the hydropower potential has been utilized and several dams have been constructed, *eg.* the Trängslet dam. These reservoirs would probably store part of the flood and damp out the flood peak and thereby reduce the lifting of the lake Siljan.

The design spring flood is computed by repeated simulations of different snowmelt scenarios where the design precipitation sequence is tried at alternative dates until the most critical combination is found. At Siljan this combination was in general when the precipitation sequence was placed just at the end of the melting period. Melt water had then raised the lake and together with the precipitation during the most critical days, an extreme combination was generated. Maximum 24-hour effective precipitation for the design spring flood was 65.3 mm where 2.8 mm was contribution from snowmelt.

At snowpack return periods exceeding about 50 years the snowmelt contribution had a more important role and the design combination was often during the most intensive snowmelt.

The proposed design autumn flood was not able to lift lake Siljan to the extreme levels of the historic flood marks. These marks are made however, at spring floods and therefore not directly comparable with autumn conditions. The autumn flood was generated by the 14-day design precipitation sequence with a maximum 24-hour value of 93.3 mm.

In autumn the choice of initial water level was crucial for the calculation. At spring there is a payoff between snowpack and water stage but at autumn the water level is a result of summer and early autumn rains. For comparison the autumn simulation was made starting at the highest recorded autumn water level (163.03 m.a.sl. 1985). This simulation gave the results 165.31 or 165.41 m.a.sl., the latter using the slope conveyance extrapolation, which is about one metre above the design level.

It is surprising that the design spring flood water stage only exceeded the highest observed level in the past threehundred and thirty years by half a metre. Consequently the return periods of the design floods were much lower than expected. The return period for both the spring and the autumn design flood was estimated to about 1,000 years opposed to beyond 10,000 years, concluded by Bergström *et.al.* (1989). This could possibly depend on that their analysis mainly concerned streamflow, while this study dealt with water levels of a lake with a large damping effect on inflow, and a long hydrological memory.

However, the frequency analysis was very sensitive to choice of correct frequency distribution and data type and did not give confident estimates of floods of such low probability as the spillway design floods. Return period differences between frequency distributions was in the order of ten to threehundered times. The second largest source of uncertainly was whether the historical floods were incorporated or not. When the historic floods were utilized, the return periods dropped about ten times. Since it is always questionable how high such floods were and if there has been any change to the outlet of the lake Siljan over time, one has to be careful to rely heavily on these old recordings. Uncertainty in modelling the outflow from lake Siljan had the least influence on return period estimation. This uncertainty was in the order of two times, on the design flood return period.

To tackle the classical problem of estimating the return period of design floods, in the new context where the floods are created by PMF type of methods, proves to be an extremely difficult task. Often, extrapolation to roughly hundered times the record length has to be done. One has certainly to bring additional information to the analysis to enable this.

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