Nationwide hydrological statistics for Sweden with high resolution using the hydrological model S-HYPE

Marie Bergstrand, Sara-Sofia Asp and Göran Lindström

ABSTRACT

A first version of nationally covering hydrological statistics for Sweden based on the S-HYPE hydrological model for the period 1961–2010 is described. A key feature of the proposed method is that observed data are used as input wherever such data are available, and the model is used for interpolation in between stations. Short observation records are automatically extended by the use of the model. High flow statistics typically differed by about ±10% from observations. The corresponding number for low flow was about ±30%. High flow peaks were usually simulated slightly too low whereas low flows were too high. In a relative sense low flows were more uncertain than high flows. The mean flow was relatively certain. The annual maximum values were fitted to a Gumbel distribution, by the method of moments, for each subbasin. Flood statistics were then calculated up to a return period of 50 years. According to a Kolmogorov–Smirnov test, less than 1% of the fitted distributions were rejected. Most rejections occurred in regulated systems, due to difficulties in simulating regulation strategies, but also due to uncertainties in the precipitation input in the mountainous region. Results at small scale are very uncertain. The proposed method is a cost-effective way of calculating hydrological statistics with high spatial resolution.

Key words | hydrological model, hydrological statistics, S-HYPE, Sweden

Marie Bergstrand (corresponding author)
Sara-Sofia Asp
Göran Lindström
Swedish Meteorological and Hydrological Institute,
S-60176 Norrköping,
Sweden
E-mail: *marie.bergstrand@smhi.se*

BACKGROUND

At the Swedish Meteorological and Hydrological Institute (SMHI) water discharge statistics, valid for the 20th century climate, have been calculated for around 3000 points in Sweden, based on observations. These statistics have been manually calculated and corrected/interpolated by subjective methods. It is therefore almost impossible, in an efficient way, to update them with data after the year 1999. However, water discharge statistics are requested within many different applications such as for warnings and forecast, dimensions, public services, climatic research, for environmental follow ups and from the water authorities. Due to the work with the European Water Framework Directive (WFD), the Swedish authorities also demand high resolution information.

To achieve the aim of flexible high resolution statistics, a hydrological model is needed. At SMHI there are two main hydrological models in use, the HBV model and the S-HYPE model. Traditionally SMHI has for many general applications used the HBV model. The S-HYPE model was chosen here since it uses more landscape information, such as soil and land-use type, and efficiently provides results with the high spatial resolution that was required. Design floods for dam safety in Sweden are calculated by flood frequency analysis of recorded discharge data (100-year return period) for low risk dams (Bergström *et al.* 1992; Svenska Kraftnät *et al.* 2007). For more important dams, hydrological simulation of design storm sequences using a hydrological model is carried out.

The aim of the present study was to develop an efficient method to calculate hydrological statistical parameters from a combination of observations and modelled discharge for the whole of Sweden with high resolution. It is also desirable that the new statistics are easy to update and can be calculated for any given time period.

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METHODOLOGY AND DATA

The hydrological model S-HYPE is a high-resolution set-up of the HYPE model code for all of Sweden. Model results from the S-HYPE model are made available for users at http://vattenwebb.smhi.se/. HYPE (**Hy**drological **P**redictions for the **E**nvironment) is a hydrological and water quality model code. It was originally developed by Lindström *et al.* (2010), but it is continuously being further developed. Some of the characteristics of HYPE that are of largest relevance for this study are as follows:

- It is intended for large applications with high spatial resolution.
- The landscape is divided into subbasins, and further into combinations of soil and land-use.
- Parameters are linked to soil type or land-use, but deviations in key parameters can also be specified for parameter regions.
- The hydrological conditions are modelled separately for soils (with up to three soil layers), rivers and lakes (including regulated lakes).

The first S-HYPE application was set up by Strömqvist *et al.* (2012). The present study was based on a slightly newer version of S-HYPE, version 1_0_2, with 37,786 subbasins and the HYPE model code version 3_5_3.

S-HYPE was used to calculate water discharge for the whole of Sweden with high spatial resolution. The catchments in the model are based on the Swedish water archive version SVAR2010 (SMHI 2011). Input data to the model such as precipitation and temperature have been taken from the Precipitation and Temperature for the hydrological model HBV (PTHBV) database (Johansson 2002). The PTHBV database contains 4 kilometre grid based precipitation and temperature data which have been developed using optimization interpolation. Data from 1961 onwards can be found in this database. The parameters in the S-HYPE model were calibrated for the period 1999–2008. The regulation routine in the model is based on storage volumes, and typical patterns of water use, for each main reservoir or system or reservoirs.

In the S-HYPE version used in this study, the runoff was updated with observation data where and when they were available. The result from a catchment area can therefore be only modelled data, only measured data or a mixture of measured and modelled data. In the normal quality control at the SMHI, data are corrected for ice problems and other data problems. The model results are almost always improved by the updated runoff data.

In this study, the following statistical parameters were calculated for 37,786 catchment areas:

- mean annual low discharge (MLQ)
- mean discharge (MQ)
- mean annual high discharge (MHQ)
- discharge with return period of 50 years (HQ50).

Also decadal variation was calculated by comparing the differences for each decade with a long term value (1961–2010). The mean annual high discharge (MHQ) was calculated as the average of every year's highest daily flow. Frequency analysis was used for calculating extreme values and was based on each year's maximum value. Lindström (1993) evaluated several extreme value distributions and parameter estimation methods, and found that distributions with three parameter distributions did not perform better than those with two parameters, in independent time periods. The Gumbel distribution (Extreme Value Type I) and parameter estimation by method of moments was found to give at least as good results as other commonly used distributions and estimation methods. Similar results were reported by Gottschalk (1983). Due to its simplicity, the Gumbel distribution estimated by the method of moments was therefore chosen for the present study.

The magnitude of a hydrological event (x_T) for a return period (T) is calculated by using frequency factors (K_T), Equation (1) and Equation (2) (Chow *et al.* 1988):

$$x_T = \bar{x} + K_T s \tag{1}$$

$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + \ln\left[\ln\left(\frac{T}{T-1}\right)\right]\right\} \tag{2}$$

where s = standard deviation, $\bar{x}$ = mean value of sample, T = chosen return period.

The goodness of fit between the model and observations was estimated by calculating the Nash–Sutcliffe Efficiency (*NSE*), the relative bias and the relative mean error. These measures were calculated for daily discharge data, annual minima and annual maxima.

$$NSE = 1 - \frac{E[c - o]^2}{E[\bar{o} - o]^2} \tag{3}$$

$$bias = \frac{\bar{c} - \bar{o}}{\bar{o}} \tag{4}$$

$$|bias| = \frac{|\bar{c} - \bar{o}|}{\bar{o}} \tag{5}$$

where $NSE =$ the Nash–Sutcliffe Efficiency, $c =$ computed values, $o =$ observed values, $E[\,] =$ the average.

The bias is given as a relative value.

To check how well the modelled annual maximum results fit to the Gumbel distribution the Kolmogorov–Smirnov test (KS) was applied (Yevjevich 1972) for the period 1961–2010. The mean ($\bar{x}$) and the standard deviation (s) were used for estimation of the Gumbel parameters (u and α), from which the fitted theoretical cumulative distribution function (*Fd*) could be estimated. The theoretical distribution is then compared to the sample cumulative distribution, in which the data are sorted in increasing order of magnitude (*Fs*):

$$Fd_i = \exp\left(-\exp\left(-\frac{(Q_i - u)}{\alpha}\right)\right) \tag{6}$$

$$\alpha = \frac{\sqrt{6}s}{\pi} \tag{7}$$

$$u = \bar{x} - 0.5772\alpha \tag{8}$$

$$Fs_i = \frac{i}{n+1} \tag{9}$$

$$KS = \max|Fd_i - Fd_i| \tag{10}$$

One *KS* value per subbasin was calculated as the largest absolute difference in frequency, *F*, along the discharge range (Equation (10)). $KS = 0$ corresponds to a perfect fit in frequency, whereas $KS = 1$ is the upper possible limit, implying no fit at all. Based on recommendations by Yevjevich (1972), *KS* values > 0.2 were considered as a poor fit and values ≤ 0.2 as accepted. The critical value of 0.2 is not an exact significance level, but rather an approximate indication of fitness. To further check the fitness, both $Fd(i)$ and $Fs(i)$ were plotted against $Q(i)$ and inspected visually for selected stations.

RESULTS

The median *NSE* during the calibration period 1999–2008 was 0.66 (401 stations) for the S-HYPE version used here (without updating). The corresponding numbers were 0.75 for the 200 unregulated basins and 0.44 for the 201 regulated basins. The agreement on a daily scale, as measured by NSE, is, as expected, lower in regulated basins. However, downstream of the reservoir the results are considerably improved since the model is updated wherever there are measured data available, as described above. This partly overcomes the problem with simulating the regulated discharge.

Table 1 summarizes the fitness between modelled and observed discharge data, for the full 50-year period used for the statistical analysis, but for only those stations that have complete data for the whole period. Out of these 50 years, 40 are thus independent. The median *NSE* on a daily scale is 78%, and the overall volume error is near zero (−1%). Typically volume errors were off by 4% in absolute numbers. The lower extremes, here represented by MLQ, were typically overestimated, with absolute deviations of some 30% as a median. The upper extremes were, on the other hand, slightly underestimated, with absolute deviations of typically 10%. For some regulated stations, the mean annual low discharge, MLQ, was zero according to the measurements. Relative deviations from this value cannot be calculated and these series were therefore excluded from the analysis.

The fitness of the modelled annual maximum results with the Gumbel distribution is shown in Figure 1. KS

Table 1 | Median fitness in the S-HYPE simulation, modelled versus observed data for 96 stations with complete data 1961–2010, updated at upstream stations.

Median:	Daily	MQ	MLQ	MHQ	HQ50
NSE	78%	–	–	–	–
bias	–	−1%	+12%	−5%	−4%
|bias|	–	4%	32%	10%	11%

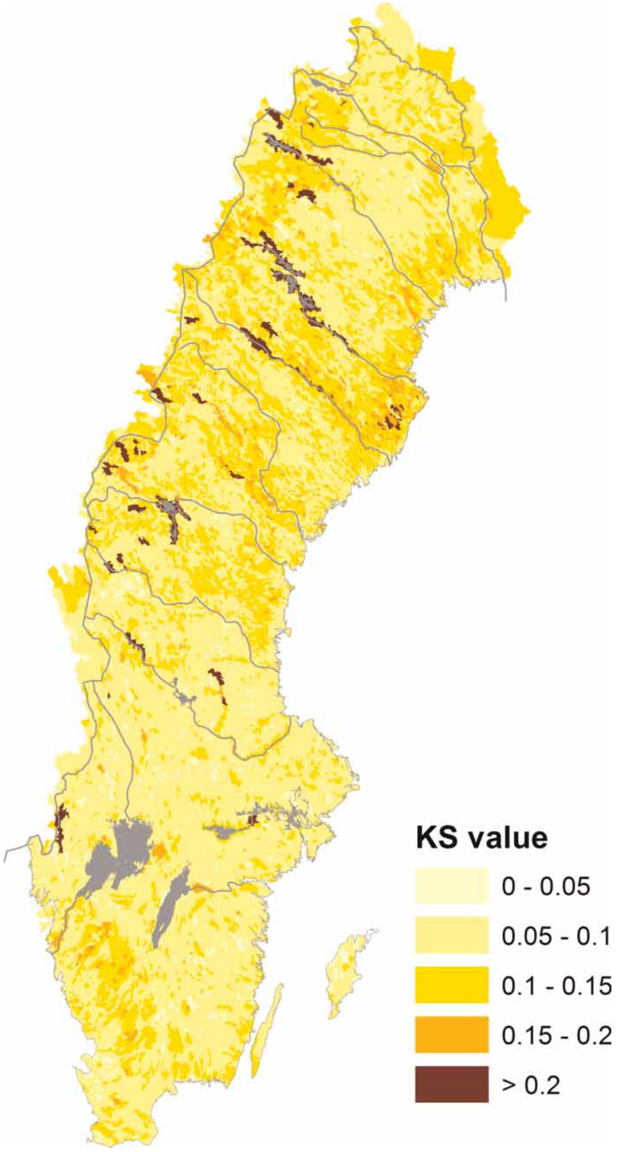


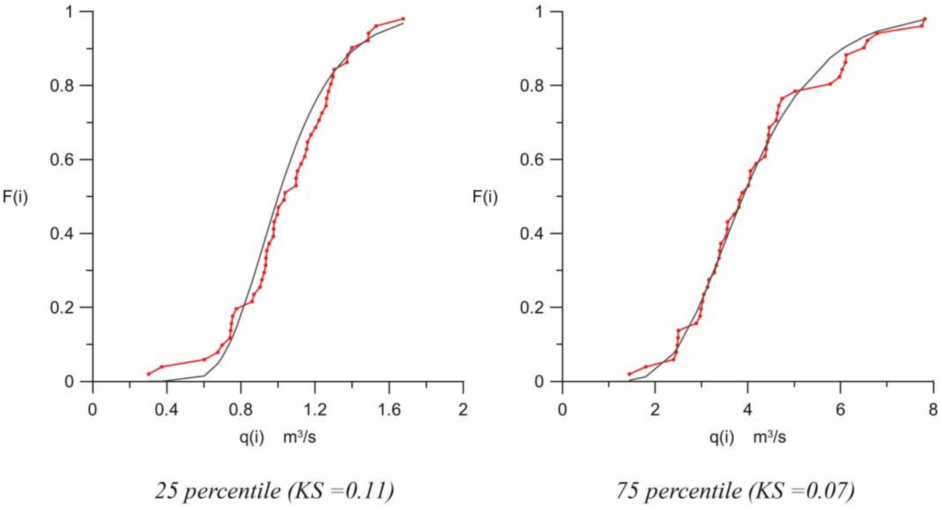
Figure 1 | Map showing KS (the Kolmogorov-Smirnov test) value for every catchment in the S-HYPE model, for the period 1961–2010. The KS test is a way to check how well the modelled annual maximum results fit the Gumbel distribution. KS > 0.2 indicates a poor fit with the Gumbel distribution.

results 0.2 or higher are considered as a poor fit. Around 240 catchments out of 37,786 (~0.6%) had a KS value equal or higher than 0.2, and were excluded from the following analyses. Most of the excluded catchments are affected by regulation. Compared to simulation of natural discharge, regulated systems are also affected by for instance short-term variations in energy demand, which are not included in the S-HYPE model. It was also noted, however, that uncertainties in the precipitation input was a considerable source of uncertainty in the simulation of the regulated systems. The timing of spill from full reservoirs depends on accurate precipitation input, which is difficult in the mountainous areas where many of the reservoirs are located. All outliers will be analysed further on, and the aim is that the results from these basins can be incorporated in the model in future versions.

Two examples of the fit from different catchments representing the 25th percentile fit and 75th percentile fit are shown (Figure 2). The 25th percentile figure shows that 25% of the modelled catchments have KS values 0.11 or higher. That is they have a poorer fit with the Gumbel distribution than the catchment shown. The 75th percentile, representing a better fit, shows that in 25% of the catchments the KS value was 0.07 or lower. In general, the model results fit well with the Gumbel distribution.

In Figure 3, the three statistical parameters MLQ, MQ and MHQ are shown. The spatial patterns are very similar between the three maps, with the rivers standing out as the most visible characteristic. In Figure 4, the statistical parameters have been normalized. The low flows are high in relation to the mean flow downstream of large lakes. It is, on the other hand, low in small, lake-free basins, basins with high fractions of thin soils, and in the mountain range with long winters. The high flow statistic HQ50 related to either MQ or MHQ is highest in the dry south-east, and in small basins in the northern inland. In the mountain range, differences between years are smaller, due to high precipitation and stable snow-melt induced floods. The south-west, with high rainfall, also regularly experiences floods, resulting in a low HQ50/MQ. The HQ50/MHQ ratio is a measure of the surprise effect. It is high in the dry south-east, and in regulated rivers, where the snow melt flood is usually stored in the reservoirs. The ratio HQ50/MHQ is low downstream of large lakes, where MLQ/MQ is low.

The difference in MQ between each decade and the long term value (1961–2010) is shown in Figure 5. According to the results, the 60 s and the 70 s were dryer than the long term value. The two following decades (the 80s and the 90s) were wetter than the long term value. The last decade, 2001–2010, is more in line with the average. This is in agreement with other results (e.g. Hellström & Lindström 2008). Catchments with removed results, due to high KS values, are shown as missing values in the figures below.



25 percentile (KS =0.11)

75 percentile (KS =0.07)

Figure 2 | Two selected catchments: 25th percentile KS fit and 75th percentile KS fit, representing a rather poor fit and a rather good fit. The KS value is the largest difference between the probabilities F(*i*) according to the theoretical, fitted, distribution and the observed sample, i.e. the largest vertical distance between the two curves.

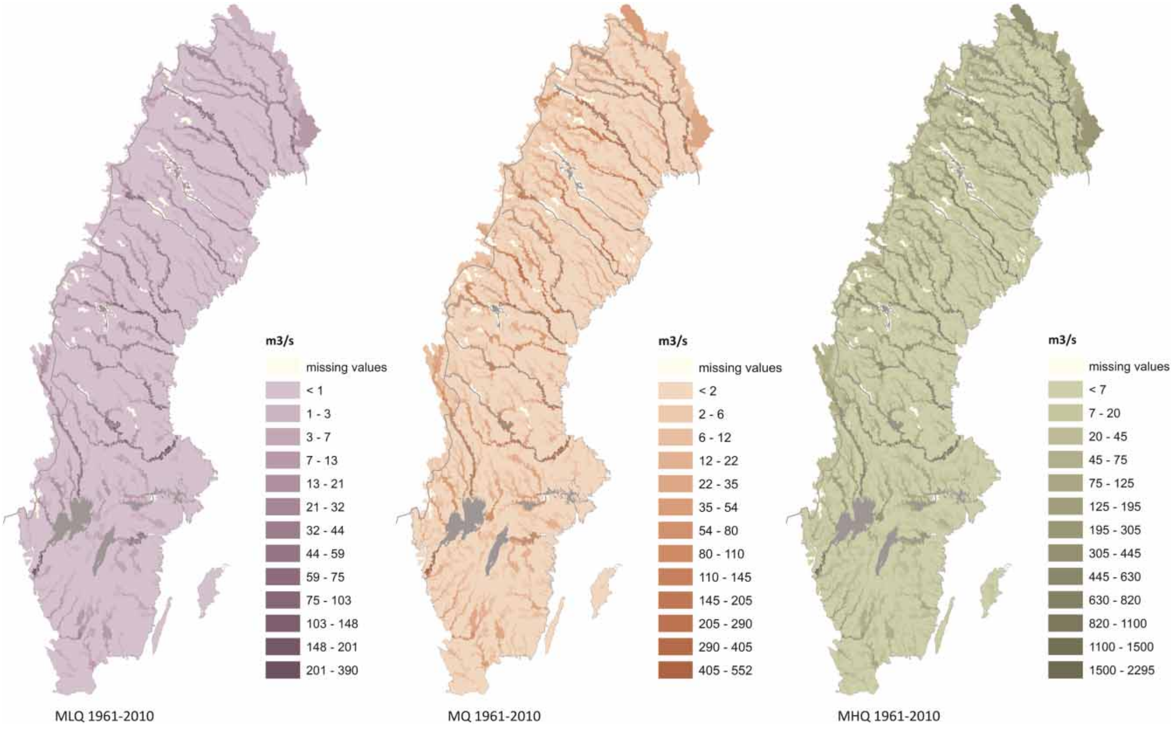


Figure 3 | Maps showing MLQ, MQ and MHQ for the period 1961–2010.

DISCUSSION

In this application the model was updated with observed data for as many stations, and for periods as long as possible. If a station became regulated sometime between 1961 and 2010, the observed water discharge series will be a mixture of unregulated and regulated data. These data therefore have limitations when calculating hydrological statistical

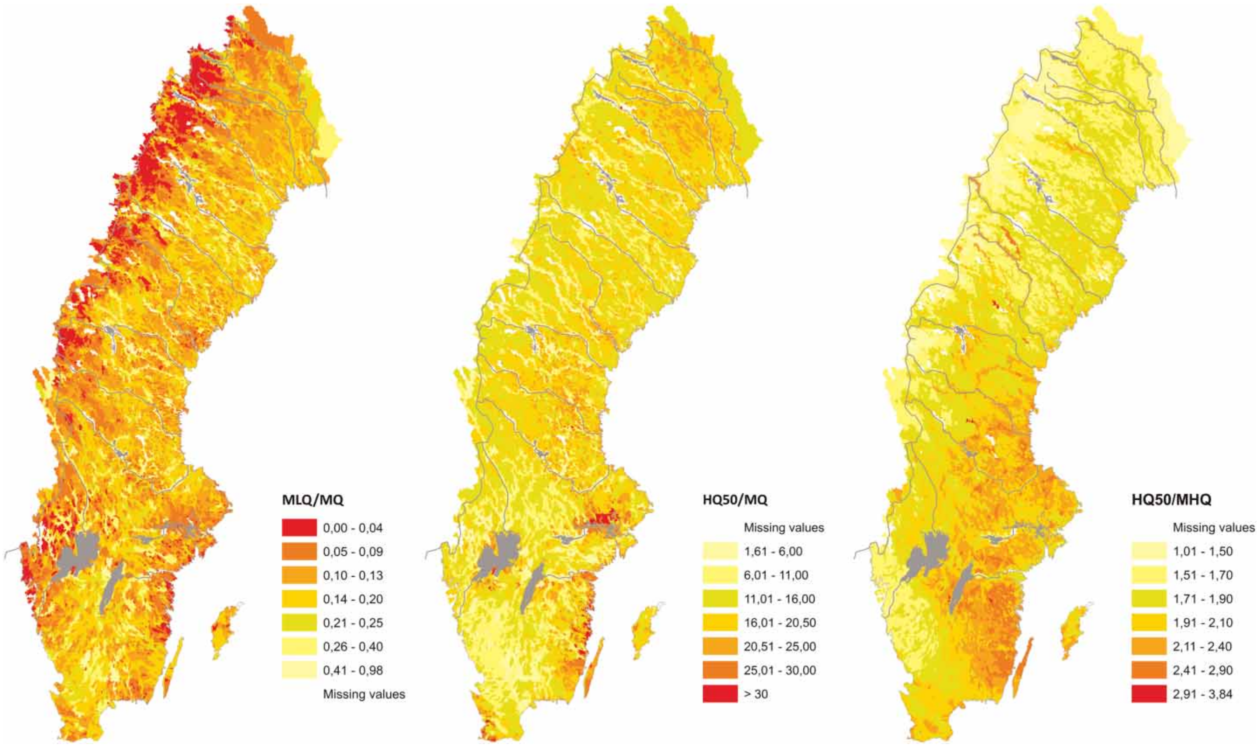


Figure 4 | Maps showing MLQ/MQ, HQ50/MQ and HQ50/MHQ, for the period 1961–2010.

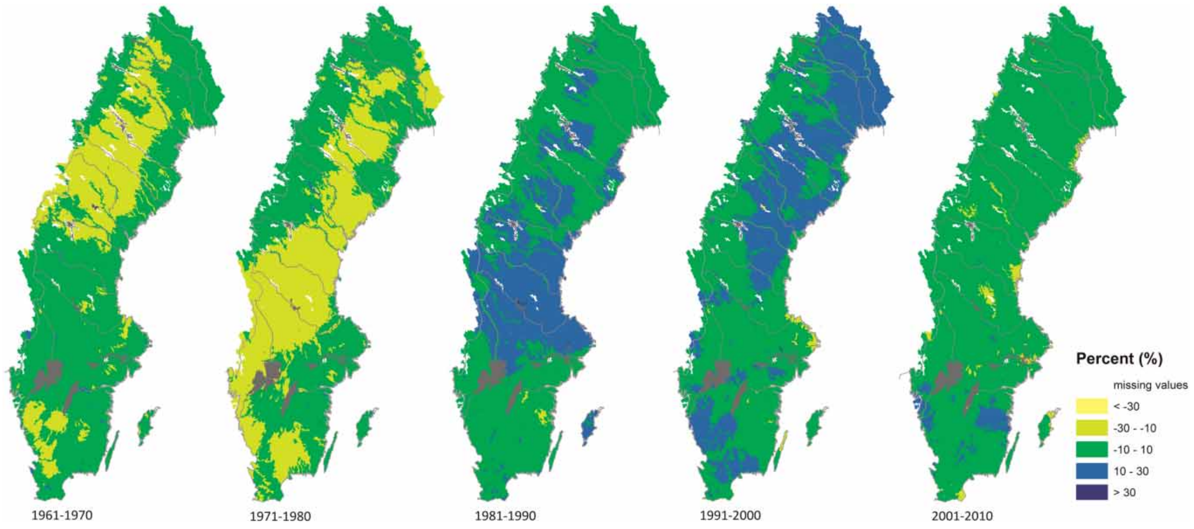


Figure 5 | Maps showing the difference between decades and the long term mean for period 1961–2010.

parameters, which are intended to describe the present conditions. In subsequent operational applications, only data from 1981–2010 are used, to avoid problems due to this mixing of unregulated and regulated conditions. Almost all of the hydropower development in Sweden, took place before 1980. Furthermore, observations that are marked as unreliable in the observational database, are excluded from the updating at measurement sites. Statistical results, obtained by using the suggested method, are presented at http://vattenwebb.smhi.se/.

The S-HYPE model also needs to be improved in the handling of bifurcations. Today only the large-scale bifurcations are included in the model. Therefore, the model results are suitable for applications in a general scale, and are not recommended for detailed studies. When used on a general scale, the importance of the regulation routines is diminished.

In this study statistics are calculated for the period 1961–2010, but the decades differ quite considerably. Depending on the used period, the same statistical parameter will therefore also differ. With the proposed method it is easy to update the statistics when new improved model versions are developed, and the choice of time period is very flexible. An advantage of using a hydrological model is that short observation records are automatically extended by the model. The model also provides a possibility for quality control of the observed data. Unrealistically high observed discharge peaks can be difficult to reveal by statistical methods alone, and they can drastically influence the calculated flood statistics.

The average size of model subbasins is approximately 12 km^2, but with large variation among the subbasins. The standard definition at the SMHI is that small subbasins have an area <200 km^2. The results for small catchments are uncertain and work is being done to quantify the uncertainty for the model results. This is an important and difficult question to answer. The results are more reliable in areas where the variation of discharge is small between years.

CONCLUSIONS

This paper describes a first version of nationally covering hydrological statistics for Sweden, based on a combination of observed discharge and a hydrological model. The results presented here should be seen as examples of work in progress rather than final results. A key feature of the method is that observed data are used as input wherever such data are available, and the model is used for interpolation in between stations. In the first version, there are minor problems that need to be improved upon in following versions of S-HYPE. Improvements need to be made in the handling of reservoirs, regulation, and bifurcations among other things.

It is easy to update the statistics when new improved model versions are developed, and the choice of time period is very flexible. Short observation records are automatically extended by the use of the hydrological model.

The following conclusions were drawn so far:

- The proposed method is a cost-effective way of calculating hydrological statistics for all of Sweden, with high spatial resolution.
- High flow statistics simulated with the S-HYPE model typically differed by about ±10% from observations. Corresponding numbers for low flow were about ±30%. High flow peaks were usually simulated slightly too low, whereas low flows were too high. In a relative sense, low flows are more uncertain than high flows. The mean flow is relatively certain.
- The modelled data usually fit well with the Gumbel distribution.
- The time period chosen for calculation of statistical parameters is important.
- Results at small scale are very uncertain. The statistics based on the S-HYPE model are so far intended for general use, and not for important detailed local design and planning.

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