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Flow modeling in Klarälven now and in the future

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1 Background

SMHI has been commissioned by the County Administrative Board in Värmland to carry out an analysis of how the flow in the Klarälven may be affected by a changing climate. This report was commissioned by the Värmland County Administrative Board in the project C5a (Cluster for Cloud to Coast Climate Change Adaptation) within the Interreg North Sea programme. Funded by the European Regional Development Fund and by the National Network of Authorities for Climate Adaptation.

Interreg
North Sea Region
C5a
European Regional Development Fund
EUROPEAN UNION

2 Purpose

Within the framework of the North Sea project, in-depth knowledge is needed about how common different types of flows will be in the future and what effects they may have on e.g. sediment transport and stakeholders along the Klarälven. One way to investigate this is to produce duration curves that show the frequency with which different types of flows can be expected to occur now and in the future. Two different emission scenarios have been used to simulate the flow to the middle and end of the century. The analysis is done for a point at Edeforsen where measured flow data is available.

3 Methodology

A flow analysis for current and future climate was carried out for the catchment area Edforsen in Klarälven. The analysis of different types of flows was based on the hydrological model HYPE which was run with current weather conditions as well as two different emission scenarios for future periods. The model-calculated flow was compared to the measured flow in Edforsen, where SMHI has set up a mirror.

3.1 Hydrological model and input data

HYPE is a hydrological model for integrated simulation of flows and turnover of water and nutrients (Ref 1). The catchment area is divided into classes depending on land use, soil type and elevation. The model's parameters are linked to this geographic information, which facilitates calculations in catchment areas without observations. The modeling is done with S-HYPE, which is a special set of the HYPE model adapted to Swedish conditions. The spatial division is the same as in the Swedish Water Archive (SVAR). HYPE simulates water flows and substances from precipitation through land and streams and lakes to the watercourse outlet (Figure 1).

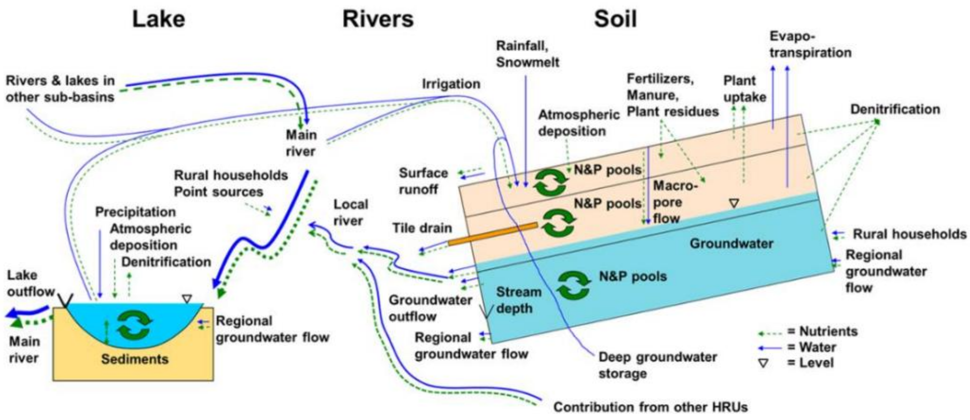

Figure 1. Schematic view of the HYPE model.

The driving data for the model are observed precipitation and temperature taken from SMHI's database with areally distributed temperature and precipitation (Ref 2, 3).

The S-HYPE sub-catchment area for Edforsen is shown in Figure 2, where the measuring station is marked at the outlet.

Figure 2. Map showing the Edforsen sub-catchment area as a purple polygon. The green triangle at the catchment area outlet shows the location of the measuring station.

The flow was simulated for three periods, see Table 1. For the periods "mid-century" and "end of the century" the model was run with two different emission scenarios, RCP 4.5 and RCP8.5 run with 9 different global climate models and downscaled with a regional climate model. RCP8.5 corresponds to a fossil-intensive future with high emissions of carbon dioxide and RCP 4.5 includes stringent climate policies such as strong emission reductions (Ref 4). For more information on climate models and emission scenarios see SMHI's knowledge bank (Ref 4). In this analysis, future results are shown as averages across the global climate models used.

Table 1. List of the three periods where the flow has been simulated.

	30-year period
Reference	1961-1990
Mid of the century	2040-2069
End of the century	2070-2099

With the concept of water flow or water flow is meant the amount of water per unit of time that flows into a watercourse and is usually stated as volume per unit of time [m3 /s]. The modeled flow in this analysis is defined as *natural,* since the variations of the flow during the year are influenced by natural conditions (snowmelt, rain, evaporation, etc.) and not by human intervention, e.g.
the regulation of watercourses for hydropower production. The reason for simulating natural flow even in a regulated watercourse like the Klarälven is due to the uncertainty of the regulation strategy in the future. This methodology thus allows a comparison of the effect of a changing climate on a model-calculated flow.

The simulated results are also compared against observed flows at the station (

Table 2, Ref 5).

Table 2. Observation source

Station name	Station number	Time series included in the analysis
Edforsen krv	1703	1961-01-01 – 1990-12-31

3.2 Statistical analyses

Calculated flow in different periods as well as observed flow were analyzed with different statistical tools.

3.2.1 Flow statistics

- MQ: average flow over a 30-year reference period
- MHQ: average of highest annual flow over 30-year reference period
- MLQ: mean of minimum annual flow over the 30-year reference period

In this analysis, flow statistics were calculated based on observed time series (Table 3).

Table 3. Flow statistics from time series in Edforsen station

	MHQ	MQ	MLQ
The flow [m3 /s]	452	126	38

3.2.2 Duration curve

A curve representing the duration of time when a flow equals or exceeds a certain flow during a certain period (Figure 3-8).

3.2.3 "Participate" methodology

In order to evaluate the effect of a changed climate on the flow in Edforsen, the so-called Delta method (Ref 6) has been used. With this method, future changes can be analyzed in a simple way by calculating flow variations due to different emission scenarios in a future period compared to a reference period.

The delta method means that the difference between future flow and simulated flow for the reference period is added to observations or modeled flow with current climate. Difference between simulation with climate model in the future and in the reference period was calculated (1), and then the difference was added to simulated flow with current climate (2).

ÿQ = Q(climate model in future period) - Q(climate model in reference period) *(1)*

QChanged = ÿQ + QSHYPE Reference Period *(2)*

Calculations were made separately for the two emission scenarios RCP4.5 and RCP8.5.

3.2.4 Histogram

A bar graph that describes the frequency of a particular range of flow over a particular period (Figure 13-15)

4 Results

The results have been calculated as daily average values for the three above-mentioned calculation periods. Model results have then been processed to present the data using the statistical tools described in section 3.2.

4.1 Duration curves

The measured flow at the Edforsen station was compared against simulated flow with S-HYPE for reference period **(Error! Cannot find reference source.).**

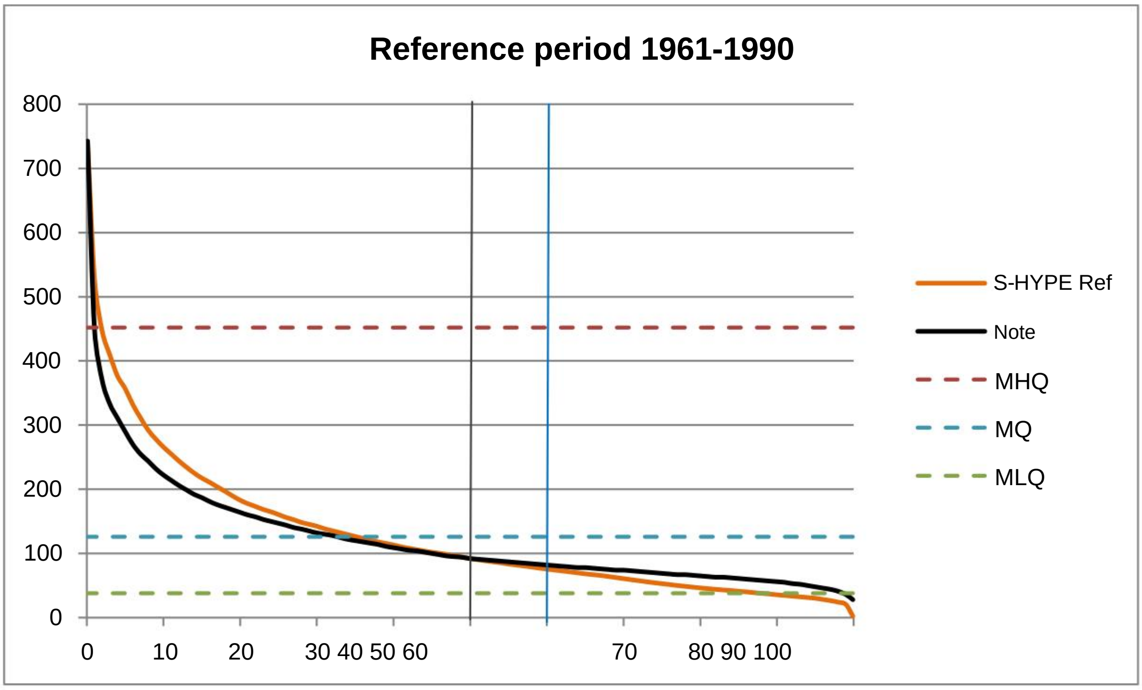

Figure 3. Duration curves for modeled water flow from the hydrological model (orange) and measured water flow in the station (black). Dashed lines show flow statistics that were calculated based on measurement series (section 3.2.1). All lines and curves apply to the calculation period 1961-1990.

Duration curves in **Error! Cannot find reference source.** shows a reflected flow dynamics between the two compared time series that causes the observed flow to occur less than 50% of the time (to left of the gray vertical line) is of less amount than that simulated by the hydrological model. The biggest difference between measured and simulated flow is around 50 m3 /s.

The amount of water flow that occurs over 60% of the time (to the right of the blue vertical line) is instead higher from measurement series than from model results. This means that the model simulates more low flows than those measured. Both time series show the same amount of extremely high flows around 750 m3 /s occurring less than 0.01% of the time.

A different distribution of flow during the time between model results and measurements can be interpreted as the difference between the natural flow simulated by the hydrological model and the actual flow that reflects regulation in the Klarälven.

Duration curves show that the impact of different emission scenarios is negligible when simulating the flow for the reference period using data from different climate models **(Error! Cannot find reference source.).**

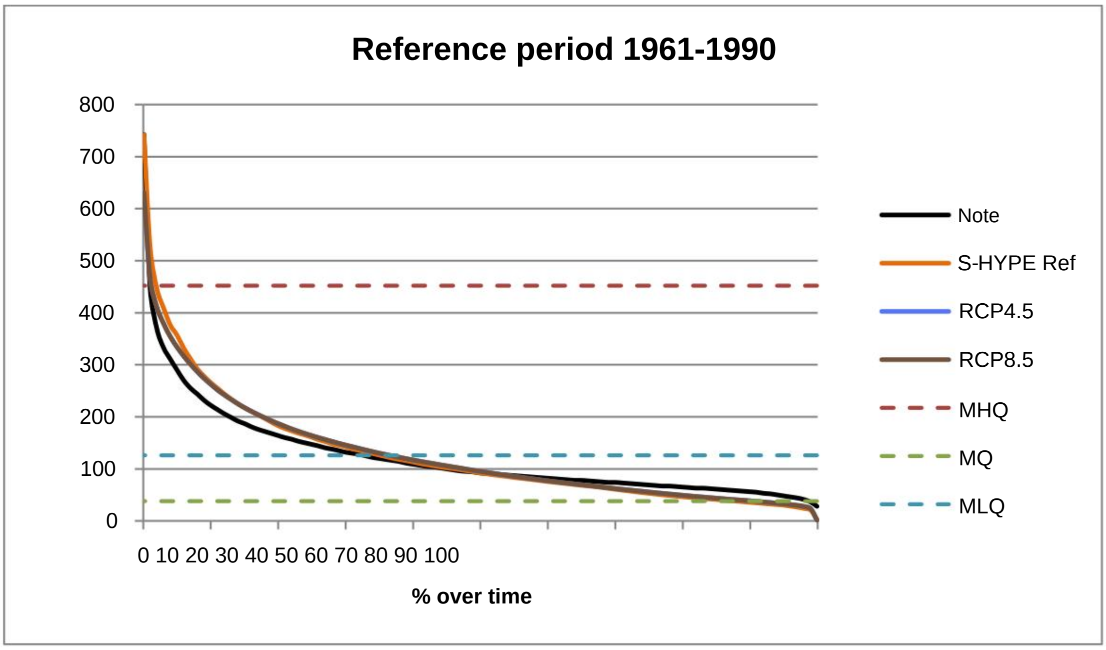

Figure 4. Duration curves for modeled water flow from hydrological model with current climate (orange), and climate scenarios with RCP4.5 (blue) and RCP8.5 (brown) and measured water flow at the station (black). Dashed lines show flow statistics calculated from measurement series (section 3.2.1). All lines and curves apply to the calculation period 1961-1990.

The flow duration simulated for both RCP4.5 and RCP8.5 for the reference period 1961–1990 is the same, and it follows quite similarly the duration curve calculated with S-HYPE for the reference period. The biggest difference is seen at the highest water flow, which differs by approx. 100m3 /s.

At mid-century, the difference between RCP4.5 and RCP8.5 is insignificant **(Error! Could not find reference source.).**

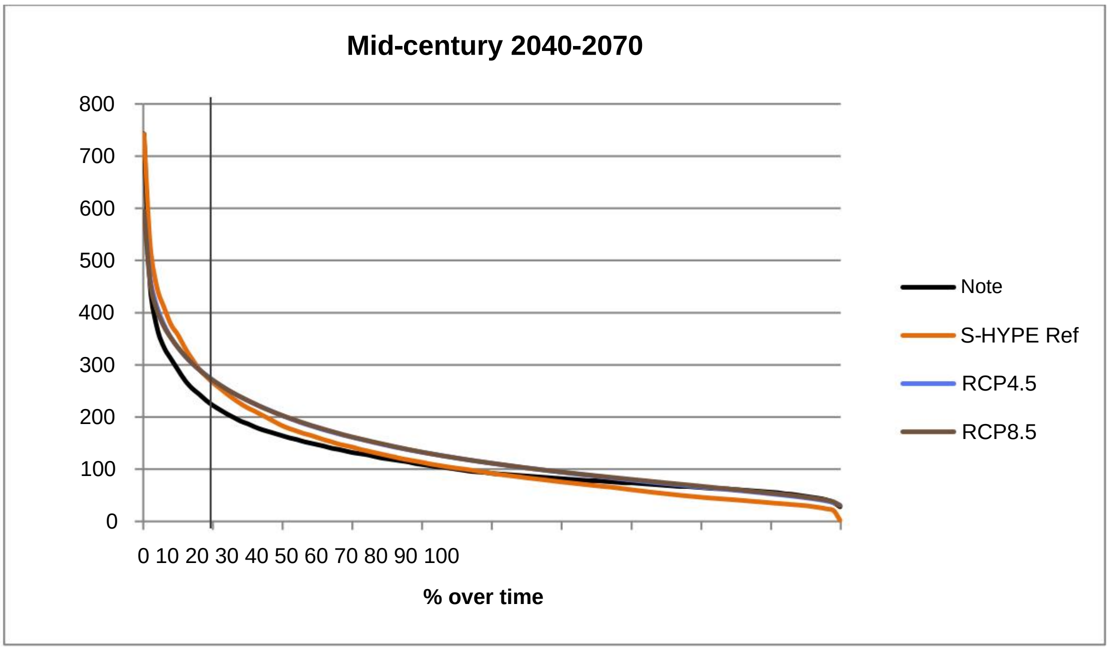

Figure 5. Duration curves for modeled water flow from hydrological model with climate scenarios RCP4.5 (blue) and RCP8.5 (brown) at mid-century (calculation period 2040-2070). These curves are compared with duration curves for the reference period 1961-1990 based on a hydrological model with current climate (orange), as well as measured water flow in the station (black).

However, flow duration with both emission scenarios differs from the dynamics in the reference period. The water flow simulated with a future climate scenario that occurs more than 10% of the time (to the right of the gray vertical line in Figure 5) is always greater than the simulated water flow during the reference period. The highest difference is 20 m3 /s. The diagram in Figure 5 also shows that simulated flow with climate scenarios is greater than measured water flow on average over time. The exception is peak flow which is expected to be less than those with the current climate. Maximum discharge with mid-century climate scenarios is less than that observed or simulated during the reference period of about 150 m3 /s. In addition, low flows in the future will occur with the same duration as those observed now in a regulated regime in Edforsen.

Simulation with climate models until the end of the century (calculation period 2070–2100) is shown in **Error! Can't find reference source..**

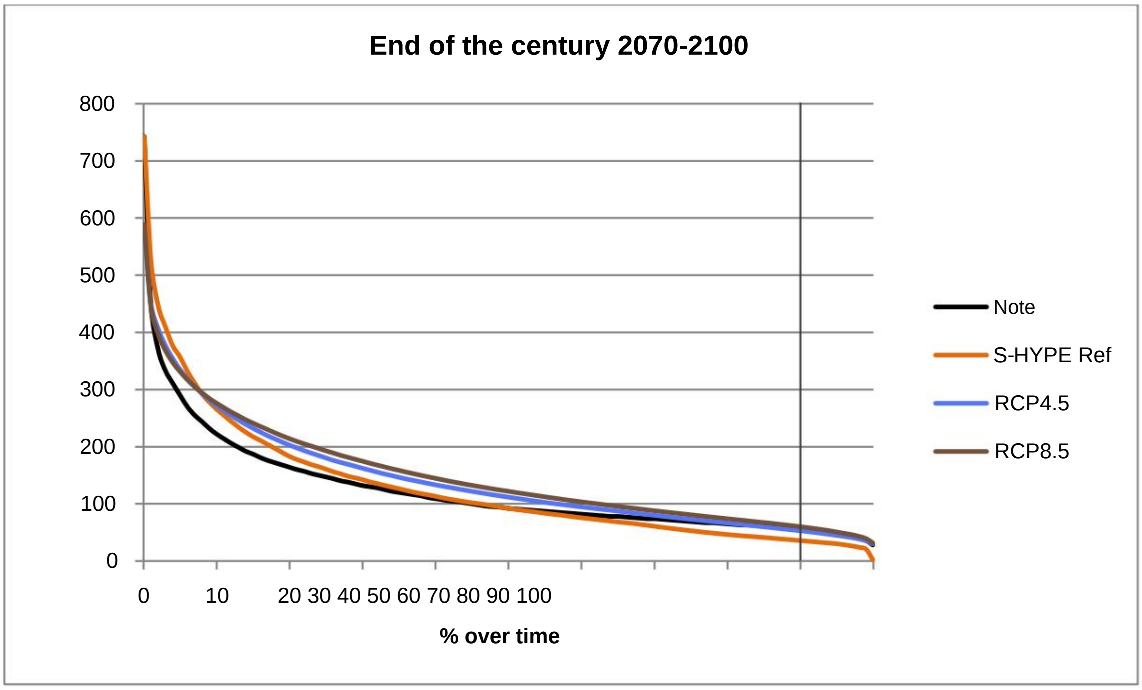

Figure 6. Duration curves for modeled water flow from hydrological model with climate scenarios RCP4.5 (blue) and RCP8.5 (brown) at the end of the century (calculation period 2070-2100). These curves are compared with duration curves for the reference period 1961-1990 based on a hydrological model with current climate (orange), as well as measured water flow in the station (black).

Both RCP4.5 and RCP8.5 have the same dynamics but for 90% of the entire period the flux with RCP4.5 is smaller than that with RCP8.5 (to the left of the gray vertical line). However, the maximum deviation is about 4m3 /s, which makes the difference between climate model results negligible also in this calculation period.
The maximum water discharge is still in the size of 600 m3 /s, the same as in model results until the middle of the century.

Duration curves have also been grouped according to climate scenario, see Figure 7 and Figure 8. In this case, the diagram shows modeled flow in the middle and at the end of the century compared to observed and simulated flow in the reference period.

Figure 7 shows modeled flow according to RCP4.5 in the middle and end of the century compared to observed and simulated flow in the reference period. The diagram shows that climate scenario RCP4.5 leads to the same simulated flow in both the middle and the end of the century. Peak flows in the future will be around 150 m3/s less than peak flows occurring in the reference period. On average over time, however, the amount of flow will be greater than normal. Measured flow in the reference period and simulated flow according to release scenario RCP4.5 have the same amount to flows that occur more than 70% over time (to the right of the gray vertical line).

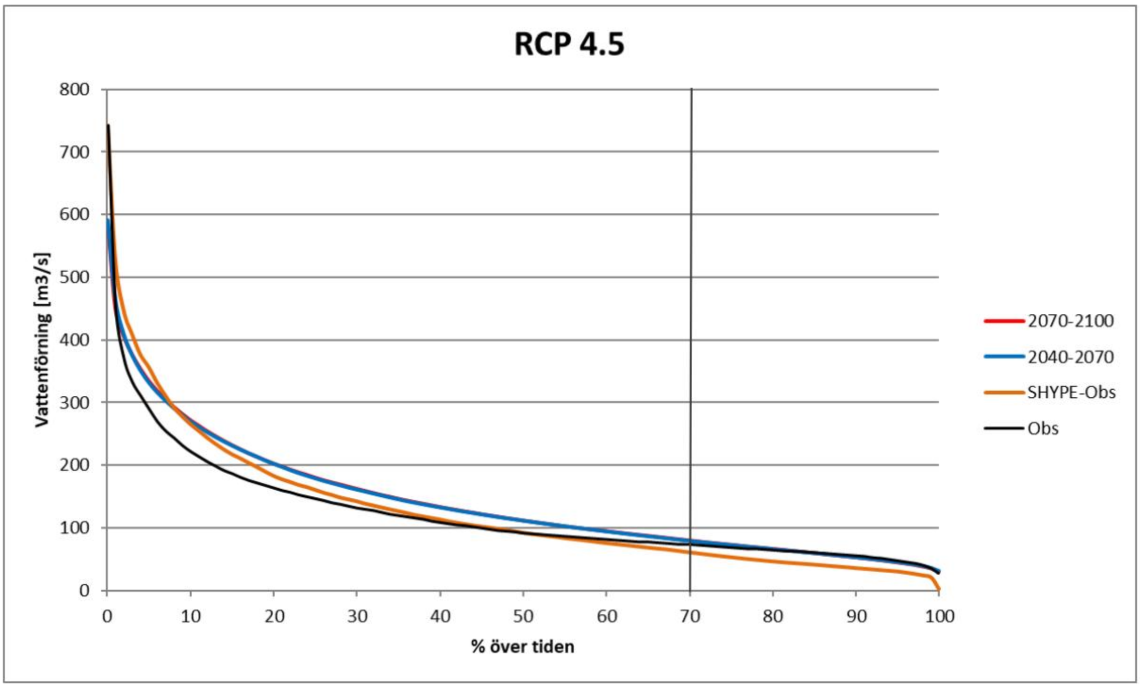

Figure 7. Duration curves for modeled water flow from the hydrological model with climate scenarios RCP4.5 in the middle of the century (blue line) and the end of the century (red line). These curves are compared with duration curves for the reference period 1961-1990 based on a hydrological model with current climate (orange), as well as measured water flow in the station (black).

Emissions scenario RCP8.5 affects modeled flux to the middle or end of the century, as seen in Figure 9.

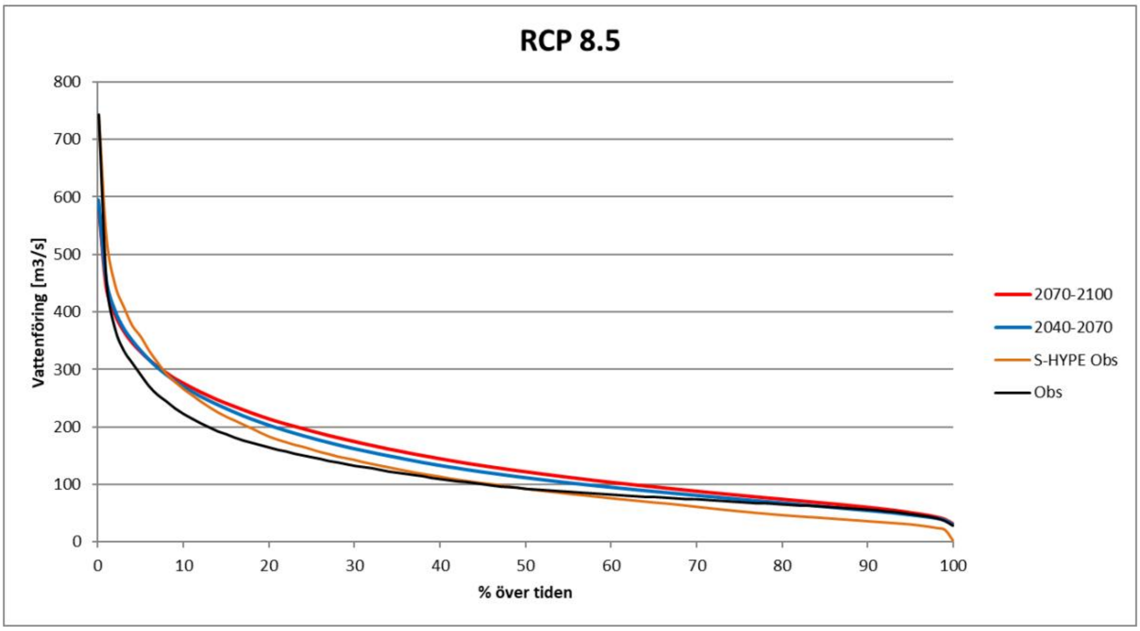

Figure 8. Duration curves for modeled water flow from the hydrological model with climate scenarios RCP4.5 in the middle of the century (blue line) and the end of the century (red line) . These curves are compared with duration curves for the reference period 1961-1990 based on a hydrological model with current climate (orange), as well as measured water flow in the station (black).

On average over the calculation period, simulated flow to the end of the century (red line in Figure 8) is greater than that simulated to the middle of the century (blue line) with a maximum deviation of 12 m3 /s. Except those highest flow where future water discharge is less than current water discharge, the amount of flow is always greater in the future compared to observations from the reference period. By the middle of the century, the flow will be on average 20 m3 /s greater than the measured flow in the reference period. Deviation will be in the size of 25 m3 /s until the end of the century.

4.2 The delta method

To estimate the effect of a changing climate on the flow at Edforsen, the delta method has been used. The method shows the impact of a changing climate on current flow by adding the flow difference in the future to simulated or observed flow for the reference period. In the first step is calculated the difference between simulated flow in a future period with climate scenario and reference period for same calculation period (30 years). Then the difference is added to simulated flow with a hydrological model driven by weather conditions from the current climate. The reason for applying the method to HYPE-simulated water flow instead of flow measurements is that the hydrological model simulates natural flow in Edforsen, while measurements reflect variations due to regulation in Klarälven.

Figure 9 and Figure 10 show duration curves from S-HYPE simulation for the reference period (with current climate) and curves for changed flow due to climate effects from scenario RCP4.5.

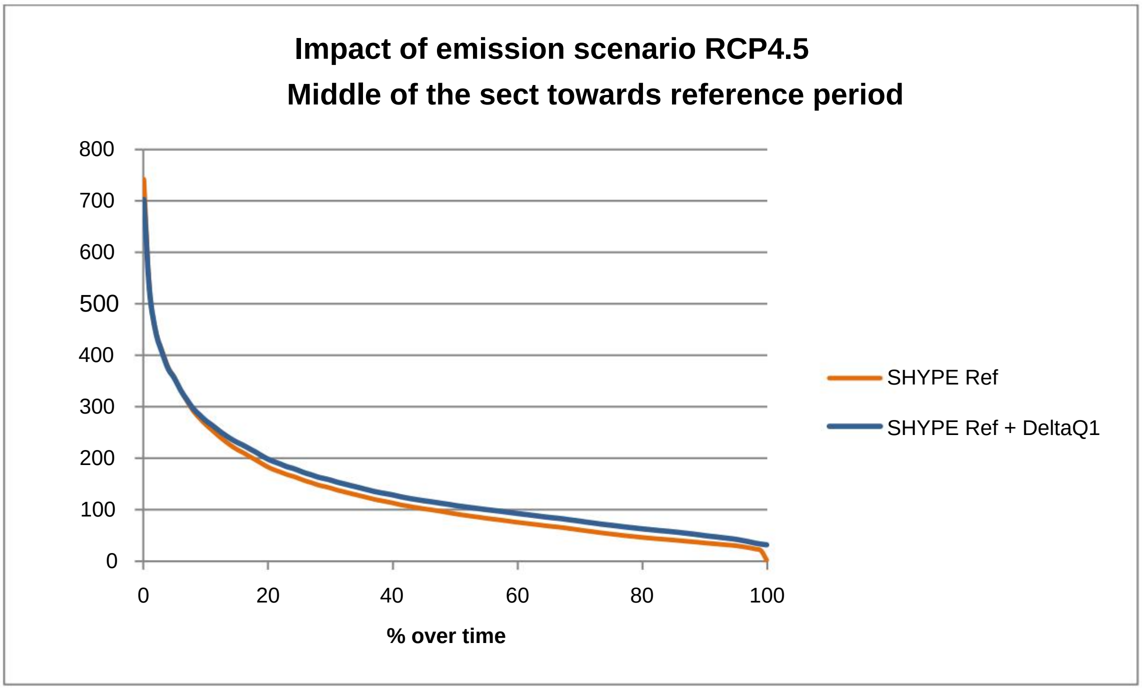

Figure 9. Duration curves for modeled water flow from the hydrological model for the reference period (orange) and calculated changed water flow using the delta method to mid-century with RCP4.5 (blue).

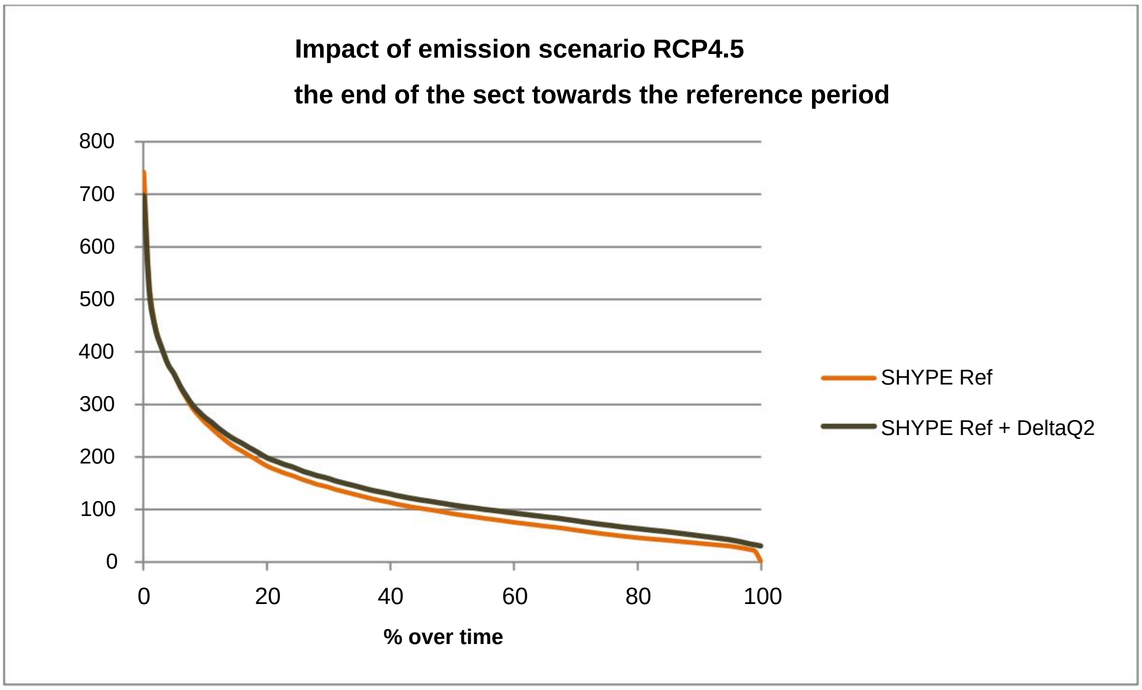

Figure 10. Duration curves for model runoff from the hydrological model for the reference period (orange) and calculated changed runoff with the delta method until the end of the century with RCP4.5 (brown).

The flow variation calculated in the middle of the century against the reference period (Figure 9 – blue line) has the same magnitude as that calculated at the end of the century against the reference period (Figure 10 – brown line). This result echoes the same conclusions from the **Error! Cannot find reference source.** and **Wrong! Cannot find reference source.,** where flow duration with climate scenario RCP4.5 gives the same flow results at mid-century and at the end of the century. The results from the delta method show a decrease of about 50 m3 /s of flow occurring less than 0.1% over time (extreme flow), while in 90% of the time the flow shows an increase of 15 m3 /s on average.

Figure 11 and Figure 12 present the results by calculating the delta based on results from climate scenario RCP8.5. The effect of a changing climate on the flux to mid-century with a fossil intensive scenario (RCP8.5) is similar to that given by the one that includes emission reduction (RCP4.5), with reduction of extreme fluxes. Duration curve shows that a flow on average 15m3 /s greater than that simulated in the reference period will have a greater frequency in the future due to a changed climate. (Figure 11). By the end of the century, the effect of scenario RCP8.5 is stronger compared to the flow in the reference period, where the flow occurring 90% of the time is on average 25m3 /s greater than the current flow (Figure 12).

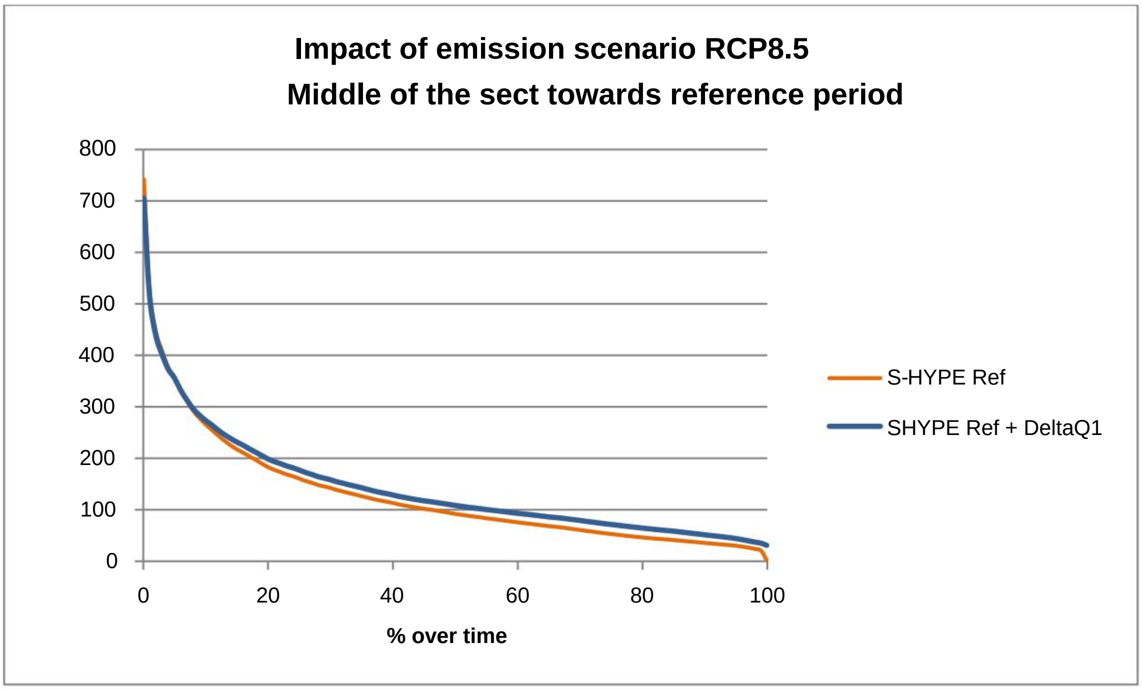

Figure 11. Duration curves for modeled water flow from hydrological model for reference period (orange) and calculated changed water flow using the delta method to mid-century with RCP8.5 (blue).

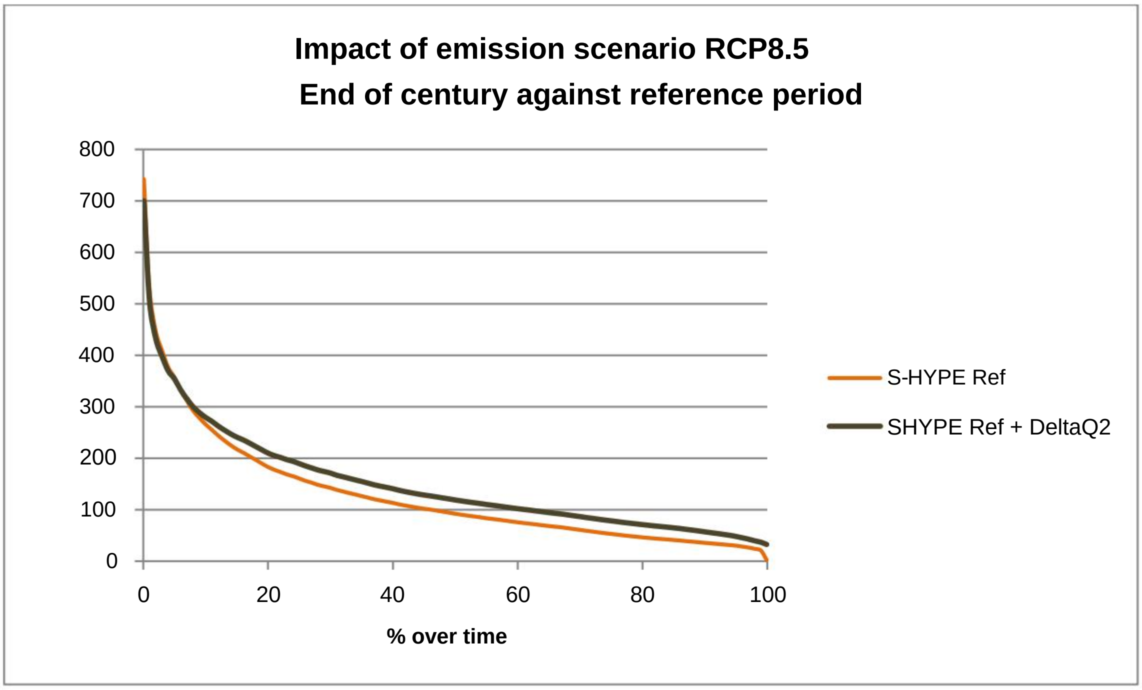

Figure 12. Duration curves for modeled water flow from the hydrological model for the reference period (orange) and calculated changed water flow using the delta method until the end of the century with RCP8.5 (brown).

4.3 Histogram

A histogram is another way of presenting results to describe how often a certain flow happens in a certain time period. In this analysis, the histogram is built describing the number of days in the calculation period (30 years ~ 11,000 total days) where a fixed flow interval occurs. Fixed flow range is visible in the x-axis and it is calculated on a logarithmic scale which gives a smoother distribution over the flow values. Histograms are shown in this section separately per calculation period, in the same way that duration curves were presented.

In the reference period, the flow distribution differs quite a lot between simulated and observed flow due to regulations in Edforsen (Figure 13).

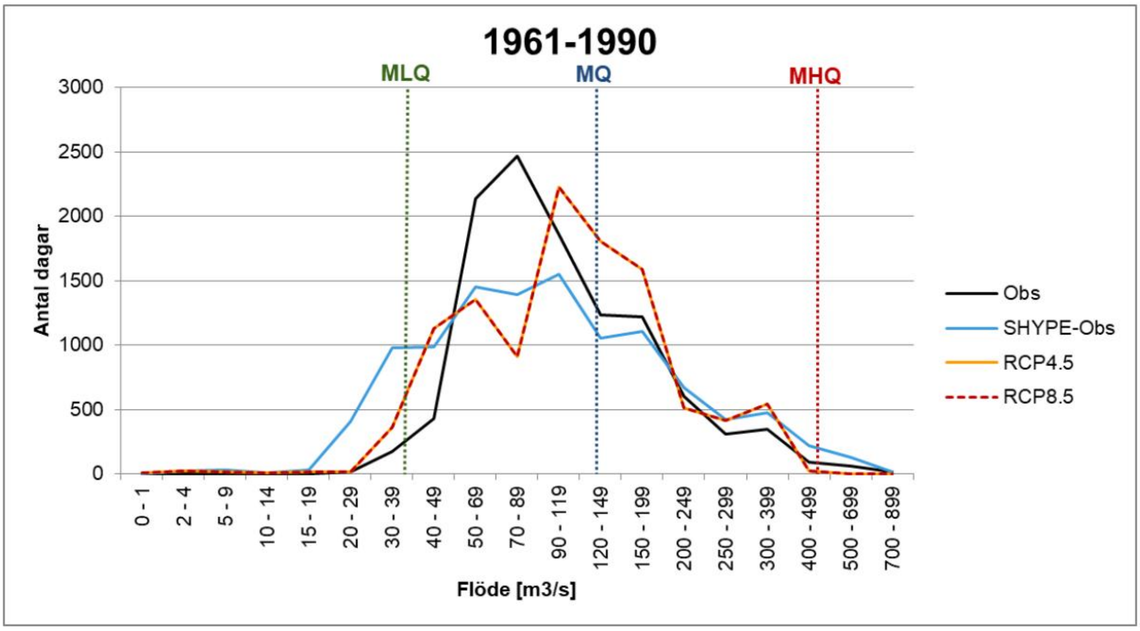

Figure 13. Histogram for measured flow (black), simulated flow with current climate (light blue) and climate scenarios RCP4.5 (orange) and RCP8.5 (dashed red) for the reference period.

Histogram based on measurements (black line in Figure 13) shows that the most common flow (that which has occurred the highest number of days during the calculation period) is within the range 50-90m3 /s where the curve has a very clear peak with 2200-2500 days where this type of flow occurs. The flow greater than mean high water (126m3 /s, MQ in the diagram) drops to 1200 days and goes to zero quickly for flow above mean high water (485m3 /s, MHQ in the diagram). The flow simulated by SHYPE has a more homogeneous distribution without large peaks. In this case, a 30m3 /s flow occurs almost 0.1% of the time (1000 days/30 years) while measurements show that this flow is more rare (about 250 days/30 years).
The same dynamics also show for high flows greater than the MHQ, where the frequency is almost double that which was calculated based on measurements. Simulated flow with RCP4.5 and RCP8.4 (orange and red dashed line in Figure 13 respectively) has the same distribution over time, which however differs quite a lot from measurements and modeled flow with current climate. For simulated discharge scenarios, the histograms show two peaks, a smaller one with flow range 40-70m3 /s occurring on average 1200 days in 30 years (~ 10% of the time), and a larger one at 90-120 m3 /s having a frequency in 20% of the time.

By the middle of the century (calculation period 2040–2070), the difference between modeled flow with the two different climate scenarios RCP4.5 and RCP8.5 is not significant (Figure **14Error! Could not find reference source.).**

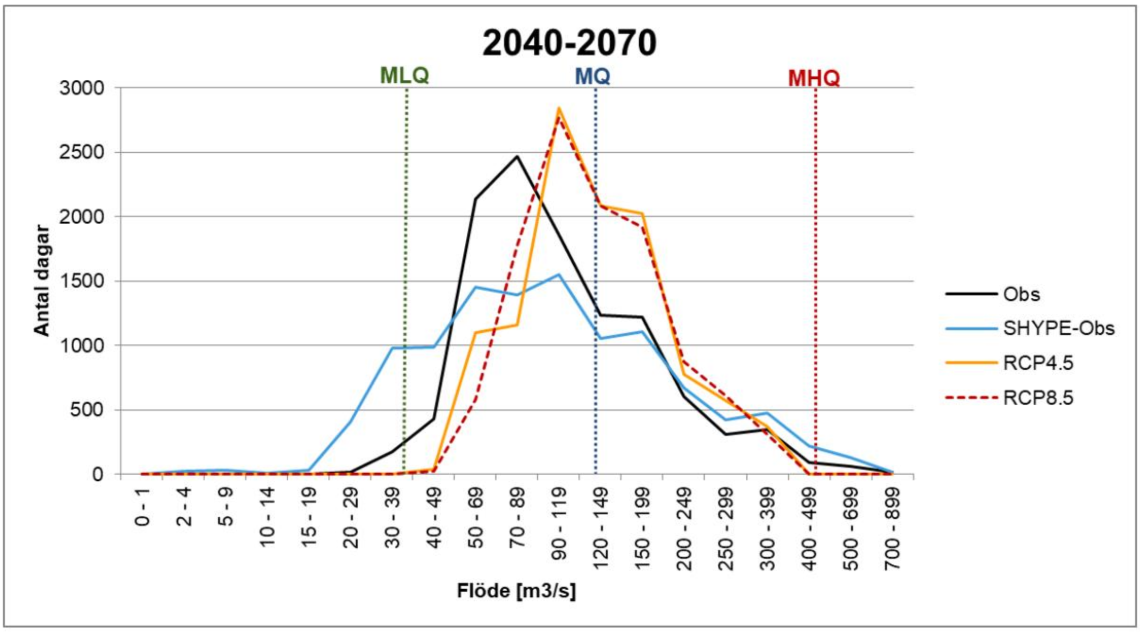

Figure 14. Histogram for simulated flow climate scenario RCP4.5 (orange) and RCP8.5 (dashed red) for the middle of the century (2040-2070). Measured flow (black) and simulated flow with current climate (light blue) are based on reference period (1961-1990).

Future flow modeled according to climate scenarios in the range of 90-120m3 /s will occur more than 25% over time (2800 days) compared to 1860 days (17% over time) with measured flow and 1540 days (14% of time) with simulated in reference period . Low flows up to 50m3 /s have a frequency of 50 days over the period (0.5% of the time), which corresponds to 5-10% number of days over the time from measured and simulated flow to the reference period. It can be interpreted as the flow to the middle of the century will not be as low as observed or simulated with the current climate. The same conclusion applies to water flow over 400 m3 /s, which will become more rare in the middle of the century.

The impact of different emission scenarios is stronger at the end of the century, where flow distribution during the calculation period changes with both climate scenarios compared to previous periods (Figure 15).

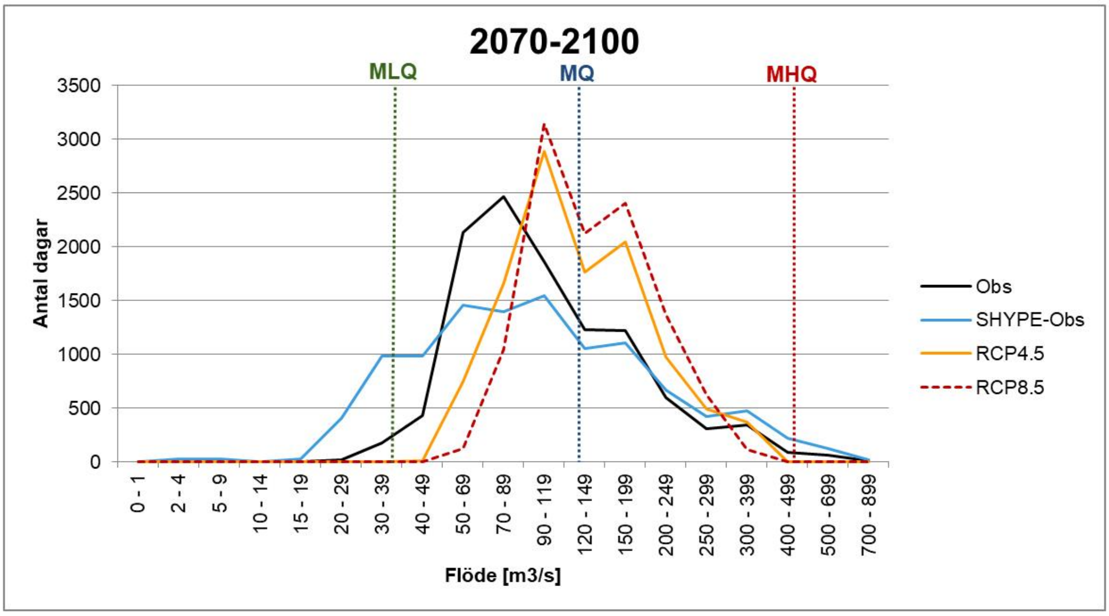

Figure 15 Histogram for simulated flow climate scenario RCP4.5 (orange) and RCP8.5 (dashed red) for the end of the century (2070-2100). Measured flow (black) and simulated flow with current climate (light blue) are based on reference period (1961-1990).

Both distributions with RCP4.5 and RCP8.5 now show two high peaks for flow ranges 90-120m3 /s and 150-200 m3 /s. The first interval occurs about 28% and 25% of the time for RCP8.5 and RCP4.5, respectively. The second watershed interval occurs 22% and 19% of the time for RCP8.5 and RCP4.5, respectively. The results show that higher flow will be more common in the future compared to the same flow amount during the reference period. Regarding low flows, results from RCP4.5 show a rapid increase in frequency from flows of size 40m3 / s, while the number of days with low flows in RCP8.5 is negligible up to water flow of 50-70m3 /s. Occurrence of flow over 300m3 /s also decreases according to results based on calculations with climate scenario RCP8.5 to around 1% compared to other calculation sources (measured and simulated flow with current climate) where the frequency is up to 4%.

The histograms have been compared with the results from the climate report "Future climate in Värmland County" carried out by SMHI in 2017 (Ref 7). The aim of the climate report was to simulate the meteorological and hydrological parameters with the impact of different climate scenarios in the future. Comparison between the hydrological results is not direct as some assumptions must be considered:

- Climate analysis of the hydrological parameters in Värmland county that was carried out in 2017 is based on results from the hydrological model HBV that was set up for the county. In this work, the Swedish version of HYPE has been used, but the model has not been locally adapted to the county or for Edsforsen.
- In the report on the future climate in Värmland county, inflow has been simulated instead of water flow. It can produce differences in results if you analyze a regulated watercourse.

Chapter 8 of the report from 2017 shows how average values for the annual inflow dynamics will change in the future due to a changed climate (Figure 16). The reference period in this study is 1963-1992 (black line in the figure) and the future period is 2069-2098. Calculations were made according to RCP4.5 and RCP8.5 climate scenarios (blue and red line respectively).

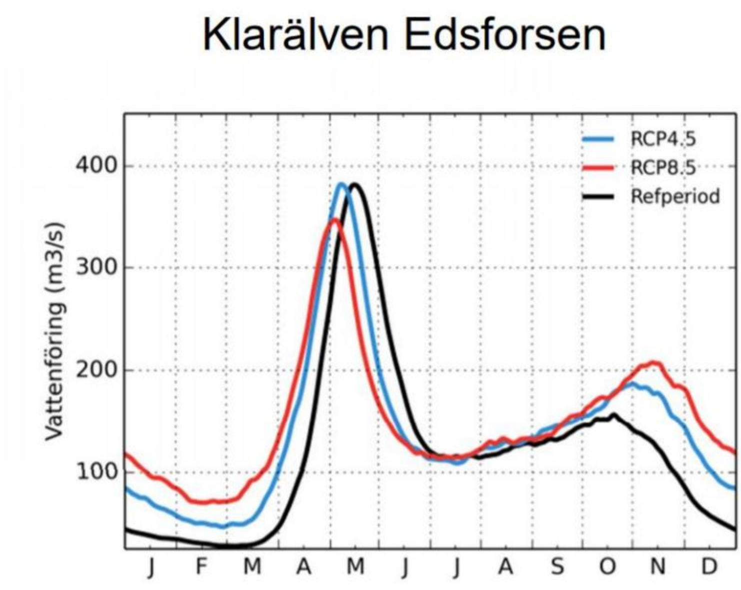

Figure 16. Annual dynamics of inflow in Edforsen. Black line represents the reference period 1963-1992 and the other two lines represent the future period 2069-2098. Blue line refers to mean values of calculations according to RCP4.5 and red line represents the equivalent for RCP8.5.

For Edforsen, the future scenarios in Figure 16 show earlier spring river peaks, higher winter and autumn flow, while the inflow during the summer is not affected.

During the winter months (January, February and March in Figure 16), the flow will be much greater than it was in the reference period according to both climate scenarios. A similar result can be seen in Figure 15, where the number of days with the flow less than 40 m3 /s is close to or equal to zero depending on the climate scenario. The increase in runoff in winters is explained by the Climate Report as precipitation generally increases in the county and that precipitation such as rain instead of snow will become increasingly common in a future warmer climate. Thus, the winter precipitation will run off during the winter instead of, as during cold winters, being stored as snow and forming runoff when the snow melts in the spring.

A changed seasonal dynamic during winter results in an earlier snowmelt time and less snow cover that accumulates during winter. It will cause earlier spring flow and also smaller spring flow peaks at the end of the century under RCP8.5. The same dynamics is also shown in Figure 15 in the form of number of days when certain flow intervals occur. With the assumption that flows above 300m3 /s correspond to the spring flood averaged over the calculation period, Figure 15 shows that there will be few or no days when the flow is above 300m3 /s at the end of the century with RCP8.5.

Autumn flow will also be higher than that of the reference period according to both climate scenarios (Figure 16). The overall increased inflow during the year corresponded to the pattern in Figure 15, which shows that larger flow intervals will become more common in the future for a 30-year period.

During the summer, the flow is not affected by climate scenarios (Figure 16). Higher temperatures will cause more water to evaporate or be used by the plants, and precipitation will also increase by 10% during the summer according to both RCP scenarios. An unchanged inflow in the future summer can be explained as the effect of increased evaporation and a longer vegetation period predicted in the future in connection with higher rainfall in the season.

5 Conclusions

- It is possible to model natural flow on a regulated watercourse with a hydrological model, but it is more difficult to compare results directly. It is preferred to simulate natural flow to the middle and end of the century because of the uncertainties of setting regulations in the watercourse 40–60 years into the future. Seasonal and annual water resource management as well as water supply in the future is unknown which would require several assumptions to be set up in the model.
- Climate analysis on hydrological indicators involves various sources of uncertainty that come partly from climate models, as well as from the hydrological model.
- During the winter months, larger flows than those in the reference period will become more common due to increased temperature, which means that precipitation will occur more in the form of rain than snow. This means that a greater amount of water runs off instead of being accumulated in the form of snow.
- Spring flow at the end of the century will occur earlier than for the reference period. According to RCP8.5, spring flow peaks will also be smaller than those observed in the reference period. Increased temperatures throughout the year cause early snowmelt times, while snow cover becomes less than normal.
- Summer flow will not be affected by climate scenarios due to a balanced effect on increased precipitation during the summer with a longer growing season and evaporation.
- Increased temperatures and precipitation affect the autumn flow, which will increase in the future.
- Effect of a strong emission reduction scenario (RCP4.5) means that the flow in the middle and at the end of the century will be on average 15m3 /s greater than the current flow 90% of the time.
- Effect of a fossil-intensive scenario (RCP8.5) causes the flow to be on average 15m3 /s greater than the current flow of 90% over time in the middle of the century. The end of the century sees an increase in the flow rate of 25m3 /s on 90% of the time.

6 References

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Content

1 Background

SMHI has been commissioned by the Värmland County Administrative Board to carry out an analysis of how the flow in the Klarälven may be affected by a changing climate. This report was commissioned by the Värmland County Administrative Board.

In the first part of the assignment, the Värmland County Administrative Board has requested an analysis of future flows at a point at Edforsen in Klarälven. The first part was part of the project C5a (Cluster for Cloud to Coast Climate Change Adaptation) within the program Interreg North Sea, financed by the European Regional Development Fund and by the national network of authorities for climate adaptation.
The distribution of different flow types to the middle and the end of the century was evaluated in Edforsen by using different statistical tools, including duration curves and histograms. Results from this analysis were presented on 10 November 2020 in the workshop "holistic perspective on climate adaptation in the Klarälv area".

The Värmland County Administrative Board has subsequently ordered a new assignment from SMHI to analyze future flows also at the outlet of Höljessjön and at Karlstad. In this report, the methodology and results from this analysis are presented.

2 Purpose

For effective climate adaptation work, in-depth knowledge is needed about how common different types of flows will be in the future and what effects they may have on e.g. sediment transport and stakeholders along the Klarälven. One way to investigate this is to produce duration curves that show the frequency with which different types of flows can be expected to occur now and in the future. Two different emission scenarios have been used to simulate the flow to the middle and end of the century.

3 Methodology

A flow analysis for current and future climate was carried out for two catchment areas in Klarälven, at the outlet of Höljessjön and at Karlstad. The analysis of different types of flows was based on the hydrological model S-HYPE which was run with historical precipitation and temperature and for two different emission scenarios for future periods. The model-calculated flow was compared against the measured flow
when data was available.

3.1 Hydrological model and input data

HYPE is a hydrological model for integrated simulation of flows and turnover of water and nutrients (Ref 1). The catchment area is divided into classes depending on land use, soil type and elevation. The model's parameters are linked to this geographic information, which facilitates calculations in catchment areas without observations. The modeling is done with S-HYPE, which is a special set of the HYPE model adapted to Swedish conditions. The spatial division is the same as in the Swedish Water Archive (SVAR). HYPE simulates water flows and substances from precipitation through land and streams and lakes to the watercourse outlet (Figure 1).

The driving data for the model are observed precipitation and temperature taken from SMHI's database with areally distributed temperature and precipitation (Ref 2, 3).

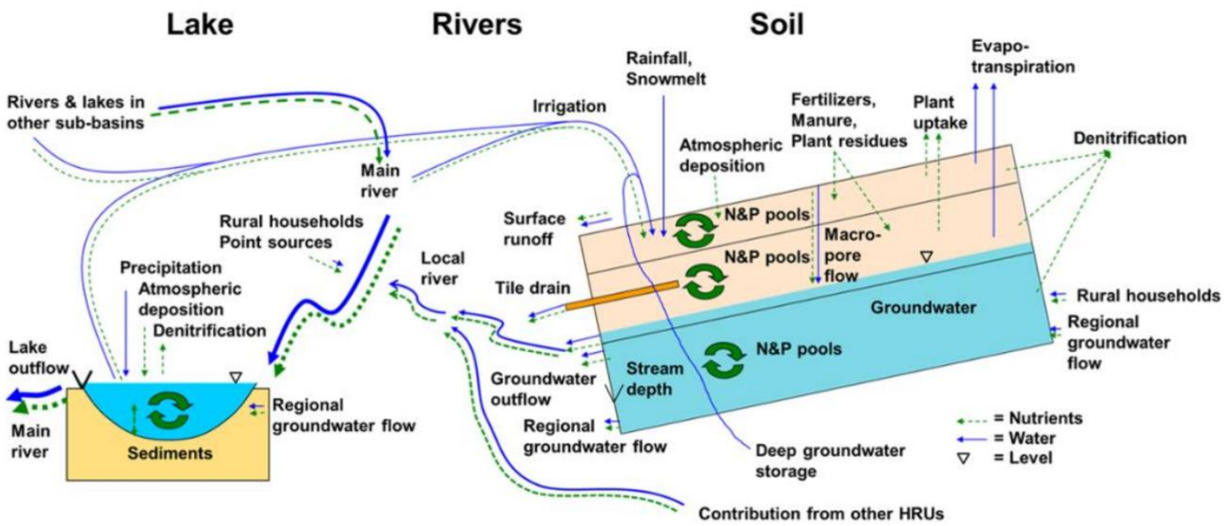

Figure 1. Schematic view of the HYPE model.

The sub-catchment areas for Höljes and Karlstad are shown in Figure 2. SMHI does not have its own station at the outlet of Höljessjön, but receives access to flow data from Fortum. Measurement data on withdrawal from Hölje's power plant includes both production and spillage, i.e. what goes through power station turbines and through the dry ditch. Hölje's power plant has been marked with a green triangle in Figure 2.

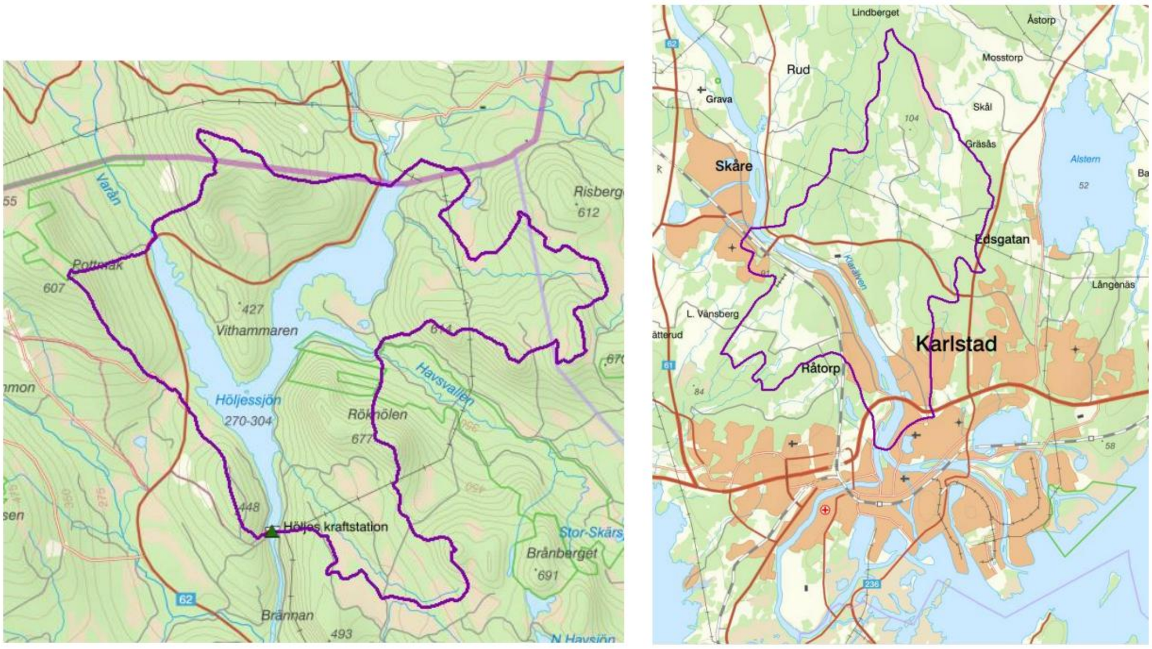

Figure 2. Map showing the Hölje sub-catchment area (on the left) and the Karlstad sub-catchment area (on the right) as violet-blue polygons. The green triangle shows the location of Hölje's power station.

The flow was simulated for three time periods, see Table 1. For the periods "mid-century" and "end of the century" the model was run with two different emission scenarios, RCP4.5 and RCP8.5 run with 9 different global climate models and downscaled with a regional climate model. RCP8.5 corresponds to a fossil-intensive future with high emissions of greenhouse gases and RCP 4.5 includes stringent climate policy with strong emission reductions (Ref 4). For more information on climate models and emission scenarios see SMHI's knowledge bank (Ref 4). In this analysis, future results are shown as averages across the global climate models used.

Table 1. List of the three periods where the flow has been simulated.

	30-year period
Reference	1961–1990
Mid of the century	2040–2069
End of the century	2070–2099

With the concept of water flow or water flow is meant the amount of water per unit of time that flows into a watercourse and is usually stated as volume per unit of time [m3 /s]. The modeled flow in this analysis is defined as *natural,* since the variations of the flow during the year are influenced by natural conditions (snowmelt, rain, evaporation, etc.) and not by human intervention, e.g. the regulation of watercourses for hydropower production. In the model, the lake takes in the entire inflow from upstream catchment areas and the outflow from the lake is described with a simplified sedimentation equation when the water level is higher than a certain threshold level. The reason for simulating natural flow even in a regulated watercourse like the Klarälven is due to the uncertainty of the regulation strategy in the future. This methodology thus allows a comparison of the effect of a changing climate on a model-calculated flow.

The simulated results in Höljes are also compared against measured withdrawals at the power plant, see Table 2 (Ref 5).

Table 2. Observation source

Station name	Station number	Time series included in the analysis
Cover's krv	2224	1962-01-01 – 1990-12-31

3.2 Statistical analyses

Calculated flow in different periods as well as observed flow were analyzed with different statistical tools.

3.2.1 Flow statistics

- MQ: average flow over a 30-year reference period
- MHQ: average of highest annual flow over 30-year reference period
- MLQ: mean of minimum annual flow over the 30-year reference period

In this analysis, flow statistics were calculated based on observed time series (Table 3).

Table 3. Flow statistics from time series at Höljes station

	MHQ	MQ	MLQ
The flow [m3 /s]	360	93	29

3.2.2 Histogram

A bar graph that describes the frequency of a particular range of flow over a particular period.

4 Results

The results have been calculated as daily average values for the three above-mentioned calculation periods. Model results have then been processed to present the data using the statistical tools described in section 3.2.

4.1 Histogram

A histogram is a way of presenting results to describe how often a certain flow happens during a certain period of time. In this analysis, the histogram is built describing the number of days for a calculation period (30 years ~ 11,000 total days) where a fixed flow interval occurs. Number of days is visible in the y-axis of the graphs. Fixed flow range is visible in the x-axis and it is calculated on a logarithmic scale which gives a smoother distribution of the flow values. Histograms are shown in this section separately per calculation period as the average of the 9 climate models over the 30-year calculation period.

At Höljes, the diagrams also show the flow statistics (MQ, MLQ and MHQ) which were calculated based on measurements according to Table 3.

4.1.1 Covered

During the reference period (1961–1990), the flow distribution differs between simulated and observed flow due to regulations in Höljes (Figure 3).

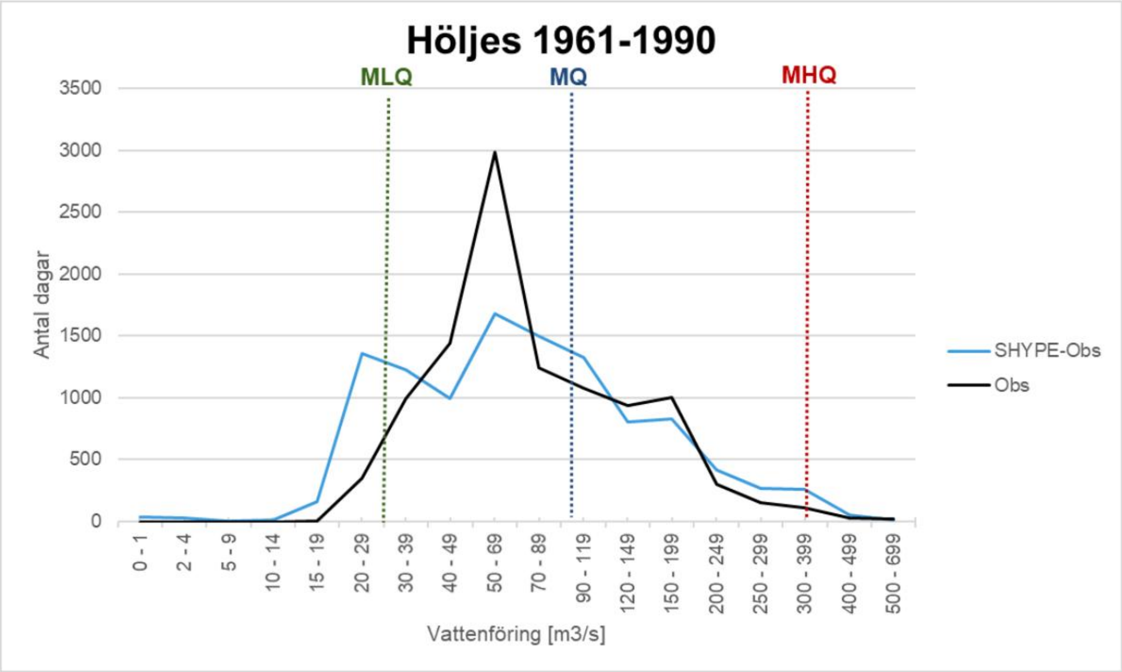

Figure 3 Histogram for measured flow (black line) and simulated flow with current climate (light blue line) for the reference period. Vertical lines are flow statistics calculated based on measurement time series during the reference period.

Histogram based on measurements (black line in Figure 3) shows that the most common flow (the one that occurs the highest number of days during the calculation period) is within the range 50–70 m3 /s where the curve has a very clear peak with 3000 days where this type of flow occurs (about 27% of the time). The same amount of flow occurs as an average during the reference period about 15% of the time according to simulation with the hydrological model S-HYPE. Regarding low flows, the histograms show that flow less than 15 m3 /s is unusual during the reference period according to measurements, while flow less than 10 m3 /s occurs according to results from model calculations. Overall, it can be said that simulated, natural low flows occur more often than observed during the reference period. The regulation can make periods of low flows shorter or higher. During the winter, the regulation in Höljes is managed by keeping the withdrawal for production as seen in Figure 3 and Figure 4 where observed low flows are rarer than those simulated in a natural way. High flows greater than MHQ (360m3 /s) occur 1–2% of the calculation period according to observations and model results, while flows above 400m3 /s are unusual at the outlet of Höljessjön.

Figure 4 shows diagrams for the reference period 1961–1990 with results from climate models run according to two different emission scenarios. Both climate scenarios RCP4.5 and RCP8.5 have the same dynamics (orange and dashed red line respectively) and show a shift in flow amount and number of days compared to the simulated during the reference period (light blue line). The simulated flow that will take place for the most part of the time (up to 3000 days which corresponds to around 27% of the calculation period) is 90-120m3 /s. A smaller peak at 1500 days (about 14% over time) happens in the flow range of 30-40m3 /s. Climate models represent extreme flows less well – both low and high – by underestimating the number of days the flows occur with current climate compared to the SHYPE simulation during the reference period (light blue line).

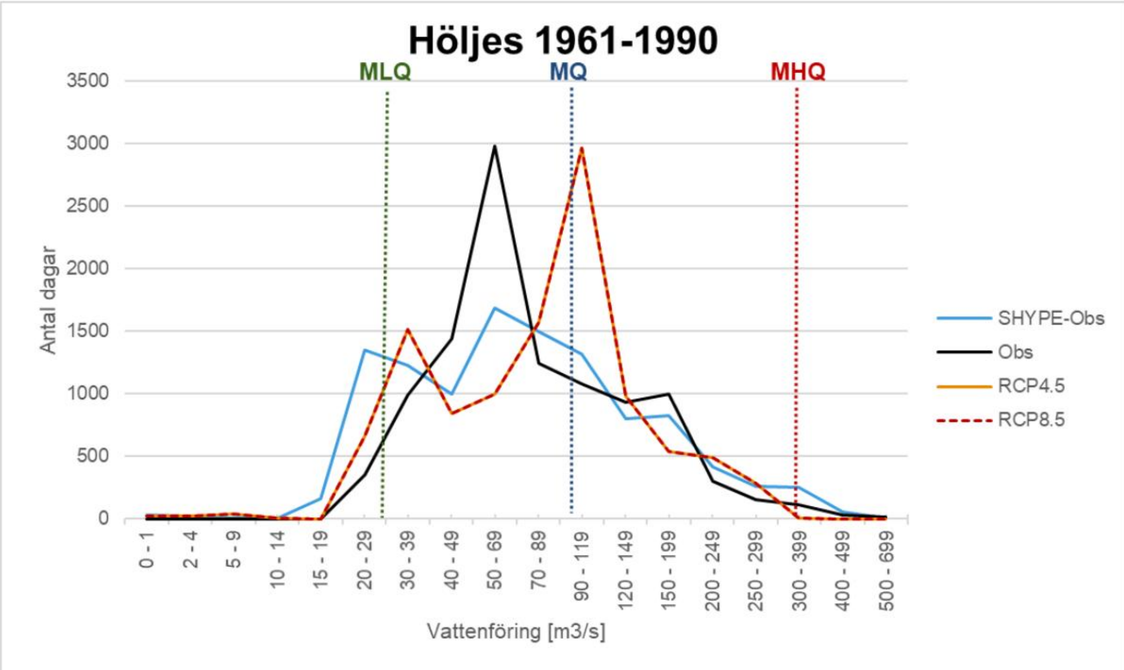

Figure 4. Histogram for measured flow (black line), simulated flow with current climate (light blue line) and climate scenarios RCP4.5 (orange line) and RCP8.5 (dashed red line) for the reference period. Vertical lines are flow statistics calculated based on a time series of measurements during the reference period.

By the middle of the century (calculation period 2040–2070), the difference between modeled flow with the two different climate scenarios RCP4.5 and RCP8.5 is not significant (Figure 5).

Future flow modeled according to climate scenarios for the ranges 90–120 m3 /s will occur 28% of time (about 3100 days) compared to simulation for the reference period, where these flows occur only 12 % of the time. Low flows less than 20 m3 /s will be unusual in the middle of the century where the number of days these flows occur is on average zero. During the reference period, a flow between 10–30 m3 /s occurs more than 10% of the time. These results can be interpreted to mean that the flow to the middle of the century will not be as low as that simulated in the current climate. The same conclusion applies to water flow above the MHQ (360m3 / s) which will become more rare in the middle of the century. Warmer temperatures in Värmland during mid-century winters affect precipitation, which will be more in the form of rain than in the form of snow during winter and autumn. This means that the spring flow peaks will be smaller than during the reference period due to less snow cover that accumulates during the winter. At the same time, the low flows that currently occur during winter will not occur because precipitation falls as rain (Ref 7).

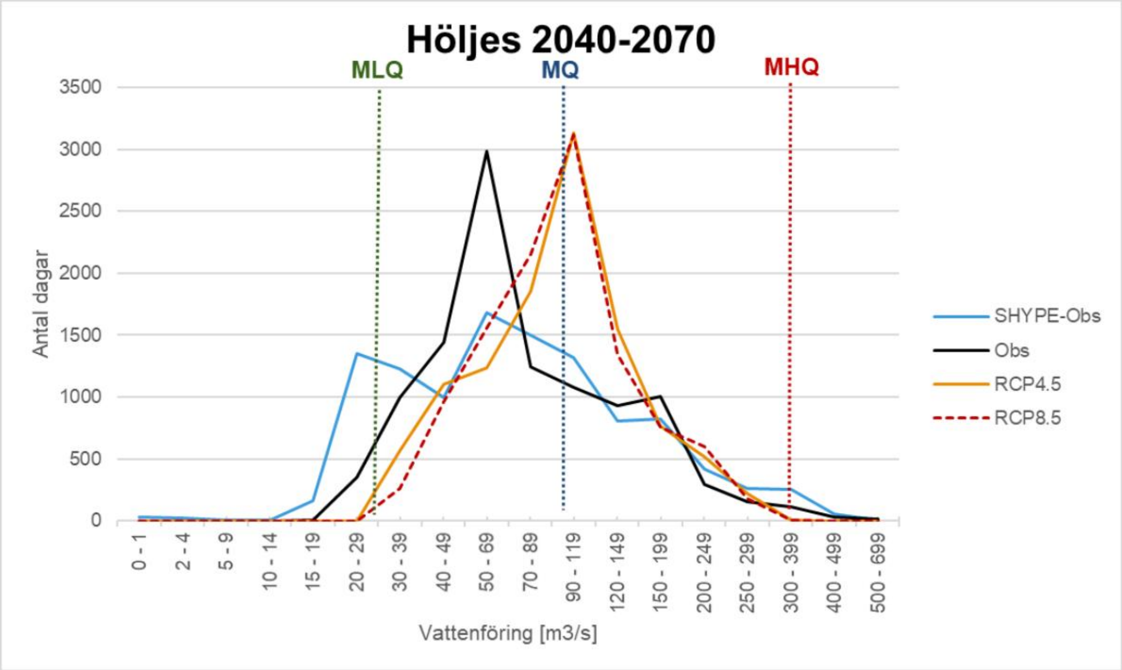

Figure 5. Histogram for measured flow (black line), simulated flow with current climate (light blue line) and climate scenarios RCP4.5 (orange line) and RCP8.5 (dashed red line) in the middle of the century. Vertical lines are flow statistics calculated based on a time series of measurements during the reference period.

The influence of different emission scenarios is stronger at the end of the century, where flow distribution during the calculation period changes with both climate scenarios compared to previous periods (Figure 6).

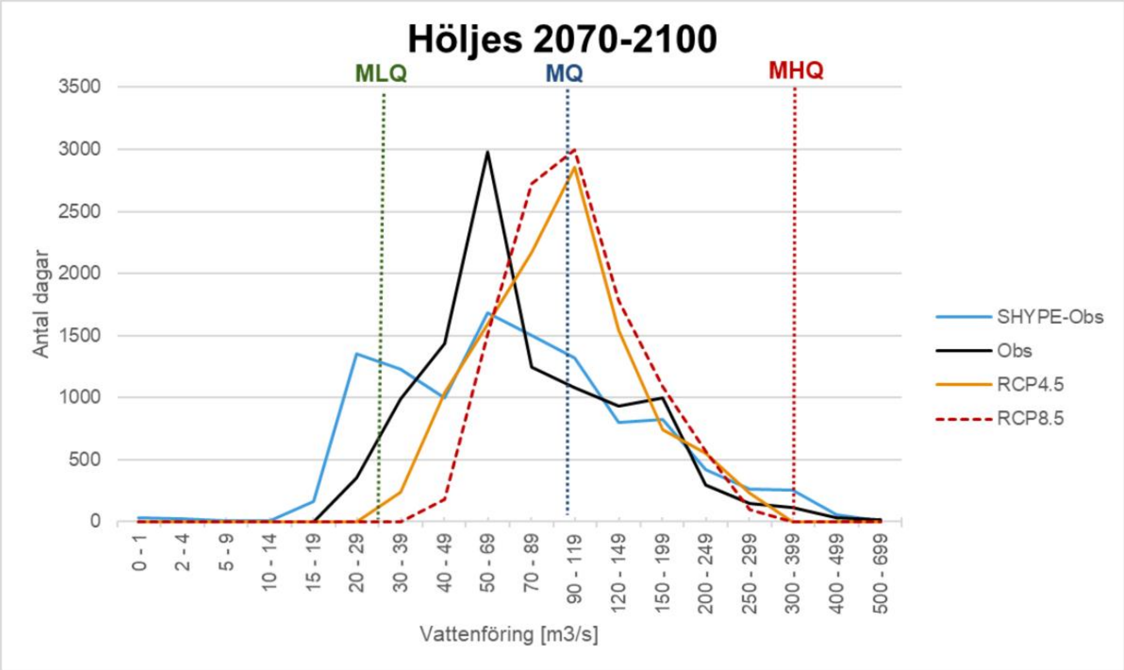

Figure 6. Histogram for measured flow (black line), simulated flow with current climate (light blue line) and climate scenarios RCP4.5 (orange line) and RCP8.5 (dashed red line) at the end of the century. Vertical lines are flow statistics calculated based on a time series of measurements during the reference period.

By the end of the century, discharges between 70–120 m3 /s will be the most frequent, on average 22% of the time (2500 days, orange line) and 26% of the time (2850 days, red dashed line) under RCP4.5 and RCP8.5 respectively. The same flow interval occurs during the S-HYPE reference period (light blue line in Figure 6) on average only 13% of the time (1400 days).

Flows between 50 to 250 m3/s will occur significantly more at the end of the century than during the reference period. On the contrary, extreme flows – both low below 30 m3 /s and high above 400 m3 /s – will not occur at the end of the century. The biggest difference between climate scenarios concerns low flows. Results from RCP4.5 show that flows below 40 m3 /s will occur only 2% of the time in the median until the end of the century, while according to RCP8.5 the same results are seen for flows up to 50 m3 /s for the period 2070–2100. During the reference period, low flows correspond to winter and autumn, while high flows correspond to spring flow peaks.

The results can be interpreted according to climate analysis in Värmland (Ref 7) as an effect on a warmer climate in the future, with warmer winters and heavier precipitation that will occur more in the form of rain than snow during cold seasons. This results in a large amount of water running off in the form of runoff/flow underneath winter and autumn and an early onset of spring flooding. The spring flow peaks will also not be as high as can be seen during the reference period.

4.1.2 Karlstad

Figure 7 shows histograms calculated in Karlstad for the reference period 1961–1990 with results from climate models run according to two different emission scenarios, RCP4.5 and RCP8.5 (orange and dashed red line, respectively) compared to simulation with S-HYPE (light blue line). Both climate scenarios RCP4.5 and RCP8.5 show the same dynamics that follow the results quite well from simulation with current climate. Simulated flows with S-HYPE (light blue line) occurring with the highest number of days are at 90–120 m3 /s and 150–200 m3 /s (16% and 13% of the calculation time, respectively). The results from climate models (orange and red dashed line) show an estimate of the number of days during the same flow interval, with an average frequency up to 18% of the time. Low flows below 15 m3 /s occur during the reference period less than 0.1% of the time, while high flows above 400 m3 /s occur about 2% of the time. Climate models do not seem to describe low and high flows during the reference period very well.

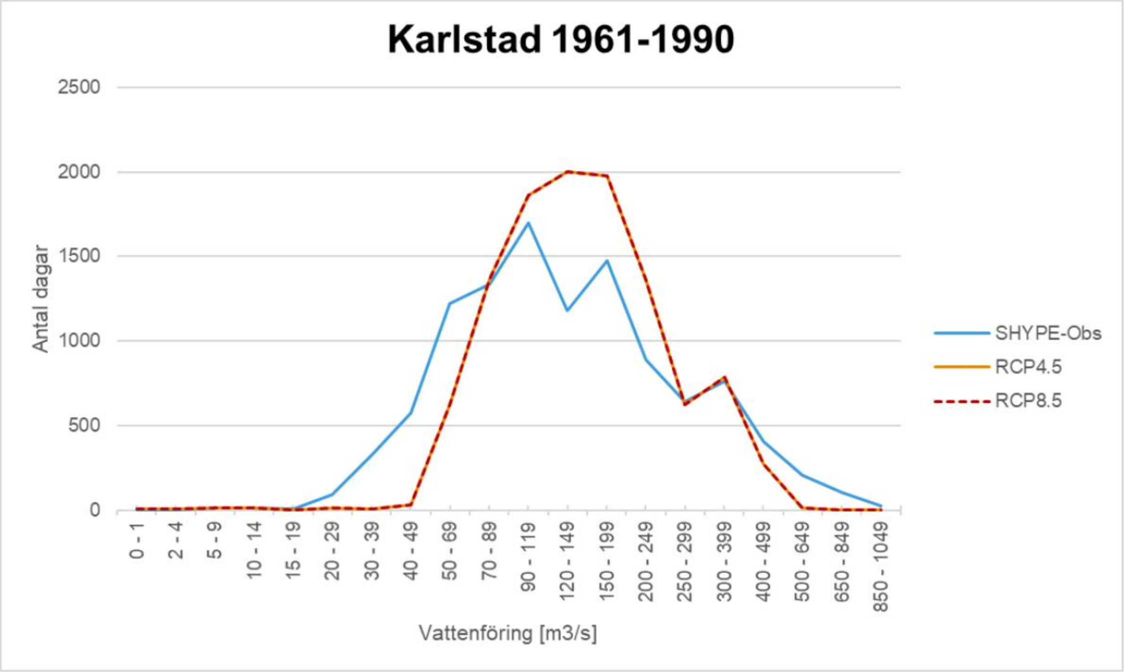

Figure 7. Histogram for simulated flow with current climate (light blue line) and climate scenarios RCP4.5 (orange line) and RCP8.5 (dashed red line) for the reference period.

Also in Karlstad, the difference between modeled flow with the two different climate scenarios RCP4.5 and RCP8.5 is not significant until the middle of the century (calculation period 2040–2070) (Figure 8). Future flows modeled under climate scenarios for the range 120–200 m3 /s will occur more than 22% (2500 days) in the median of the time compared to 12% of the time simulated for the reference period. Low flows, less than 70 m3 /s, will be uncommon in the middle of the century where the number of days these flows occur is zero on average. During the reference period, a flow between 15-70 m3 /si occurs on average 5% of the time, and only between 40-70m3 /s during 10% of the time. These results can be interpreted as the flow to the middle of the century will not be as low as that simulated in the current climate. A similar conclusion can be drawn for water flow over 500 m3 /s which corresponds to spring flood peaks which will not be as large as during the reference period.

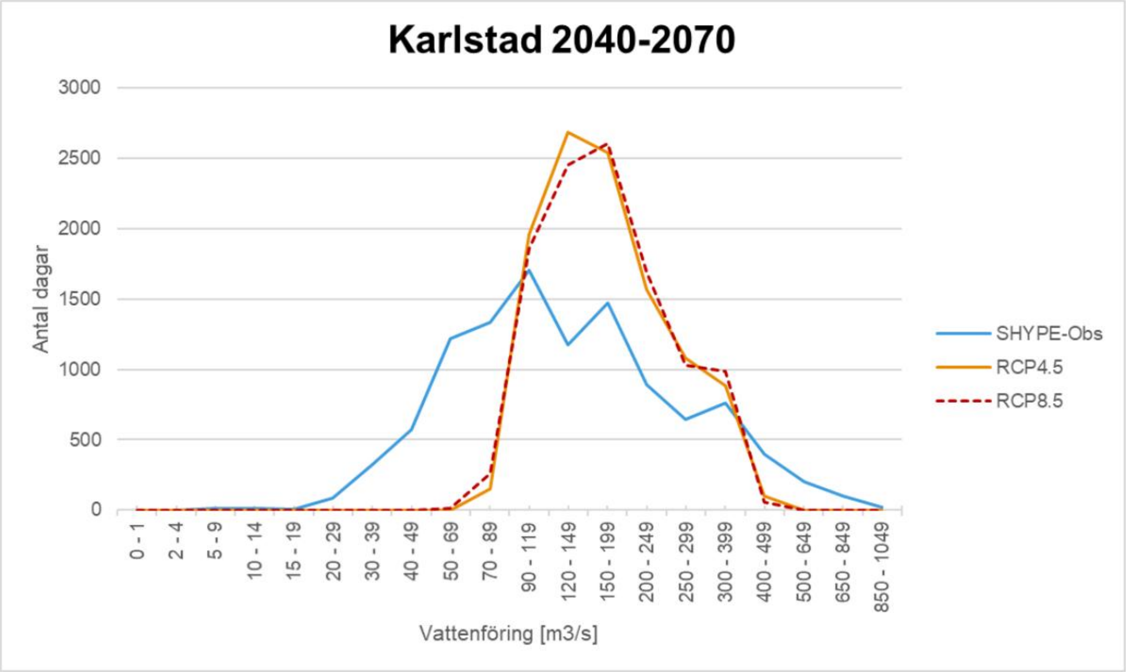

Figure 8. Histogram of simulated flow with current climate (light blue line) and climate scenarios RCP4.5 (orange line) and RCP8.5 (dashed red line) to the middle of the century.

At the end of the century (calculation period 2070–2100), the impact of different emission scenarios is a little stronger and this is reflected in the flow distribution run with RCP4.5 and RCP8.5 (Figure 9).

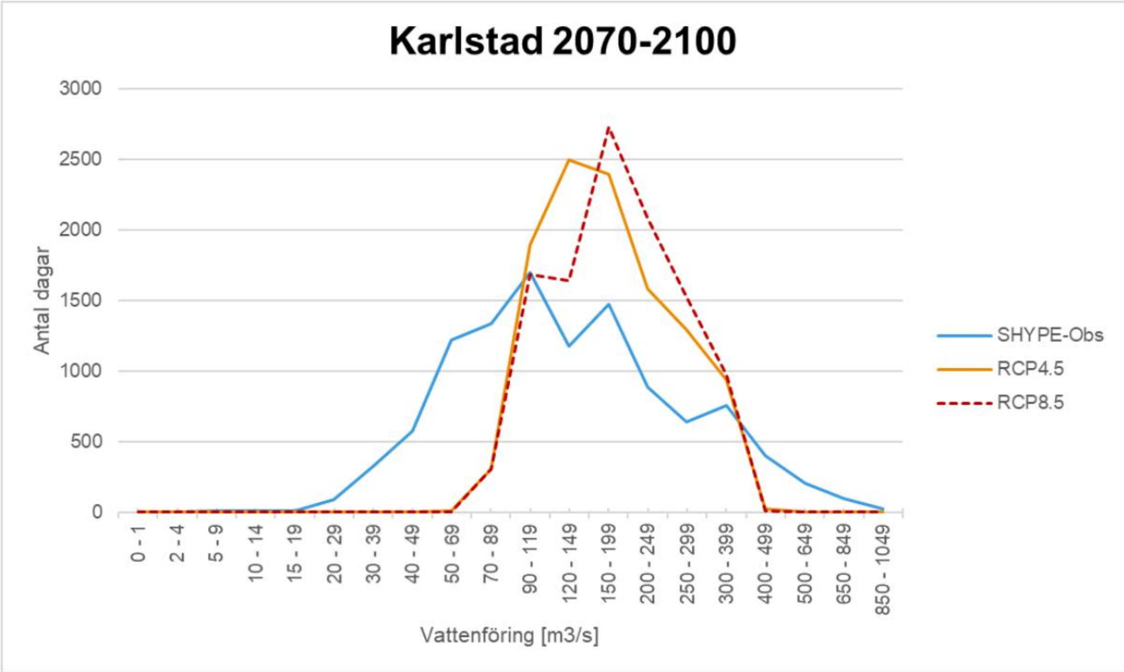

Figure 9. Histogram for simulated flow with current climate (light blue line) and climate scenarios RCP4.5 (orange line) and RCP8.5 (dashed red line) until the end of the century.

By the end of the century, water flow between 120–150 m3 /s according to RCP4.5 will be what occurs most often, on average 23% of the time (2500 days, orange line in Figure 8). The same flow interval occurs during the reference period according to S-HYPE (light blue line in Figure 8) only 11% of the time (1200 days). The results from simulation with RCP8.5 show that the most common flow is in the range of 150–200 m3/s and it will occur 25% of the time (2700 days, dashed red line in Figure 8) as the median until the end of the century.

Results for flows less than 70m3 /s to the end of the century are similar to those to the middle of the century, i.e. low flows in the period 2070–2100 will be rarer than in the reference period. The same conclusion applies to high flows exceeding 500m3/s.

The results from this analysis show that at the end of the century there will not be as many different flow distributions during the year as there were during the reference period. Water discharge until the end of the century will be on average of a greater amount with less deviation between the extremes.

The histograms in Karlstad have been compared with the results from the climate report "Future climate in Värmland County" carried out by SMHI in 2017 (Ref 7). The aim of the climate report was to simulate meteorological and hydrological parameters with the impact of different climate scenarios in the future. Comparison between the hydrological results is not direct because climate analysis of the hydrological parameters in Värmland county that was carried out in 2017 is based on results from the hydrological model HBV that was set up for the county. In this work, the Swedish set of HYPE has been used, but the model has not been locally adapted for the county or for Karlstad.

Chapter 8 of the report from 2017 shows how average values for the annual dynamics of the inflow will change in the future due to a changed climate in the point called "Klarälven Vänern" (Figure 10) which corresponds to the sub-catchment area that was used to produce histograms in this analysis.
The reference period in the climate study is 1963–1992 (black line in the figure) and the future period is 2069–2098. Calculations were made according to RCP4.5 and RCP8.5 climate scenarios (blue and red line respectively).

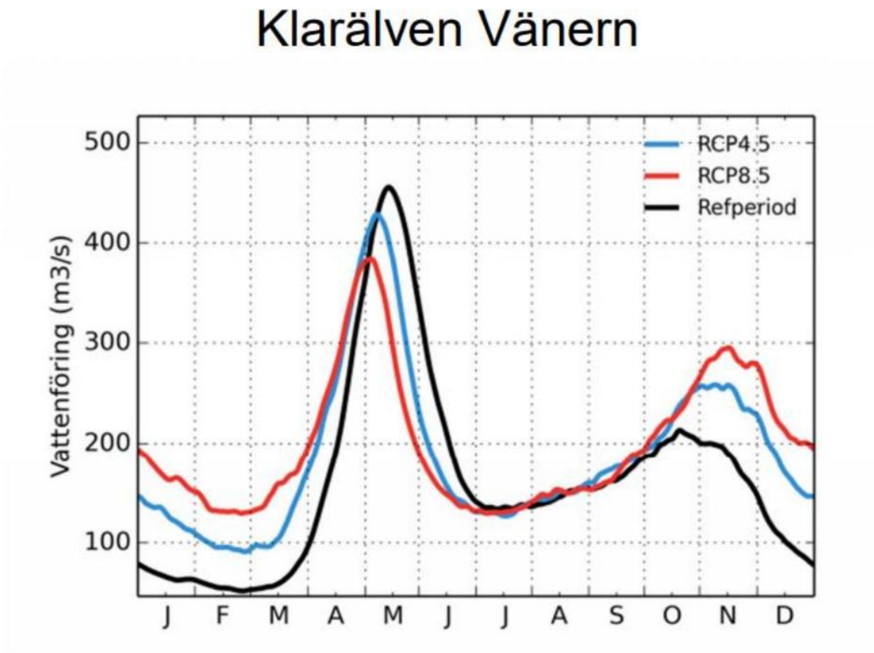

Figure 10. Annual dynamics of inflow in Karlstad. Black line represents the reference period 1963–1992 *and the other two lines represent the future* period 2069–2098. *Blue line refers to mean values of calculations according to RCP4.5 and red line represents the equivalent for RCP8.5.*

For the inlet to Lake Vänern, the future scenarios in Figure 10 show earlier spring flow peaks, higher winter and autumn flow, while the inflow during the summer is not affected.

During the winter months (January, February and March in Figure 10) the flow will be much higher than it was during the reference period according to both climate scenarios. The increase in runoff during the winters is explained by the climate report with the fact that precipitation generally increases in the county and that precipitation such as rain instead of snow will become increasingly common in a future warmer climate. Thus, the winter precipitation will run off during the winter instead of, as during cold winters, being stored as snow and forming runoff when the snow melts in the spring. The future dynamics during the winter explain results that can also be seen in Figure 9, where the number of days with flow less than 70 m3 /si on average will be close to or equal to zero at the end of the century depending on the climate scenario.

A changed seasonal dynamic during the winter results in an earlier snowmelt time and less snow cover that accumulates during the winter. It will cause earlier spring flow and also smaller spring flow peaks at the end of the century according to both climate scenarios in Figure 10. However, a stronger effect is seen in the simulation with RCP8.5. The same dynamics are also shown in Figure 9 in the form of the number of days when certain flow intervals occur. With the assumption that flows above 300 m3 /s correspond to the spring flood in the average of the calculation period, Figure 9 shows that there will not be days when the flow exceeds 400 m3 /s at the end of the century with simulations with both emission scenarios.

Autumn flow will also be higher than that during the reference period to the end of the century according to both RCP scenarios (Figure 10).

The overall increased inflow during the winter and autumn seasons results in an increased inflow throughout the year on average over the calculation period (Figure 10). It corresponds to results seen in the histogram in Figure 9, which shows that a larger flow amount (120 up to 400 m3 /s) will become more common by the end of the century as a median for a 30-year period.

Until the end of the century, the summer flow is not affected by different emission scenarios (Figure 10). Higher temperatures will cause more water to evaporate or be used by plants, and precipitation will also increase until the end of the century, according to the climate report. An unchanged inflow of future summer flows can thus be explained as an effect of increased evaporation and a longer vegetation period in the future as well as higher rainfall during the season.

5 Conclusions

- Due to uncertainties in future regulation strategy in the watercourse, it is preferred to model natural flow to analyze the impact of a changing climate on future flows, even though the watercourse is regulated. Modeling future seasonal and annual water resource management in the future had required a number of assumptions to be built into the model.

- Climate analyzes of hydrological indicators involve various sources of uncertainty that partly come from climate models, as well as from the hydrological model.

Impact of future climate on flows in Värmland County:

- During the winter months, larger flows than those during the reference period will become more common due to increased temperature which means that precipitation will occur more in the form of rain than snow. This means that a greater amount of water runs off instead of being accumulated in the form of snow.
- Spring flow will occur earlier than for the reference period at the end of the century. Also spring flow peaks will be smaller than those observed during the reference period. This effect holds for both climate scenarios, but with a stronger impact with RCP8.5. Increased temperatures throughout the year cause early snowmelt times, while snow cover becomes less than normal.

- Summer flows will not be affected by climate scenarios due to a balanced effect on increased precipitation during the summer with a longer growing season and evaporation.
- Increased temperatures and precipitation affect the autumn flow, which will increase in the future. • According to the climate analysis report (Ref 7), both the annual average temperature and precipitation will increase more strongly in the northern parts of Värmland than in the south. For example, the temperature increase in Höljes is estimated to be on average 1 degree higher than in Karlstad at the end of the century according to RCP8.5. The increase in precipitation will also be greater in Höljes, and it will be more in the form of rain than snow due to warmer temperatures. This causes a 20–25% increase in local mean runoff in Höljes by the end of the century compared to the RCP8.5 reference period. Under the same conditions, the increase in local average inflow will be in the order of 10–15% in Karlstad. Also the total inflow, i.e. the accumulated flow contribution from all catchment areas located upstream will increase in Värmland.

  However, the climate report shows that the least increase applies to areas closest to Lake Vänern.

Local climate impact on flow type in Höljes and Karlstad:

- Higher winter and autumn flow corresponds to a higher flow amount overall at the end of the century, and a reduction in the time during which current low and high flows will occur. • At the outlet of Höljessjön, flow intervals of 90–120 m3 /s will occur in the middle and by the end of the century on average about 15% more often than simulated during the reference period, according to both RCP scenarios. Flow range 50–150 m3 /s will be what happens most often in the middle and end of the century, while low flows less than 30 m3 /s or high flows over 300 m3 /s are not captured

  of climate models.
- At Karlstad, flow intervals of 150–200 m3 /s in the middle and by the end of the century will occur on average about 10% more often than simulated during the reference period, according to both RCP scenarios. A similar future dynamic as in Höljes means that low and high flows that currently occur cumulatively around 10% of the time during the calculation period will not take place until the middle and end of the century.
- In both Höljes and Karlstad, in the future there will not be as many different flow distributions during the year as there are during the reference period. Water discharge until the end of the century will be on average of a greater amount with less deviation between the extremes.

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