Naturalization of the flow rate downstream from the Vesdre reservoir

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Abstract

Dams are used worldwide for the purpose of water management. In this thesis we naturalized the discharge of the Vesdre (Belgium) at the location of the dam in order to quantify the storage effect of the Vesdre reservoir. This research does not study the influence of the water flow diversion from the river Helle towards the dam, its contribution is still included in the naturalized discharge. First, we compute the total inflow into the reservoir for which the contributing parts are the Helle tunnel, the Getzbach river, the upstream of the Vesdre river, and the portion of the reservoir water catchment that is drained but ungauged. This total inflow discharge is considered the natural discharge of the Vesdre. Then the outflow discharge from the Vesdre dam is computed based on a mass balance equation. These discharges were computed for the period of January 1995 to April 2022. 18 flood events were distinguished from the total inflow time series. For these 18 events, the inflow and outflow discharge were compared. The main findings are: that the dam reduces the peak head discharge by 14 to 85%, the dam is able to shift the peak discharge by 5 to 69 hours, the dam is able to reduce the flood volume by 2 to 83%. A flood frequency analysis was also applied on these data, and shows that the dam reduces the magnitude of flood peaks by a factor of two. This last result does not apply when the reservoir is saturated due to extreme flood events. The extreme flood event of July 2021 was not studied due to the unreliability of the data.

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1 Introduction

Dams are used extensively worldwide for the purpose of water management. They are used either for water supply, hydroelectricity generation or flood management. Dams induce a change in flow regime (total discharge, flood flows, baseflows, the shape of the seasonal and flood hydrographs, seasonal and interannual variability) [Batalla et al., 2004] and their consequences have been widely analyzed around the world.

Graf [2006], Magilligan and Nislow [2005], Ely et al. [2020], Song et al. [2020], Assani et al. [2006] used the Indicators of Hydrologic Adjustment (IHA) in order to investigate the Dam-induced hydrologic changes. It is a software package that uses records of data discharge from before and after the construction of the dam in order to compute 32 indices sorted into five categories: 1) Magnitude of monthly water condition, 2) magnitude and duration of annual extreme water conditions, 3) timing of annual extreme conditions, 4) frequency and duration of high and low pulses, 5) rate and frequency of changes in conditions.

With this method, they generally found that dams reduce annual peak discharge and the range of daily discharge because low flow increases and maximum flow decreases. Dams increase the number of reversals in discharge and decrease the mean rate of hydrograph rise and fall. Also, dams modify the timing of high and low flows.

Graf [2006] studied the hydrologic and geomorphic changes that induce dams on the downstream part of the river. Their research included 36 of the largest dams in the United States. They show a reduced average annual peak discharge of 67% and a decrease in the ratio of annual max/mean flow of 60%.

Batalla et al. [2004] developed an index called the impounded runoff index (IR), which is simply the ratio between the reservoir capacity and the mean annual flow in order to quantify the hydrologic effect of the reservoir when no long record of data pre- and post-dam are available. They also analyzed changes in flood magnitude by taking the ratio between post- and pre-dam flood values. They studied the change induced in daily flow thanks to a flow duration curve. For their research on the Ebro-river basin, they found that dams induce a significant decrease in flood frequency and magnitude and that this diminution is inversely proportional to the IR index. Most of their gauging stations showed a reduction in the variability of their mean daily values but 40% showed an increase because of lower low flow.

Mei et al. [2016] compares the pre- and post-dam annual mean peak discharge over 38 rivers in the US. They concluded that the dams were responsible for a decrease in the annual mean peak discharge from 7 to 95% over these 38 rivers. They also noticed a change in the probability density curve of the annual peak. Indeed the magnitude and range of discharge decreased with the dam. In order to evaluate the influence of a dam, they also computed the ratio between the reservoir size and the mean annual discharge. The bigger the storage capacity, bigger will be the reduction of the annual mean peak discharge. They also deducted that on average the dam enables a reduction of the 2-year, 5-year, 10-year, and 50-year flood discharge of 41.34%, 44.87%, 46.22%, and 46.21% respectively.

Stecher and Herrnegger [2022] assessed the impact of dams on floods for 8 rivers in Austria. They showed that flood peak reduction is more significant for periods with higher return periods. Indeed, events with a return period longer than 30 years were showing an average flood peak reduction of 33%. They also stated that flood peak reduction is linked to the ratio between the storage capacity and the catchment area. In this study, they did not have any records of the discharge before the construction of the dam, they then had to compare the observed discharge peak with the estimated one. The pre-dam discharge was estimated by taking the discharge from an unaffected catchment. The unaffected reference catchment has to have more or less the same area, the same amount of precipitation and to be close to the affected catchment. They show an average flood peak reduction of 27%.

Batalla et al. [2004], Mei et al. [2016] also stated that the effect of a reservoir is a function of its storage capacity with respect to river runoff, the main function of the dam. Batalla et al. [2004] added that it is also a function of the operating rules of the dam. Mei et al. [2016] showed that the effect of the dam will also depend on its geographic location.

According to Terrier [2016] there are different methods of naturalization depending on the data available (Table 1). *The Water Balance method* consists of applying a water balance on the source of influence which is considered an open system. *The reconstitution method* consists of creating a time series of data in the past without any current data available. The principle is to create a model in which the climatic data are entered as well as the effect of the anthropogenic influences. Once the settings of the model are forced with the influences, the influences are canceled. *The extension method* consists in extending an already existing data series thanks to a hydrological model. This is done with uninfluenced data and climatic conditions of the period of study. *The paired catchment method* consists of simulating the natural discharge of a catchment by using the natural discharge of this catchment before influence and the natural discharge of surrounding catchment with similar behaviour over the period of study. *The neighbourhood method* consists in building and forcing a hydrological model for surrounding uninfluenced catchments. Using these settings for the studied influenced catchment and then an average is made of the discharges simulated with the different settings.

		Methods				
		Water Balance	Reconstitution	Extension	Paired Catchment	Neighbourhood
Data required	Influenced observed streamflow	X	X			
	Uninfluenced observed streamflow			X	X	
	Natural observed streamflow on neighbourhood catchment pre-influence				X	
	Natural observed streamflow on neighbourhood catchment within the study period				X	X

Table 1: Data needed according to the method of naturalization used according to Terrier [2016].

In this thesis, the purpose is to compare the discharge of the Vesdre with and without the dam. Therefore the only influence from which we want to remove the effect is the Dam in order to quantify the storage effect of the dam. The inflow into the reservoir is considered the natural discharge of the Vesdre as it is the discharge that the Vesdre would have if the dam had not been built. We do not study the effect of other influences. This is the reason why, in this thesis, the main focus is the comparison between the outflow (Qout) and inflow (Qin) discharge of the reservoir from 1995 to 2022. Indeed, the main results are about the percentage of decrease in peak flow, the delay in the time to peak for major events, the decrease in the gradient of the outflow compared to the inflow discharge and the decrease in the 10-year, 25-year, 50-year and 100-year flow rate induced by the dam.

There is no record of the discharge of the Vesdre before the dam. This means that the extension and paired catchment methods are not applicable (Table 1). There is no uninfluenced catchment for which we have easy access to the data that has similar behavior to the one of the Vesdre, which rules out the neighbourhood method. The water balance method is the one chosen because we only need the influenced observed streamflow.

In the first part of this thesis, a presentation of the Vesdre dam is given and an explanation is provided on what were the data available for the analyses and how they were obtained. Then the method for computing the outflow discharge from the Vesdre is described as well as the different filters applied to the data. The method section also contains a part that explained how the flood frequency analysis was performed.

The second part focuses on the processes that are applied to the data in order to compute the total inflow discharge. An analysis was also made on the corrections that were applied to the reservoir water level data. Finally, we studied the effect of the corrections made by the IRM on the precipitation data in order to see if the data of precipitation that were not corrected were usable.

The third part is about the results and the discussion of these results. The main results shown and discussed are the comparison between the observed outflow discharge and the computed one for 18 major events, the comparison between maximum peak inflow and outflow discharge during major events, the comparison between the maximum gradient for outflow and inflow discharge for the major events, the comparison between the cumulated inflow and outflow volume for the 18 major events and the flood frequency analyses on the inflow and outflow discharge.

2 Data and Method

2.1 Case study

This research focuses on the Vesdre reservoir that is situated in Belgium, in the Province of Liège at the intersection between the Vesdre and the Getzbach river (Figure 1). The Vesdre is a 70 km long river that takes its source in the High Fen in Germany. It is a tributary of the Ourthe river that is itself the main tributary of the Meuse river.

This reservoir was achieved in 1949 by the end of the construction of a gravity dam for which the main role is to ensure the supply of drinking and industrial water to the areas of Verviers, Spa, Herves and around the city of Liège. Another role of the dam is to produce hydropower in order to ensure the electrical supply for the treatment of the water that is distributed and the oversupply is put into the grid. The dam also contributes to the regulation of flood and low-flow events.

The water catchment of the Vesdre reservoir has an area of 692 km^2, to which 368 km^2 was added by the construction of the deviation tunnel of the Helle river [ministère des Travaux Publics et al., 1986]. This tunnel is generally open and a minimum environmental flow is returned to the Helle river. The tunnel should be closed in case of a flood event. The surface of the reservoir is of 126 ha and it can contain up to 25 hm^3 of water [ministère des Travaux Publics et al., 1986].

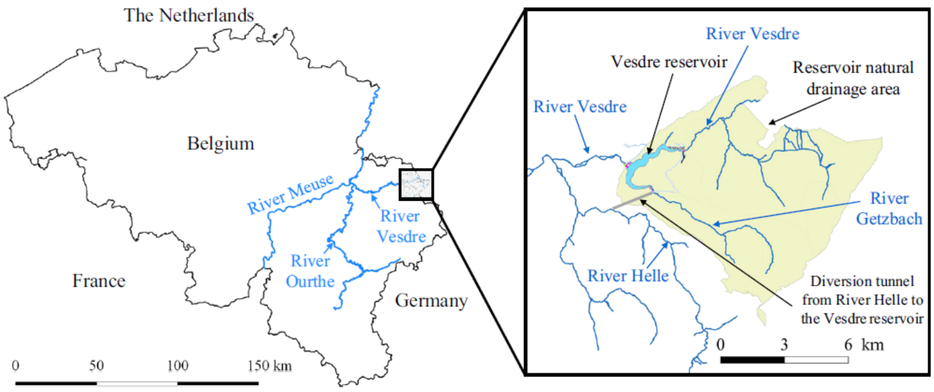


Figure 1: Location of the Vesdre reservoir [Cuvelier et al., 2018].

2.2 Management of the dam

The management of the dam depends on past and forecasted precipitations. Indeed it is important that the reservoir always contains enough water for supplying the population with drinking water but at the same time, it has to be able to contain an abrupt significant input of water.

There are three ways for the dam to release water [Zeimetz et al., 2021, ministère des Travaux Publics et al., 1986]:

- 4 turbines (production of electricity and restitution to the river, maximum combined discharge: 4.5 m^3/s)
- 2 bottom outlets valves (maximum discharge per valve: 35 m^3/s)
- 1 spillway (maximum discharge: 230 m^3/s)

Figure 2 shows the operating rules of the dam since 05-2021. If the level of water is below the minimum restitution curve, no electricity is produced and only the water necessary for supplying the river ($0.22m^3/s$) and the population ($55000\ m^3/d$) is released.

If the level of water is between the minimum restitution and the restitution of $0.4m^3/s$, then only one turbine is used for the production of electricity during the day and the amount of water that passes through the turbine is at a minimum during the night. Above the $0.4m^3/s$ restitution, the turbines can be used at their maximum power.

The valve of the spillway has to be kept at a level of 358.5m except in the case of flood where it can be allowed to increase (maximum 360.8) in order to store the water and avoid a too large discharge downstream. If the water level goes above 360.8m, the water going in is directly evacuated [Zeimetz et al., 2021].

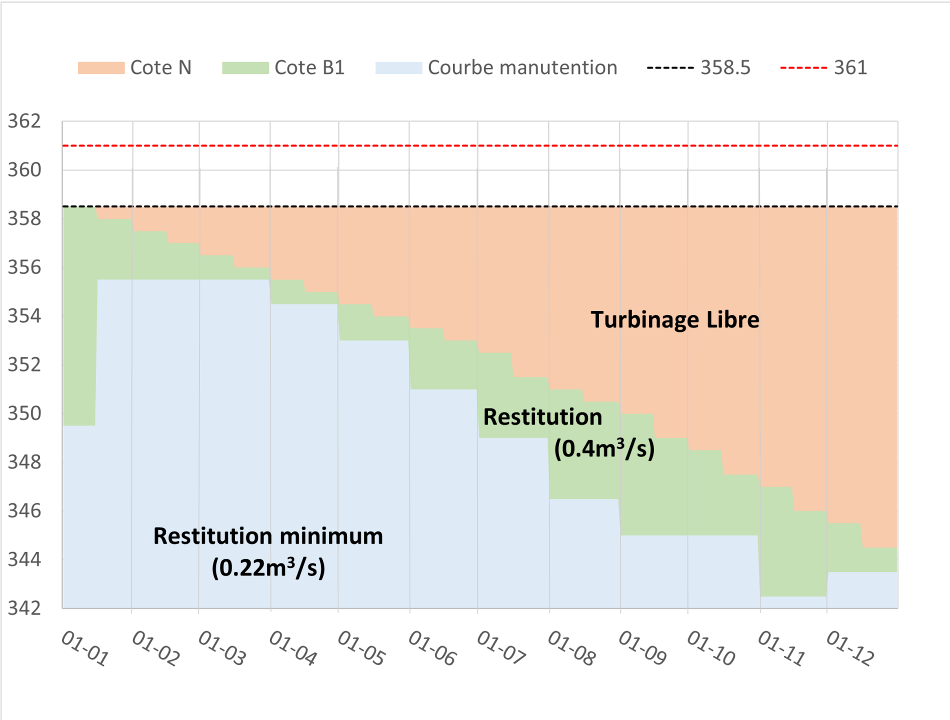


Figure 2: Operating rules of the Vesdre dam ([Zeimetz et al., 2021] for which the source was "note de manutention du SPW MI version 05-2021").

2.3 Available data

Thanks to my internship at the SPW DGH, a lot of data were made available to me which helped a lot with this research.

2.3.1 Inflow discharge

For the Vesdre reservoir, there are five sources of inflow to be taken into account in order to compute the total discharge input into the reservoir: The upstream of the Vesdre and the Getzbach river, the deviation tunnel of the Helle river (Figure 3) and the part of the water that comes directly from the water catchment into the reservoir and the contribution of the precipitation that falls directly onto the reservoir (Section 3.1.2).

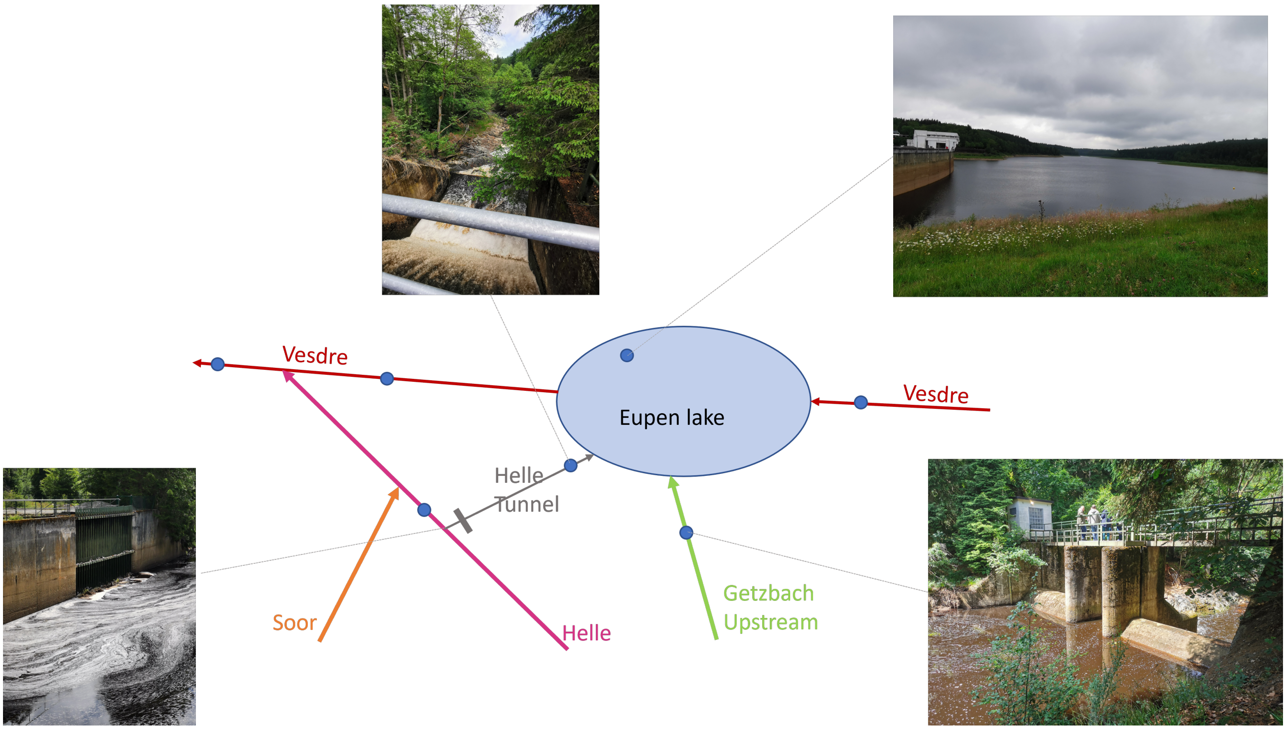


Figure 3: Schematic layout of the Vesdre reservoir. The blue dots correspond to the measuring stations from which the time series are available.

It is important to notice that the data for the Getzbach and the Vesdre rivers represents 100% of the gauged drained area in the Vesdre water catchment but this only accounts for 87% of the total drained area because 13% is ungauged (Figure 4). In the share called "Lake and Surroundings", 1.26 km^2 out of the 9.08 is the surface area of the reservoir.

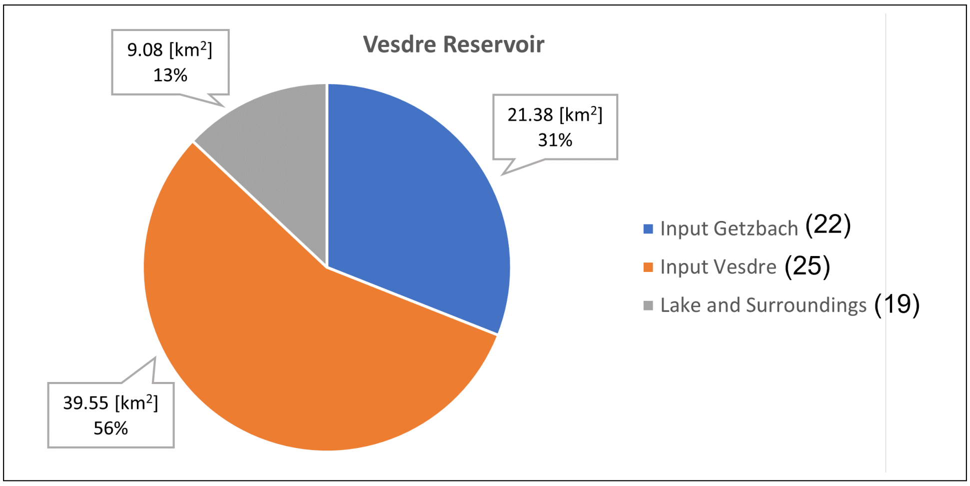


Figure 4: Share surface of drained area for the Getzbach and the Vesdre river as well as the ungauged drained surface. The numbers refer to the ones in Figure 5.

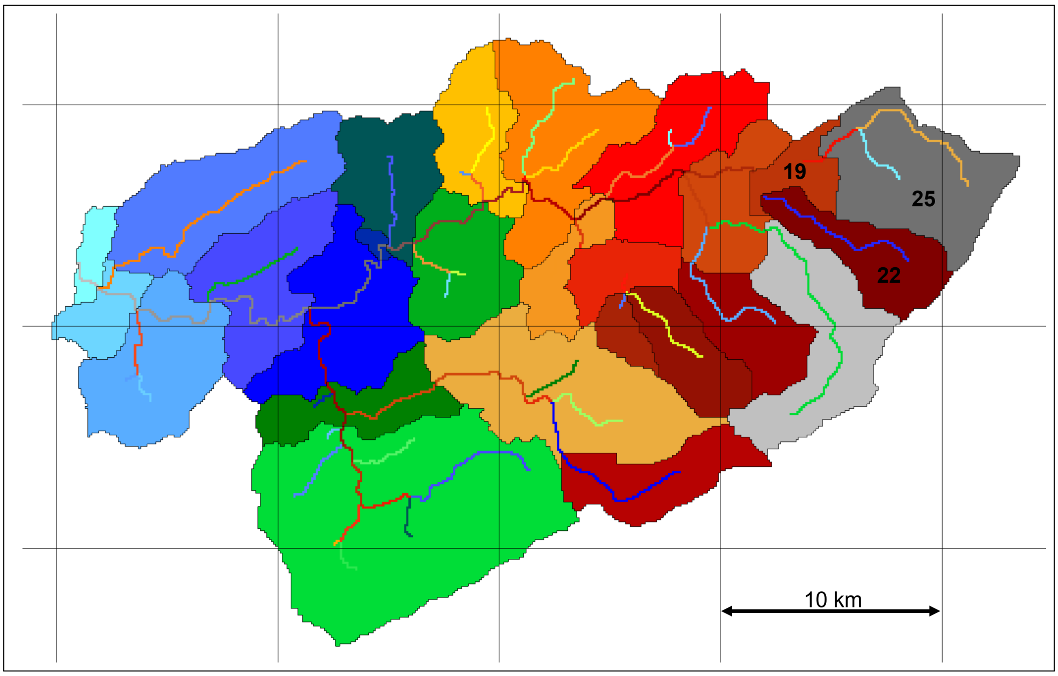


Figure 5: Sub-catchments of the Vesdre catchment.

The inflow discharge at each station upstream of the main river that goes into the reservoir is not directly measured. What is measured is the height of the water at a concrete weir thanks to water level sensors, and this is then transformed into discharge thanks to rating curves.

For the period between 1995 and 2014, two different sets of discharge are available for each station. This is due to the fact that in Calles [2015], they worked on the corrections of the measured data. Before 2015, collaboration on the curation of hydrological data was limited between the Direction de la Gestion Hydrologique (DGH) and the division in charge of dam management. The latter focused primarily on the most vital data for the day-to-day management of the dam, and thus long-term storage, correction and validation of historical data was not given a high priority.

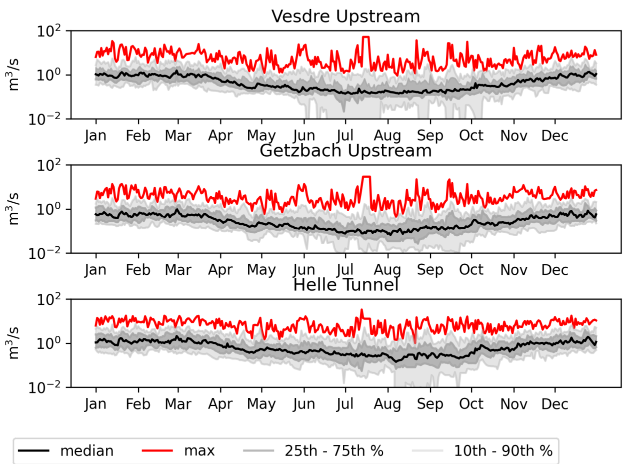
Part of the master thesis of Calles [2015] was then to correct the height of the recorded data that was obviously wrong. The correction was made based on the recorded height of other stations and the recorded precipitation. These corrections were done manually (See Figure A.1 for the correction dates). Another part of her thesis was to correct the rating curve for each weir. Indeed, the conversion tables that were used before 2015 in order to transform the height into discharge had no known origin. By making new gauging measurements, she was able to correct these rating curves.

From 2015, the DGH and the Dam management worked together and the data from then on is of better quality.

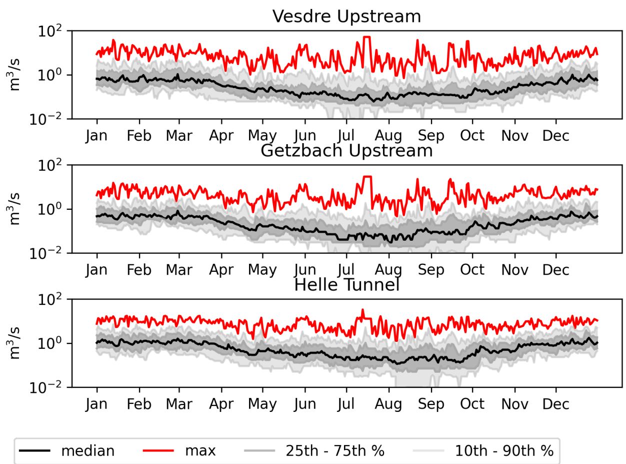
Figure 6 displays the daily median of the inflow discharge for each day of the year over 27 years (1995 - 2022) for the data corrected and not corrected by Calles [2015]. This figure also shows the range between the 10-90 percentile and the 25-75 percentile. The data were taken at the station represented by a blue dot in Figure 3 corresponding to their respective stream.

Figure 7 displays a statistical analysis over the winter, the summer and all years of the graphs shown in Figure 6. The year was separated into two seasons: Winter and Summer. The winter months are from October to March and the summer months are from April to September. Figure 7 shows that the inflow discharge is generally higher from the Helle tunnel, then from the Vesdre and finally from the Getzbach. However, Figures 6c and 6d show that the extreme inflow discharges are higher from the Vesdre than from the Helle. The Getzbach has the smallest water catchment of 21.38 km^2, then it is the Helle with 36.73 km^2 and finally the Vesdre with 39.55 km^2. Figure 7 also shows that as expected the discharges in winter are higher than in summer. Indeed the median, percentile 75 and 90 are more or less three times higher in winter than in summer.

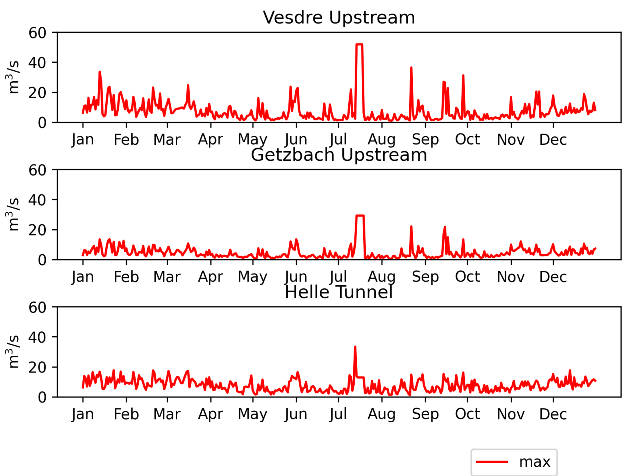
Figure 7 also compares the data corrected by Calles [2015] and non-corrected. It shows that the corrected data contains smaller values of discharge than the uncorrected ones. Figure 6 also compares the hourly maximum discharge over 27 years for the corrected and uncorrected data. There are some differences but globally it is the same, which shows that the corrections do not fundamentally change the data.



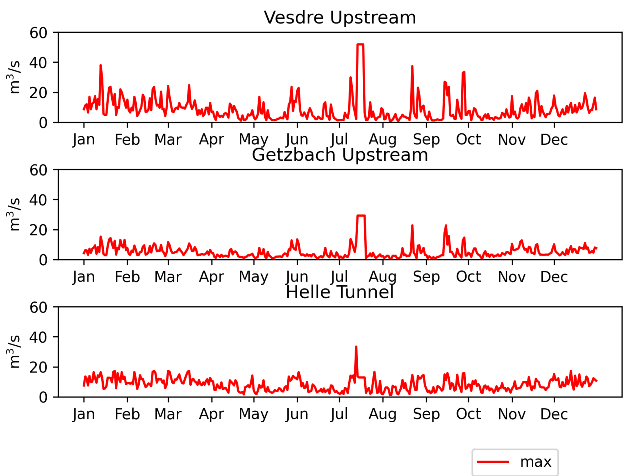
(a) Not corrected



(b) Corrected by Calles [2015]

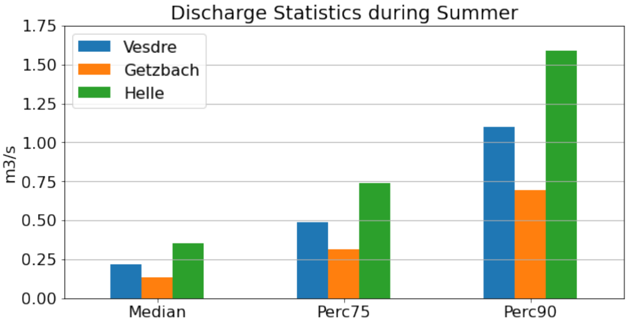


(c) Not corrected

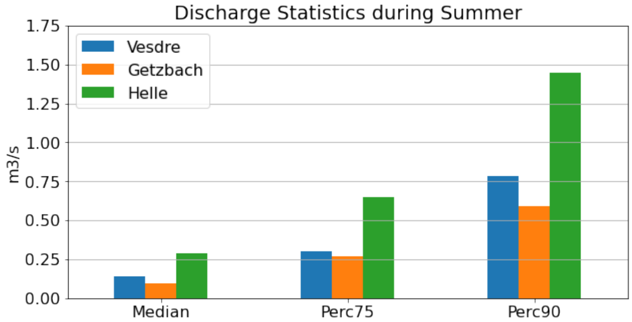


(d) Corrected by Calles [2015]

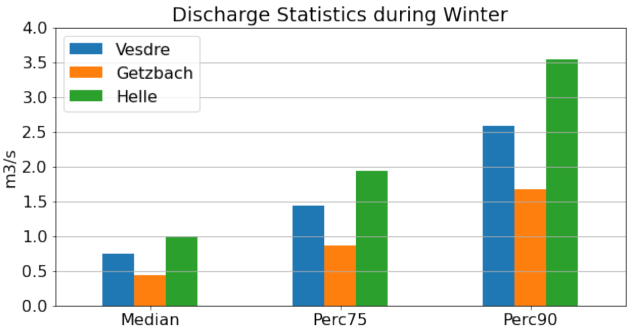
Figure 6: Daily median, max and variation (Percentile 10 - 90 and 25-75)) of the inflow discharges over 27 years of the Upstream branch of the Vesdre and Getzbach rivers as well as the deviation tunnel of the Helle river.



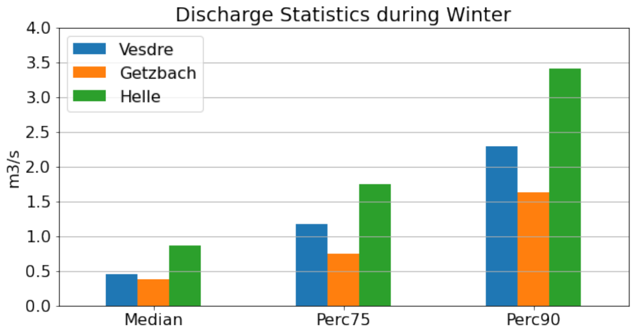
(a) Summer: Not corrected



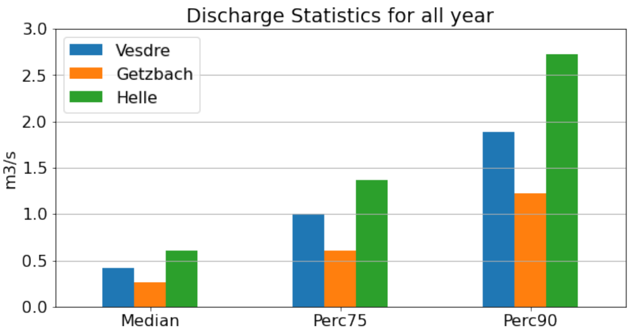
(b) Summer: Corrected by Calles [2015]



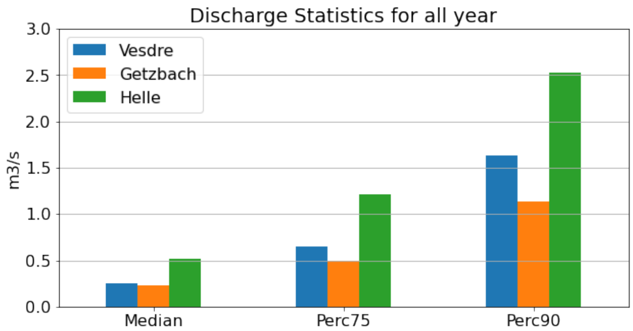
(c) Winter: Not corrected



(d) Winter: Corrected by Calles [2015]



(e) All year: Not corrected



(f) All year: Corrected by Calles [2015]

Figure 7: Median, Percentile 75 and 90 for the inflow discharge coming from the Vesdre, the Getzbach and the Helle tunnel. Statistics made over 27 years (1995 to 2022) and for the sets of data that are not corrected (left) and corrected (right) by Calles [2015].

2.3.2 Reservoir water level

Again from 1995 to 2015, two sets of data are available in an hourly time step: One that is corrected by Calles [2015] and one that is not. Figure 8 displays the corrected and the uncorrected time series. The Figure above shows the water level time series from January 1995 to May 2022 whereas the Figure below shows the time series for the year 2007. This last Figure highlights the fact that the corrections were not made only where the water level peaked downward.

The year 2007 was chosen because it is the year with the most corrections on the reservoir water level. Indeed from 1995 to 2015, corrections were made on 85 periods where 16 were in 2007 (Figure A.1). In the appendix, in Figure A.2, the corrections for these 16 periods are shown. It is difficult to find the logic behind some of these corrections.

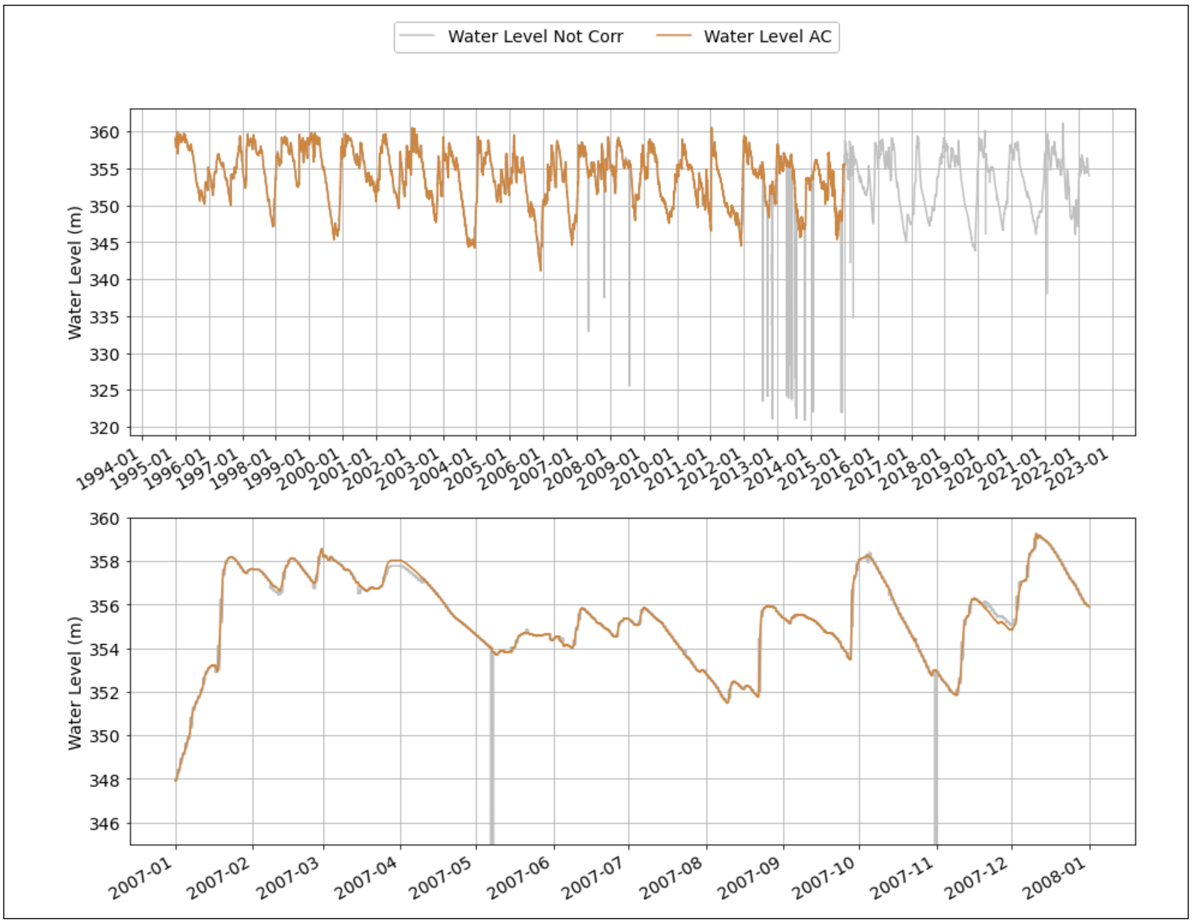


Figure 8: Comparison between the corrected times series by AC of water level in the reservoir and the uncorrected one. Above) 1995 - 2022, Below) 2007.

The reason that we need the water level in the reservoir is so that the volume of water in the reservoir can be determined. Thanks to a stage-volume curve made after some gauging measurements, it is possible to know for some water level values what is the corresponding volume of water in the reservoir. These values are displayed in yellow in Figure 9.

Two methods were used in order to interpolate volume for the water level that does not have a corresponding volume on the stage-volume curve:

- Linear regression: Blue curve in Figure 9.
- Third degree polynomial fitting: Orange curve in Figure 9 for which the equation was:

$$V = 1.24053066 \times 10^2 H^3 - 1.12828744 \times 10^5 H^2 + 3.42147586 \times 10^7 H - 3.45937567 \times 10^9$$

Figure 9 shows that the differences between using the linear regression or the polynomial fitting are very slim. The effect that it has on the computation of the outflow discharge is shown in section 4.1.

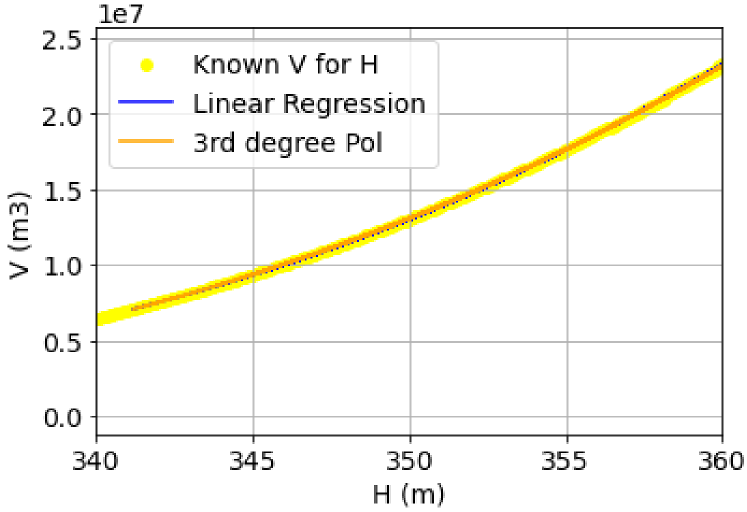


Figure 9: Interpolation via linear regression or via a third-degree polynomial of the height into volume.

2.3.3 Precipitation

The closest rain gauge station from the Eupen reservoir and also the only one in its water catchment is the one of Ternell (Figure 10). Thanks to the SPW, it was possible to have the corrected precipitations measurements from 2002 to 2022 in an hourly time step. since 2002 precipitation values are corrected by the IRM that compares them with their radar information.

Before 2002, there is precipitation data available but they are not corrected. These data were also made available by the SPW from 1996. The SPW also provided us with data from 2010 that were not corrected by the IRM so that the comparison between corrected and uncorrected data was possible.

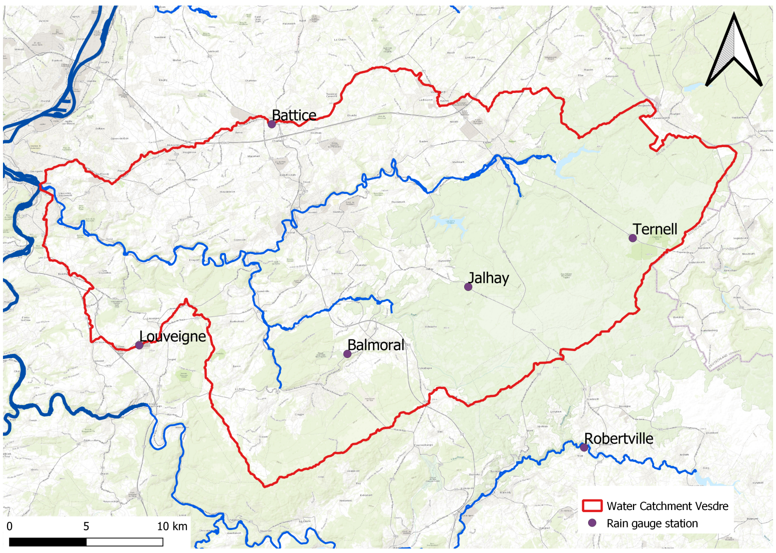


Figure 10: Rain gauge stations that are in and around the Vesdre catchment.

2.3.4 Restitution Discharge of the Vesdre

The SPW provided us with the restitution discharge from the reservoir to the Vesdre river in a hourly time step. The amount of water that was used for the production of electricity is taken into account.

It is known that during High-water periods these data are underestimated. Indeed when the discharge valves are used, the discharged water does not even pass by the restitution basin, it passes over the water level measurement tool and is then not taken into account in the measurements.

2.3.5 Water intake by the SWDE

The main purpose of the Eupen reservoir is to provide water for 400 000 inhabitants [Bruwier et al., 2015]. The water that is pumped by the SWDE is then not negligible.

The SPW provided us with the hourly water intake of the SWDE from 1995 to 2022. These data added to the restitution discharge of the Vesdre should give information about the total outflow discharge from the reservoir.

2.3.6 Summary of available data

Table 2 shows a summary of the data that were available for this research and that are discussed above.

Name	Period	Time step	Comments
Height in the Vesdre Weir (upstream)	1995 - 2022	Hourly	Transformed into discharge via rating curve
Height in the Vesdre Weir (upstream) corrected by AC	1995 - 2015	Hourly	Transformed into discharge via rating curve
Height in the Getzbach Weir	1995 - 2022	Hourly	Transformed into discharge via rating curve
Height in the Getzbach Weir corrected by AC	1995 - 2015	Hourly	Transformed into discharge via rating curve
Height in the Helle Tunnel (exit)	1995 - 2022	Hourly	Transformed into discharge via rating curve
Height in the Helle Tunnel (exit) corrected by AC	1995 - 2015	Hourly	Transformed into discharge via rating curve
Height in the Vesdre reservoir	1995 - 2022	Hourly	Transformed into volume via stage-volume curve
Height in the Vesdre reservoir	2013 - 2022	5 minutes	
Height in the Vesdre reservoir corrected by AC	1995 - 2015	Hourly	Transformed into volume via stage-volume curve
Precipitation Ternell corrected by IRM	2002 - 2022	Hourly	
Precipitation Ternell not corrected by IRM	1995 - 2002	Hourly	
Correction applied Precipitation Ternell	2010 - 2022	Hourly	

Restitution Discharge of the Vesdre	1995 - 2022	Hourly	
Water intake by the SWDE	1995 - 2022	Hourly	

Table 2: Summary of the available data

2.4 Method

2.4.1 filters

At first, the corrected data of Calles [2015] were not available. It was then attempted to correct the noise of the water level data in the reservoir. For that, a filter that we called the "In-house developed filter" was used. Also, corrections made by Calles [2015] are only for the Vesdre reservoir water catchment. It was then tried to find a filter that could correct the data in a way that gives the most similar results possible to the correction of Calles [2015]. The chosen filter is the one of Savitzky-Golay [Savitzky and Golay, 1964]. These two filters are explained below:

- In-house developed filter: The filter was applied on the time series of the hourly water level in the reservoir. First, values that were inferior to 341.1m were set to NaN. When looking at the time series, it did not make sense to have values below that threshold. Then each value was compared to a centered moving median with a window of 30 values. If the absolute difference between the value and the moving median was superior to 0.5m, the value was set to NaN. The value of 0.5 was decided via trial and error. After that, each value that was set to NaN was interpolated linearly. Finally, the filter was applied a second time.

- Savitzky-Golay filter: This filter consists in choosing a window of value and a polynomial degree. A polynomial of the degree chosen will fit the window of data and interpolate them, which allows the smoothing of the time series.

2.4.2 Mass balance

In order to compute the outflow discharge from the reservoir, equation 1 is used. At first, only the inflow discharge (Q_{in}) into the reservoir is known. However, for some levels of water in the reservoir, the volume (V) is known. A linear regression between two points can then be done in order to compute the volume corresponding to any level in the reservoir. Now that the Volume variation is known as well as the inflow discharge, it is possible to estimate an outflow discharge (Q_{out}).

$$\frac{V(t+\Delta t)-V(t)}{\Delta t} = Q_{in}(t+\Delta t) - Q_{out}(t+\Delta t) \tag{1}$$

2.4.3 Flood frequency analysis

In order to compare the return period of flood peaks with and without the dam we used the Pyextremes package [Bocharov, 2022] of Python. First, the annual maximum outflow and inflow were extracted from the time series. The analysis is done over hydrological year, thus from the 1st of October to the 30th of September. The maxima of the outflow time series were checked in order to be sure that they were not due to noise in the computed time series.

Then a generalized extreme value distribution (GEV) was fitted to the annual maximum events. The maximum events that belong to years for which the data are not reliable were removed. According to the comparison made in the paper of Mei et al. [2016], GEV was the best statistical distribution for analysing flood frequency. This is the reason why it was used here. The GEV distribution contains three parameters that need to be fitted: a location parameter, μ; a scale parameter, σ; and a shape parameter, ξ [Coles, 2001].

The Markov Chain Monte Carlo (MCMC) algorithm was used to fit the GEV distribution [Foreman-Mackey et al., 2013]. Then it was made sure that the shape of the return period curve was the same for the inflow and outflow time series in order for them to be comparable. The shape of the return period curve depends on the sign of ξ.

Finally, the quantile and probability plots are displayed in order to assess the fit of the model with the observed values. For both of these graphs the points should lie near the diagonal, if not it is a sign of model failure [Coles, 2001].

3 Data processing

This section aims to explain the analysis and the corrections applied to the inflow discharge data, the water level and the precipitation data. This section is then split into three subsections with respect to these three topics.

3.1 Inflow discharge

In this subsection, first, different ways of estimating the contribution from the ungauged portions of the catchment are detailed (Section 3.1.1). Then the total inflow discharge is evaluated (Section 3.1.2).

3.1.1 Ungauged drained area

Corrections are needed to take into account the water coming from the ungauged drained surface. Two approaches were explored in order to correct for the ungauged drained area:

1. Assuming that the flow rate originating from the ungauged drained area is proportional to the area of the corresponding catchment.

2. Assuming that the rain that falls on the ungauged drained area directly falls onto the reservoir and assuming a runoff coefficient equal to unity.

For both approaches, the total inflow was corrected for the precipitation that falls directly onto the reservoir (Section 3.1.2). It is important to notice that the precipitation from Ternell gauging station has been corrected by IRM since 2002 and they have been available since 1996.

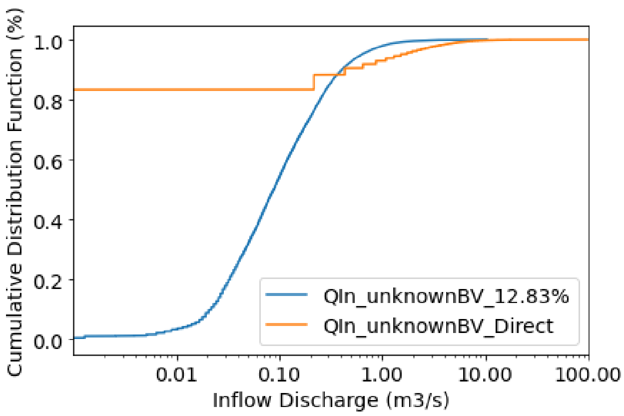
For the first approach, the dynamic of the model is underestimated. Indeed it assumes that the water reaches the lake at a slower pace than in reality. For the second approach, the dynamic of the model is overestimated as there is no lag between the rain falling and the time the water reaches the reservoir. It is therefore believed that the reality lies somewhere between these two approaches. The results are shown with these two approaches, to provide an envelope.

Figures A.3 and A.4 show the time series of the corrected inflows discharge according to the two approaches. When looking at these Figures we can see that when we consider that the rain reaches directly the reservoir, there is discharge only for the hours that it rains. This approach is referred to as direct precipitation (directPrec) in the thesis. When we consider that the discharge is proportional to the area of the sub-basin, for every hour there is water flowing into the reservoir, it is not an on/off situation. Therefore the recharge of the reservoir is more gradual and the peaks are lower for this approach than for the approach that considers that the precipitation reached directly the lake. This last approach is referred to as proportional surface area (propSA) in this thesis.

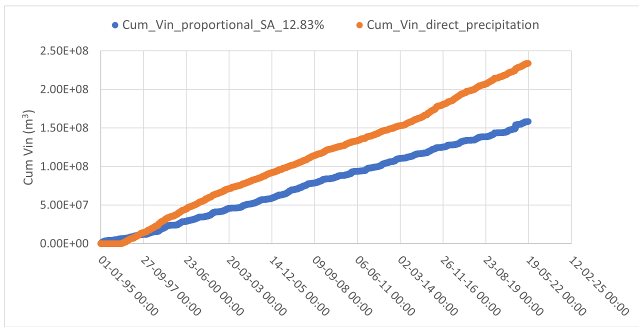
Figure 11a shows the cumulative distribution function of the inflow discharges coming from the ungauged sub-basin computed according to both approaches. It shows that for the approach assuming that the precipitations reach directly the reservoir, 83% of the data is below 0.001 m^3/s whereas, for the approach where the discharge is proportional to the area of the sub-basin, only 0.4% of the data are below 0.001 m^3/s. However, the discharge reaches more important values for the "Direct" approach than for the "Proportional" one. Indeed the maximum value of the "Direct" approach is 97.53 m^3/s against 10.41 m^3/s for the "Proportional" one.

Figure 11b shows the cumulative volume that entered the reservoir from 1995 to 2022 according to both approaches. According to this graph, after 27 years, there is 30% more water that flowed into the reservoir with the "Direct" approach than with the "Proportional" one. With the "Direct" approach, a runoff coefficient of one was chosen, this means that all the water from the precipitation reaches the lake.

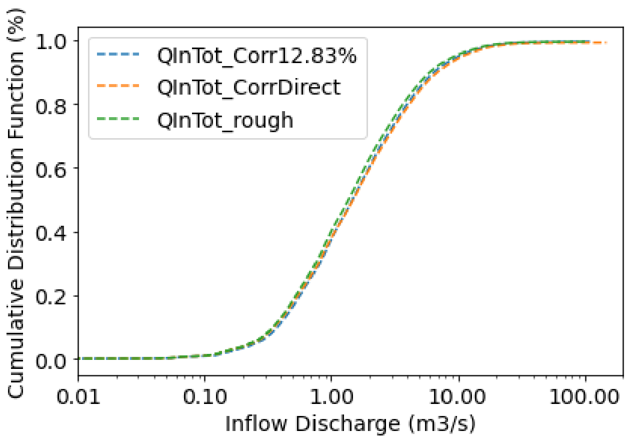
Figure 11c shows the cumulative distribution function of the total inflow discharge if it is not corrected for the ungauged sub-basin and if it is corrected according to the two different approaches. As expected, this Figure shows that not taking the ungauged sub-basin into account gives smaller values of inflow discharge. For total inflow discharge under 1.5 m^3/s the total Qin corrected with the "Proportional" approach is higher than the one corrected with the "Direct" approach. For values above 1.5 m^3/s, it is the opposite.



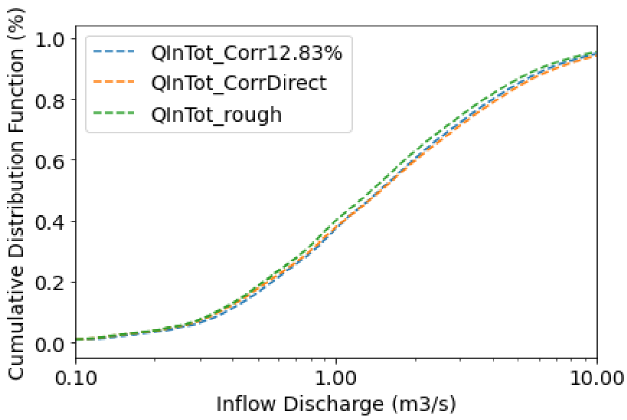
(a) Cumulative distribution function for the Qin, coming from the ungauged catchment, corrected considering the two approaches.



(b) Cumulative volume into the reservoir from the ungauged catchment considering the two approaches from January 1995 to April 2022.



(c) Cumulative distribution function for the total inflow discharge corrected considering the two approaches and not corrected.



(d) Zoom of subfigure c

Figure 11: Comparison between both approaches for handling contributions from ungauged portions of the catchment: 1) The inflow discharge is proportional to the area of the water catchment (Blue), 2) The precipitation that falls into the ungauged drained area falls directly onto the reservoir (Orange). The not corrected total inflow discharge is shown in green (c,d).

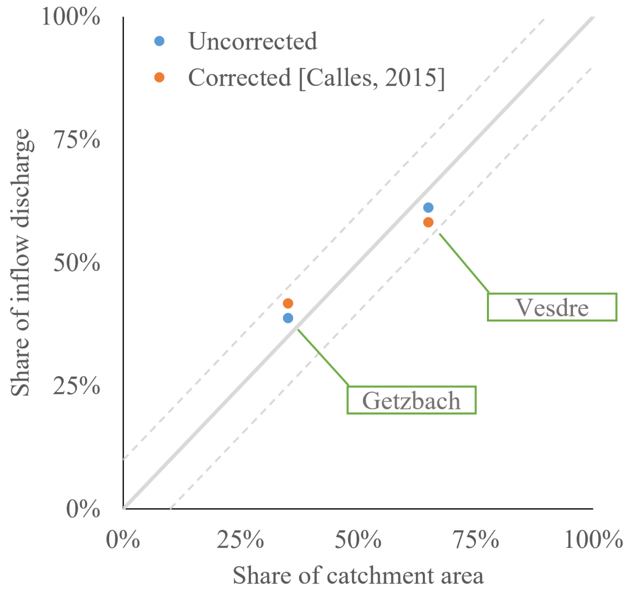


Figure 12: Percentage of the area of the Vesdre and Getzbach sub-catchments, compared to the percentage of cumulative inflow volume into the reservoir from these sub-catchments

Figure 12 compares the inflow from the upstream of the Vesdre into the reservoir with the inflow from Getzbach to the reservoir. The goal is to see if the inflow is proportional to their area in order to discuss the validity of assessing the hourly discharge based on the area of the ungauged catchment. When looking at the uncorrected data, it can be seen that if we take only into account the Vesdre and the Getzbach, 61% of the inflow comes from the Vesdre and its catchment accounts for 65% of the two catchments. Comparing the cumulative volume over a long period with the catchment area showed that it is a realistic assumption to say that the inflow is proportional to the catchment area. Whereas if we take into account the inflow discharge corrected by Calles [2015] only 58% of the inflow discharge comes from the Vesdre. The values are then slightly further apart but not enough to question the validity of the assumption that the inflow is proportional to the catchment area.

Figure 13 displays the inflow discharge from the Getzbach and from the Vesdre, both normalized with respect to the area of their respective catchments. If the discharge were exactly proportional to the area of the water catchment, there would be a perfect superposition of the two lines. It can be seen that the normalized inflows are never very different from each other. However there are no regular patterns, indeed sometimes the normalized inflow of the Getzbach is higher than the one of the Vesdre and sometimes it is the opposite. Also, the peak can be at the same time or an hour earlier or later when comparing both normalized inflows. Figure 13 shows four representative events (see Figure A.5 for all major events).

Figure 14 shows the ratio of the normalized inflow discharge of the Getzbach with the normalized inflow discharge of the Vesdre as a function of time. This Figure allows us to quantify the difference between both normalized inflows. In this Figure, when the ratio is above one it means that the Getzbach has a higher runoff (discharge per area of the catchment) than the Vesdre. We can see that the ratio tends to stay around 1 for most of the event. Table 3 shows the percentile 90 for each event of the ratio between the normalized inflow of the Getzbach and the Vesdre (G/V, corresponds to the graphs in Figure 14) and vice-versa (V/G). When looking at the ratio V/G, 17 out of 18 events have 90% of their value below 2.0. When looking at the ratio G/V, it is 12 out of 18 events that have their percentile 90 below 2.0.

Figure 15 shows the average between the two normalized inflows as a function of the ratio of the Getzbach inflow by the Vesdre inflow. The aim of this Figure is to see if the quotient stays around 1 or not. This Figure shows that 65% of the data have a quotient between 0.5 and 2 (red lines) and that 88% of the data have a quotient between 0.25 and 4 (green lines).

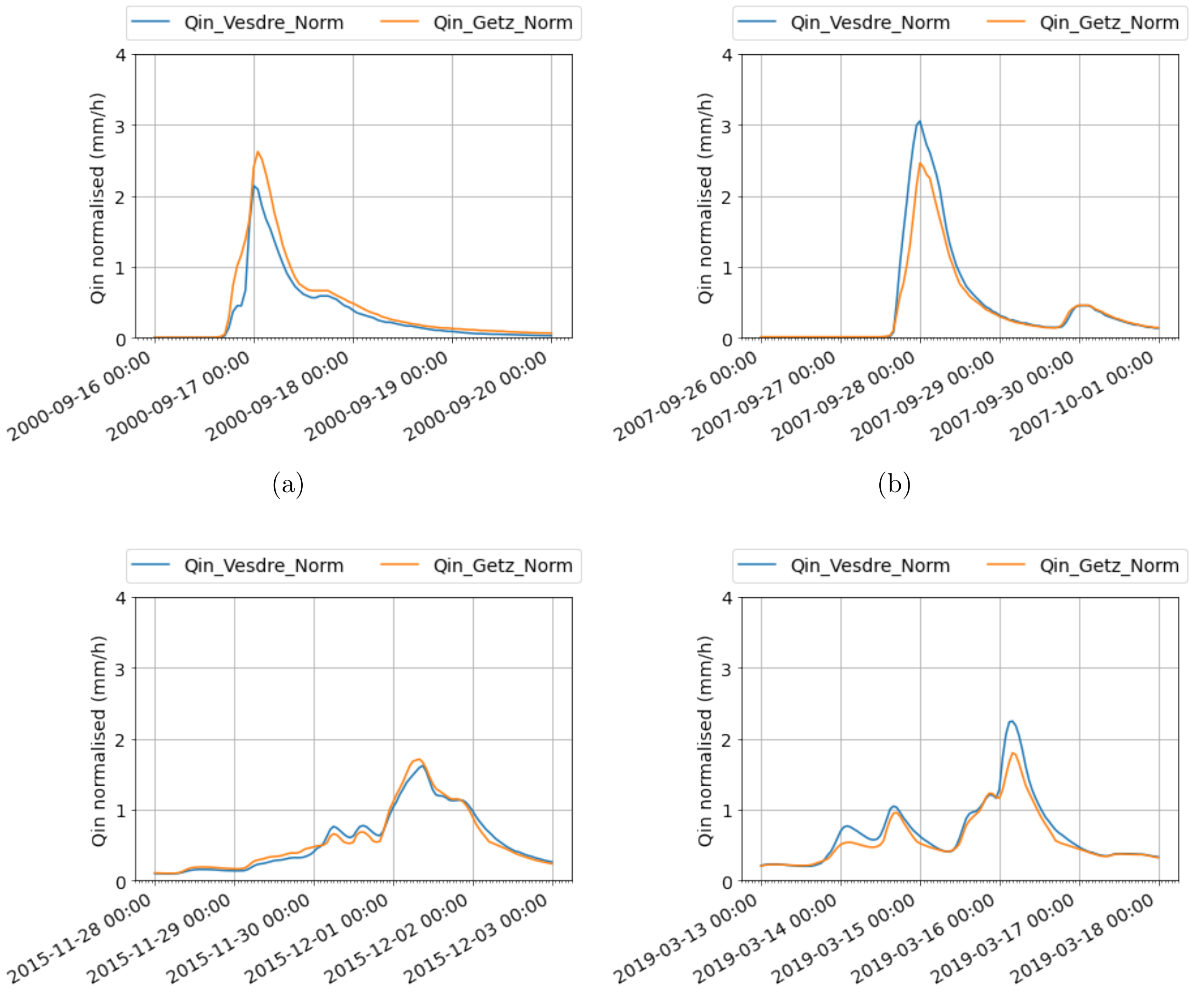
Figure 16 shows the normalized inflow from the Getzbach as a function of the normalized inflow from the Vesdre for the period 1995 to 2015, 2015 to 2022 and 1995 to 2022. The first period corresponds to the period for which the data were corrected by Calles [2015]. The second period is the period for which the data were not corrected but the DGH has been closely collaborating with the Dam management section and hence the data are of better quality.

The outlier points are highlighted and their periods are specified above the graph. From the three periods to which the outlier points belong, there is only one that corresponds to a major event, it is from 14-07-2021 to 19-07-2021. It is known for sure that the data of this period are not reliable because pieces of equipment were damaged during the flood.

Figure 16 shows that for most of the data points for the period between 2015 and 2022, the normalized inflow discharge of the Getzbach and the Vesdre fall within the ± 10% interval of the 1:1 line which is less the case for the period between 1995 and 2015 but the normalized inflow are still relatively close from each other.

Start Date	**Perc90 ratio V/G**	**Perc90 ratio G/V**
1995-01-21	0.79	2.53
1998-09-13	0.89	2.41
1999-02-19	1.58	1.28
2000-09-16	0.86	2.47
2004-01-19	1.05	1.27
2006-05-25	0.97	1.24
2007-08-20	1.16	2.11
2007-09-26	1.20	1.44
2011-01-12	1.56	1.43
2014-07-07	1.11	1.48
2015-11-28	1.16	1.25
2016-02-20	1.27	1.14
2016-05-30	1.23	1.05
2018-05-29	3.06	1.80
2019-03-13	1.28	1.02
2021-01-27	1.62	0.93
2021-07-14	1.12	8.42
2022-02-04	1.16	2.32

Table 3: Percentile 90 for the ratio between the normalized inflow of the Vesdre and the Getzbach (V/G) and vice versa (G/V).



(a) (b) (c) (d)

Figure 13: Comparison between the inflow discharge from the vesdre and the inflow discharge from the Getzbach, both normalised with respect to the area of their water catchment for four extreme events (These data were corrected by Calles [2015] before 2015, see Figure A.5 for all major events).

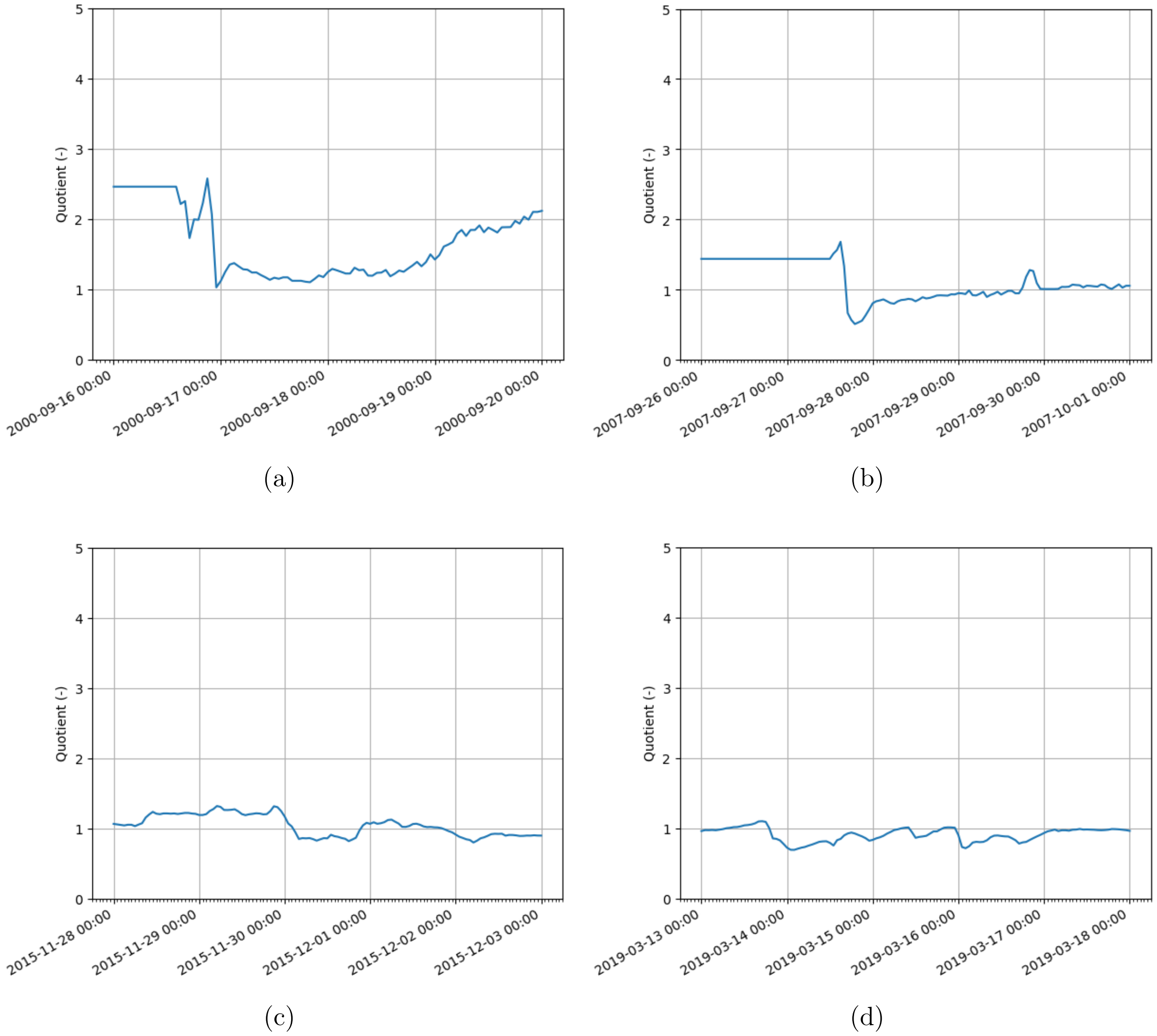


Figure 14: Ratio between the normalized inflow discharge of the Getzbach and the normalized inflow discharge from the Vesdre. For the graph of each event see Figure A.6.

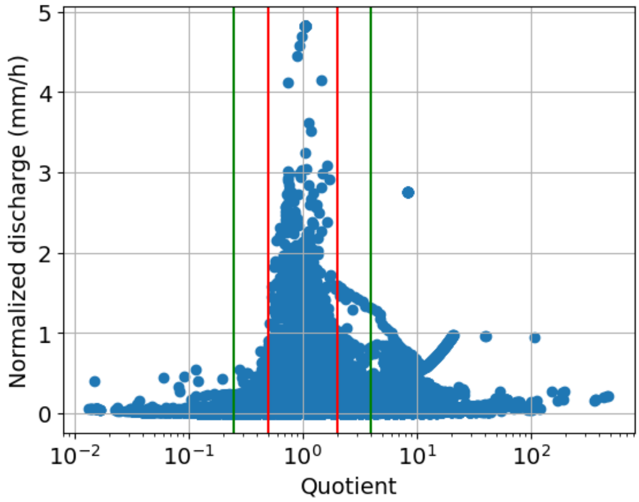


Figure 15: Ratio between the normalized inflow discharge of the river Vesdre and Getzbach function of the average between the normalized inflow discharge of these two rivers. The data used are the hourly data from 1995 to 2022.

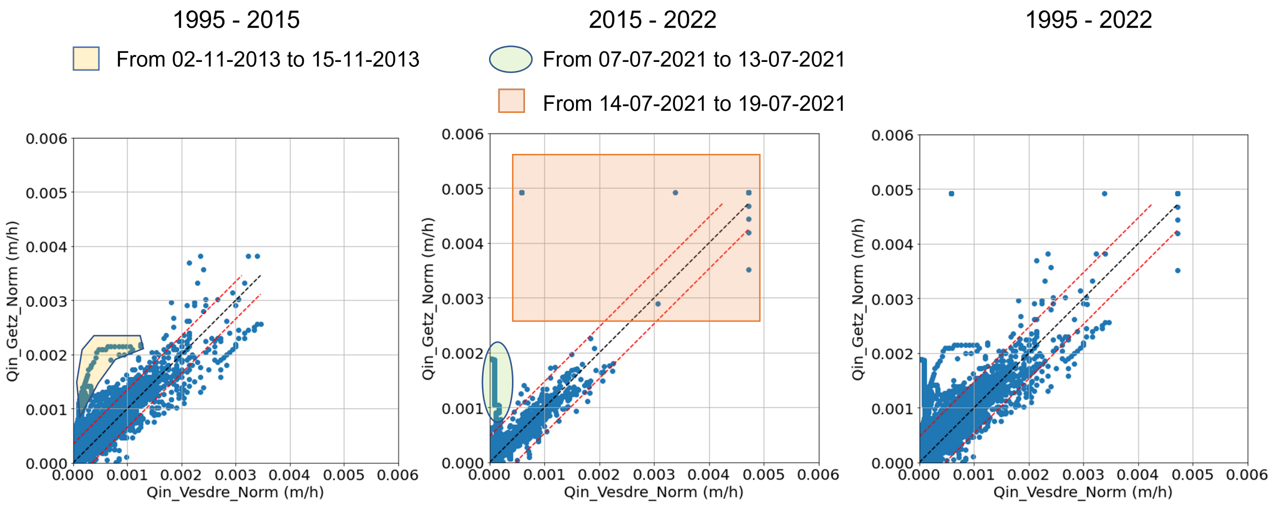


Figure 16: Normalised inflow discharge from the Vesdre VS normalized inflow discharge from the Getzbach.

3.1.2 Total inflow discharge

Two total inflow discharges were computed, one that considers that the inflow discharge going into the reservoir is proportional to the area of the sub-basin (equation 2) and the other that considers that the rain falling onto the ungauged sub-basin reaches the reservoir directly (equation 3). These two approaches are better explained in the previous subsection.

The major events labeled in Figure 17 are the ones for which the total inflow discharge is equal or superior to $50 m^3/s$. Thanks to the IRM website it was possible to confirm that these events correspond indeed to officially registered calamities (Table A.1). This Figure shows 15 major events, in this thesis, we will usually speak of 18 major events. Indeed, 3 events that happened after 2015 and that have an inflow discharge slightly lower than $50 m^3/s$ were added. These events are 21-02-2016, 28-01-2021 and 06-06-2022.

In order to correct for the precipitation that falls directly onto the reservoir, the precipitation data from the Ternell gauging station were used. Knowing the area of the reservoir, and the millimeters of precipitation per hour, it was easy to transform them into discharge (m^3/s) (Figure 18). The same method was used for computing the discharge from the precipitation falling onto the ungauged water catchment (equation 3), except that we used the surface of the ungauged water catchment and not only the lake.

The area of the reservoir is 126 ha according to ministère des Travaux Publics et al. [1986] so it was the value taken for the computation. It is important to notice that the surface of the reservoir is level dependent and that this was not taken into account when computing the discharge from the precipitation falling directly onto the lake. In the appendix (Section A.8), an analysis is made on the effect of taking into account the level dependency of the reservoir area or taking a fixed surface of 126 ha.

$$Q_{\text{in Vesdre reservoir propSA}} = Q_{\texttt{in Helle}} + Q_{\texttt{from precipitation lake}} + (Q_{\texttt{in Vesdre}} + Q_{\texttt{in Getzbach}}) \times \frac{100}{87} \quad (2)$$

$$Q_{\text{in Vesdre reservoir directPrec}} = Q_{\texttt{in Helle}} + Q_{\texttt{from precipitation ungauged area}} + Q_{\texttt{in Vesdre}} + Q_{\texttt{in Getzbach}} \quad (3)$$

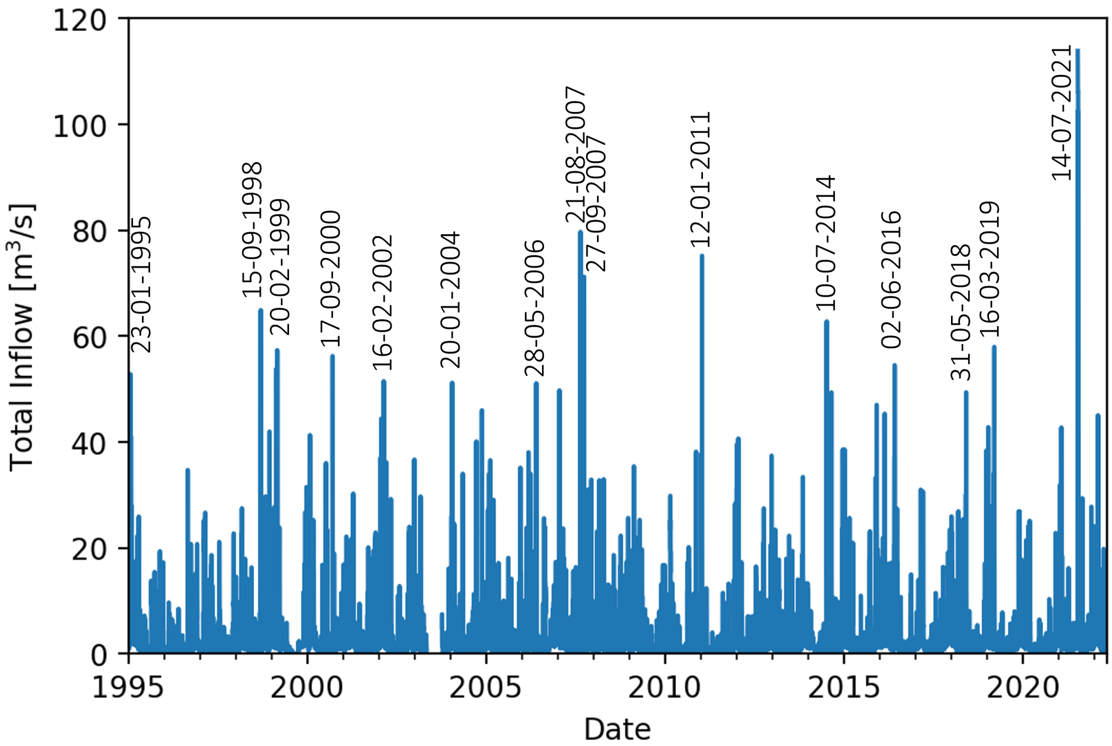
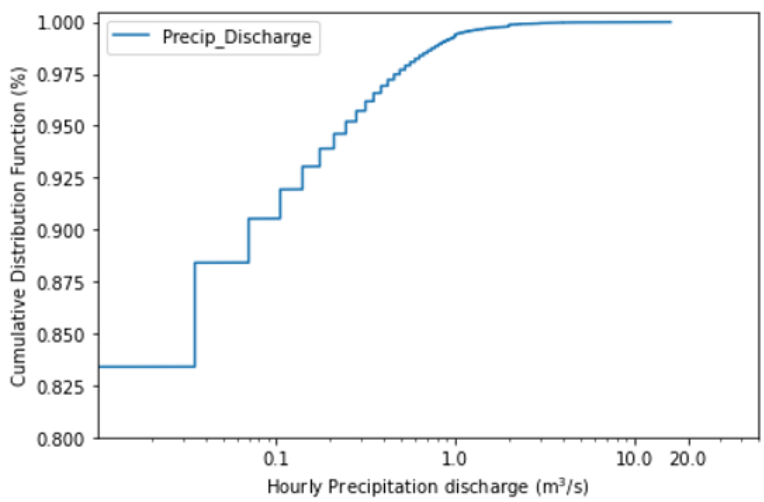


Figure 17: Total inflow discharge into the Vesdre reservoir computed via equation 2.



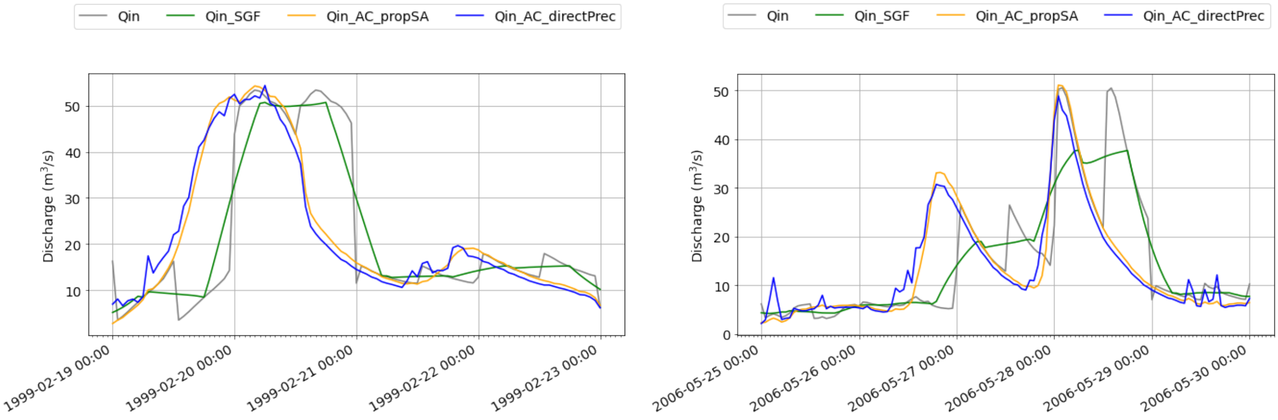
30-05-2003 19:00	29-05-2008 07:00	29-06-2005 15:00
16 m^3/s 44.9 mm	13 m^3/s 36.9 mm	10 m^3/s 29.3 mm

Figure 18: "Value of precipitation falling directly onto the reservoir surface from 2002 turned into discharge. The table displays the three highest values.

3.1.3 Filtering uncorrected inflow discharge data

At first, it was decided that the goal of this thesis would be to naturalize the catchment of the Vesdre and the Gileppe reservoir. However, the data linked to the Gileppe reservoir for the period before 2015 were not corrected by anybody and therefore the results were unreliable. It is for this reason that it was attempted to use a Savitzky-Golay filter on the total inflow discharge in the Vesdre reservoir in order to obtain data that are close to those corrected by Calles [2015]. A window of 11-time steps and a polynomial of the first degree were chosen. These settings were chosen after some trial-error attempts. Taking a polynomial of degree two or three led to negative inflow discharge values, therefore a polynomial of degree one was preferred.

Figure 19 shows the correction made on the inflow discharge for the events of February 1999 and May 2006 (see Figure A.8 for all events before 2015. Indeed after 2015, the inflow discharge data do not need correction). We can see that for most of the events the Savitzky-Golay filter reduces the main peak. This method for correcting the inflow discharge data is then not ideal because it underestimates the major event peaks.

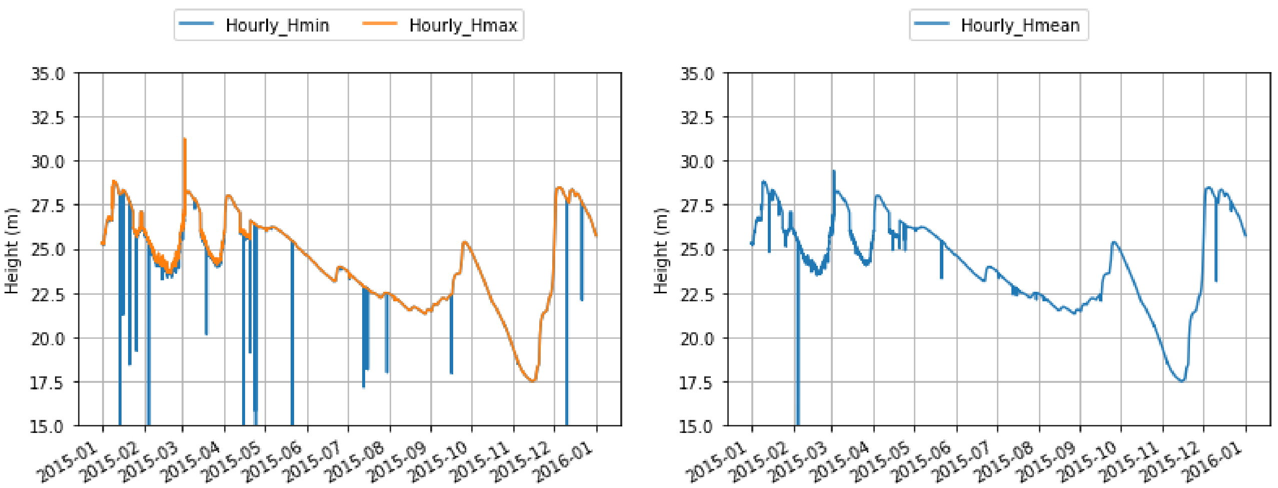


(a) (b)

Figure 19: Qin not corrected (Qin), Qin corrected by Calles [2015] (Qin_AC) and Qin corrected by the Savitsky-Golay filter (Qin_SGF) for the event of February 1999 and of May 2006. For all events see Figure A.8.

3.2 Reservoir water level

In this subsection, first, we compare the fact to take an hourly average with respect to taking the hourly minimum or maximum of the 5-minutes water level data (Section 3.2.1). Then we explain and compare the different ways of correcting the water level data (Section 3.2.2).



(a) The maximum water level per hour (blue) and the minimum water level per hour (orange).

(b) The average water level per hour.

Figure 20: Average, the minimum and the maximum hourly Water level in the Vesdre reservoir from January 2015 to January 2016.

3.2.1 Analysis of the minimum and the maximum water level over an hour

The water level data that are used, represent the hourly average of data that were taken every 5 minutes. Figure 20 shows that the noise is higher if the minimum value of each hour were taken whereas the noise is significantly reduced if the maximum value of every hour is taken. Taking the average reduces the noise but not as much as taking the maximum value. Figure 20a shows that there is not a large difference between the maximum hourly value and the minimum hourly value. The main difference is that by taking the maximum hourly value, the abnormal low values are not considered. The five minutes water level data in the Vesdre reservoir is available only since august 2013. Before this date, only the hourly average was stored.

3.2.2 Corrections

Figure 22 shows various corrections that were applied to the water level in the Vesdre reservoir. From this image, it can be seen that the correction made by Calles [2015] are the best of all. Indeed the downward peaks are totally removed. In Figure 22, it seems that the Savitzky-Golay filter is less good than the house filter, but when looking at Figure 23, it is obvious that the Savitzky-Golay filter allows a better smoothing of the data. Figure 23 shows the correction made on the water level in the reservoir for the events of February 1999 and May 2006. See Figure A.9 for all events before 2015.

Figure 21 compares the water level in the reservoir with and without the corrections made by Calles [2015]. We can see that most of the corrections were made in order to raise the too low water level as we can see in Figure 22, where there is a sudden important drop off of level water (± 20m). However, it was not the only correction made. Indeed, Figure 21 shows that sometimes the data were lowered or raised by a small amount (maximum 5m).

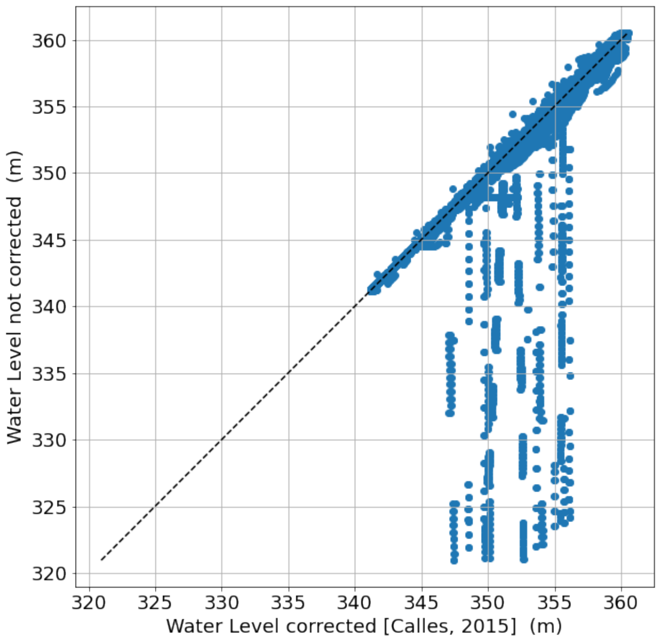


Figure 21: Comparison between the water level in the reservoir corrected [Calles, 2015] and not corrected for the period 1995 to 2015.

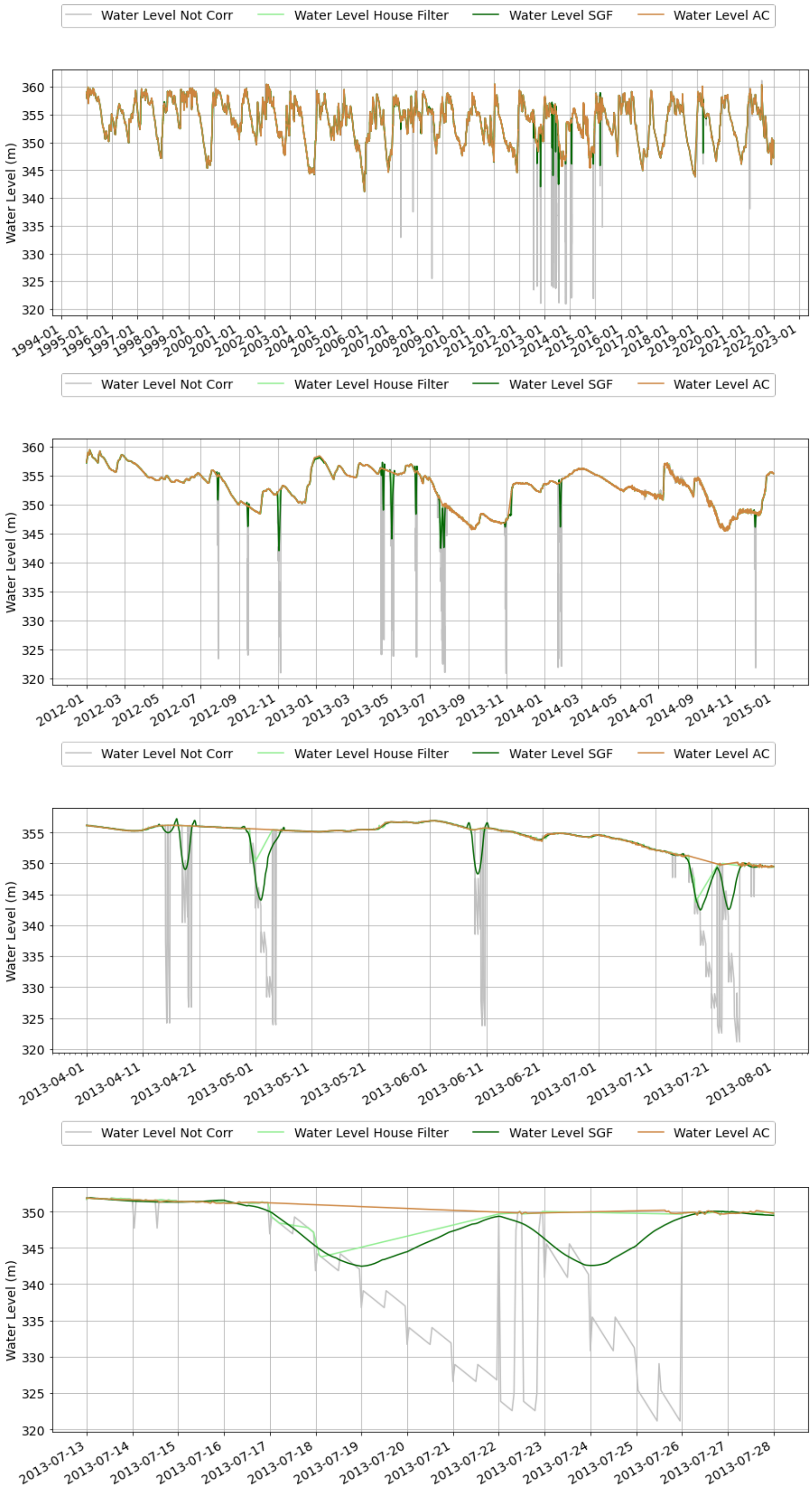


Figure 22: Water level in the reservoir without any correction (gray), corrected via the house filter (light green), corrected by Calles [2015] (brown) and corrected via the Savitzky-Golay filter (dark green). The top image shows it for the period of 1995 to 2022 and then the following images zoom on smaller and smaller periods.

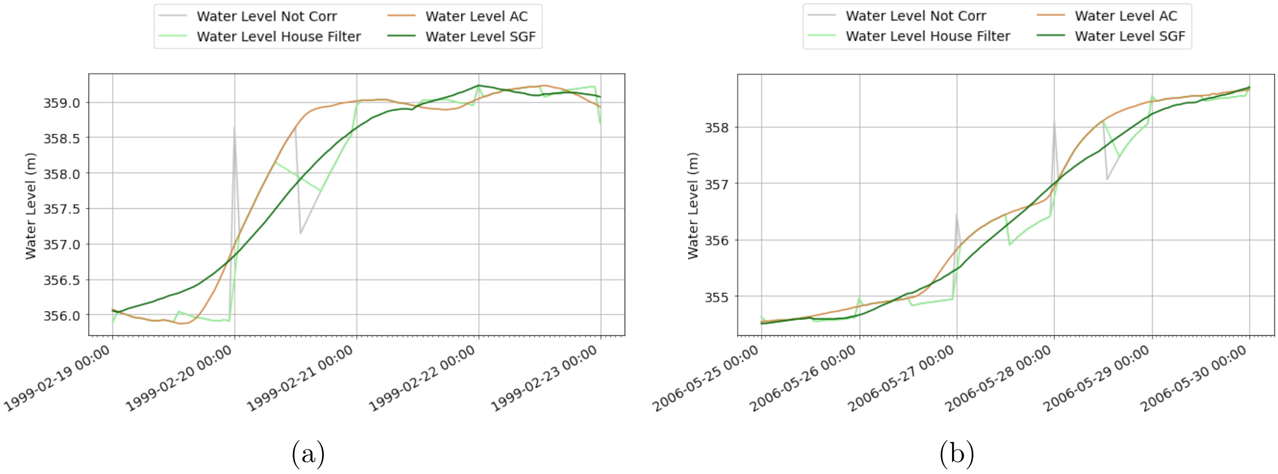


Figure 23: Water level in the reservoir without any correction (gray), corrected with the house filter (light green), corrected by Calles [2015] (brown) and corrected with the Savitzky-Golay filter (dark green) for the event of February 1999 (a) and of May 2006 (b). For all extreme events see Figure A.9.

3.3 Precipitation

From the year 2002, the precipitation data of the Ternell rain gauge were checked and corrected by the IRM. It is then with confidence that the inflow discharge data are corrected with the precipitation that falls directly onto the lake from this year. However, these precipitation inputs should also be added for the years between 1996 and 2002. This section analyses if there is an important difference between the corrected and the uncorrected precipitation data. It was possible to have these two sets of data only from the year 2010.

Figure 24 shows the cumulative precipitation over 12 years (a) and the cumulative distribution over 12 years for three sets of data:

- Blue (a: Cum_source_NA_0, b: Precip_source): The uncorrected precipitation for which the NA value were turned into 0;
- Orange (a: Cum_corr, b: Precip_corr): The precipitation that was corrected by the IRM;
- Green (a: Cum_corr_Ifsource_NA_0, b: Precip_corrModif): The precipitation that was corrected by the IRM for which, when the source date was equal to NA, the corrected data was changed to 0. This allows us to see if the difference between the corrected data and the source data only comes from data with NA values.

Figure 24 shows that the source data have more nul and poor values. Apparently, the source data also have higher extreme values. This means that when looking at such an extended period there is a compensation between the corrected and the source data on the cumulative precipitation. The relative error between the source and the corrected data at the end of the 12 years is 0.8%. It is not easy to conclude anything when analysing the data over 12 years.

Figure 25 shows the relative error between the source cumulative data and the corrected cumulative data for the months of summer and winter. The period of summer takes into account the months from April to September and the period of winter the months from October to March. The relative error (RE) compares only the last data at the end of the cumulative curve.

$$RE = \frac{Source - Corrected}{Corrected} \times 100$$

From Figure 25, it is obvious that the corrections in summer have less impact than in winter. This makes sense because the frequency of precipitation is less in summer than in winter. This Figure also shows that the corrections tends to increase the values of the source data.

Figure 26 shows the cumulative precipitation as well as the cumulative distribution function of precipitation over the months of winter and over the months of summer for the year 2016-2017. From this figure, it is obvious that for this year the corrections in summer are less important than in winter. Figure 26a allows us to see that the difference between the source data and the corrected are not only due to the non-available data.

We can conclude that the IRM corrections on the source data tend to increase the value of the source data. This makes sense because the source data contains more NA values. The corrections do not only aim to correct NA value though. For the purpose of our study, it seems that we can use the source data of precipitation for the years 1996 to 2002, as the source data are reasonable. Also, as seen in Figure 18, for more than 98% of the data, the precipitation only participates for 1 m^3/s or less in the hourly total inflow discharge.

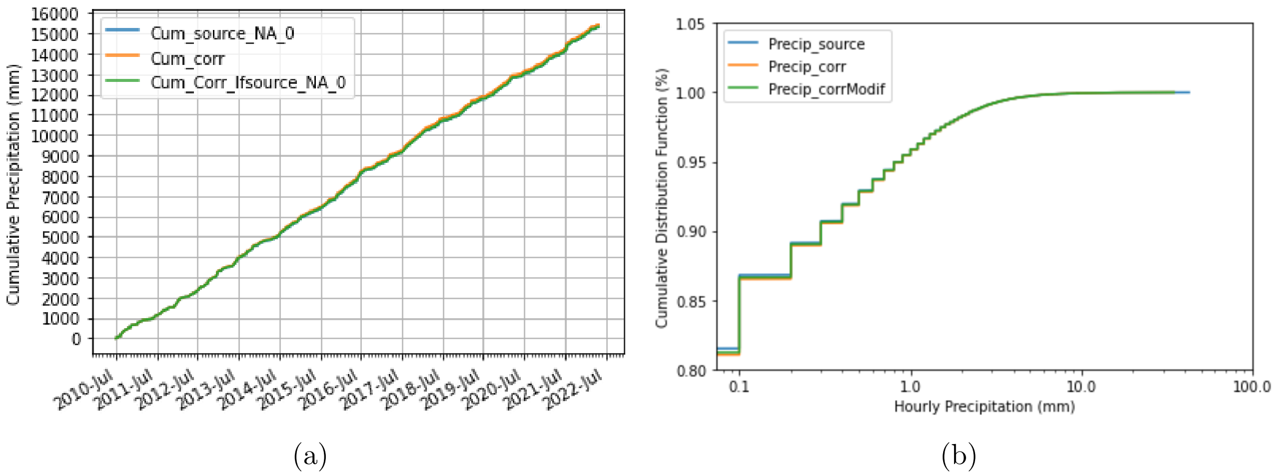
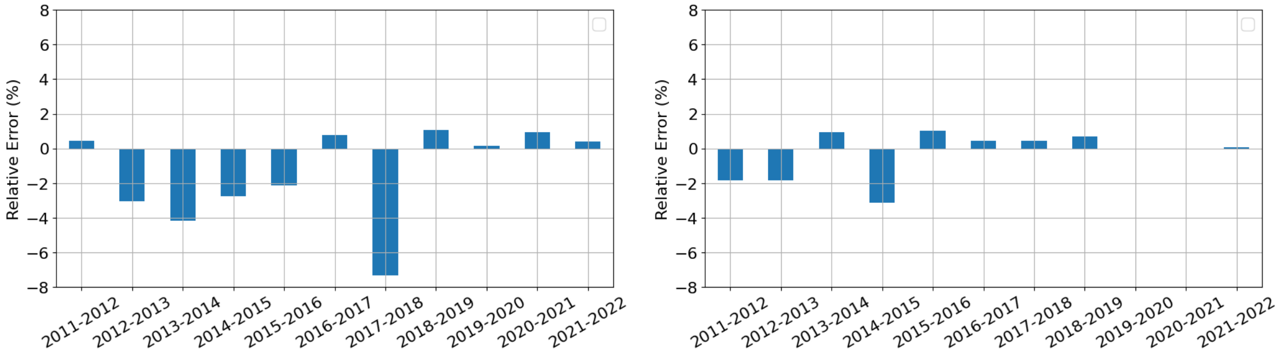
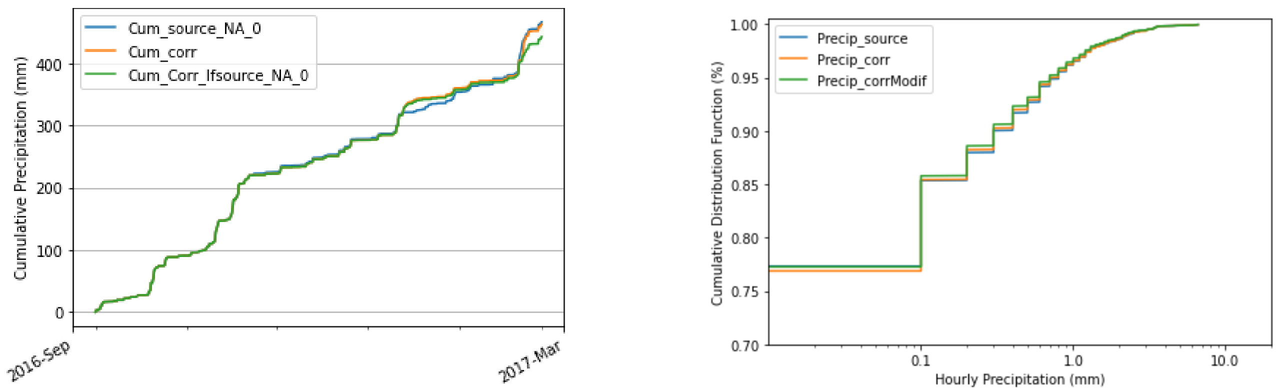


Figure 24: (blue) The uncorrected precipitation for which the NA values were turned into 0, (Orange) The precipitation that was corrected by the IRM, (Green) The precipitation that was corrected by the IRM for which when the source date was equal to NA, the corrected data was changed to 0. Graph (a) shows the cumulative precipitation and (b) the cumulative distribution function over 12 years.

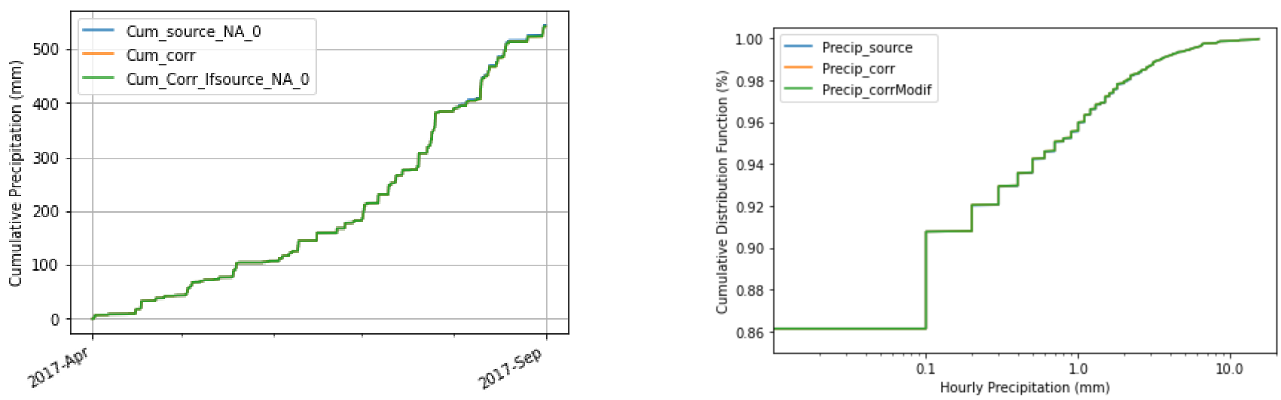


(a) Winter (b) Summer

Figure 25: Relative error (%) at the end of each winter (a) and summer (b) from the year 2011-2012 to the year 2021-2022.



(a) Winter (b) Winter



(c) Summer (d) Summer

Figure 26: (blue) The uncorrected precipitation for which the NA values were turned into 0, (Orange) The precipitation that was corrected by the IRM, (Green) The precipitation that was corrected by the IRM for which when the source date was equal to NA, the corrected data was changed to 0. For the year 2016-2017 (a) is the cumulative precipitation over winter (b) is the cumulative distribution function of precipitation during winter (c) is the cumulative precipitation over summer (d) is the cumulative distribution function of precipitation during summer.

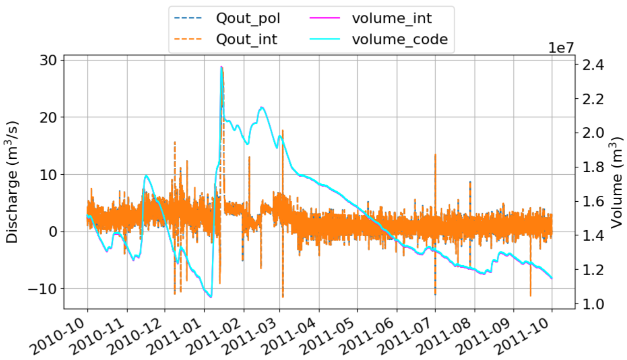
4 Results and discussion

4.1 Effects of Third-degree polynomial fitting VS linear interpolation of the stage-volume curve on the outflow discharge results

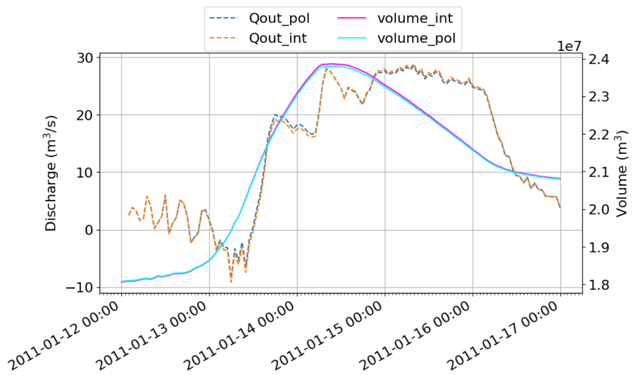
As seen in the next section, the result time series of the outflow discharge is noisy. This is partly due to the data on variation in water level in the reservoir. It was then believed, that the way of interpolating the stage-volume curve could have an influence on the shape of the outflow discharge curve. As explained in section 2.3.2, two methods were attempted: Linear regression and third-degree polynomial fitting.

Figure 27a shows the outflow discharge that was computed with the volume linearly interpolated or fitted via a third-degree polynomial and the time series of the volume of water in the reservoir interpolated via the two methods for the hydrological year 2010-2011. This Figure shows no obvious differences between the discharge computed via the two methods. Figure 27b shows a zoom on the event of January 2011. This zoom shows only slight differences in the discharge computed with the two methods and no changes in the amount of noise in the time series. Figure A.10 shows the results for each event.

As the outflow discharge computed with the two methods is very similar, linear interpolation is the one chosen in the rest of the thesis.



(a) 2010 - 2011



(b) Zoom on event of January 2011

Figure 27: Time series of outflow discharge computed with the volume linearly interpolated or fitted via a third-degree polynomial.

4.2 Outflow discharge computed with different filters or data sets

Figure 28 displays the time series of computed outflow discharge for the raw data set, the raw data set filtered with the in-house developed filter, the raw data set filtered with the Savitzky-Golay filter and the data set corrected by Calles [2015] from 1995 to 2015 and then filtered by the In-house filter from 2015 to 2022. As detailed in Section 3.1.1, two correction approaches were used on her data set in order to rectify the unknown contribution of a part of the water catchment; the corresponding discharge was assumed either proportional to the area of the ungauged catchment (propSA) or the precipitation falling on the catchment was assumed to directly reach the lake (directPrec).

In this Figure, it is obvious that from April 2015, there is less noise in the raw data. It is from this time that the Direction of Hydrology management of the SPW started collaborating with the Dam management section, as a result, the data measured are of better quality.

The corrections implemented by Calles [2015] reduce significantly the noise in the outflow discharge compared to the outcomes of computations based on the raw data. However, it seems that the "directPrec" time series shows a lot more noise than the 'propSA' time series. This is due to the fact that there will be higher discharge for the 'directPrec' than for the 'propSA' time series days when it rains and vice versa for days when it does not rain.

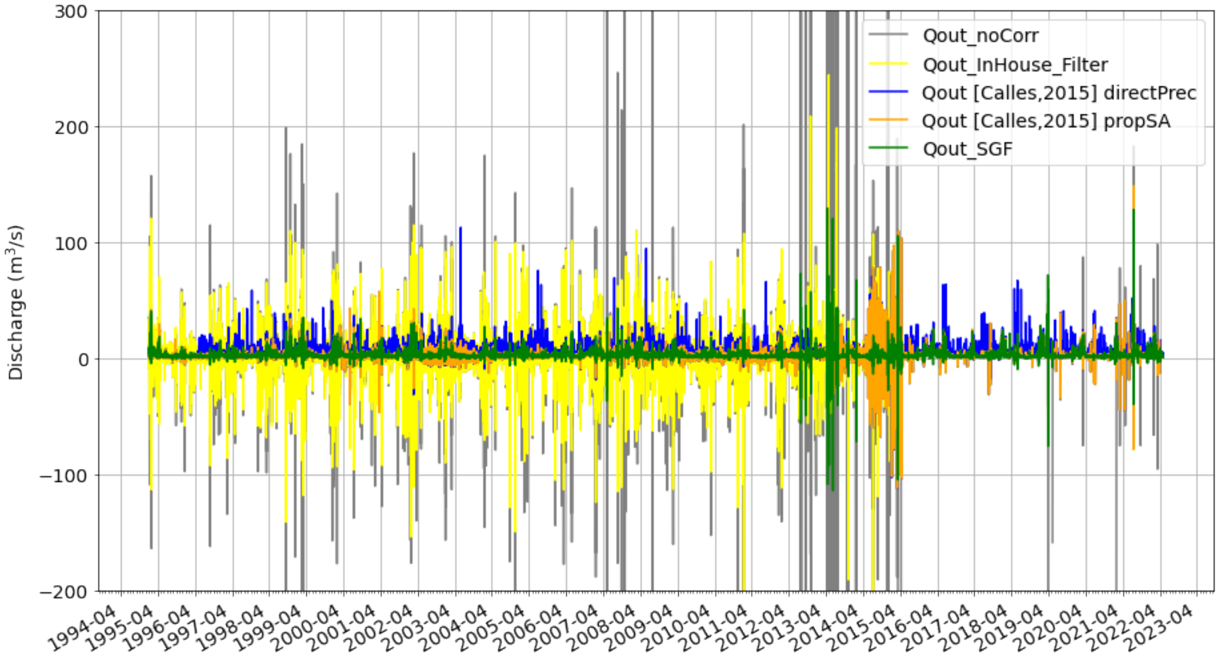


Figure 28: Time series from January 1995 to May 2022 of the outflow discharge computed via the raw data, the data corrected by Calles [2015] with the two approaches for correcting Qin, the data corrected with the In-House filter and the data corrected with the Savitzky-Golay filter. There is a zoom on the y-axis for the complete figure see Figure A.11.

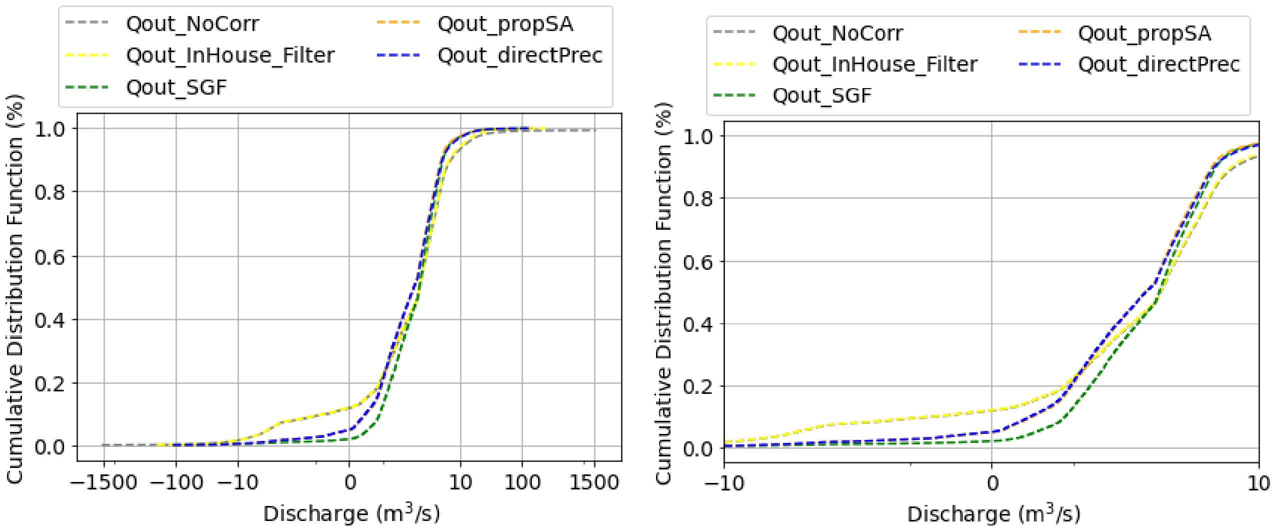
Figure 29 shows that the corrections of Calles [2015] decrease the percentage of negative value from 12% to 5%. Also, it reduces the extreme negative and positive values. Indeed the minimum outflow discharge value went from -1624.4 to -112.0 (propSA) and to -112.5 (directPrec) m^3/s and the maximum outflow discharge value went from 1594.8 to 147.9 (propSA) and to 138.8 (directPrec) m^3/s. Negative values here are still unphysical, but it is progress. A maximum outflow discharge of 1594.8 m^3/s has absolutely no sense as the maximum outflow discharge possible is of 300 m^3/s [ministère des Travaux Publics et al., 1986]. Even if the data were corrected until 31-12-2014, the time series still shows a lot of noise from April 2014 to April 2015. So the time series computed in this time interval are less reliable.

The negative values come either from the fact that the total inflow discharge is underestimated and therefore cannot totally explain the increase in the volume of water in the reservoir, or it comes from the data on the water level in the reservoir, that shows a bigger increase of water level than in reality.

The In-house developed filter reduces the noise in the raw data by reducing the value of the extreme values but does not decrease the percentage of negative values. The minimum outflow discharge value went from -1624.4 to -206.2 m^3/s and the maximum outflow discharge value went from 1594.8 to 243.9 m^3/s. These new values make more sense than the ones computed with the raw data set but are still less good than the ones obtained by Calles [2015].

The Savitzky-Golay filter reduces the noise of the time series even further than the correction of Calles [2015]. The minimum outflow discharge value went from -1624.4 to -114.4 m^3/s and the maximum outflow discharge value went from 1594.8 to 128.9 m^3/s. It also decreases the percentage of negative values from 12% to 2%.

It seems that the best computed outflow discharge to take into account is either the one corrected by Calles [2015] or the one filtered with the Savitzky-Golay filter. It makes more sense to take the one computed by Calles [2015] as it was a targeted correction made manually on the time series for different justified reasons whereas the Savitzky-Golay filter is automated for the only purpose to reduce the noise of the time series. Also, the Savitzky-Golay filter is used in order to see if it can correct the outflow discharge result obtained from the raw data set in order to be closed from the outflow discharge obtained via the correction of Calles [2015].



(a) (b) Zoom

Figure 29: Cumulative distribution function for the outflow discharge computed with different filters: No Correction, Correction by AC before 2015 then In-house developed filter after 2015 for Qin corrected as discharge proportional to water catchment and for Qin corrected with direct precipitation, correction with Savitzky-Golay filter and correction with In-house developed filter.

4.3 Comparison of the computed outflow discharge with the measured restitution discharge and the SWDE intake

The purpose of this section is to compare the outflow discharge computed via the corrected data sets of Calles [2015] and the sum of the measured restitution discharge and the intake discharge by the SWDE. This allows a validation of the computed data. However, it is important to keep in mind that the measured restitution data are not 100% reliable as explained in section 2.3.4.

Figure 31 displays the cumulative distribution function for the observed data (SWDE+REST) and the computed ones (AC). In the computed outflow discharge there are 12% of negative values when there are none in the observed data which is not surprising. This Figure also shows that the computed data contains higher discharge values. Indeed there are 90.82 % and 89.76 % of the values that are below 5 m$^3/s$ for the computed data respectively 'propSA' and 'directPrec' against 97.34 % for the observed values.

Figure 30 shows the three time series for four events, the other events are shown in Figure A.12. What is striking when looking at these time series is that for most of the major events, the trends are the same for both time series but the one showing the restitution discharge + the SWDE intake, is always underestimating the discharge compared to the one computed with the data of Calles [2015]. This could be explained by the fact that for major events, when the discharge valves are used, the water does not pass by the restitution basin and then the measure is flawed. The underestimation is more important for some events than it is for others. One possible theory is that it depends on which valve is used, as these valves are never used together. It is however not possible for now to test that theory because there are no records of the valves management.

Figure 32 shows the ratio between the computed and observed values for each data point of four events (the other events are displayed in Figure A.14). In this Figure, it is obvious that the observed data are most of the time lower than the computed ones. Table 4 displays the mean ratio and the median ratio for each event. When looking at the median, they are all above one, which means that for most of each event the observed data show a discharge value that is inferior to the computed data value. When looking at the mean, there are three events that show a negative mean and five other events that display a mean under one. These are due to the fact that in the computed discharge there are negative values.

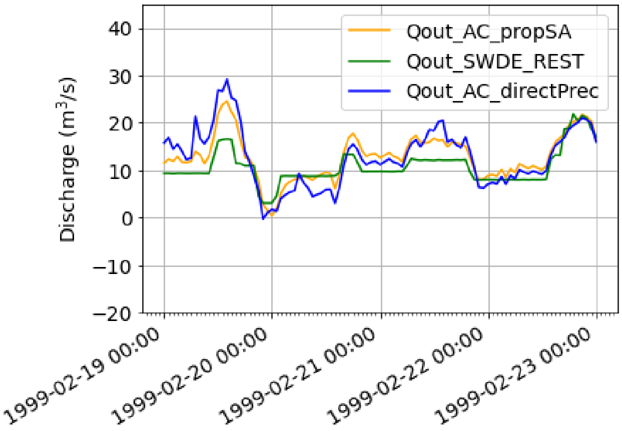
$$Ratio = \frac{Computed}{Observed}$$

Also, the SWDE+Restitution discharge is a smoother time series with no negative values compared to the time series computed with the correction of Calles [2015]. Sometimes it seems that the equipment to measure the restitution discharge was out of order because the SWDE+Restitution time series displays a flat line (Figures A.12g and A.12h).

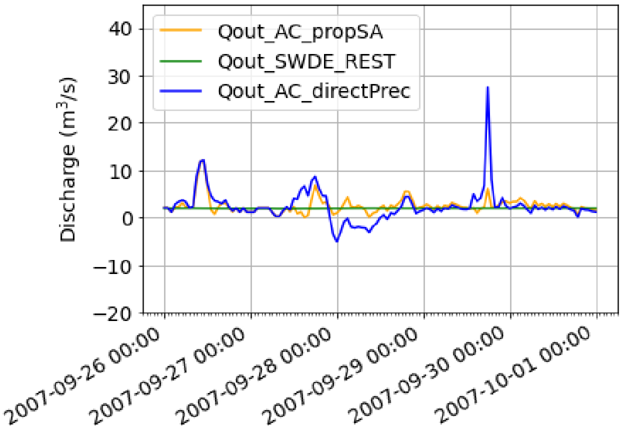
Figure 33 shows the correlation between the Annick Calles times series and the SWDE+ Restitution time series for four events, the same events that are shown in Figure 30. The other events are shown in Figure A.13. The correlations were computed according to the Pearson method. When looking at this figure it can be seen that for most of the events (16/18), the outflow discharge computed with the proportional approach shows a better correlation with the observed outflow discharge than the one computed with the direct precipitation approach. These two events are the ones of January 2011 and July 2021. We know that we cannot trust the data of July 2021. It can also be noticed that for 7 out of 18 events, the correlation is below 60% for the "proportional area" approach. These events are displayed in Table 5.

For the two events of 2007, the measured data shows a flat line, which is thought to be due to the breakdown of the sensor. For the event of 2021, it is because the equipment was damaged at the start of the event, then the data are not reliable. For the event of 2014 when looking at Figure 28, it is noticeable that the time series with the correction of Calles [2015] is still very noisy. For the event of 1998, 2006 and 2015, the poor correlation comes from the fact that there are peaks in the computed outflow discharge that are not present in the measured one. For the events of 1998 and 1996, when looking at Figures A.15b and A.15f, it seems that the outflow peaks are small, almost non-existent, compared to the inflow peak. It is then likely that the sensor was not working correctly. For for the event of 2015, the computed time series is very noisy compared to the measured one.

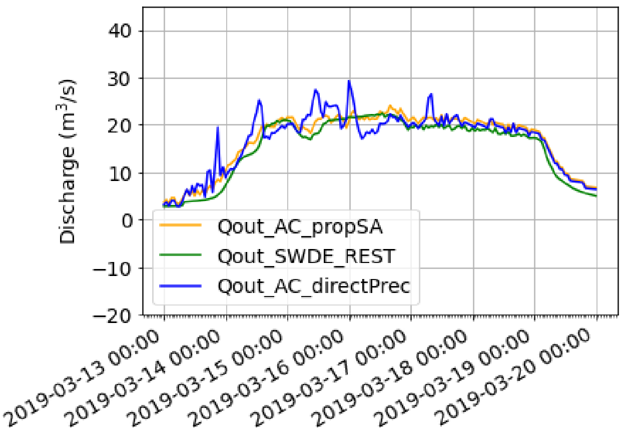
Figures 30, 32, 33 allow us to draw the same conclusion for the 'propSA' and 'directPrec' time series when comparing to the observed time series. This means that the way to take into account the discharge coming from the ungauged water catchment does not affect our results too much. However, the results from the direct precipitation approach match the observed time series less well.



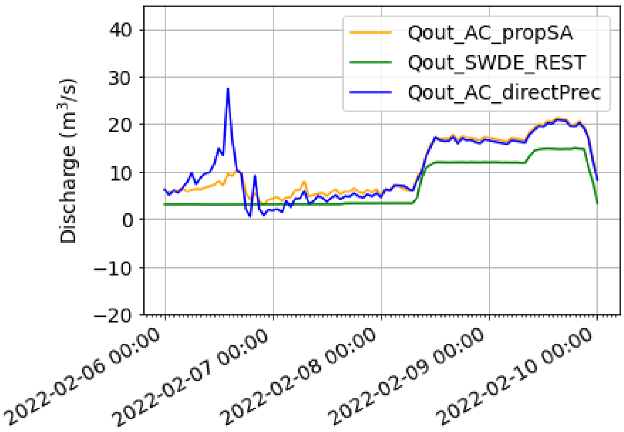
(a)



(b)

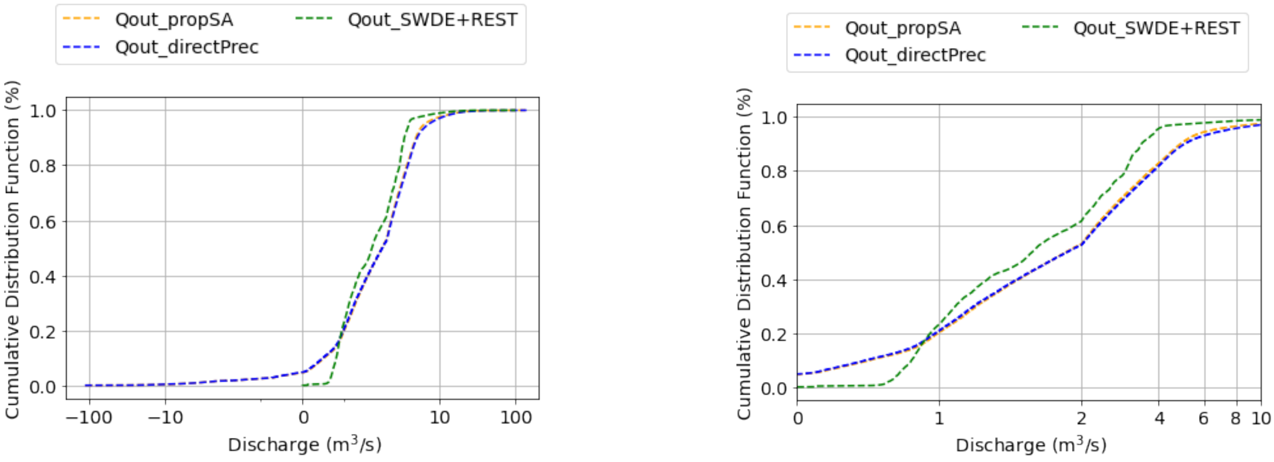


(c)



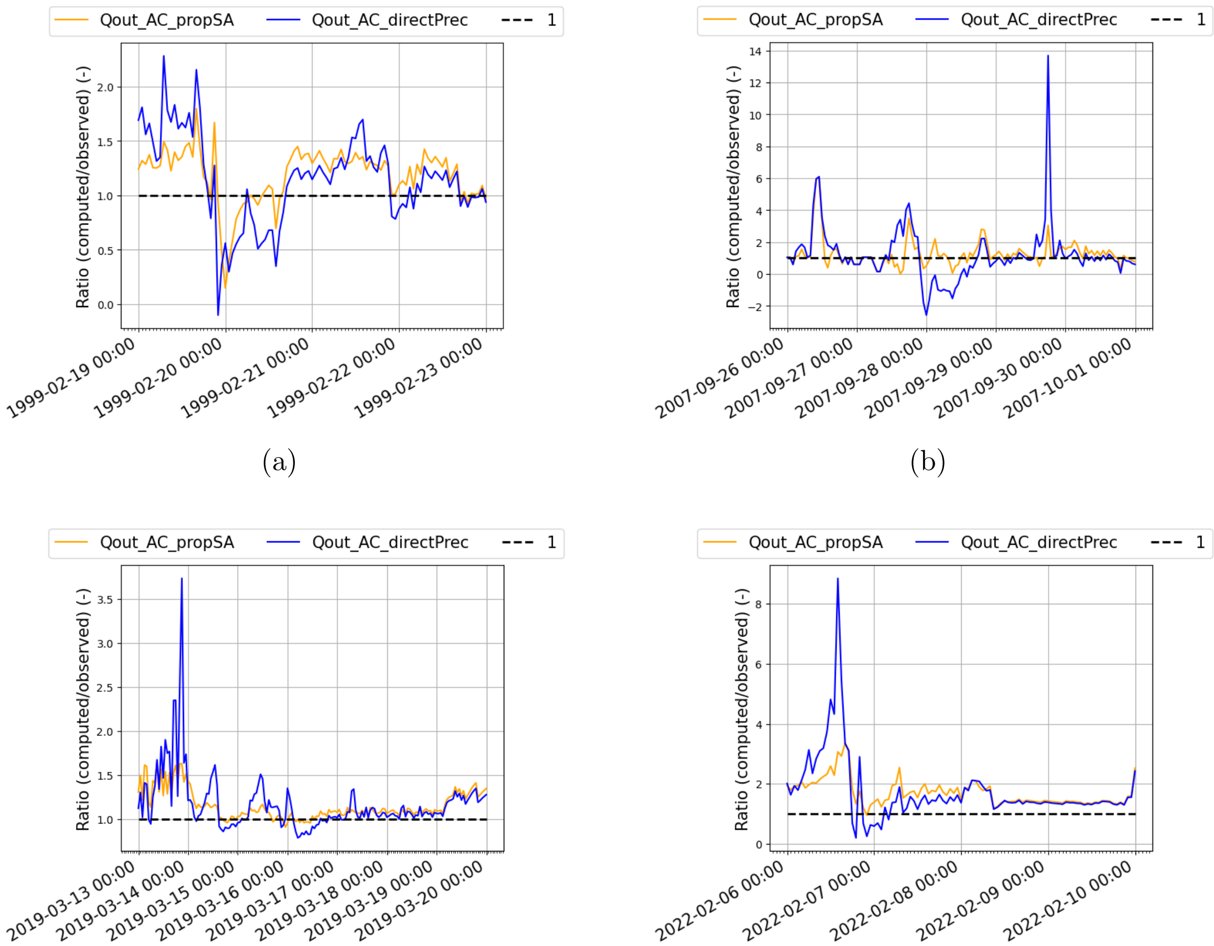
(d)

Figure 30: Computed outflow discharge with the data corrected by Calles [2015] and with the Qin corrected as being proportional to the surface (orange) and the Qin corrected as if the precipitation directly falls in the lake (blue) and the sum of the restitution discharge of the Vesdre dam with the water intake by the SWDE (green)



(a) (b) Zoom

Figure 31: Cumulative distribution function for the outflow discharge computed with the correction of AC and the two approaches for correcting Qin and the outflow discharged measured (SWDE+REST).



(c) (d)

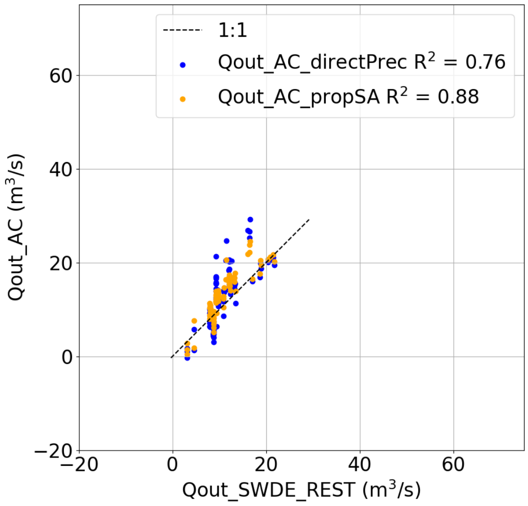
Figure 32: Ratio between computed and observed data for the two approaches correcting for the ungauged water catchment.

Date	mean propSA	mean directPrec	median propSA	median directPrec
1995-01-21	1.04	0.98	1.12	1.04
1998-09-13	0.60	0.19	2.24	1.91
1999-02-19	1.23	1.69	1.26	1.18
2000-09-16	-5.14	-5.15	1.17	1.49
2004-01-19	0.66	0.56	1.16	1.08
2006-05-25	0.92	0.82	1.47	1.26
2007-08-20	1.13	1.74	1.35	1.35
2007-09-26	1.04	1.04	1.10	1.03
2011-01-12	0.03	-0.11	1.11	1.08
2014-07-07	-12.61	-12.63	1.60	0.99
2015-11-24	1.44	1.27	1.64	1.49
2016-02-20	1.15	1.09	1.30	1.26
2016-05-28	2.04	1.84	1.48	1.29
2018-05-29	0.97	0.95	1.33	1.16
2019-03-13	1.31	1.12	1.10	1.08
2021-01-28	1.37	1.29	1.19	1.15
2021-07-14	-12.66	-12.71	5.43	4.86
2022-02-06	1.94	2.01	1.54	1.39

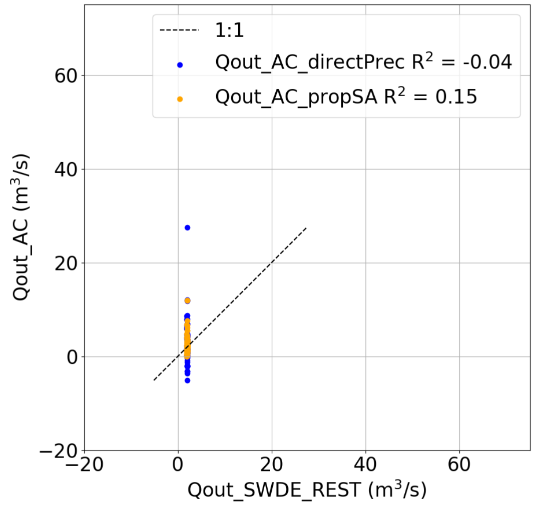
Table 4: Mean and median relative error for each event between computed and measured data for the two approaches correcting for the ungauged water catchment.

Date	Time Series	Scatter plot	Relative Error
13-09-1998	A.12b	A.13b	A.14b
25-05-2006	A.12f	A.13f	A.14f
20-08-2007	A.12g	A.13g	A.14g
26-09-2007	A.12h	A.13h	A.14h
07-07-2014	A.12j	A.13j	A.14j
24-11-2015	A.12k	A.13k	A.14k
14-07-2021	A.12q	A.13q	A.14q

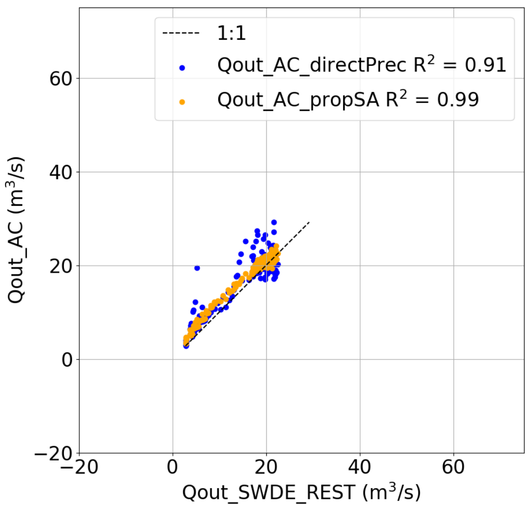
Table 5: Events for which the correlation between the outflow discharge computed (propSA) and the one measured (SWDE+Restitution) is below 60%.



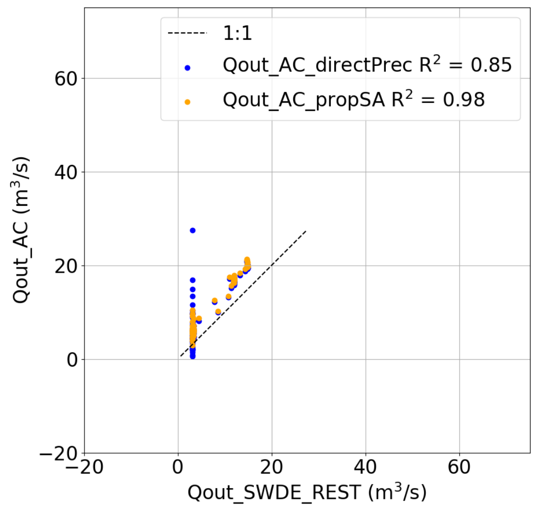
(a) February 1999



(b) September 2007



(c) March 2019



(d) February 2022

Figure 33: Correlation between the computed outflow discharge via the data corrected by Calles [2015] and the measured outflow discharge (SWDE+Restitution).

4.4 Comparison Inflow and Outflow discharge

Figure 34 compares the peak of the outflow discharge with the peak of the inflow discharge for 18 events. It does it for different sets of data, these sets are explained below :

- Corr_AC_propSA_bf2015: Data that were corrected by Calles [2015] and correspond to the events before 2015. No correction was made by her after 2015. The Qin of the ungauged drained water catchment was assumed to be proportional to the area of the catchment (propSA).
- Corr_AC_directPrec_bf2015: Data that were corrected by Calles [2015] and correspond to the events before 2015. No correction was made by her after 2015. the Qin of the

ungauged drained water catchment was assumed to be like if precipitation falling on the water catchment was directly falling into the lake (directPrec).

- outliers: Data that are corrected by Calles [2015] or from after 2015 but that are considered as outliers because they are above the 1:1 line. These events correspond to the 07-07-2014 and to the 14-07-2021 for propSA. These events correspond to the 07-07-2014 and to the 28-05-2016 for directPrec.
- FM_bf2015:Data corrected with the In-house developed filter before 2015. We decided to show the outflow discharge computed with this filter instead of the outflow data without correction in order to be able to limit the X and Y axis to a smaller number.
- Corr_FM_propSA_af2015 and Corr_FM_directPrec_af2015: Data corrected with the In-house developed filter after 2015 (but almost no correction was made compared to the source data because the source data were of better quality).
- SGF_bf20150101: Data corrected with the Savitzky-Golay filter before 2015.
- SGF_af20150101: Data corrected with the Savitzky-Golay filter after 2015 but it should not be needed as the data after 2015 are of better quality.

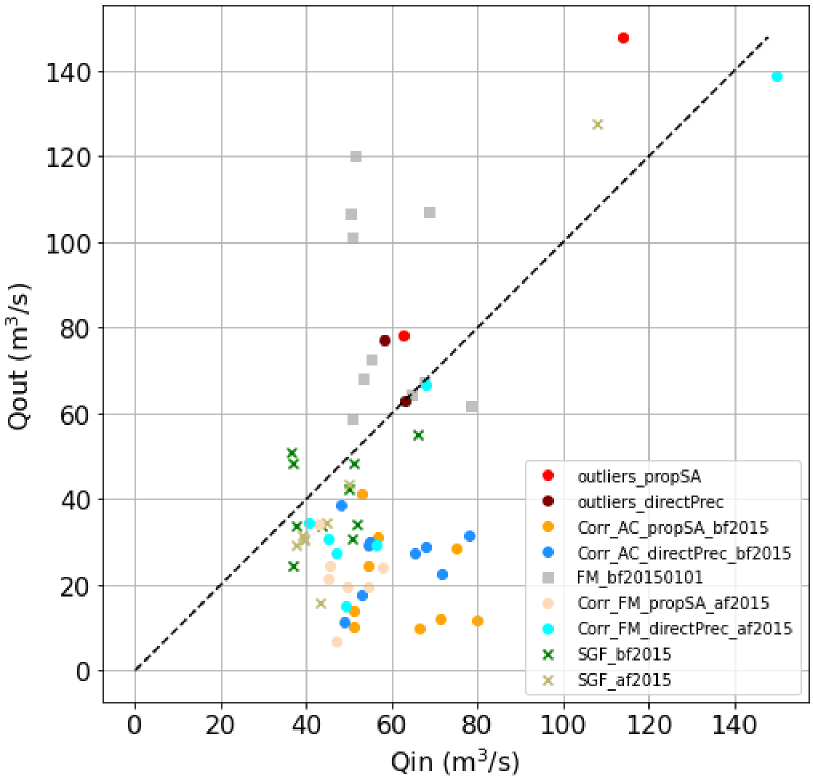


Figure 34: Outflow discharge (Qout) function of the inflow discharge (Qin). The inflow discharge represents the natural outflow discharge. AC = Annick Calles correction, FM = In-house developed Filter correction, SGF = Savitzky-Golay filter correction.

The time series of Inflow discharge, outflow discharge and water level in the reservoir for these 18 events and the different sets of data are displayed in the appendix in Figure A.15. Four of these events are shown in Figure 35.

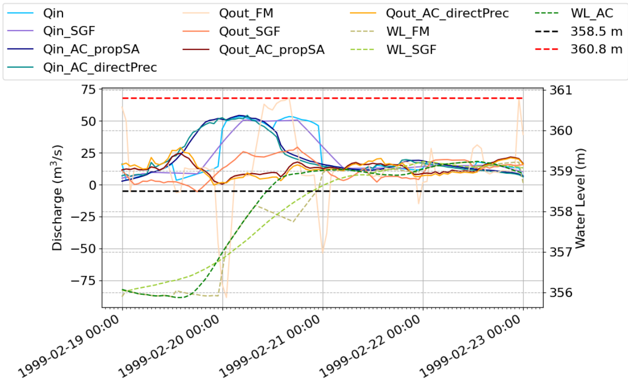
Figure 34 shows that for the data corrected by Calles [2015] and those measured after 2015, the maximum inflow discharge is always higher than the maximum outflow discharge except for two outliers. These two outliers correspond to the events of 07-07-2014 (Figure A.15j) and 14-07-2021 (Figure A.15q) for the propSA time series. It was already established that the data from the event of July 2021 were not reliable. There are also uncertainties in the data for the event of July 2014 as the outflow discharge time series displays a lot of noise. For the directPrec time series, there is also the event of 28-05-2016, but it is almost on the 1:1 line so it is not really considered an outlier. When looking at the other events it can be concluded that the dam is able to reduce the peak discharge by 20 to 85% for the 'PropSA' time series and by 14 to 77% for the 'directPrec' time series.

When comparing the In-house developed filter with the correction of Calles [2015] in Figure 34, we can see that the In-house filter is still overestimating the value of the peak discharge of the major events. As seen in Figure 29 it still reduces the magnitude of the extreme values compared to the raw data.

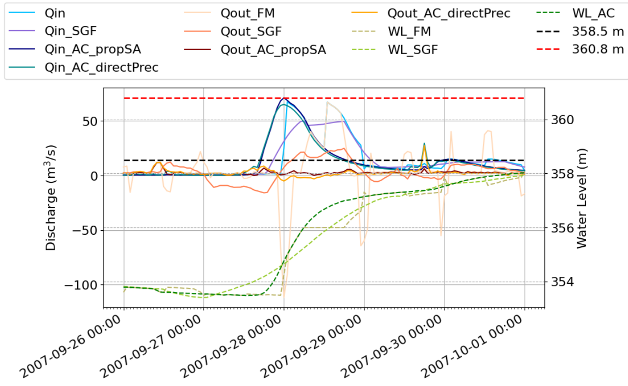
The Savitzky-Golay filter was used on the water level in the reservoir and the inflow discharge in order to try to replicate the best, the corrections of Calles [2015]. Figure 34 shows that this filter reduces the peak of the outflow discharge, but not as much as the corrections of Calles [2015]. Also by smoothing the inflow discharge, it also underestimates the peaks of the inflow discharge compared to the data computed with the corrections of Calles [2015]. It does give results that have more sense than those obtained by the In-house developed filter. Maybe by tuning a bit more the settings of the filter, it is possible to obtain results that are even closer to those of Calles [2015].

Figure A.15 (a sample is shown in Figure 35) enables us to analyse the outflow discharge as a function of the inflow discharge and the water level in the reservoir. It shows that the outflow discharge is highly linked to the water level in the reservoir. Indeed when the water level reaches the value of 358.5m, that is the level at which the water is released via the spillway, the outflow discharge tends to increase. If at the beginning of the major event, the water level is already above that threshold, the outflow discharge follows the same evolution as the inflow discharge but it is more spread and the peak is less important (Figures A.15a, A.15l, A.15o).

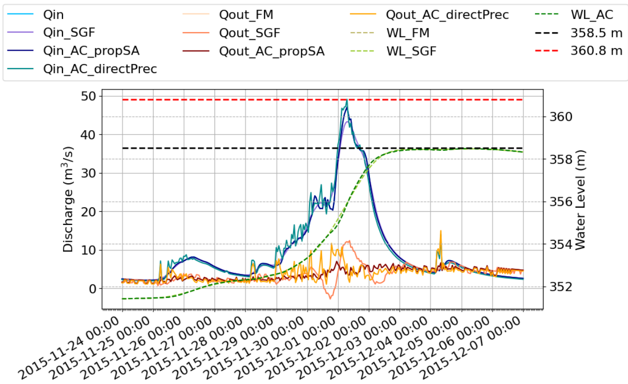
If the water level do not exceed the threshold during the events, there should be no real peak in the evolution of the outflow discharge because the spillway is not used. This is indeed true for the two major events of 2007 (Figures A.15g and A.15h), but not for the major event of the year 2000 (Figure A.15d). For the event of 2022 (Figure A.15r), although the water level does not reach 357.5m, there is a gradual increase in the outflow discharge, this leads us to believe that the bottom outlets were used. The operating rule of the dam changed after july 2021. It is important to keep in mind that the operating rules of the dam changed many times between 1995 and 2022.



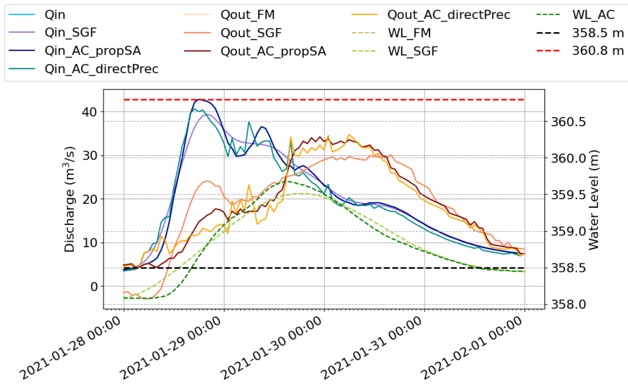
(a)



(b)



(c)



(d)

Figure 35: Comparison between Inflow discharge (Qin), Outflow discharge (Qout) and Water level (WL) in the reservoir for various corrections. FM: house filter, SGF: Savatzky-Golay filter, AC: Annick Calles.

4.5 Comparison time to peak for outflow and inflow discharge

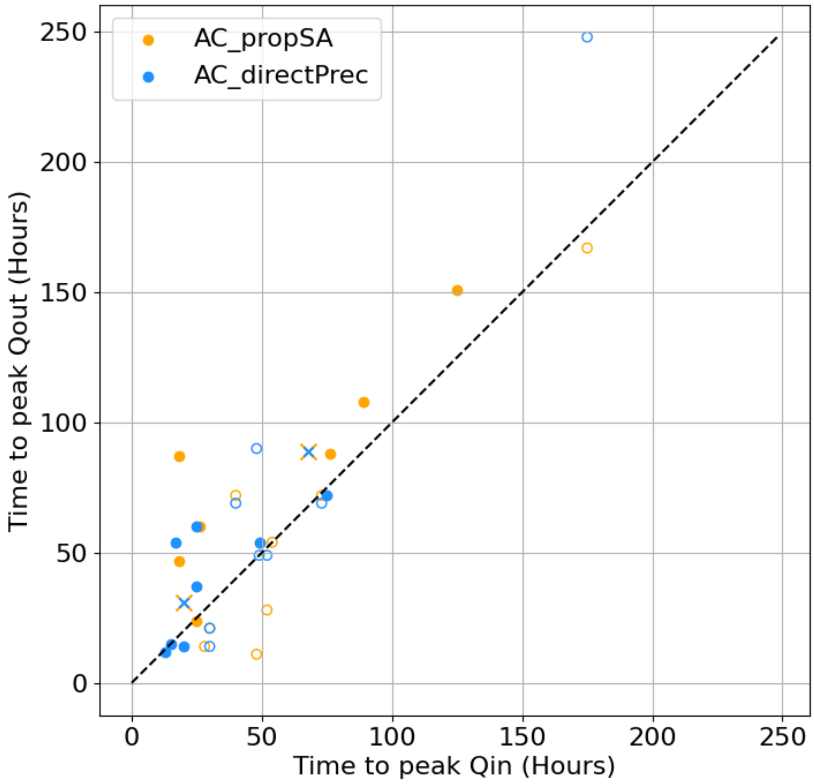
Figure 36 compares the time to peak for the inflow and outflow discharge since the beginning of each event. For 66.67% of the events, the time to peak for the outflow discharge is delayed compared to the inflow discharge. This delay is 5 to 69 hours for 'propSA' time series and of 5 to 73 hours for 'directPrec' time series.

Out of 18 events, there are only 8 events that show a marked Qout peak and for which we trust the data (● in Figure 36). For these 8 events, the delay is of 5 to 37 hours for the 'directPrec' time series and still 5 to 69 hours for the 'propSA' time series.

Table 6 displays the starting date of the events for which the peak of the inflow discharge happened sooner than the peak of the outflow discharge. For these events, it is important to look at Figure A.15, because for most of them there is an obvious peak for the inflow discharge but not for the outflow discharge. It is already noticeable when looking at the maximum inflow and outflow discharge displayed in Table 6.

For the 'propSA' time-series events, the peak for which the inflow discharge occurs sooner than the peak of the outflow discharge happens before 2015, therefore in the set of data that were corrected by Calles [2015] except for the event of 2015. For the event of 2015, when looking at the time series, there is no obvious peak for the outflow discharge.

For the 'directPrec' time series, there are three events in common with the 'propSA' time series. The main difference between these two time series is the timing of the peak, as one correction underestimates the time of the water for reaching the lake and the other overestimates it. Therefore it is not surprising that it is not all the same events that have the inflow discharge occurring after the outflow one. Also with the 'directPrec' time series, the peak in the inflow discharge can be directly influenced by the precipitation. Indeed, when looking at the recorded precipitation on the 29-05-2018 at 12.00 and 13.00 they are 25.9 and 26.7 mm respectively. When looking at Figure A.15n the peak in the Qout and Qin is happening there for the 'directPrec' but not for the 'propSA'. Also, there is more noise in the 'directPrec' time series.



❍	1998-09, 1999-02, 2004-01, 2006-05, 2007-08, 2007-09, 2011-01, 2015-11
●	1995-01, 2000-09, 2016-02, 2016-05, 2018-05, 2019-03, 2021-01, 2022-02
✕	2014-07, 2021-07

Figure 36: Comparison time to peak from the start of the event for outflow and inflow discharge.● events with a marked Qout peak, ❍ events without a marked Qout peak, ✕ events for which the data are not reliable.

propSA					
Start Date	Time to peak Qin (hours)	Time to peak Qout (hours)	Max Qin (m^3/s)	Max Qout (m^3/s)	Time Series Figure
13-09-1998	52	28	66.23	9.89	A.15b
19-02-1999	28	14	53.86	23.59	A.15c
16-09-2000	25	24	56.26	30.7	A.15d
19-01-2004	30	21	51.22	13.96	A.15e
25-05-2006	73	72	51.11	10.17	A.15f
26-09-2007	48	11	71.22	11.93	A.15h
24-11-2015	175	167	47.03	7.03	A.15k
directPrec					
Start Date	Time to peak Qin (hours)	Time to peak Qout (hours)	Max Qin (m^3/s)	Max Qout (m^3/s)	Time Series Figure
19-02-1999	30	14	54.38	29.18	A.15c
19-01-2004	30	21	52.96	17.65	A.15e
25-05-2006	73	69	48.91	11.19	A.15f
20-08-2007	52	49	71.54	22.47	A.15g
29-05-2018	13	12	67.82	66.77	A.15n
13-03-2019	75	72	56.47	29.21	A.15o
06-02-2022	20	14	47.11	27.48	A.15r

Table 6: Events for which the inflow discharge peaks after the outflow discharge.

4.6 Comparison between maximum gradient for outflow and inflow discharge

Figure 37 compares the inflow and the outflow discharge rising rates. For all the major events except two (Table 7), the inflow discharge rising rate is faster than the outflow one. The inflow discharge rising rate is between 1.25 (Figure A.15p) and 6.70 (Figure A.15b) times faster than the outflow rising rate for the 'propSA' time series and between 1.00 (Figure A.15m) and 4.37 (Figure A.15f) times faster for the 'directPrec' time series. The two events for which the outflow rising rate is faster than the inflow one are two events for which it was already explained earlier that their data were not reliable. Indeed for the event of 2014, the time series of the outflow discharge is very noisy and for the event of July 2021, the measurement equipment quickly became out of order.

The way the rising rate (RR) was computed is:

$$RR = \frac{Q_{max} - Q_{t0}}{t_{Qmax} - t_0}$$

Where the unit of discharge (Q) was in m^3/s and the unit of time (t) was in s. t_0 is the time corresponding to the first positive Qout value of the event. Therefore for most of the events t_0 = 0 second.

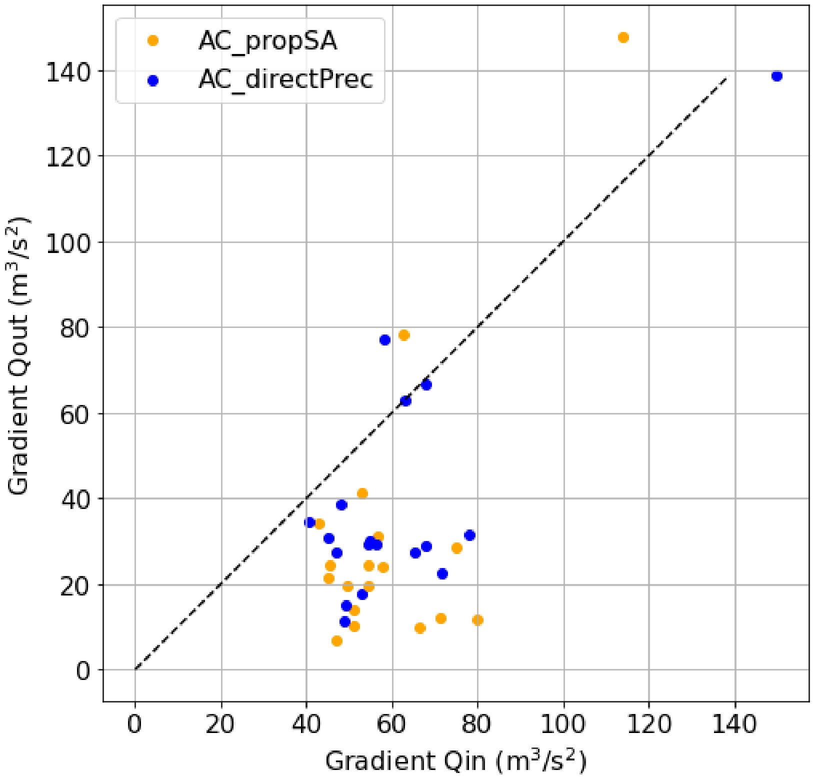


Figure 37: Comparison between maximum gradient for outflow and inflow discharge.

propSA			
Start Date	Gradient Qin	Gradient Qout	Time series
	(m^3/s^2)	(m^3/s^2)	Figure
07-07-2014	62.81	78.24	A.15j
14-07-2021	113.88	147.86	A.15q
directPrec			
07-07-2014	58.10	76.99	A.15j

Table 7: Events for which the maximum gradient of the outflow discharge is higher than for the inflow discharge.

4.7 Comparison Cumulated inflow volume and outflow volume

Figure 38 compares the cumulative volume that flows into the reservoir and the cumulative volume that flows out of the reservoir from the beginning of the event for each major event. The cumulative volume that flows into the reservoir is from 2% (Figure 39d) to 83% (Figure 39b) bigger than the one that flows out of the reservoir for both time series. The event of July 2021 is not taken into account in this analysis. In Figure 38, we can notice that for one event, the cumulative outflow volume is 26% bigger than the cumulative inflow volume. This event corresponds to the one of January 1995 (39a). The percentage of decrease (DV) of outflow volume compared to inflow volume is computed like this:

$$DV = \frac{V_{in} - V_{out}}{V_{in}} \times 100$$

Table 8 displays the percentage of decrease in cumulated outflow volume compared to the inflow volume for each major event. The median percentage of cumulated volume decrease due to the dam is 42%.

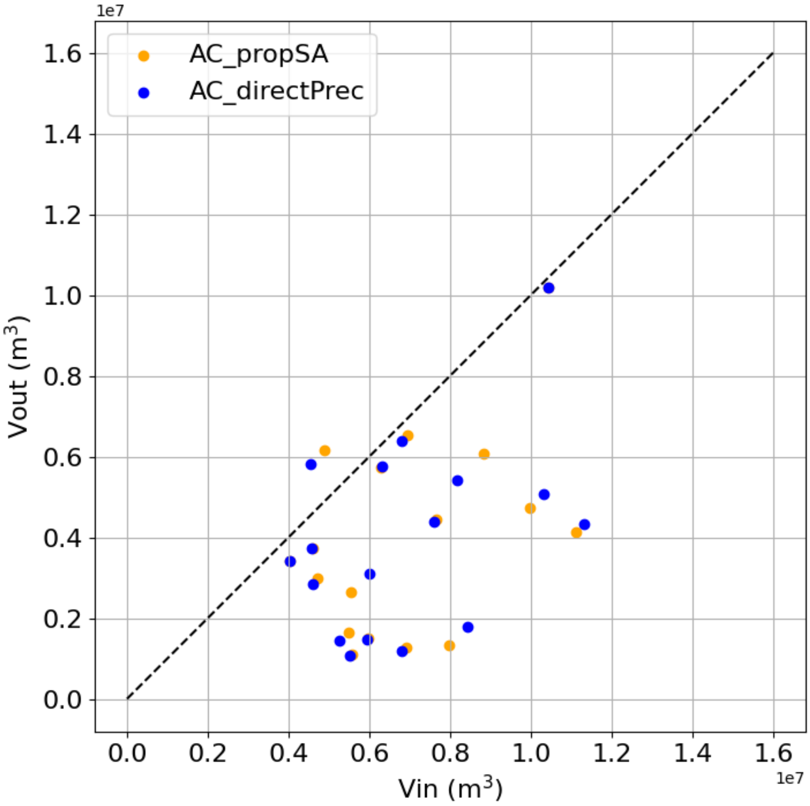


Figure 38: Cumulative Volume flowing inside (Vin) the reservoir function of the cumulative volume flowing outside (Vout) the reservoir for each major event (Does not take into account July 2021).

Figure 39 displays for four major events, the cumulative volume flowing into and out of the reservoir, as well as the volume stored within the reservoir. The volume stored in the reservoir corresponds to the difference between the cumulative inflowing volume and the cumulative outflowing volume. It is the volume stored for the event, it does not take into account the volume already present inside the reservoir before the beginning of the event. For both time series, the volume stored by event is the same because the outflowing volume is computed according to:

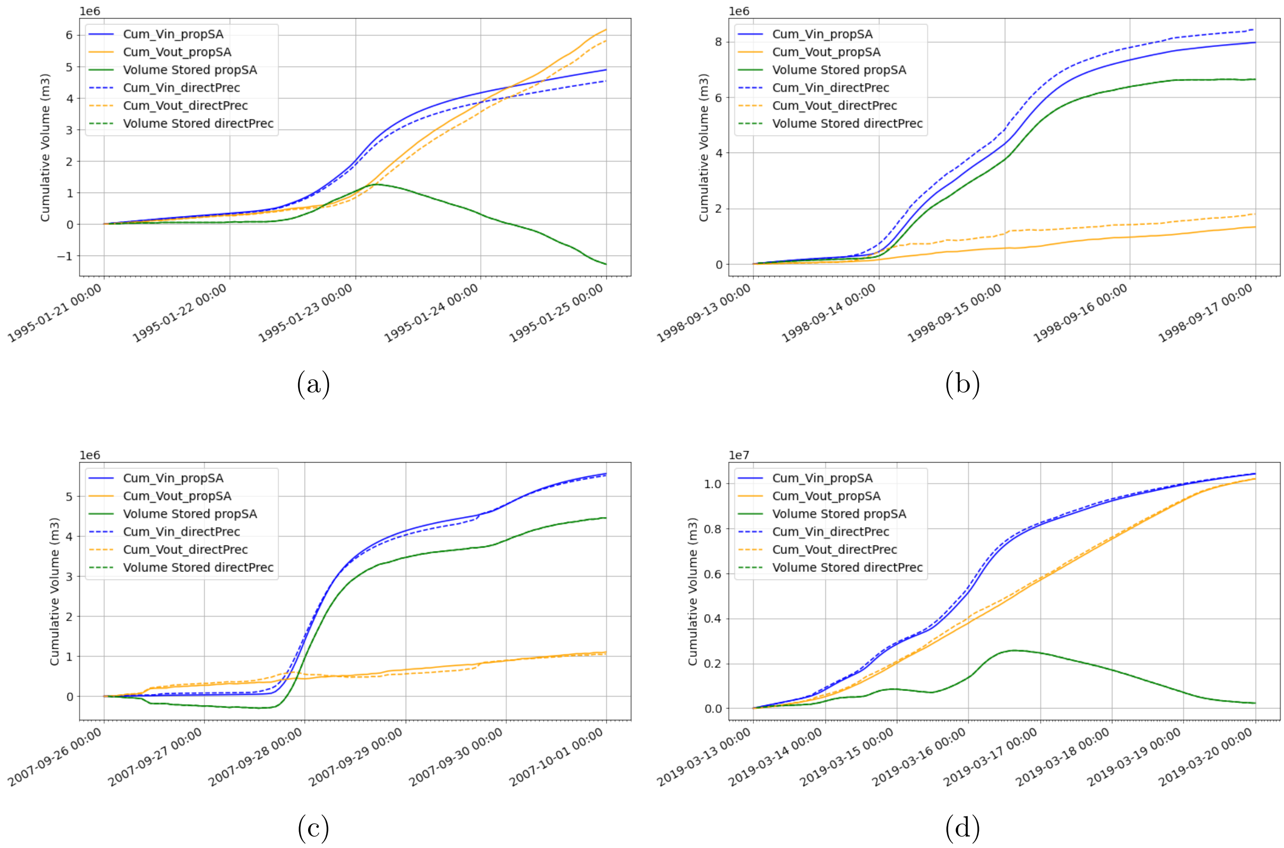
$$V_{out} = V_{in}[t] - (V[t] - V[t-1])$$

Where 'V_{in}' is the inflowing volume computed via the inflow discharge into the lake and 'V' is the volume inside the reservoir that is estimated from the measured water level in the reservoir and transformed into volume thanks to the curve of volume function of height. Therefore 'V_{in}' is different for the two time series ('propSA' or 'directPrec') whereas 'V' is the same.

The Figures that show the cumulative inflow and outflow volume as well as the stored volume for each major event are displayed in the appendix in Figure A.16.

Start Event	Volume decrease (PropSA)	Figure
1995-01-21	-26%	A.15a
1998-09-13	83%	A.15b
1999-02-19	42%	A.15c
2000-09-16	15%	A.15d
2004-01-19	37%	A.15e
2006-05-25	75%	A.15f
2007-08-20	70%	A.15g
2007-09-26	80%	A.15h
2011-01-12	31%	A.15i
2014-07-07	81%	A.15j
2015-11-24	63%	A.15k
2016-02-20	9%	A.15l
2016-05-28	53%	A.15m
2018-05-29	52%	A.15n
2019-03-13	2%	A.15o
2021-01-28	6%	A.15p
2022-02-06	19%	A.15r

Table 8: The percentage of decrease in cumulated outflow volume compared to the inflow volume for each major event.



(a) (b) (c) (d)

Figure 39: Comparison between the cumulative volume flowing into the reservoir (Cum_Vin) and outside the reservoir (Cum_Vout) as well as the volume stored per event.

4.8 Flood frequency

Figure 40 shows the annual maximum inflow and outflow rate over a hydrologic year. The years for which the bars are not colored are the years for which the data are considered not reliable. Indeed from April 2014 to April 2015, the computed outflow data are very noisy, the annual maxima are then due to the noise in the data. For the year 2020-2021, we know that the annual maximum happened in July but that the data are not reliable because of damaged equipment.

The time series of the annual maximum outflow rates are shown in the appendix (Figure A.17). Therefore, over 26 hydrological years, there are 3 years for which the data are not considered reliable enough to trust the annual maximum peak of outflow discharge. When looking at Figure A.17 there are also 4 years for which we have doubts on the reliability of the annual maximum peak of outflow discharge.

These 4 events are shown in Figure 41. For the hydrological years 1997 - 1998, 1999 - 2000 and 2006 - 2007, there is a peak of outflow discharge that is only due to a sudden drop in water level in the reservoir. Indeed, we cannot see any important increase in the inflow discharge. These releases of water could be planned by the service of dam management in the prediction of heavy precipitation or they could be due to an error in the records of the water level in the reservoir.

Figure 40 shows that the natural flow (Qin) is always higher than the controlled flow (Qout) if we do not take into account years that are for sure unreliable. It is important to notice that over 23 hydrological years, there are only 5 years for which the maximum outflow and inflow peaks correspond in time. These events are shown in Figure 42. The fact that for most of the years the annual maximum outflow discharge does not correspond in time to the maximum inflow discharge is due to the buffer role of the dam. In the appendix, Figure A.18 shows the time series of the annual maximum inflow rates with the corresponding outflow rate.

The annual peaks of natural (Qin) and controlled (Qout) were compared over 23 hydrological years. It was found that the dam reduces the average annual peak discharge by 49%. This result is in line with Mei et al. [2016], which shows a reduction in average peak flow from 7 to 95% over the 38 analysed dams. Graf [2006] shows an average flood peak reduction of 67% on the 36 studied dams and Stecher and Herrnegger [2022] shows an average flood peak reduction of 33% on the 8 studied dams. It is difficult to compare all these results because the situation of the dams is not similar. They are not in the same climatic conditions, they do not have the same purpose.

Figures 43 and 44 display the diagnostic plots for GEV fit to the inflow and outflow rate data respectively. The return period flow for 10, 25, 50 and 100 years are shown in Table 9. According to the value of the flow rate in this Table, the dam reduces by half the magnitude of flood events. This finding does not apply to extreme floods, like in July 2021, due to the saturation of the reservoir. These results are very similar to the ones of Mei et al. [2016] that found that the dams reduce the 10-year and 50-year flood discharge by 46%.

When looking at the probability density plot, the conclusion is the same as for Mei et al. [2016]. Indeed, we can see that the dam reduces the number of high flood events and then lowers the variation range of the flow rate. So the peak goes from a flat peak distributed over a wide range of values to a sharp peak that is shifted towards the left and a narrower range of values.

The parameters of the GEV distributions are displayed in Table 10. The quantile and probability plots for the inflow and outflow data show a good fit of the model with a high correlation coefficient.

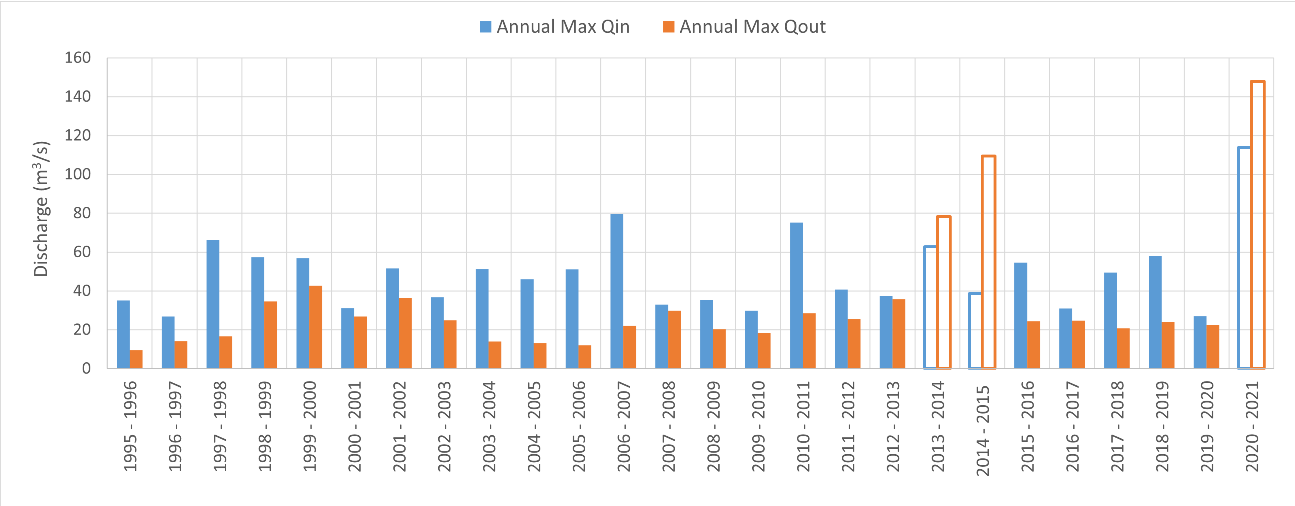
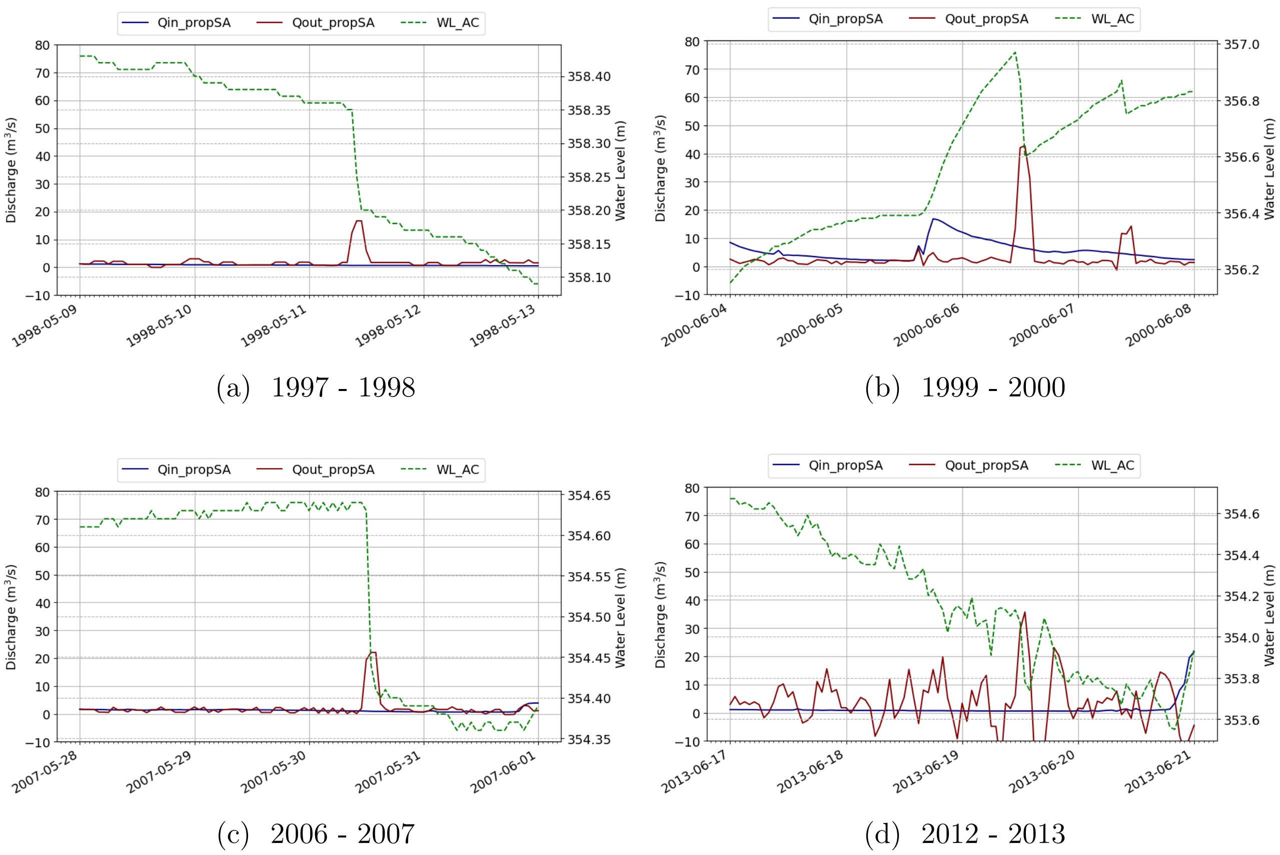


Figure 40: Maximum of inflow and outflow rate within a hydrologic year from 1995 to 2021. The transparent bars are for years that were not taken into account in the flood probability analysis.



(a) 1997 - 1998

(b) 1999 - 2000

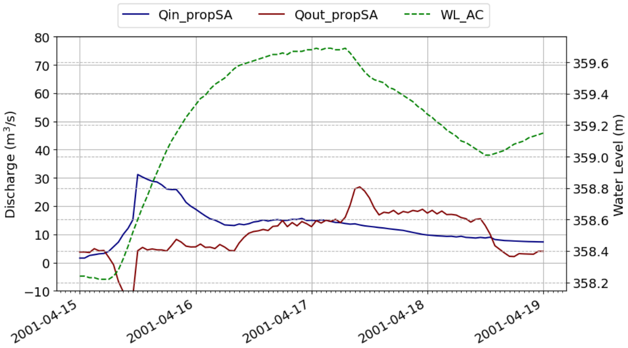
(c) 2006 - 2007

(d) 2012 - 2013

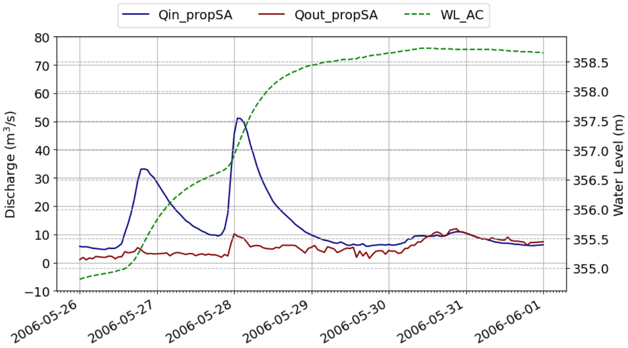
Figure 41: Time series of the maximum annual peak of Qout (red) with corresponding Qin (blue) and level of water in the reservoir (green) for years for which there is a doubt on the maximum annual Qout.

	Q 1/10y (m^3/s)	Q 1/25y (m^3/s)	Q 1/50y (m^3/s)	Q 1/100y (m^3/s)
Qin propSA	68.80	76.87	81.46	85.10
Qout propSA	34.28	38.39	40.78	42.72
reduction (%)	50.2	50.1	49.9	49.8

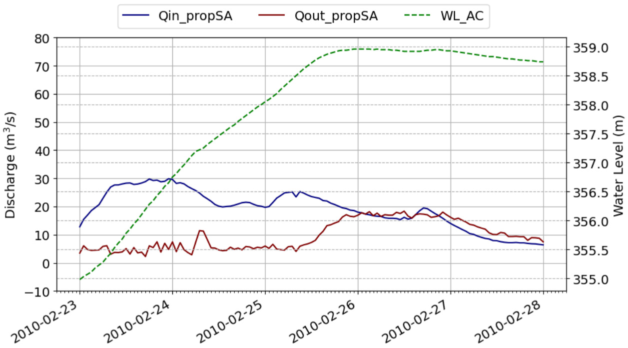
Table 9: Probability of the flow rate happening once every 10 years, 25 years, 50 years and 100 years with (Qout) and without the dam (Qin) (from Figures 43 and 44).



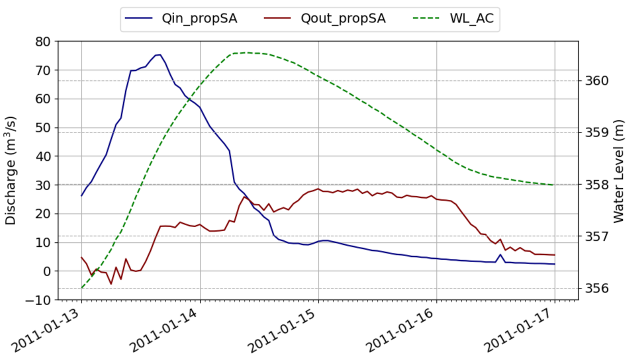
(a) 2000 - 2001



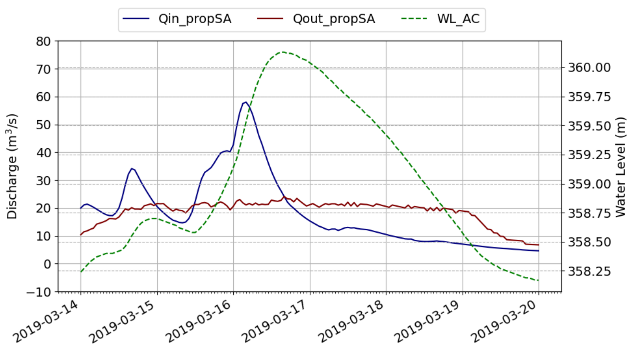
(b) 2005 - 2006



(c) 2009 - 2010



(d) 2010 - 2011



(e) 2018 - 2019

Figure 42: Time series of the maximum annual peaks of Qout (red) and Qin (blue) correspond in time.

	μ	σ	ξ
Qin propSA	37.073	19.998	0.317
Qout propSA	18.617	9.451	0.287

Table 10: Parameters of the GEV distribution

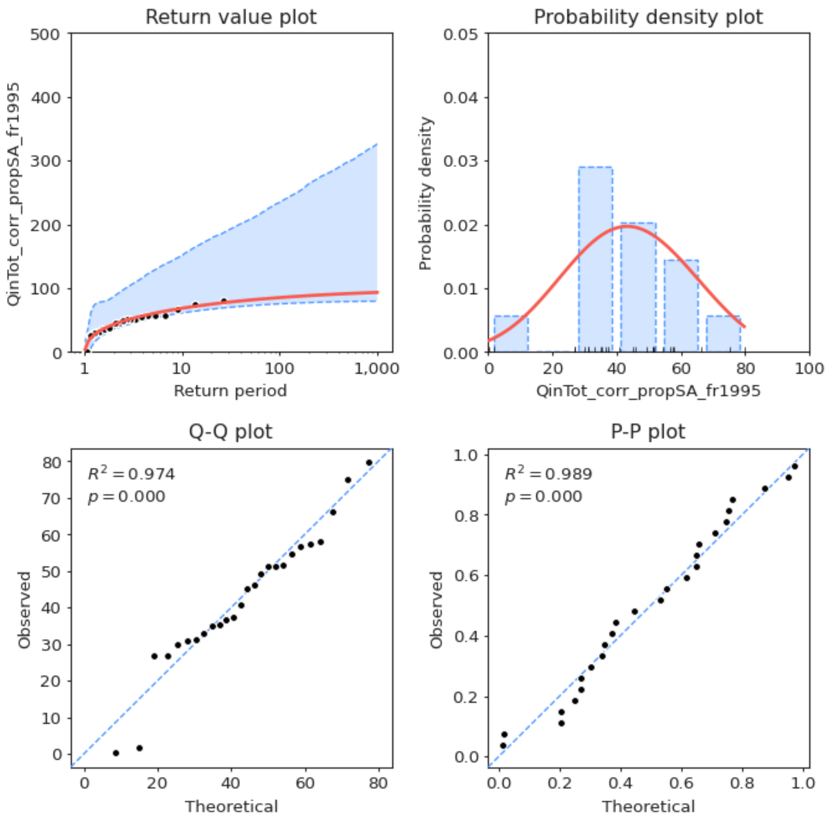


Figure 43: Diagnostic plots for GEV fit to the inflow rate data.

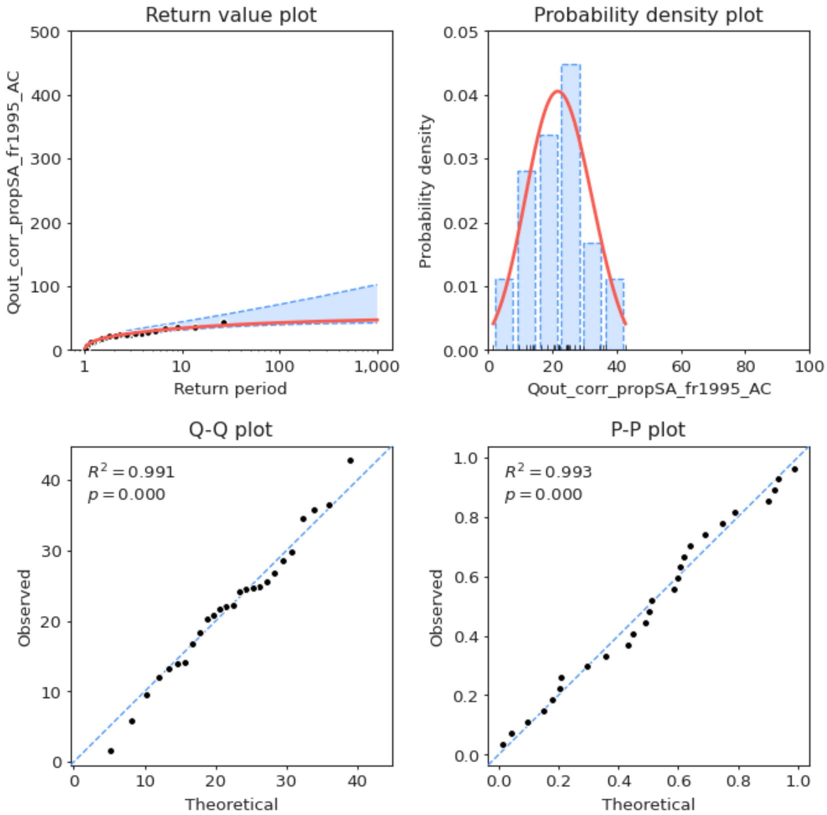


Figure 44: Diagnostic plots for GEV fit to the outflow rate data.

4.9 Impounded runoff index

Graf [2006] and Batalla et al. [2004] describe the ratio between the capacity of the reservoir and the catchment yield as an indicator of the potential of the dam to affect the downstream flow regime. Indeed if the ratio is superior to one, it means that the reservoir can store the flow for more than a year. If it is inferior to one, it means that the reservoir can only store a fraction of the annual inflow. This ratio is called the impounded runoff (IR) [Batalla et al., 2004].

$$IR = \frac{\texttt{Capacity of the reservoir}}{\texttt{Average annual runoff}}$$

The capacity of the Vesdre reservoir is 25hm^3 and the average annual runoff over the 28 studied years is of 77.9 hm^3 if we take the total inflow computed via the "proportional" approach and of 80.9 hm^3 if we take the total inflow computed via the "direct precipitation" approach. The impounded runoff is then 0.321 and 0.301 respectively. This means that a third of the annual runoff can be stored in the reservoir. The bigger this ratio, the bigger the influence on the downstream flow regime.

This ratio can also be computed for the Gileppe, keeping in mind that the data of inflow discharge from the Gileppe and Loubas weirs were not corrected. For the computation of the total inflow into the reservoir, we take into account the fact that 44 % of the reservoir catchment is drained but ungauged. We applied the proportional approach to correct for that. The capacity of the Gileppe reservoir is 26.4 hm^3 [ministère des Travaux Publics et al., 1986] and the average annual runoff over the 28 studied years is of 50.6 hm^3. The impounded runoff is then 0.522. This means that a little bit more than half of the annual runoff can be stored in the reservoir.

The drainage area of the Vesdre reservoir is 1060 km^2 whereas the one of the Gileppe reservoir is 540 km^2 [ministère des Travaux Publics et al., 1986]. As the drainage area of the Vesdre is almost twice bigger than the one of the Gileppe and the reservoir capacity is a little bit smaller, it is without surprise that the impounded runoff index of the Gillepe is larger than the one of the Vesdre.

The average annual runoff was computed by summing the volume of water entering the reservoir for each hydrological year (from 1995 to 2021) and then by taking the average of the annual inflow volume.

5 Conclusion

The goal of this research was to quantify the storage effect of Eupen dam on the flow rate of the Vesdre at the dam location. This was done mainly by comparing the outflow discharge with the inflow discharge of the dam from 1995 to 2022. The inflow discharge is still influenced by flow diversion from river Helle towards the reservoir; but our main objective was focused on disentangling the storage effect of the reservoir from the times series of flow rate.

First, the total inflow discharge was computed. This was done by summing the flow rate of the Getzbach and Vesdre rivers upstream from the dam as well as the flow rate coming from the Helle tunnel. In addition to the Vesdre and Getzbach sub-basins, there is also a drained but ungauged sub-basin that contributes to the total inflow into the reservoir. In order to take this contribution into account, two approaches were tested and considered as upper and lower bounds of the real contribution of this sub-basin. The first approach assumes that the discharge is proportional to the surface of the catchment. The second approach assumes that the rain falling onto the ungauged basin, directly falls into the reservoir. Finally, for the first approach, the input of the precipitations that fall directly into the reservoir was added.

Second, the outflow discharge from the reservoir was computed based on a mass balance. It was assumed that the variation of volume in the reservoir equals the difference between the total amount of water flowing into reservoir and the total amount exiting the reservoir. To assess the sensitivity of the results to uncertainties in the data, the outflow discharge was computed following five slightly different procedures. The most plausible results were obtained by using data corrections previously implemented by Calles [2015]. The computed time series of outflow discharge were compared to the observed ones, which were assumed equal to the sum of the measured release discharge and the SWDE intake of water. This observed outflow discharge is known to be flawed in the case of major events because when the bottom outlets are used, the water release do not go in the restitution basin.

Finally, the total inflow and outflow discharges were compared for 18 flood events. These events were selected on the basis of their high inflow discharge values. Based on the examined data (which do not include extreme flood cases, since 2021 data were excluded as considered unreliable), the main findings of this thesis are:

- The dam is able to reduce the peak head discharge by 14 to 85%;
- The dam is able to shift the peak discharge by 5 to 69 hours;
- The dam is able to reduce the flood volume by 2 to 83%;
- The dam is able to slow down the rising rate by 1.0 to 6.7 times the rising rate it would be without the dam.
- In term of flood frequency, the dam reduces the magnitude of flood peaks by a factor of two. This finding does not apply to extreme floods, like in July 2021, due to the saturation of the reservoir.

Of course, these results are not exempt from uncertainties. There are uncertainties coming from the equipment, indeed we saw that the record of water level in the reservoir, even after 2015 still shows outliers. It would be better to take the hourly maximum height instead of the hourly average of the 5-minutes data. The 5-minutes records have been stored only since 2013. Also for the events of July 2021, the equipment was damaged. There are also uncertainties coming from the correction of Calles [2015]. Indeed we know that she corrected manually the obvious errors in the data and also that she developed new rating curves, but not all corrections can be explained. There are uncertainties coming from the precipitation. In our computation, we used the precipitation before 2002 knowing that these precipitation values were not corrected by IRM. However, it was considered that these data were still reliable. When computing the discharge from the rain falling directly onto the lake, the fact that the surface of the lake is dependent on the water level was not taken into account. However, the impact of not taking it into account was studied and considered negligible. The effect of evaporation from the reservoir was not taken into account.

For further research, it would be interesting to create a hydrological model in order to compute the total inflow discharge from precipitation and temperature data. This has the potential to lower the uncertainty linked to the drained ungauged sub-basin. It would also allow a more reliable inflow discharge for the years with high uncertainties, such as 2014 and 2021. It would also be interesting to quantify the effect of evaporation on the reservoir on the computed outflow discharge. Finally, this research was not applied to the Gileppe dam, because the data before 2015 were not reliable enough, indeed Calles [2015] did not make any corrections to these data. It would then be useful to find a way to correct the data on the water level in the reservoir and inflow discharge for the Gileppe catchment. It is for this reason that in this research we used the Savitzky-Golay filter, in order to see if it would be sufficient to correct the raw data. It did significantly remove the noise of the data, and it would give better results than just using the raw data, but it also alters part of the data set that does not need to be corrected.

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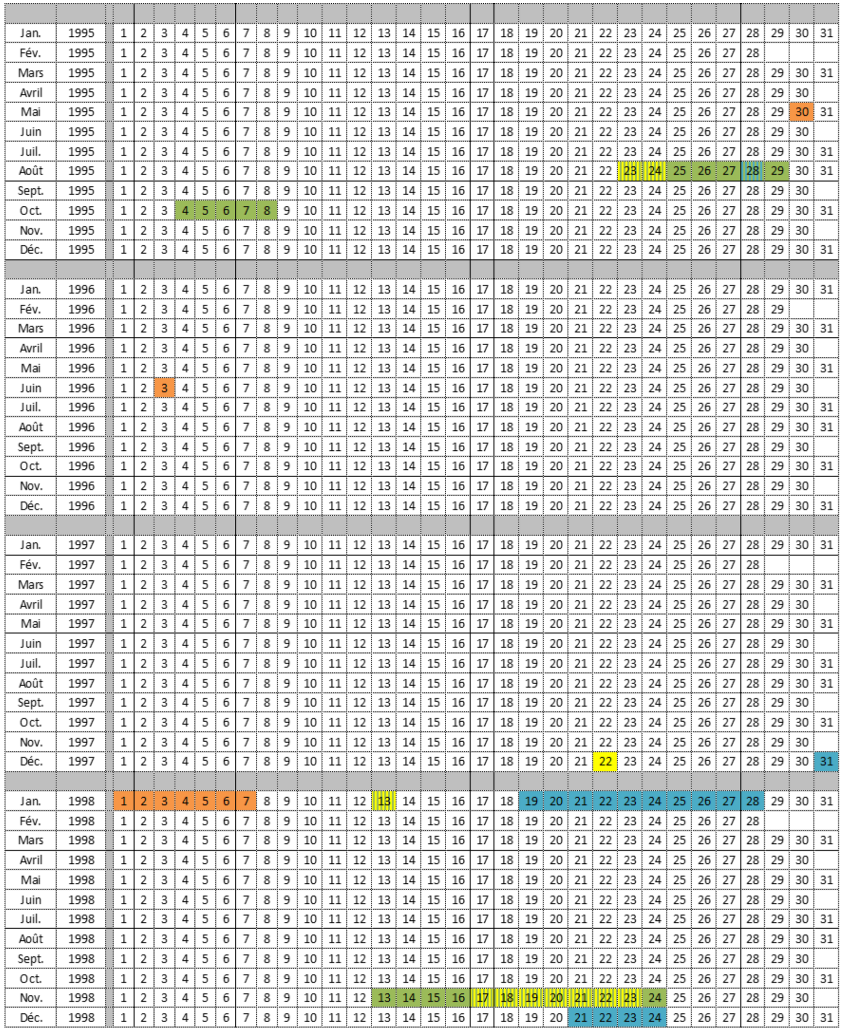
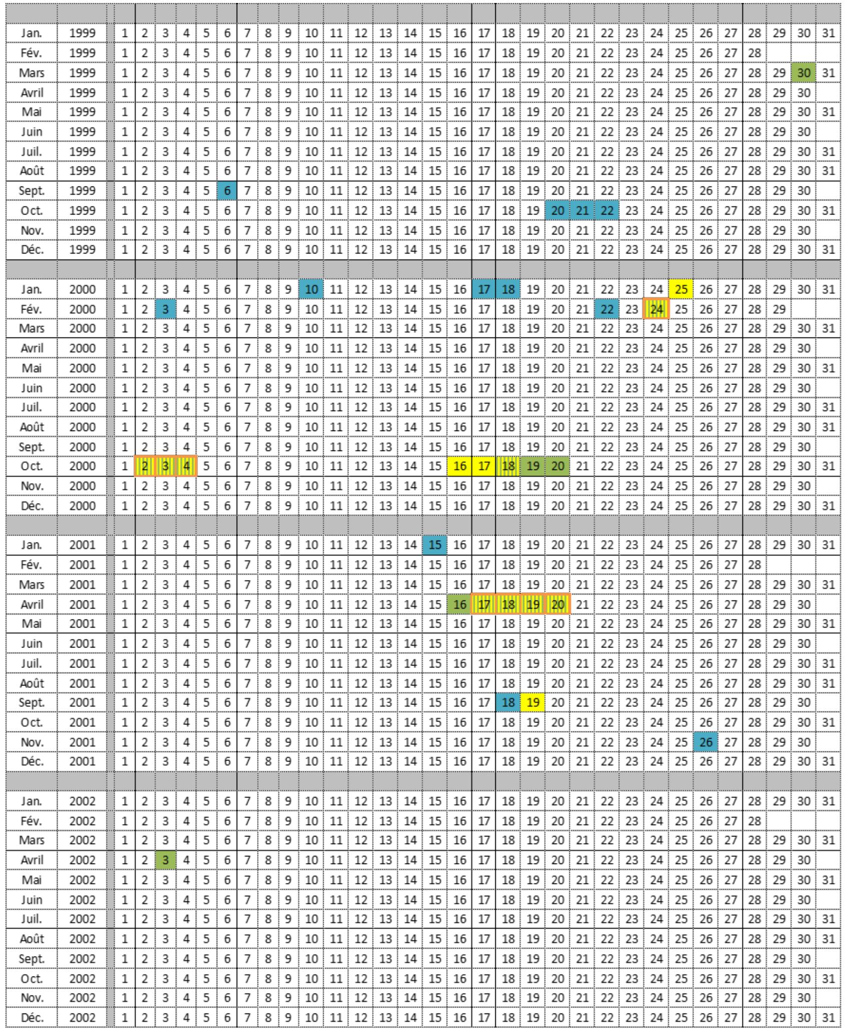
A Appendix

A.1 Data and method: Calendar of Annick Calles Corrections



(a) 1995-1998



(b) 1999-2002

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Juin	2003	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
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(c) 2003-2006

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(d) 2007-2010

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Juil.	2012	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
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Sept.	2012	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
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Nov.	2012	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Déc.	2012	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Jan.	2013	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Fév.	2013	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28			
Mars	2013	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Avril	2013	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Mai	2013	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Juin	2013	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Juil.	2013	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Août	2013	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Sept.	2013	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
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Nov.	2013	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
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Jan.	2014	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Fév.	2014	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28			
Mars	2014	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Avril	2014	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Mai	2014	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
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Juillet	2014	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
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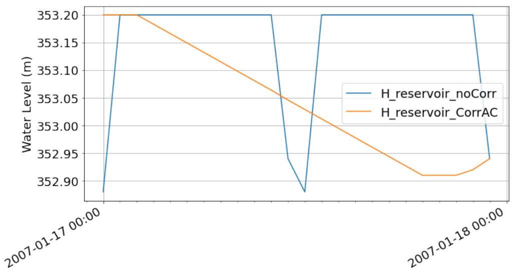
Oct.	2014	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Nov.	2014	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Déc.	2014	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31

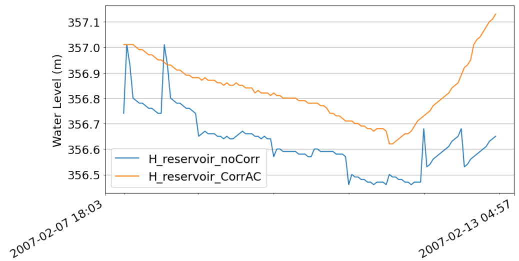
(e) 2011-2014

Figure A.1: Dates for which the corrections were applied by Annick Calles for the Vesdre (green), the Getzbach (yellow), the Helle tunnel (orange) and the reservoir (blue).

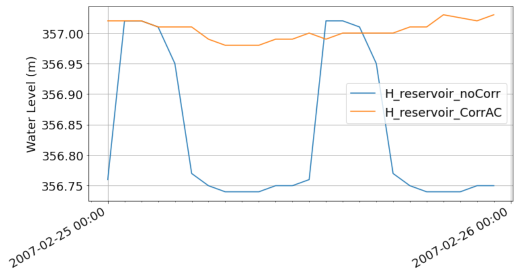
A.2 Data and Method: Comparison between corrected water level in the reservoir by AC and not Corrected for the year 2007.



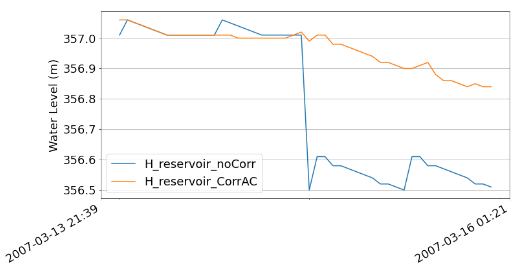
(a)



(b)



(c)



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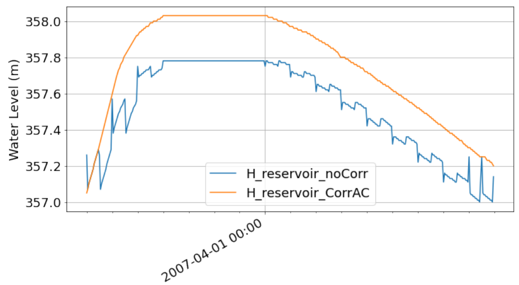

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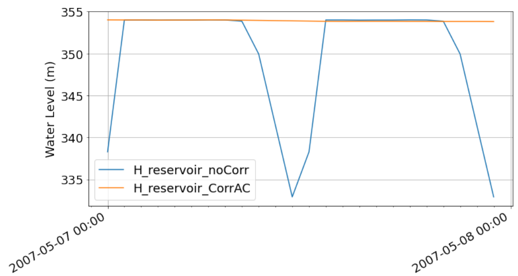

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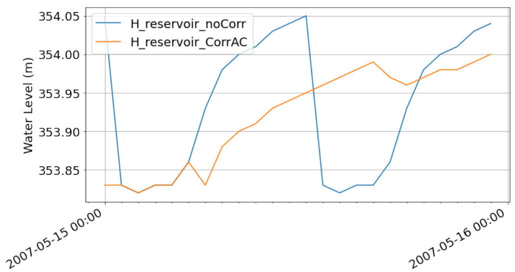
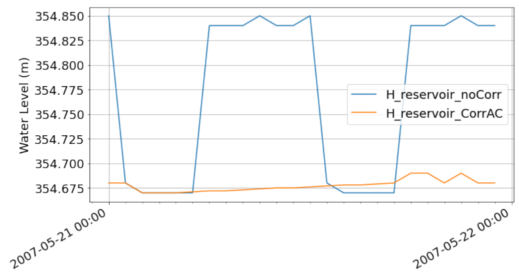
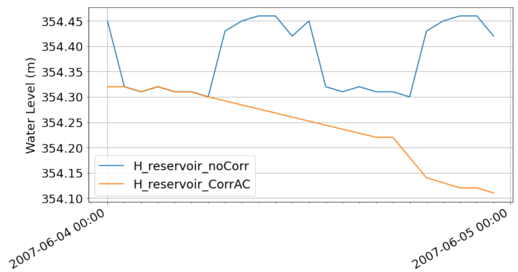


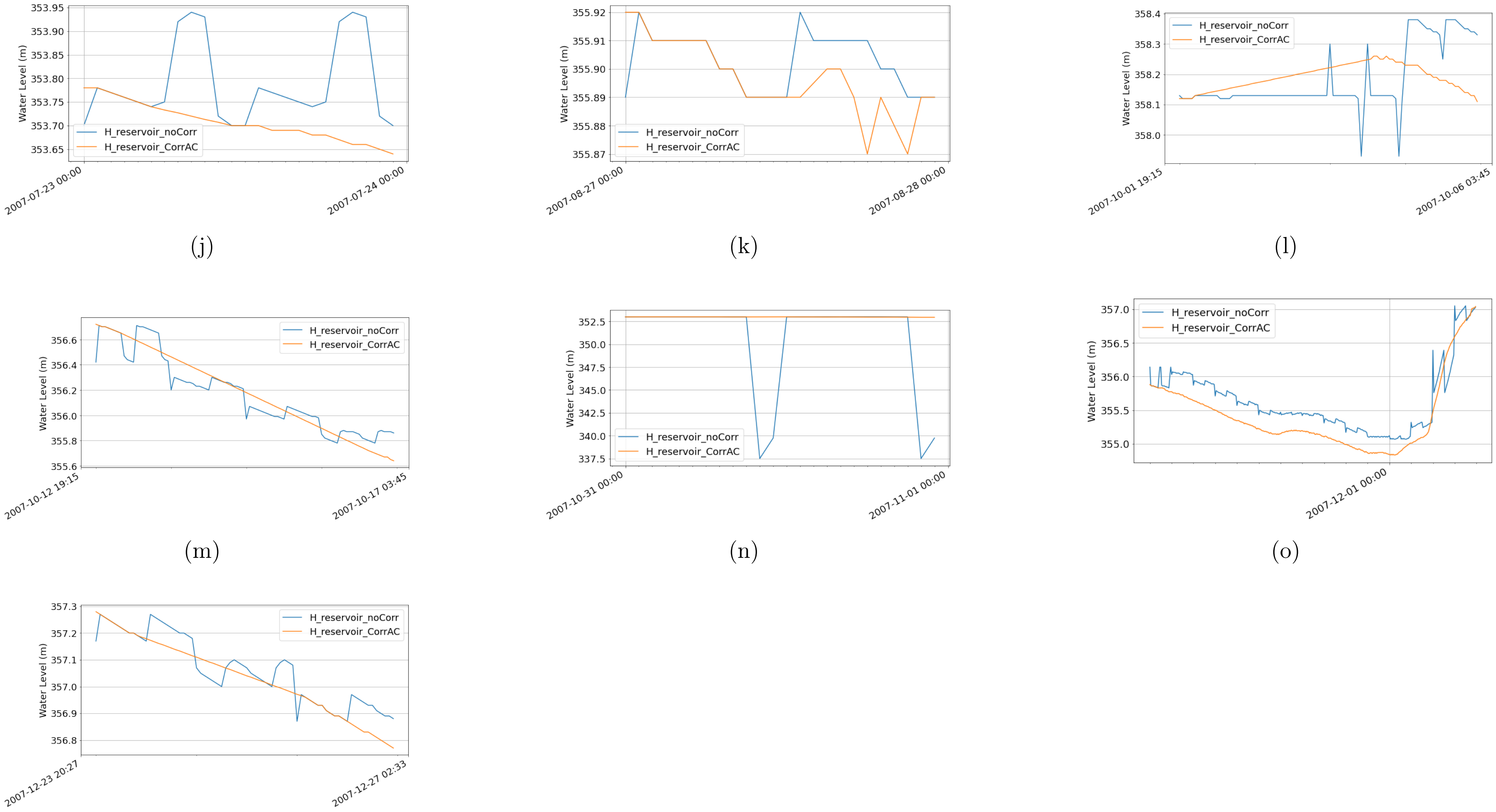
(g)



(h)



(i)



(j) (k) (l)

(m) (n) (o)

(p)

Figure A.2

A.3 Data processing: Inflow discharges corrected for ungauged drained surface area (linear scale)

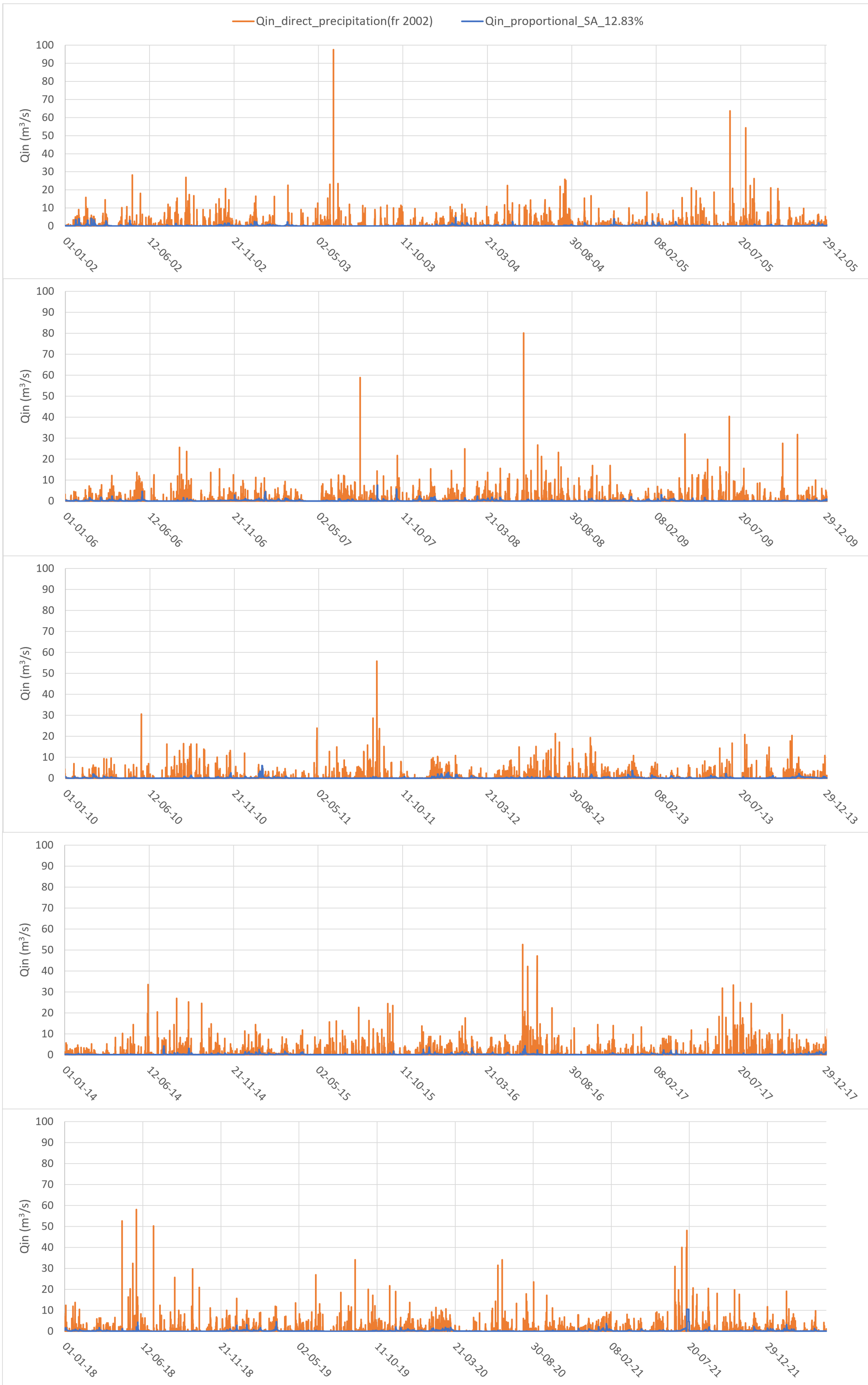


Figure A.3

A.4 Data processing: Inflow discharges corrected for ungauged drained surface area (log scale)

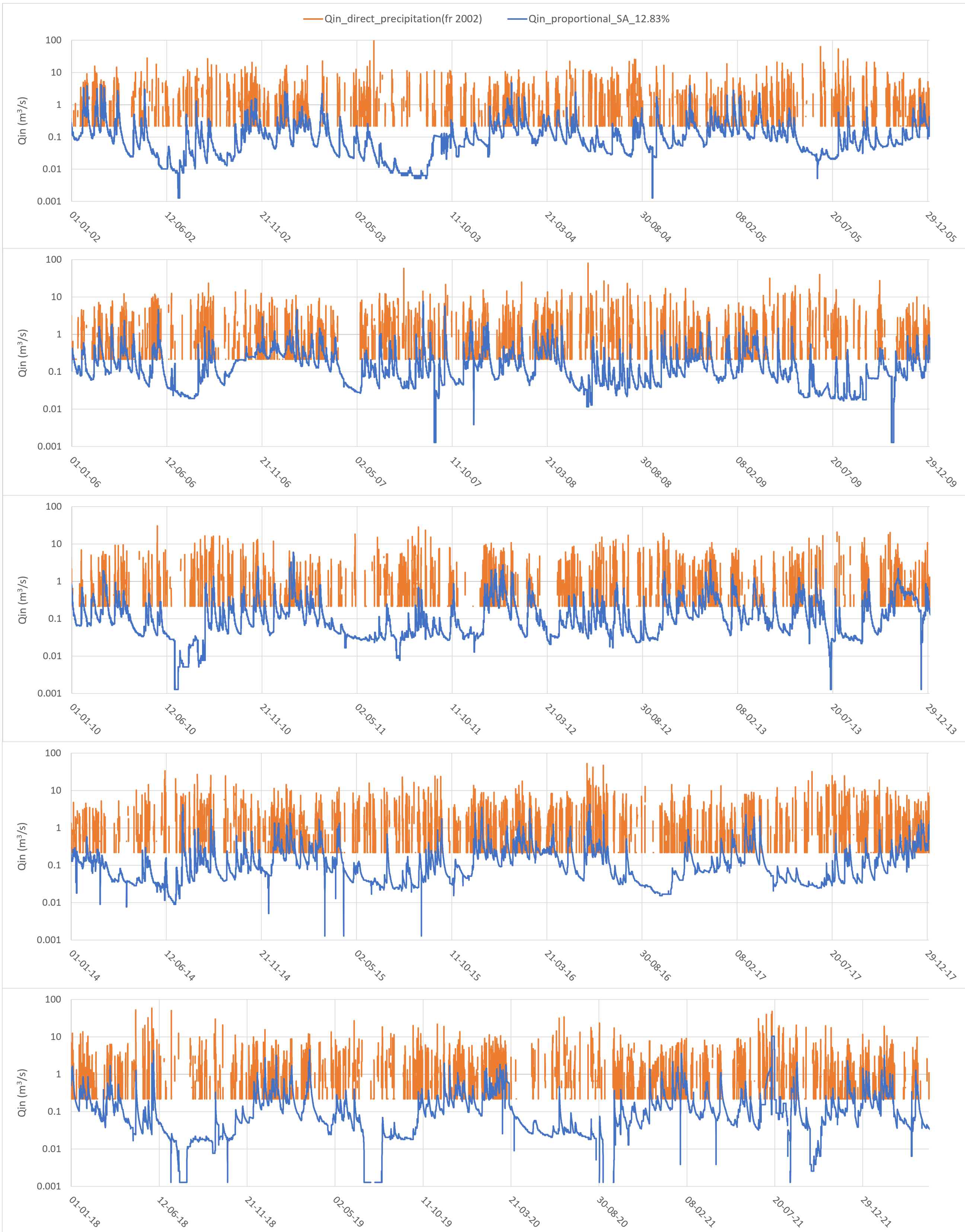
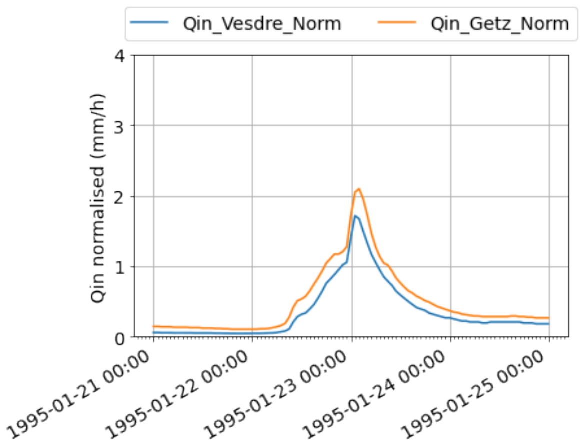
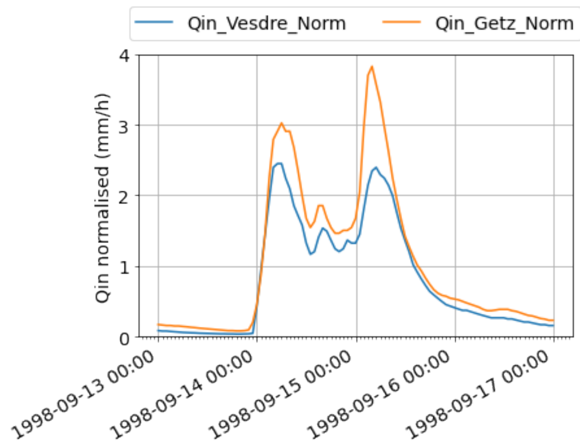


Figure A.4

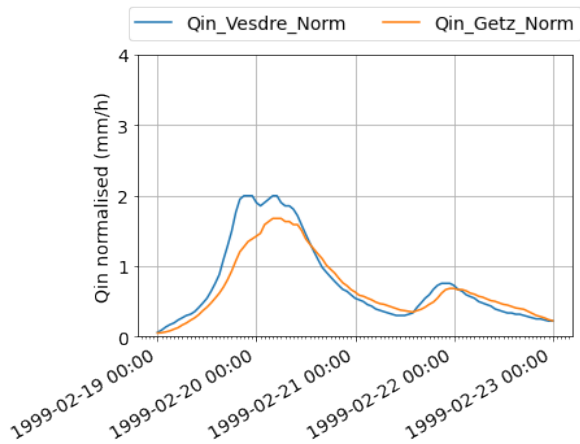
A.5 Data processing: Inflow discharges normalised with respect to the Water catchment surface area for the Vesdre and the Getzbach



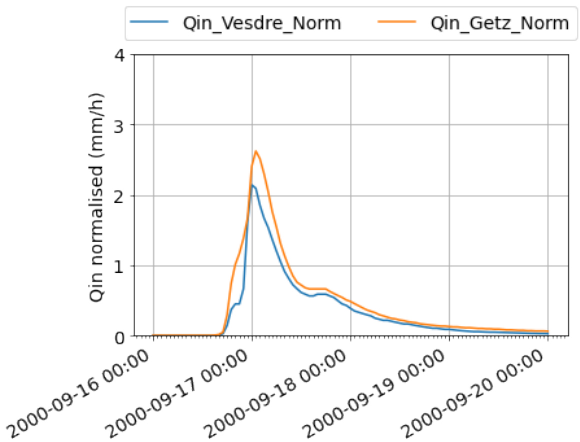
(a)



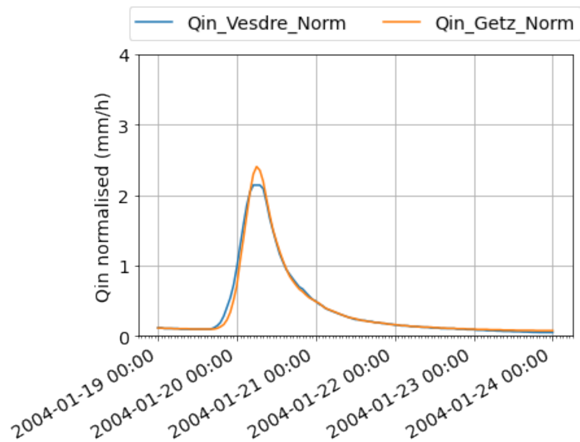
(b)



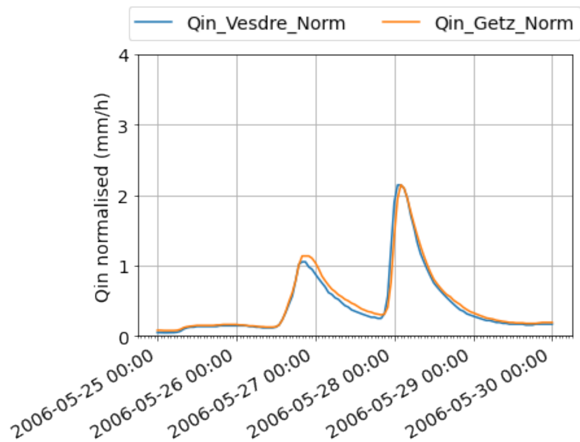
(c)



(d)



(e)



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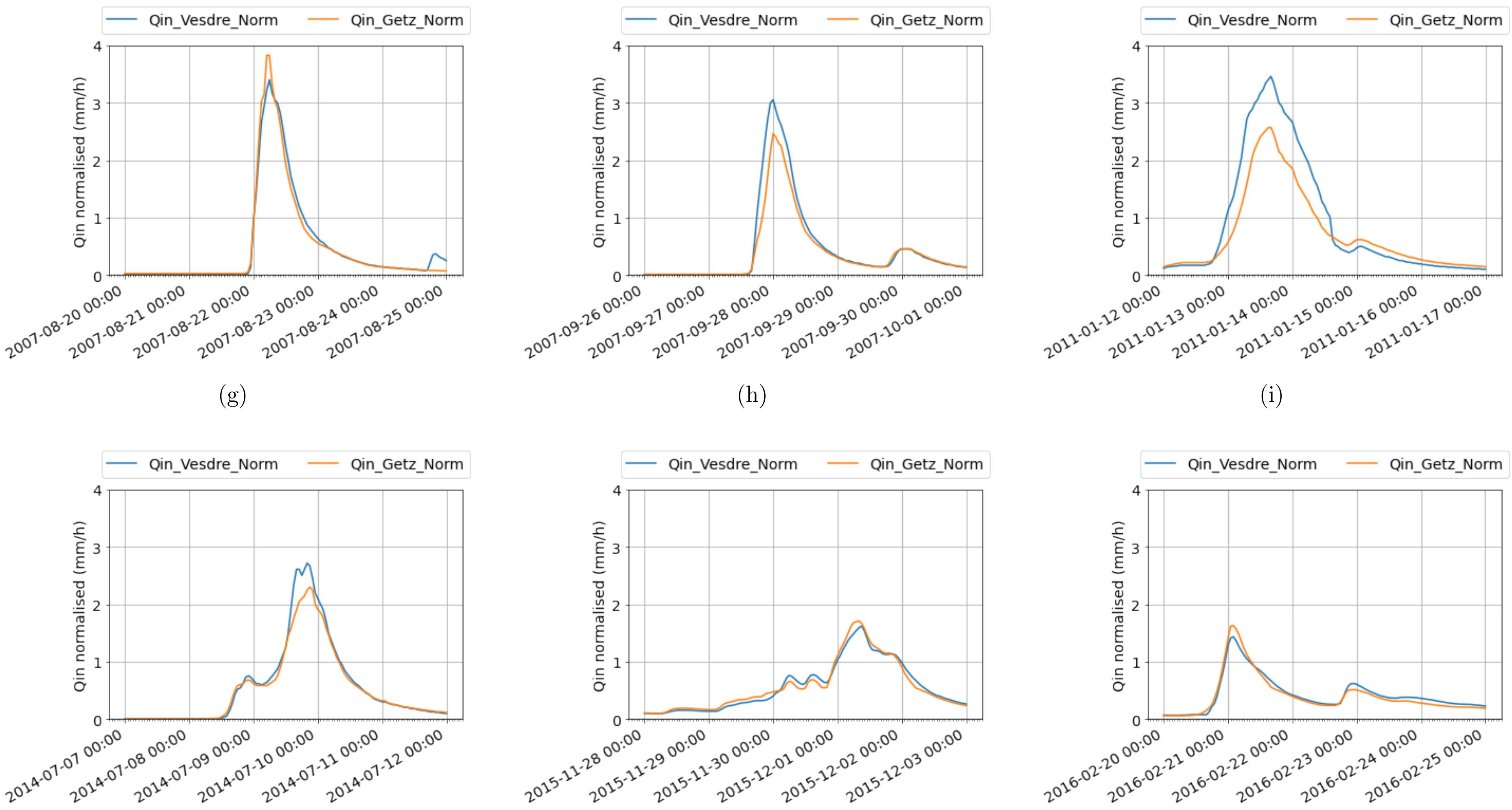
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Qin_Getz_Norm
Qin normalised (mm/h)
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2007-08-21 00:00
2007-08-22 00:00
2007-08-23 00:00
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2007-09-29 00:00
2007-09-30 00:00
2007-10-01 00:00
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2011-01-14 00:00
2011-01-15 00:00
2011-01-16 00:00
2011-01-17 00:00
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2015-12-01 00:00
2015-12-02 00:00
2015-12-03 00:00
2016-02-20 00:00
2016-02-21 00:00
2016-02-22 00:00
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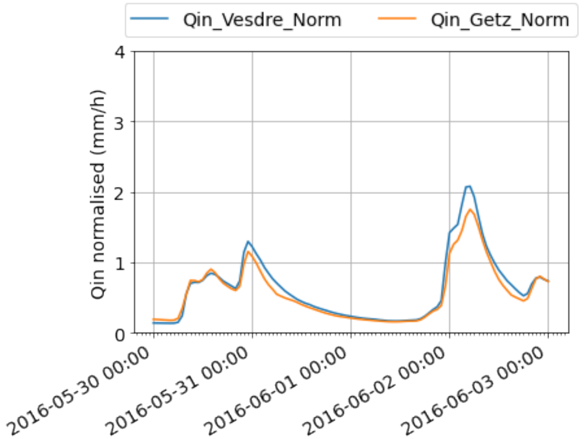
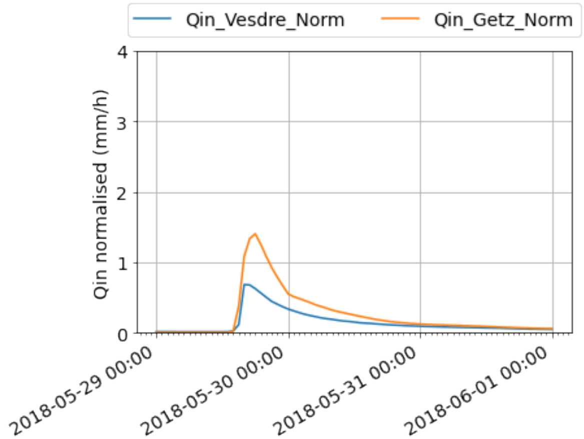
2016-02-24 00:00
2016-02-25 00:00

(g) (h) (i)

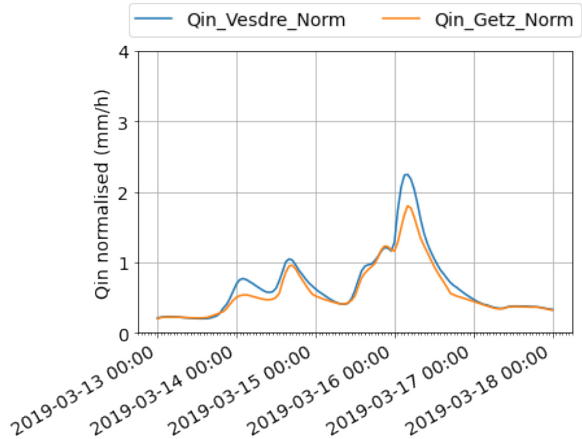
(j) (k) (l)



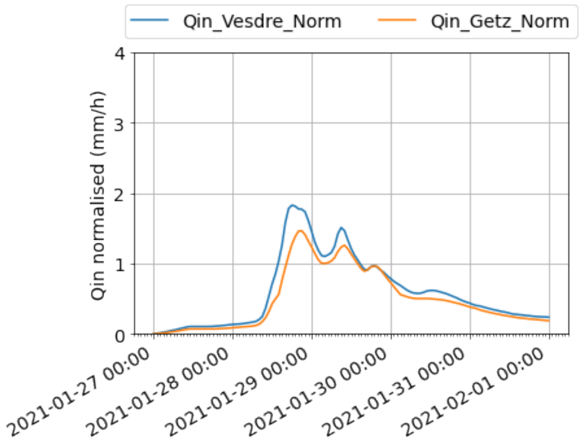
(m)



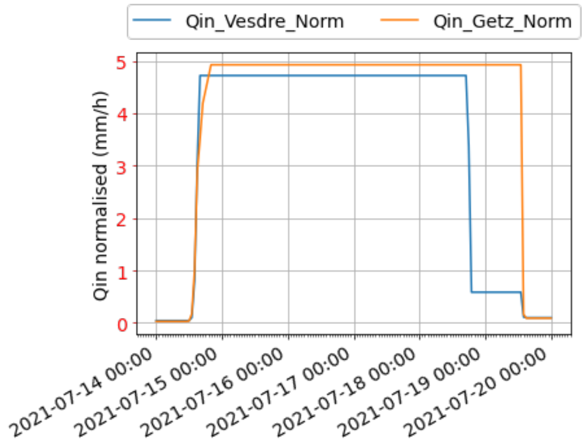
(n)



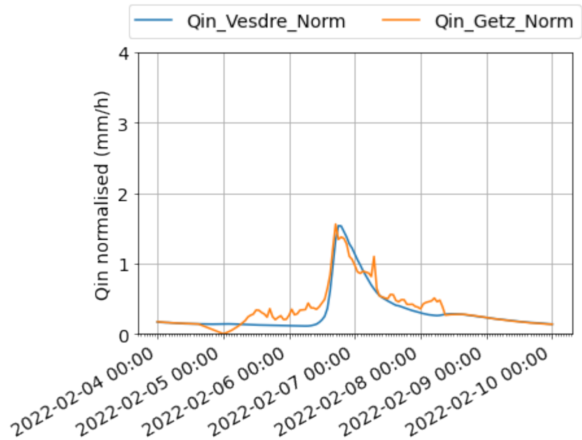
(o)



(p)



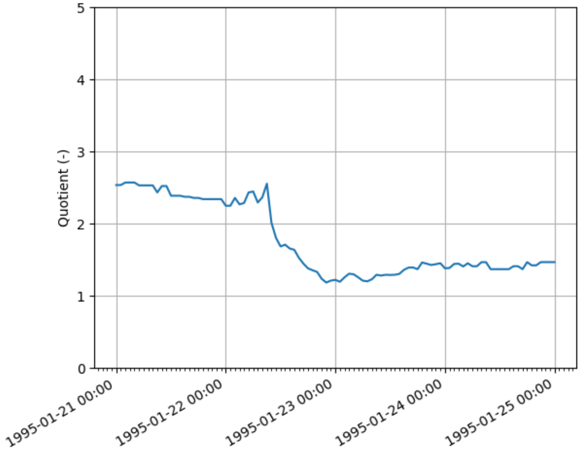
(q) Not reliable



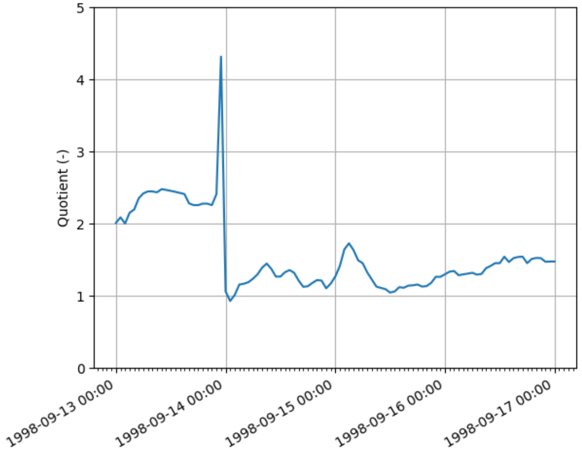
(r)

Figure A.5

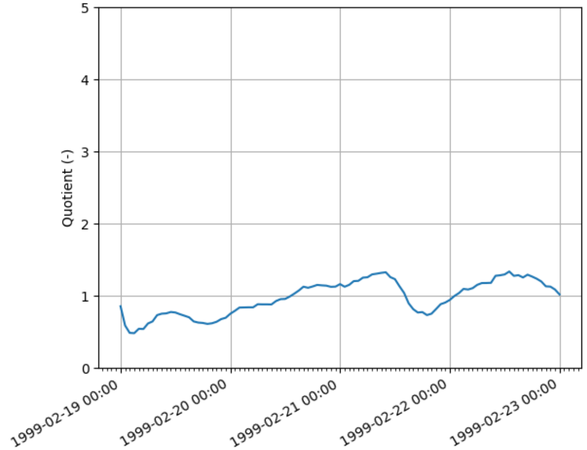
A.6 Data processing: Ratio between the normalised inflow discharge from the Getzbach and the normalised inflow discharge from the Vesdre.



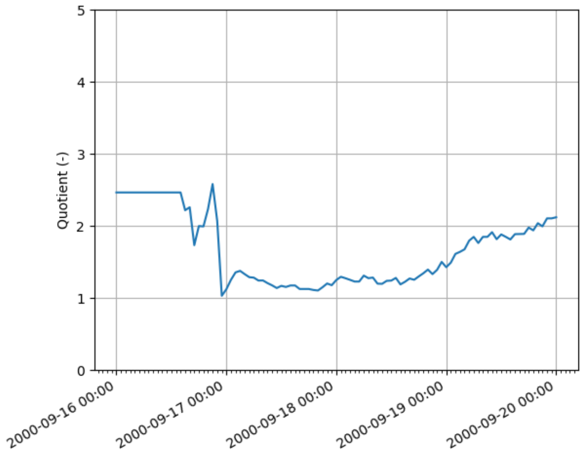
(a)



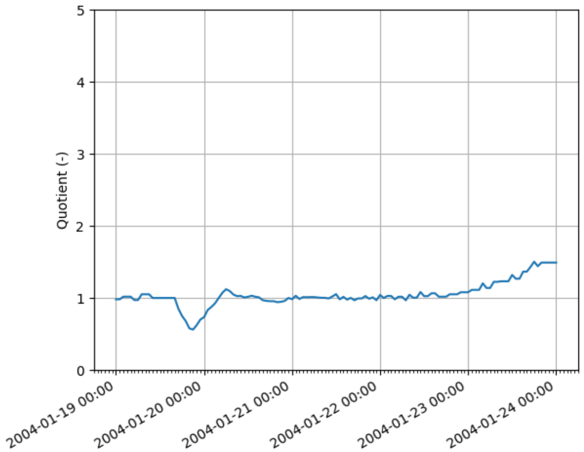
(b)



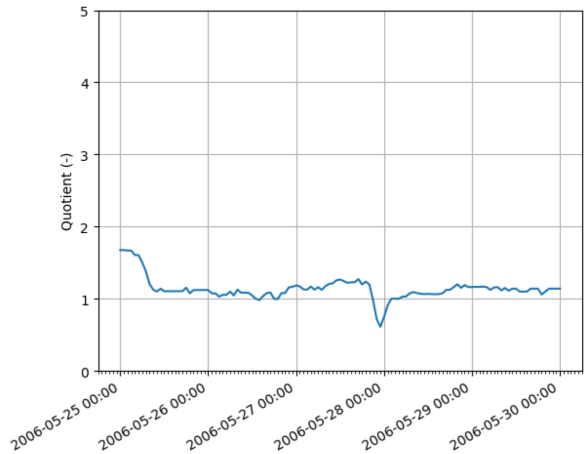
(c)



(d)



(e)



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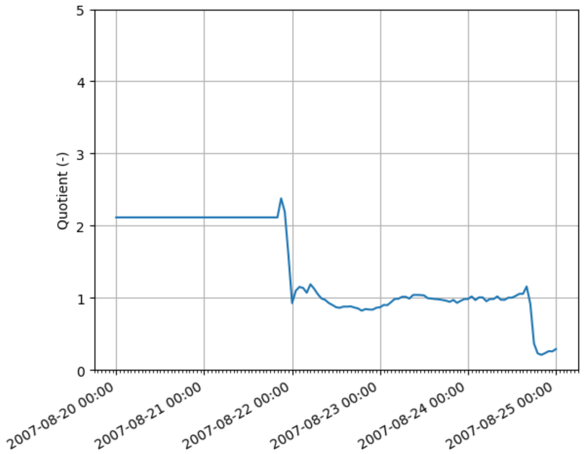
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5
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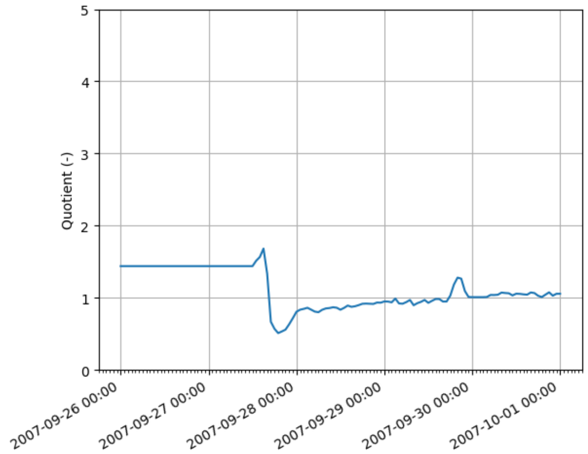
2007-08-25 00:00

(g)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3
4
5
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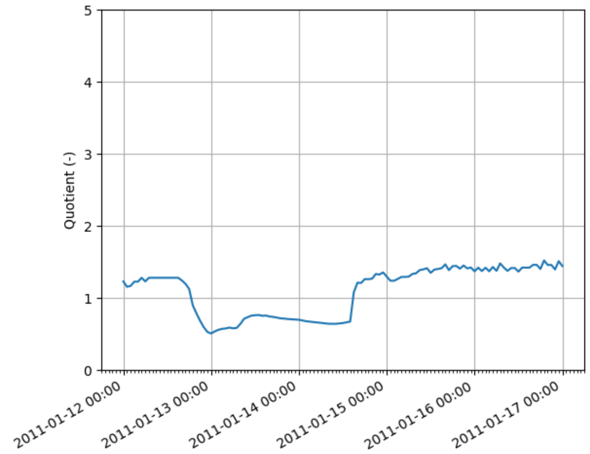
2007-09-29 00:00
2007-09-30 00:00
2007-10-01 00:00

(h)


Quotient (-)
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1
2
3
4
5
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2011-01-13 00:00
2011-01-14 00:00
2011-01-15 00:00
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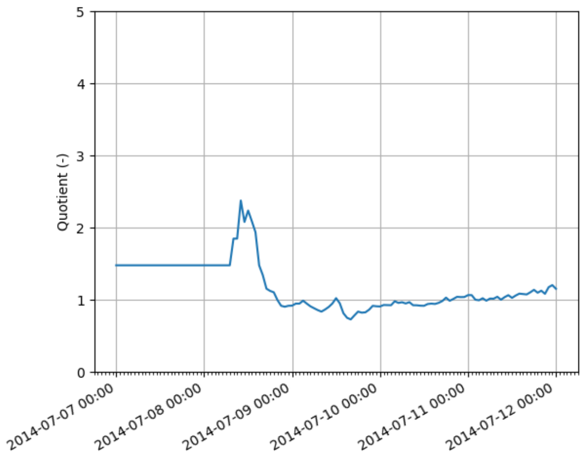
2011-01-17 00:00

(i)


Quotient (-)
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2
3
4
5
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2014-07-08 00:00
2014-07-09 00:00
2014-07-10 00:00
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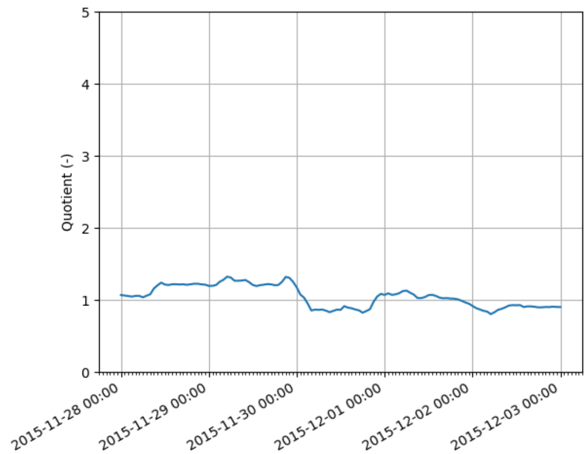
(j)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2
3
4
5
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2015-11-30 00:00
2015-12-01 00:00
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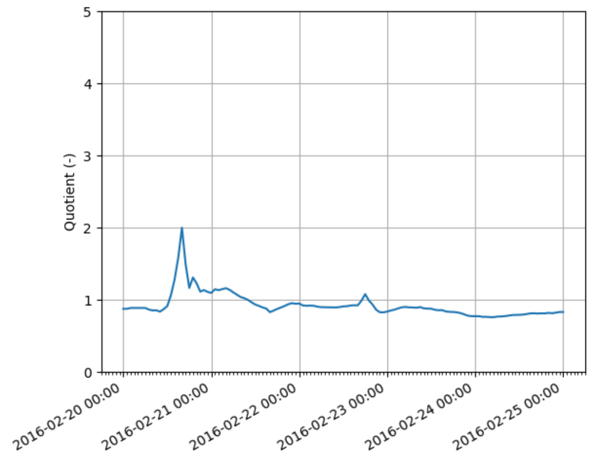
(k)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1
2
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4
5
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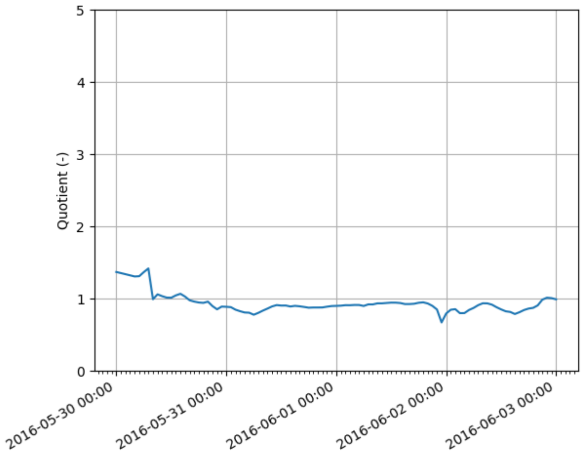
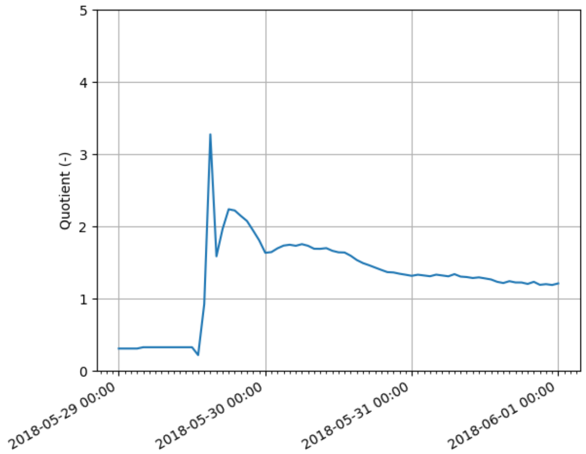
2016-02-25 00:00

(l)



(m)



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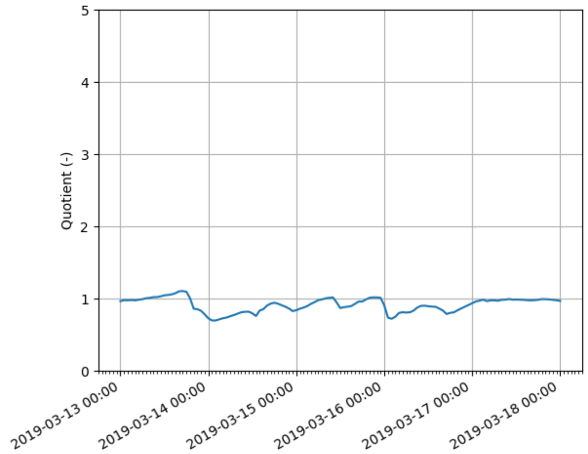
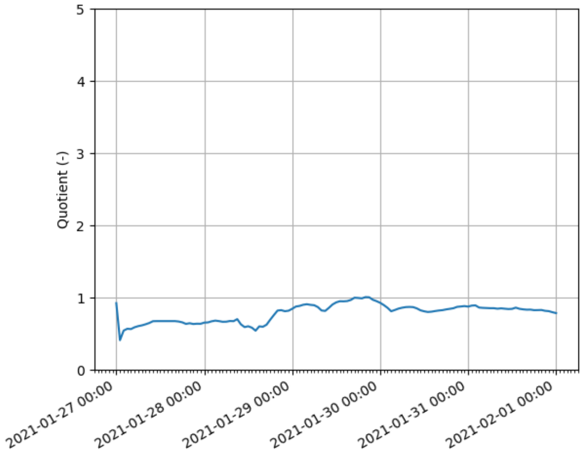


(o)



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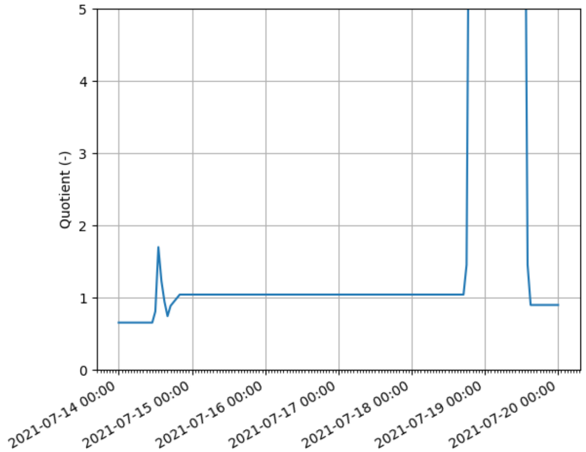
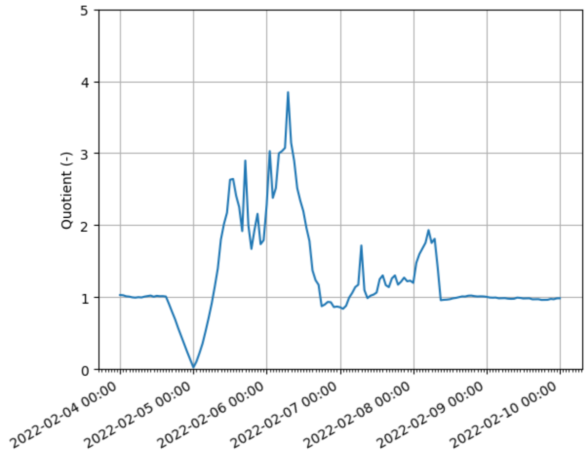


(q) Not reliable



(r)

Figure A.6

A.7 Data processing: Extreme precipitation events recorded by the IRM

Date	Event
22-01-1995	" Les inondations de ce mois de janvier sont à nouveau d'une ampleur tout à fait exceptionnelle, touchant principalement le bassin de la Meuse. Elles s'expliquent surtout par les pluies abondantes qui arrosent le pays depuis la fin décembre 1994."
13-09-1998	"Journée exceptionnelle par l'abondance des précipitations, principalement dans les provinces de Flandre-Orientale, Anvers, Brabant flamand, Limbourg et Liège."
28-02-1999	"Entre les mois de septembre 1998 et février 1999, les précipitations ont été extrêmement abondantes dans le pays"
15-09-2000	" Le nord du pays, en particulier les régions de Zwalm, d'Erpe-Mere et d'Anvers, est touché par plusieurs tornades lors de violents orages. Des inondations se produisent aussi dans les régions de Gand et de Courtrai."
13-02-2002	"Les rivières débordent dans de nombreuses régions du pays, principalement au sud du sillon Sambre-et-Meuse."
20-02-2002	"Des cours d'eau débordent dans les provinces d'Anvers, du Brabant flamand, du Brabant wallon, du Hainaut, de Namur, de Liège et du Limbourg. Certaines rivières quittent leur lit pour la troisième fois de l'année."
20-01-2004	"Avec 102,4 mm, la décade qui s'achève est la plus pluvieuse de toutes les décades de janvier depuis le début des observations en 1901 (normale : 21,6 mm)."
27-05-2006	"Les moyennes régionales des précipitations furent toutes très supérieures aux valeurs normales. Aux dates du 8, ou 27 29, des pluies journalières de plus de 40 mm ont été obervées"
21-08-2007	"L'excès est anormal dans la régions Gileppe et Warche et en Ardenne ; les écarts à la normale sont normaux ailleurs. Les précipitations journalières les plus abondantes ont varié de 2 mm à plus de 115 mm et furent observées le plus sou-vent le 9 ou le 21. Des cotes journalières de plus de 40 mm se sont produites le 7, le 9 ou le 21 ; à cette dernière date on a dépassé relevé 118,0 mm à Géromont"
27-09-2007	"Les moyennes régionales des précipitations furent variables autour des valeurs normales. Elles varièrent de 69% de la normale dans le Tournaisis à 145% dans la région Gileppe et Warche. L'excès est anormal dans la région Gileppe et Warche ; ailleurs, les écarts sont normaux. Les cotes journalières les plus abondantes dans le pays varièrent de 5 mm à plus de 90 mm et furent relevées principalement le 17 ou le 27."
07-01-2011	"A l'est du sillon Sambre-et-Meuse, la combinaison d'un redoux brutal au cours de la nuit écoulée et de précipitations abondantes tombées à cette même période explique que localement, des rivières sont sorties de leur lit, provoquant des dégâts." voir si neige juste avant

10-07-2014	"Les cotes journalières les plus abondantes ont varié de 10 mm à plus de 85 mm et se sont produites les 8, 9, 27 et 29. Des cotes journalières de plus de 40 mm ont été observées à ces mêmes dates, la plus remarquable étant celle relevée le 9 à Sprimont (85,9 mm)."
02-06-2016	"Les moyennes régionales des précipitations mensuelles furent partout supérieures aux valeurs normales. Elles ont varié de 149% de la valeur normale dans la région de l'Entre-Sambre-et-Meuse à 251% en Campine. Les écarts furent exceptionnellement élevés en Campine et dans le Pays de Herve, très anormalement élevés dans le Tournaisis, les Brabants, la Hesbaye, le Borinage, le Condroz et la région Gileppe et Warche. Des quantités de précipitations supérieures à 40 mm ont été relevées le 1, du 5 au 7, le 11 et le 23. "
31-05-2018	"Les moyennes régionales des précipitations mensuelles fluctuèrent autour des valeurs normales. Elles ont varié de 52% de la normale dans les deux Brabants à 142% dans la région Gileppe et Warche. Des cumuls journaliers supérieurs à 40 mm ont été relevés dans le pays les 16, 22, 23, 24, 28, 29 et 31"
16-03-2019	"Dans le pays, les moyennes régionales des quantités de précipitations mensuelles ont partout été supérieures aux valeurs normales. Elles ont varié entre 109% de la normale dans le Condroz et 146% de la normale dans le Pays de Herve. Ces valeurs régionales sont normales. Ce n'est que très localement que les quantités de précipitations mensuelles ont pu être un peu inférieures aux normales. Les quantités journalières les plus élevées ont été observées le 15. Au Mont-Rigi (Waimes), on a relevé à cette date jusqu'à 60,0 mm"
14-07-2021	"Dans le reste du pays, les plus fortes précipitations ont été observées le 14. Ce jourlà, quatre des stations du réseau de l'IRM ont mesuré plus de 100 mm. La quantité la plus importante a été enregistrée à Hockai (Stavelot), avec 179,0 mm. Les grandes quantités de précipitations tombées en milieu de mois ont entraîné de nombreuses inondations avec, malheureusement, un bilan humain très lourd, puisqu'une quarantaine de personnes ont perdu la vie. Les provinces de Liège, Namur et Luxembourg ont été particulièrement touchées et seul l'ouest du pays a été épargné. "

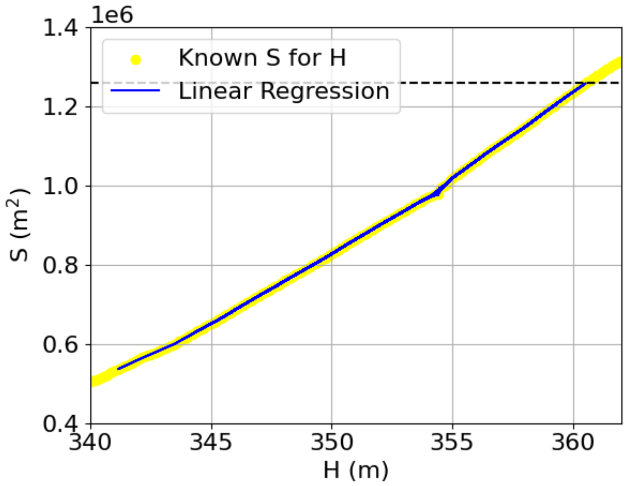
Table A.1: from IRM website, still have to translate, maybe should be in appendix?

A.8 Analysis on considering level dependent area of the reservoir or fixed at 126 ha for the computation of the inflow coming from the precipitation falling directly onto the reservoir

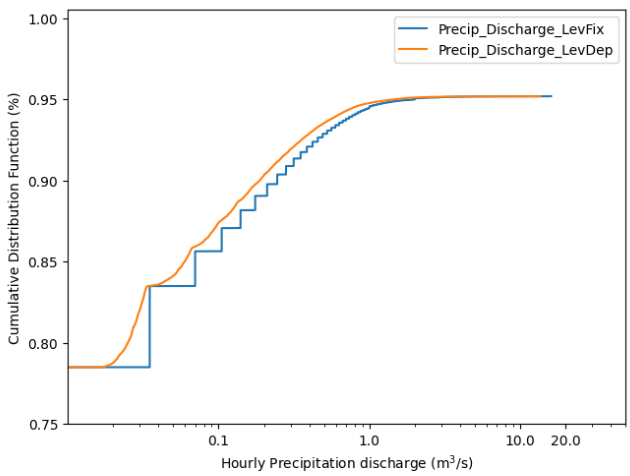
Figure A.7a shows the surface of the reservoir function of the water level in the reservoir. This curve was made by the SPW in 2022. The blue line shows the interpolation between the points already known (yellow). The dashed black line corresponds to a surface of 126 ha. We can see that this surface corresponds to a water level of 360.57m. This is a high water level when knowing that the percentil 90 of the height corrected by Calles [2015] is 358.15m.

Figure A.7b shows the cumulative distribution function of the discharge coming from the precipitation falling directly onto the reservoir for a fixed area of the reservoir (blue) and for the area that depends on the water level (orange). By using a fixed area, the computed discharge was overestimated. When computing the relative error between the discharge computed with a fixed area and with a water level-dependent area, we found that the average relative error is 5.6%.

When looking at Figure A.7b, we can see that 90% of the values are below or equal to 1 m^3/s. Therefore this relative error of 5.6% is negligible when computing the total inflow discharge.



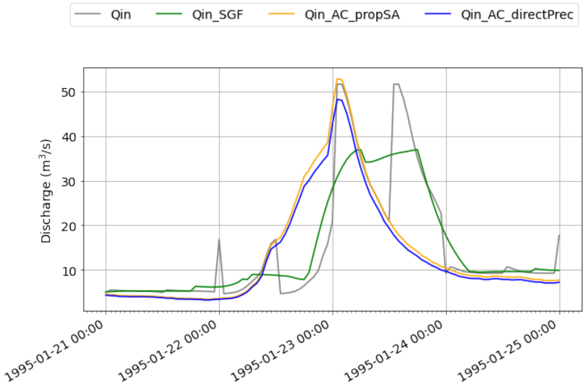
(a)



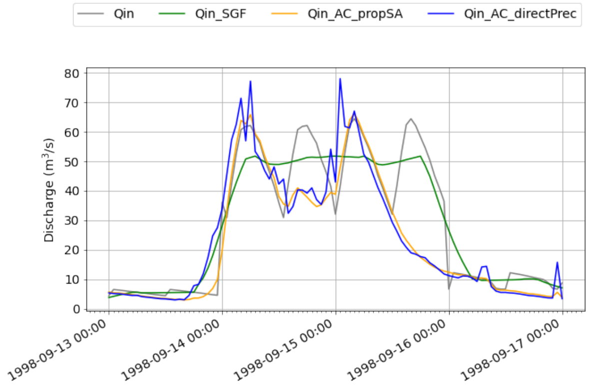
(b)

Figure A.7: (a) Area of the reservoir function of the water level in the reservoir. Data given by the SPW. Linear interpolation between the known points. The horizontal dashed line corresponds to a surface of 126 ha. (b) CDF for discharge values coming from precipitation falling directly onto the lake computing with a fixed area of 126 ha (blue) and an area dependent on the level of water (orange) for the period 1996 to 2022.

A.9 Data processing: Comparison of not corrected, corrected by Annick Calles and corrected by Savitzky-Golay inflow discharge



(a)



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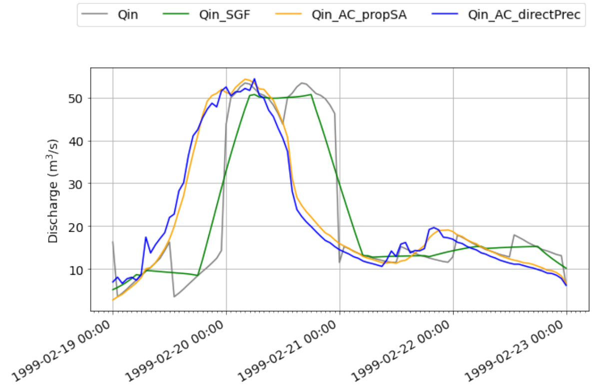
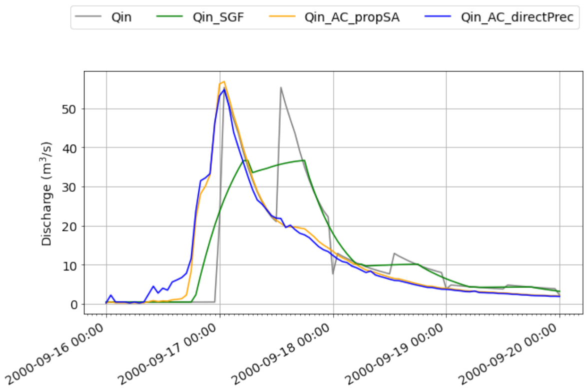


(c)



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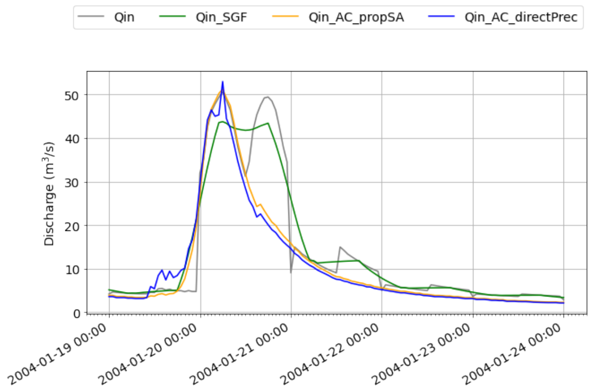
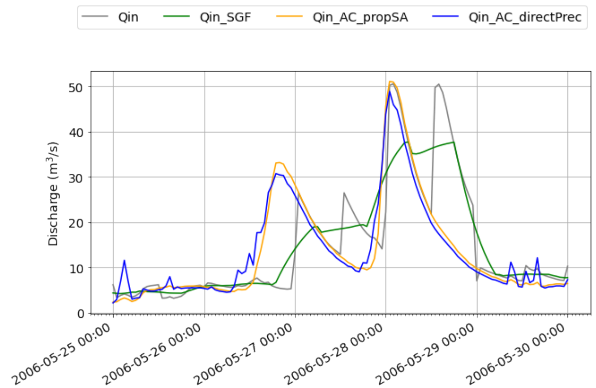


(e)



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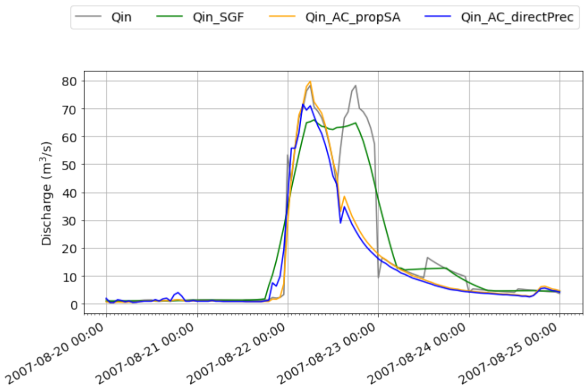
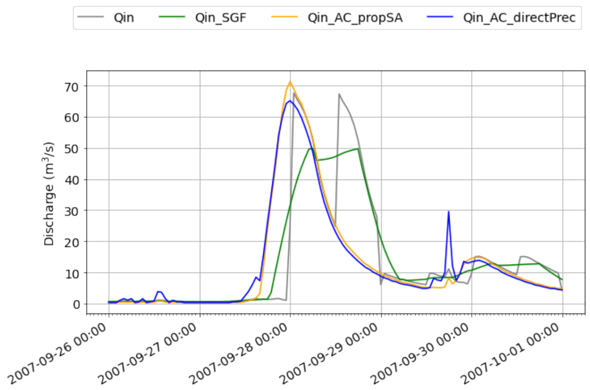
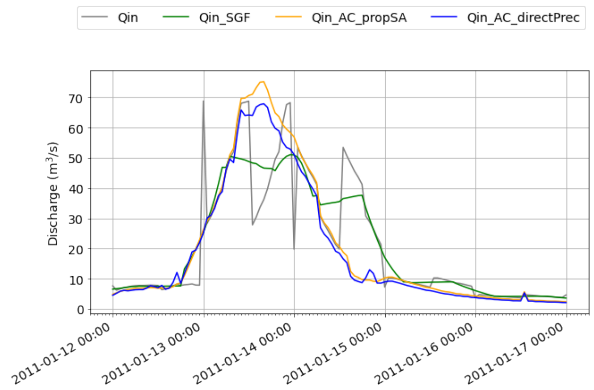


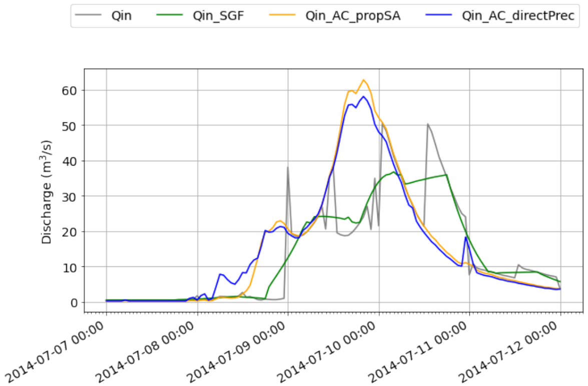
(g)



(h)



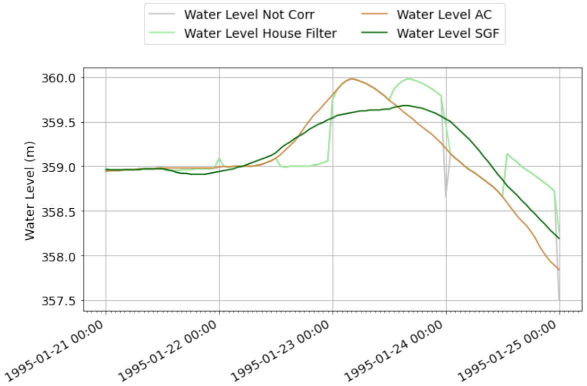
(i)



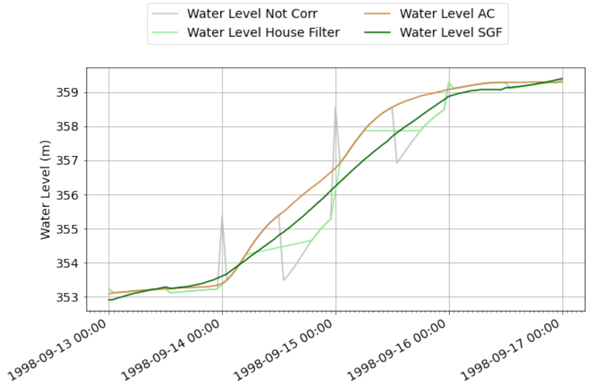
(j)

Figure A.8

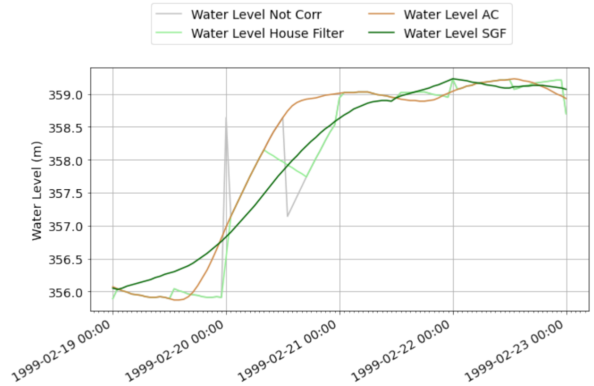
A.10 Data processing: Comparison of not corrected, Corrected by the house filter, corrected by Annick Calles and corrected by Savitzky-Golay water level in the Vesdre reservoir



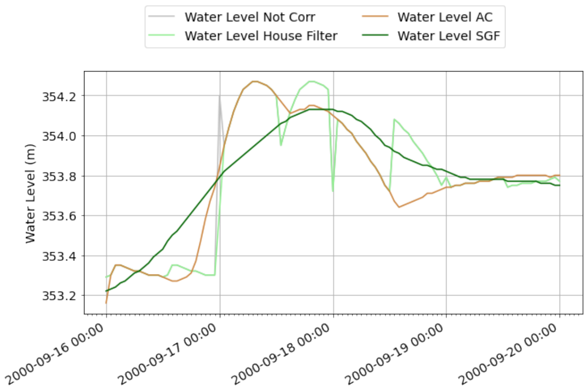
(a)



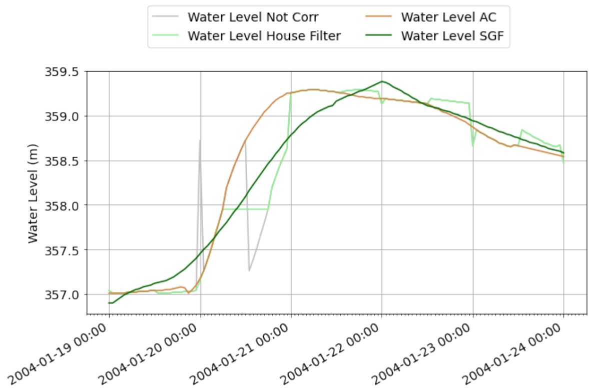
(b)



(c)



(d)



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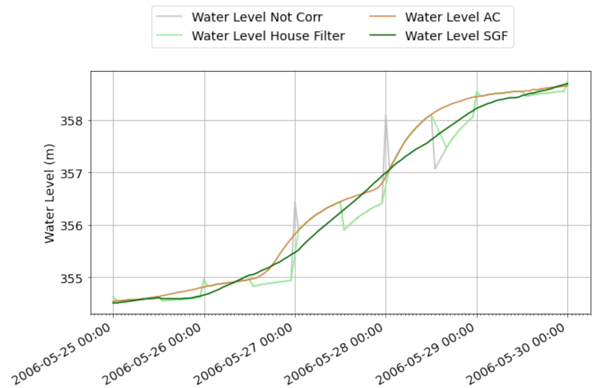
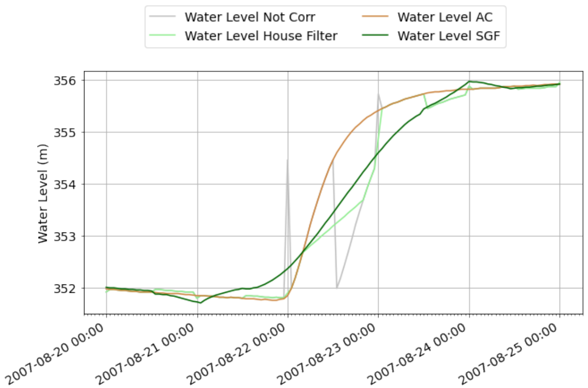
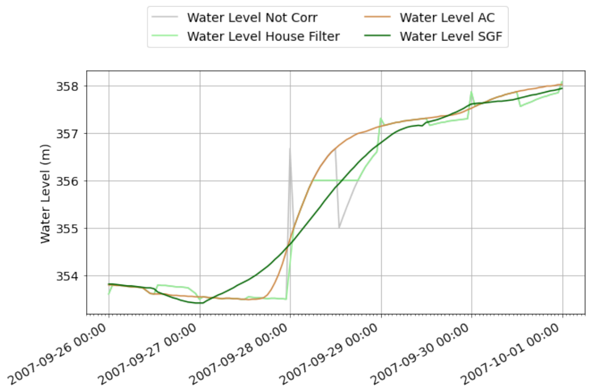


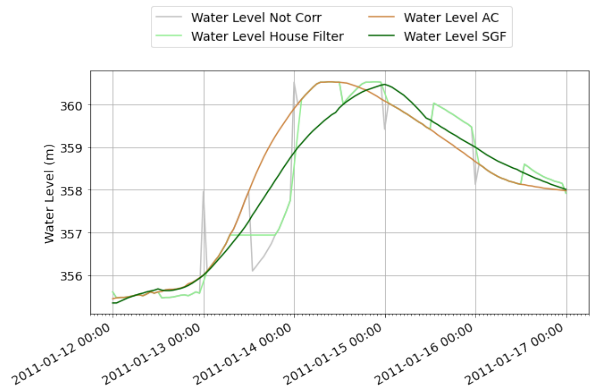
(f)



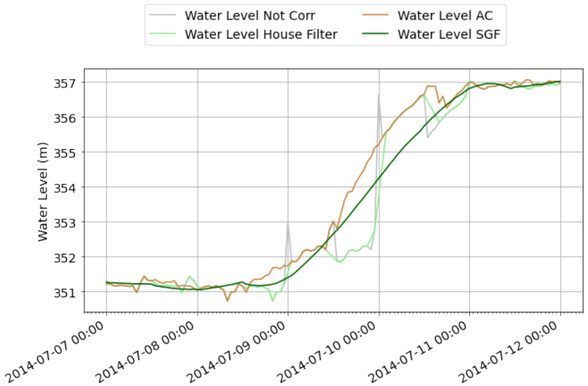
(g)



(h)



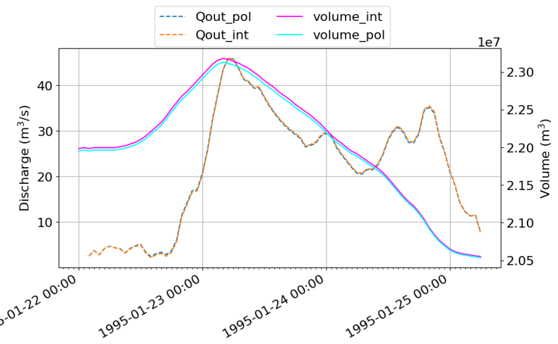
(i)



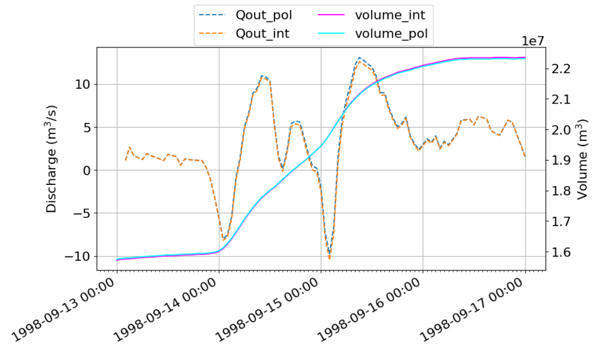
(j)

Figure A.9

A.11 Results: Effect of the method of interpolation of the stage-volume curve on the Qout



(a)



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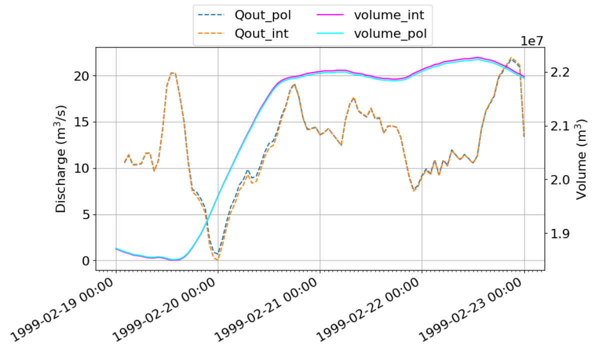

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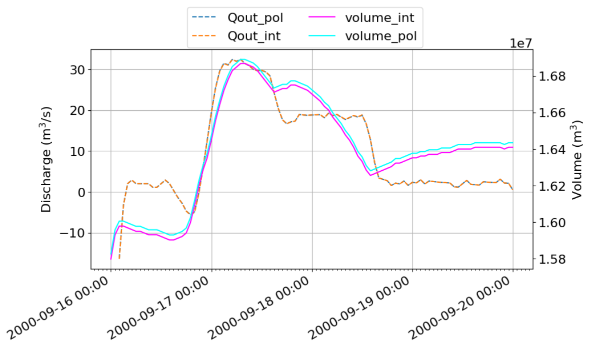

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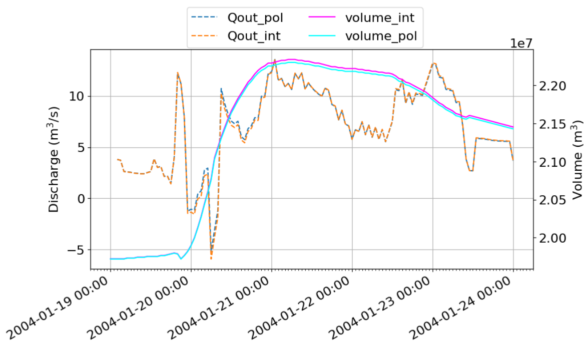

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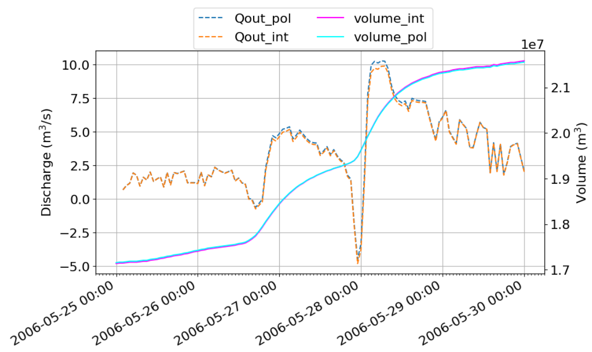
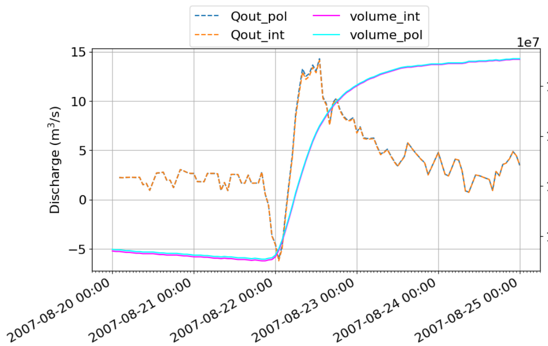


(f)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volume_int
volume_pol
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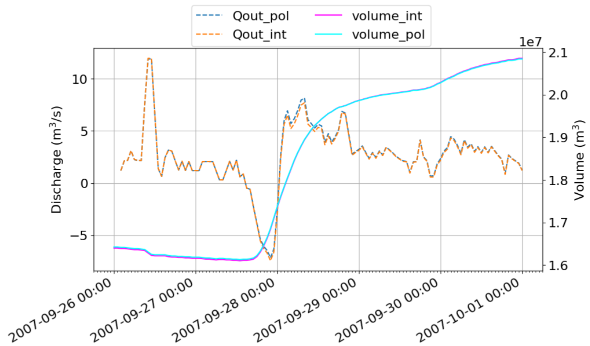
Volume (m^3)
1e7

(g)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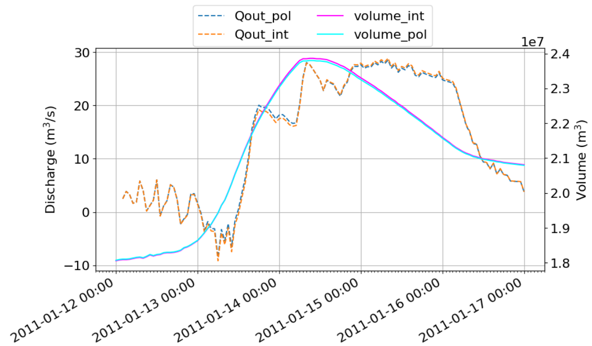
Qout_int
volume_int
volume_pol
Discharge (m^3/s)
Volume (m^3)
1e7

(h)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volume_int
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Discharge (m^3/s)
Volume (m^3)
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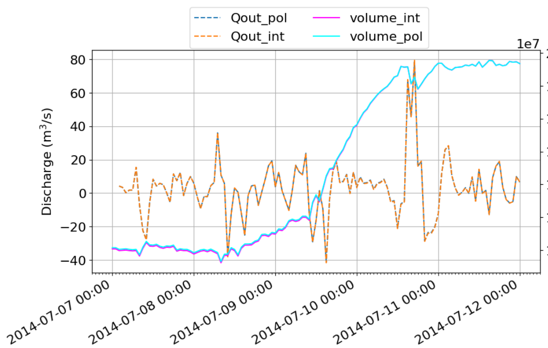
(i)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Qout_int
volume_int
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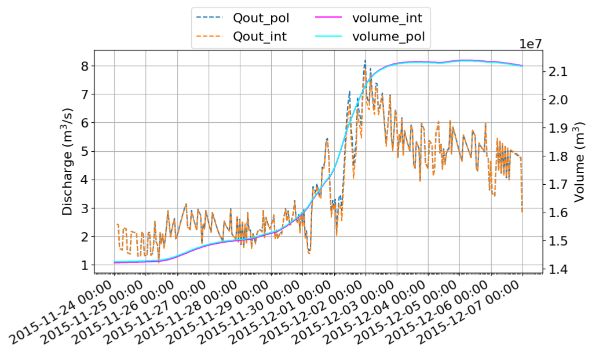
Discharge (m^3/s)
Volume (m^3)
1e7

(j)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volume_int
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Volume (m^3)
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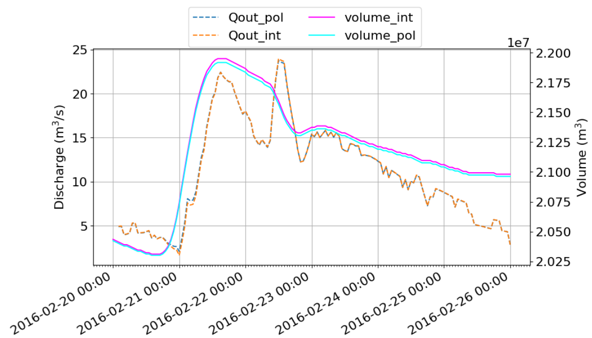
(k)


Qout_pol
Qout_int
volume_int
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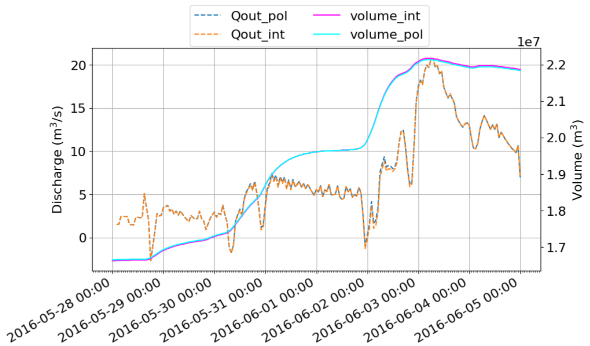
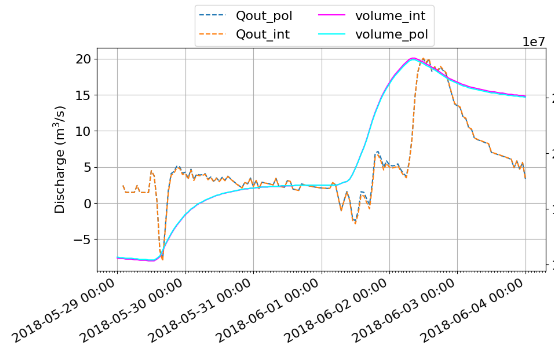
Discharge (m^3/s)
Volume (m^3)
1e7

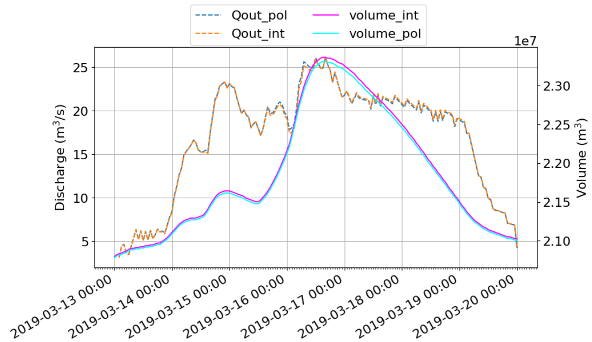
(l)



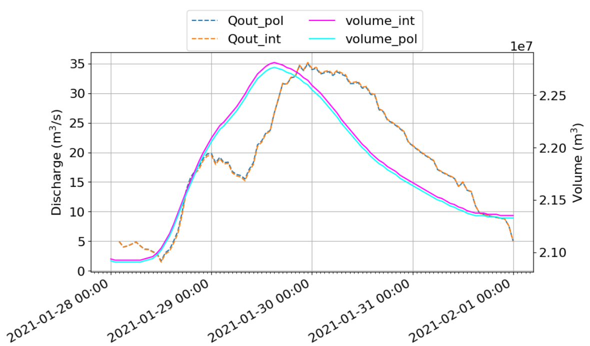
(m)



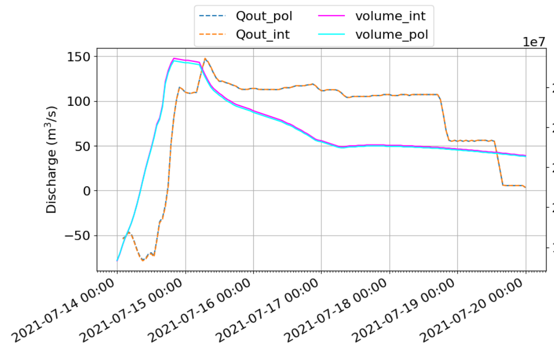
(n)



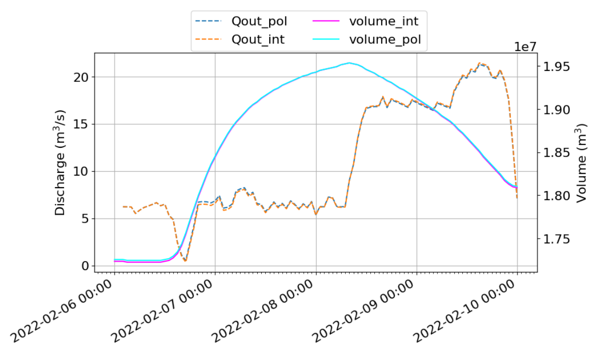
(o)



(p)



(q) Not reliable



(r)

Figure A.10

A.12 Results: Time series of the Qout computed with different Qin or/and filters

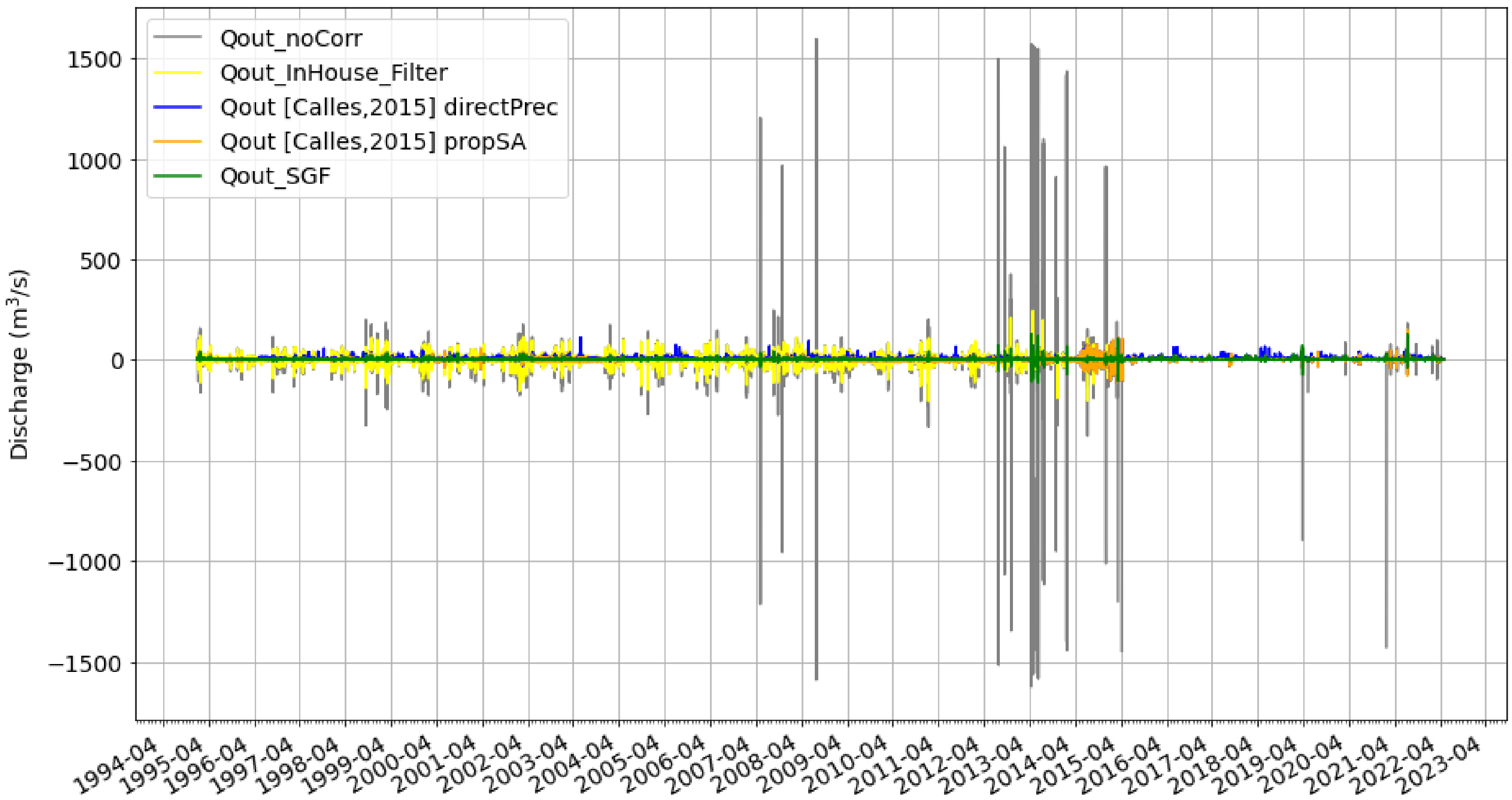
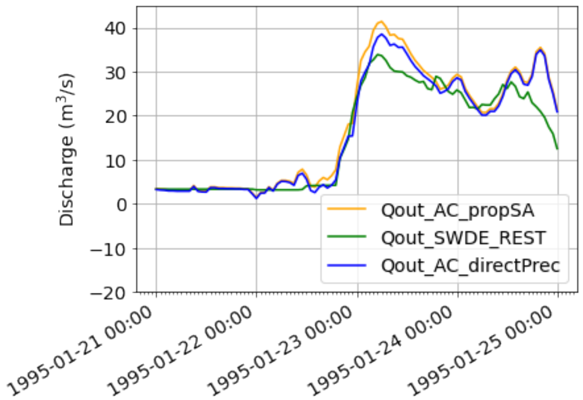


Figure A.11: Caption

A.13 Results: Comparison between the computed Qout and the sum of the measured restitution Qout and the discharge pumped the SWDE - Time Series



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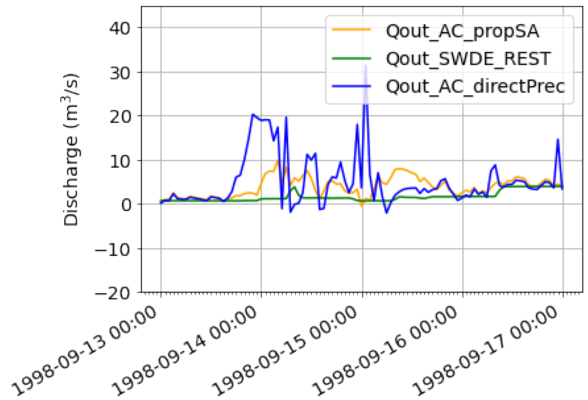

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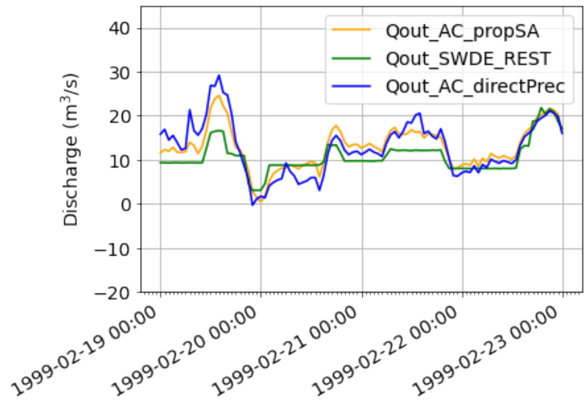
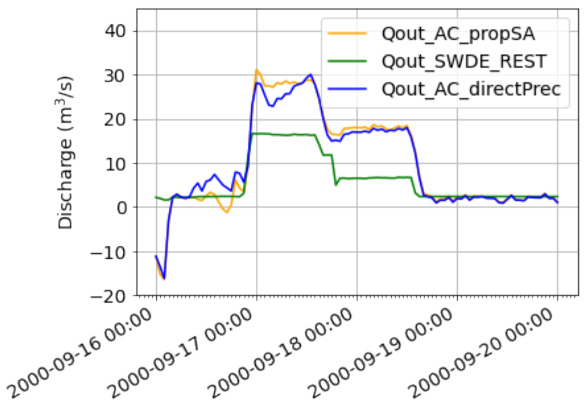
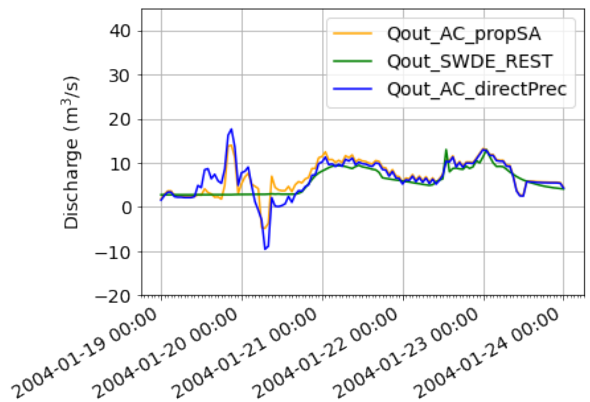


(c)



(d)



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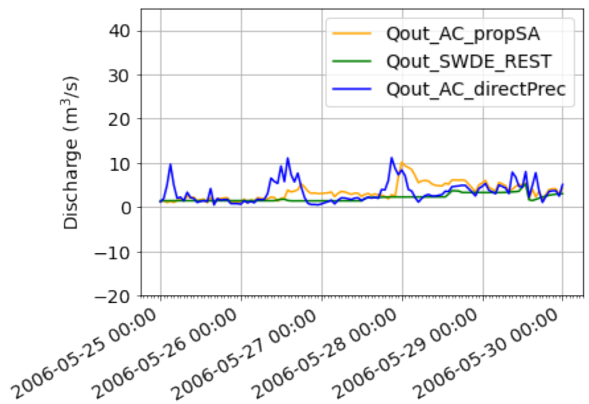

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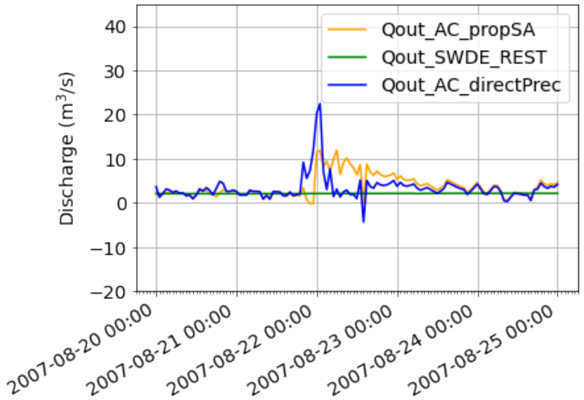
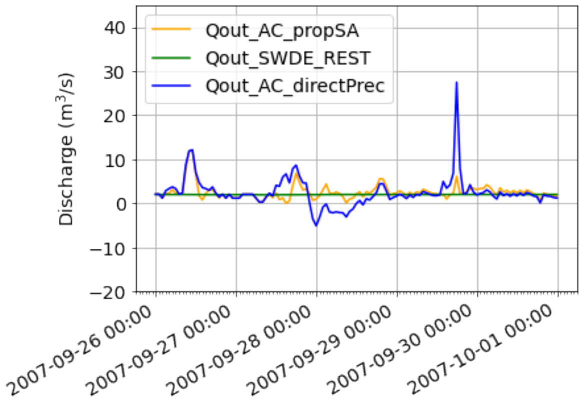
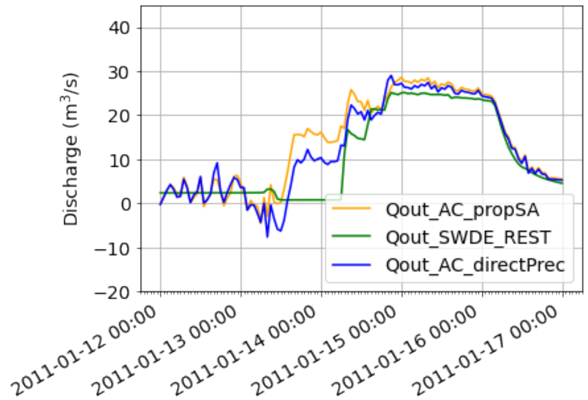


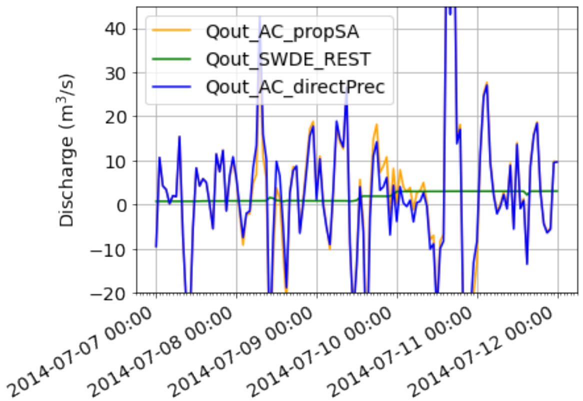
(g)



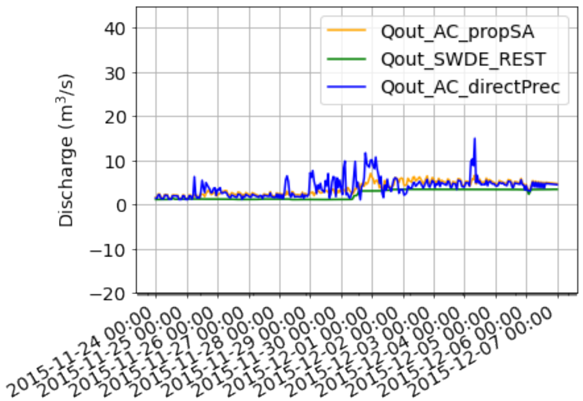
(h)



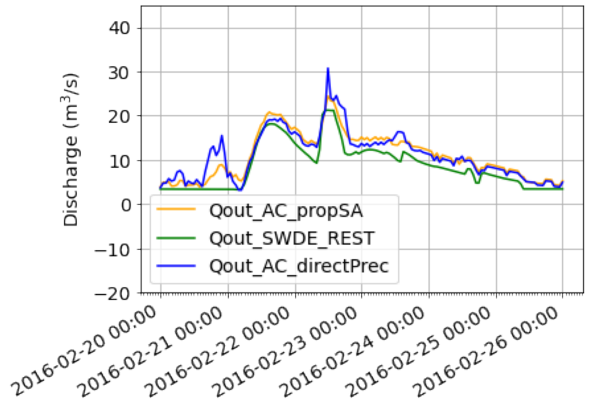
(i)



(j) Not reliable



(k)



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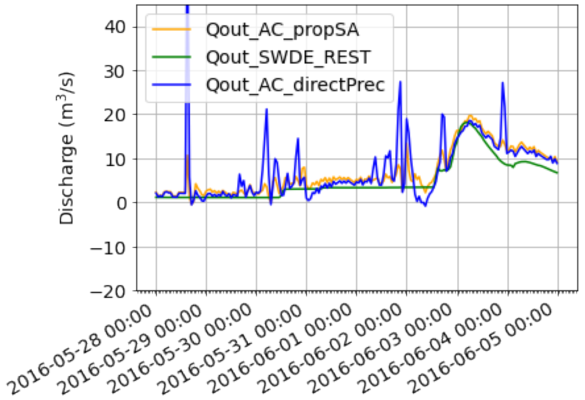

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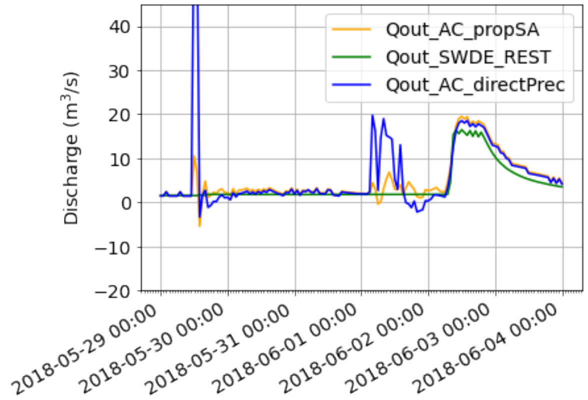

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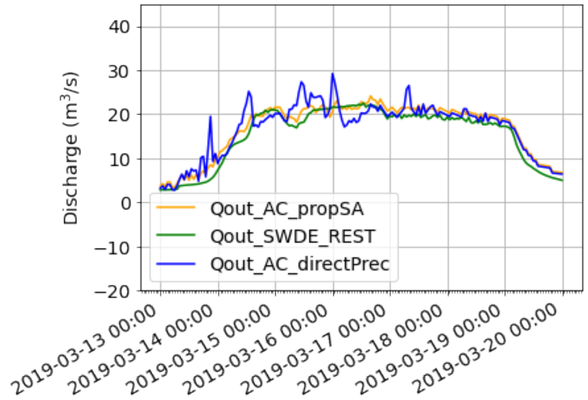

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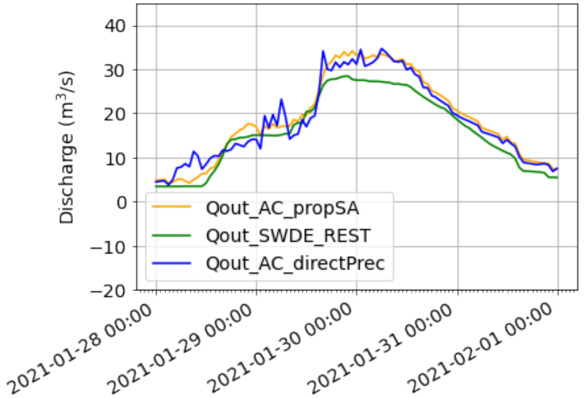
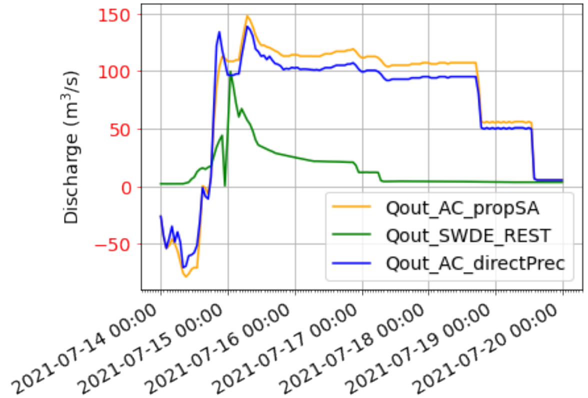
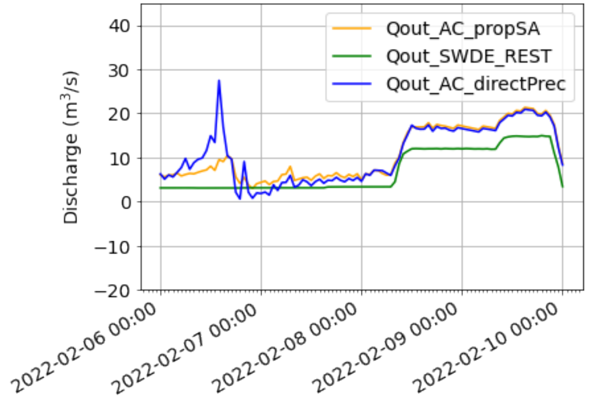


(p)



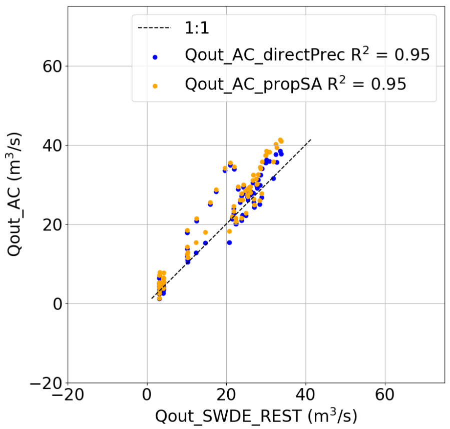
(q) Not reliable



(r)

Figure A.12

A.14 Results: Comparison between the computed Qout and the sum of the measured restitution Qout and the discharge pumped the SWDE - Scatter plot



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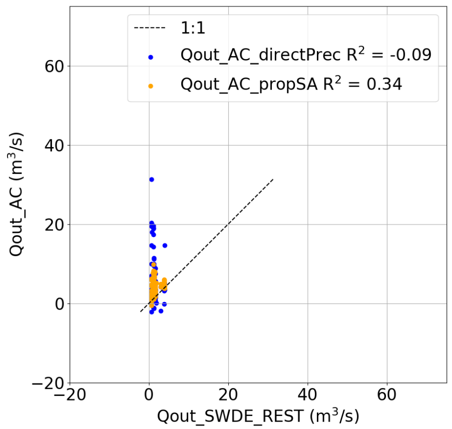
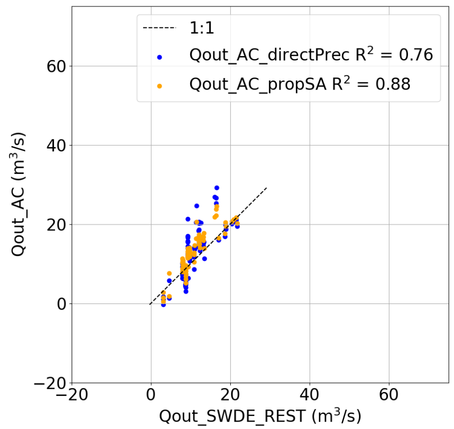
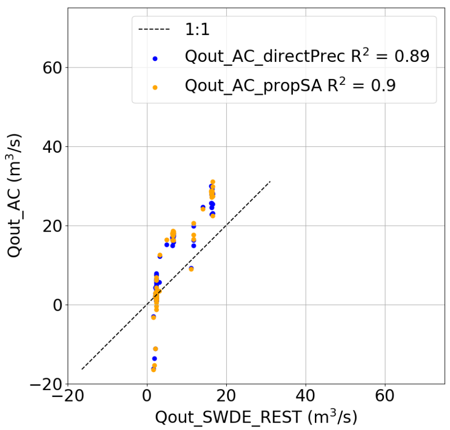


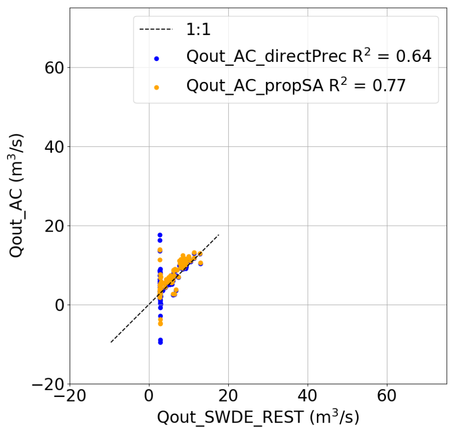
(b) September 1998



(c) February 1999



(d) September 2000



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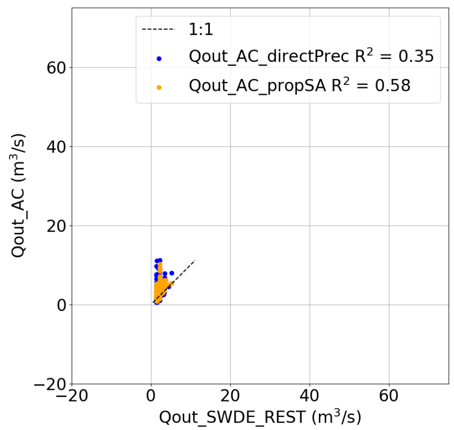
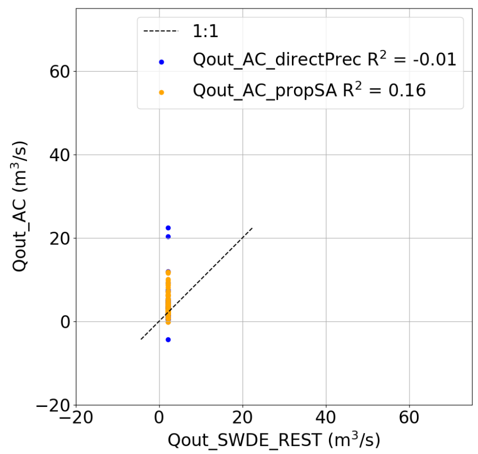
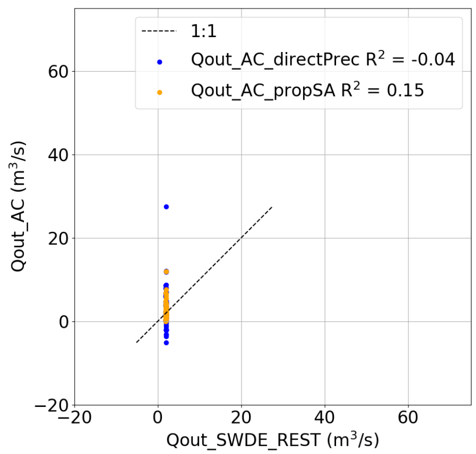


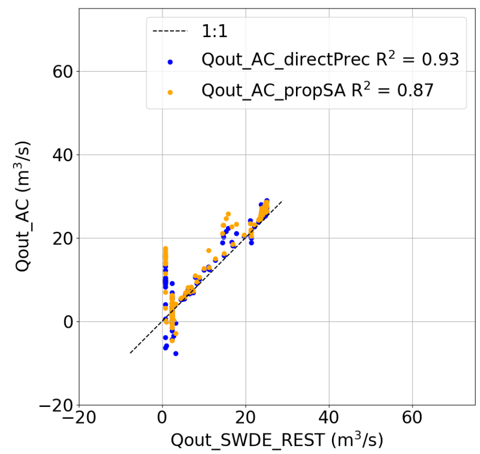
(f) Mai 2006



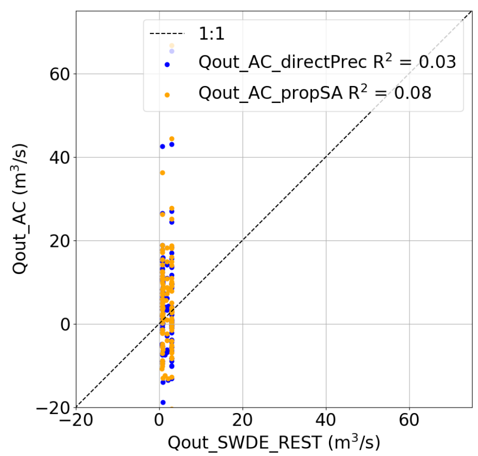
(g) August 2007



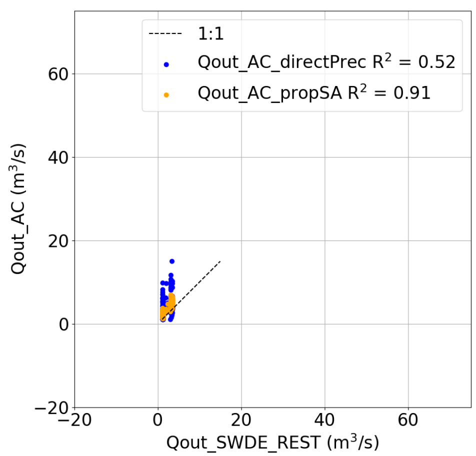
(h) September 2007



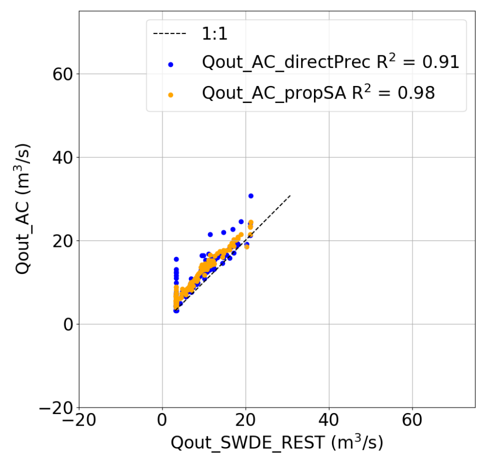
(i) January 2011



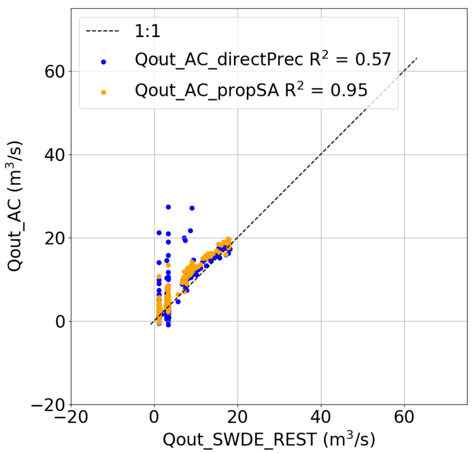
(j) July 2014 (Not reliable)



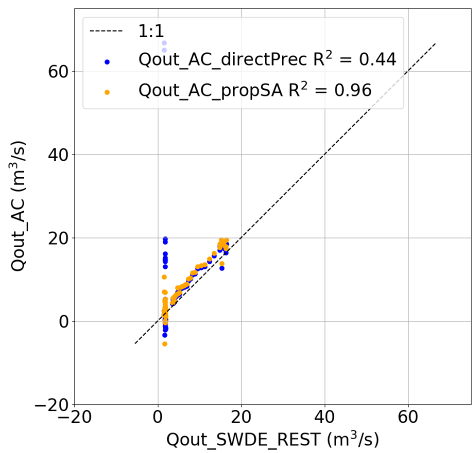
(k) November 2015



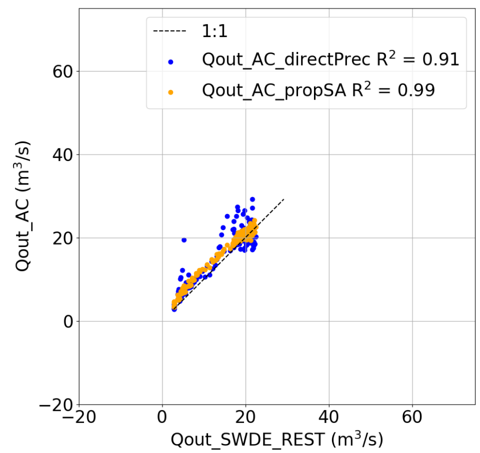
(l) February 2016



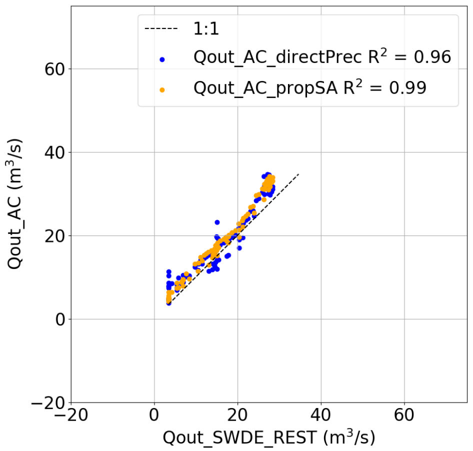
(m) Mai 2016



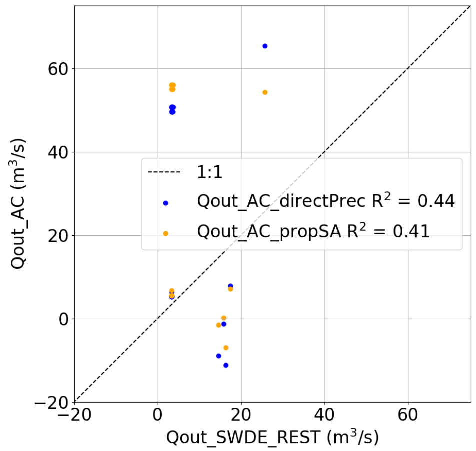
(n) Mai 2018



(o) March 2019



(p) January 2021



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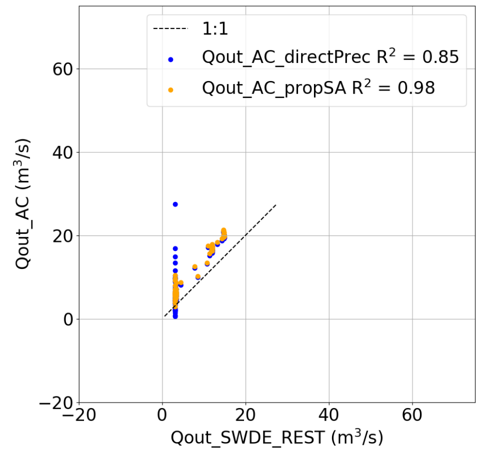
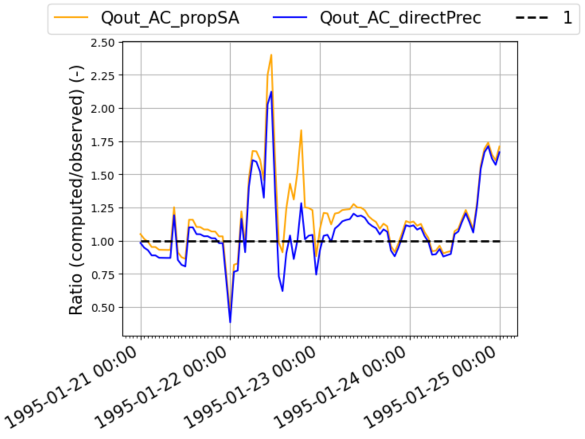


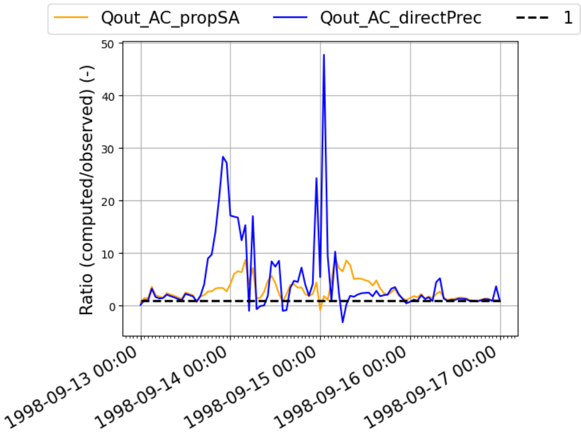
(r) February 2022

Figure A.13

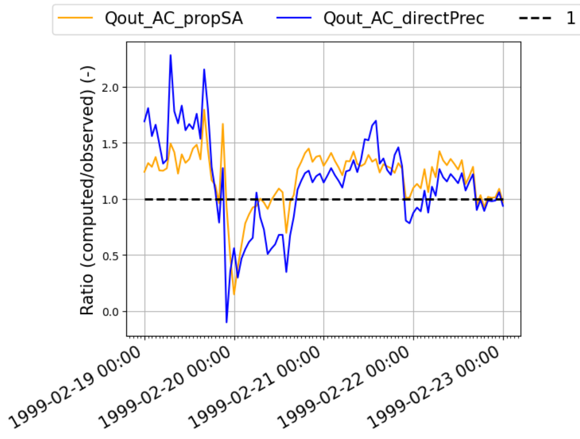
A.15 Results: Relative Error between the computed Qout and the sum of the measured restitution Qout and the discharge pumped the SWDE - Time Series



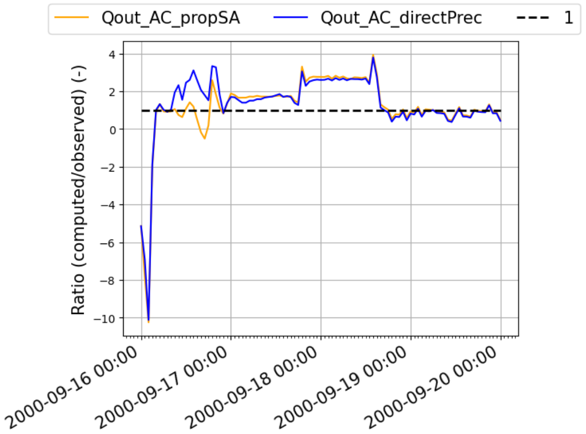
(a)



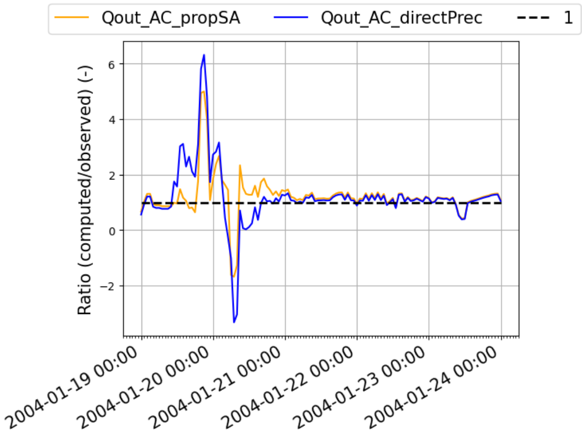
(b)



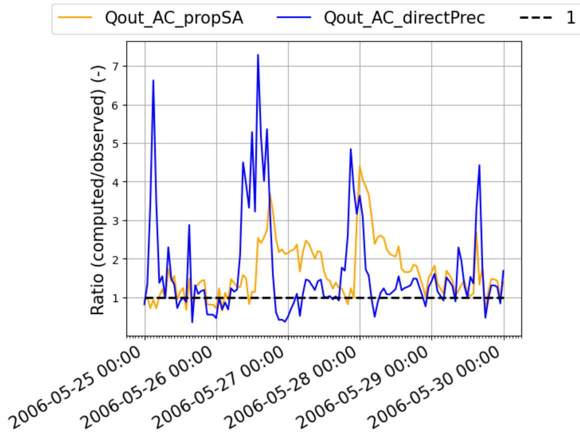
(c)



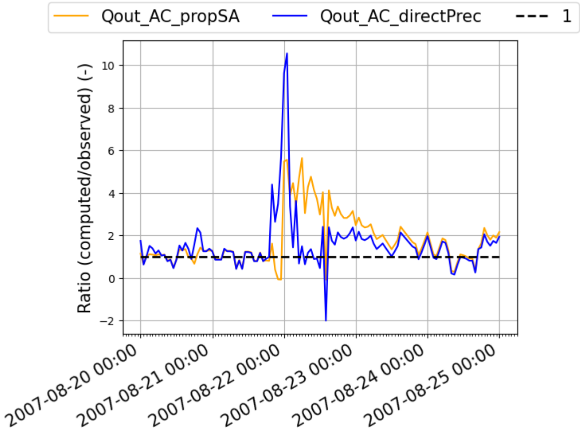
(d)



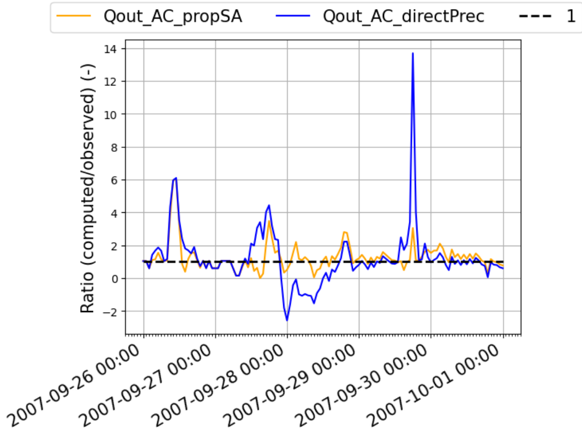
(e)



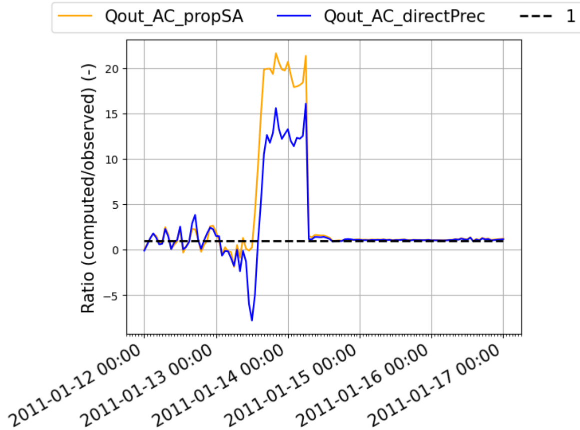
(f)



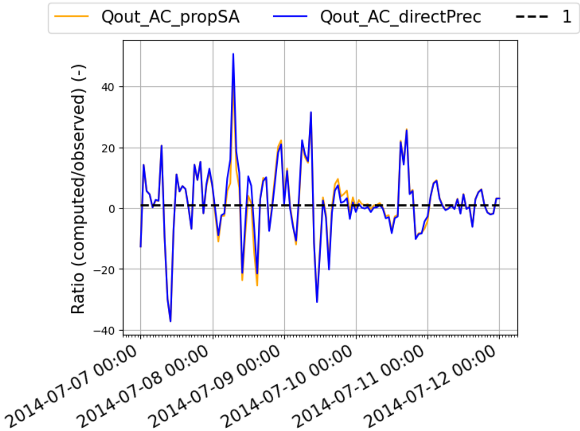
(g)



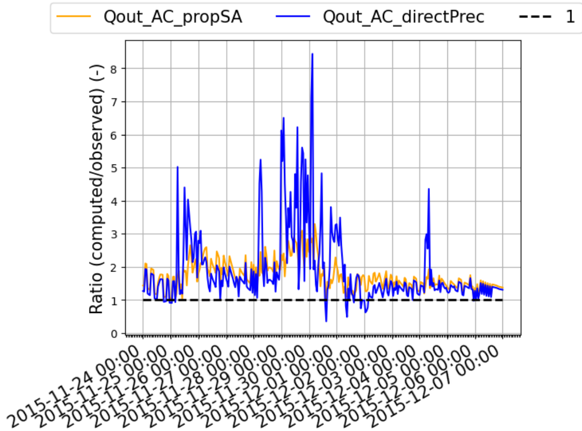
(h)



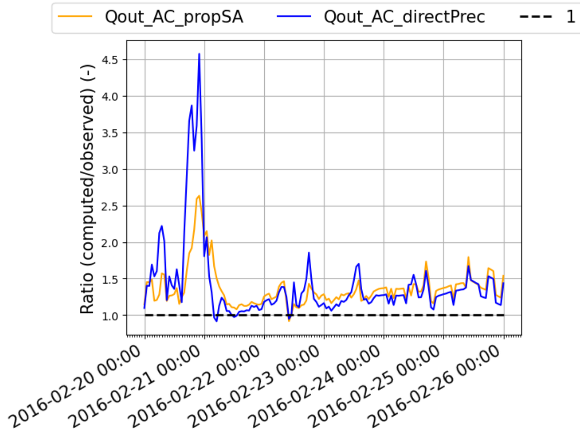
(i)



(j) Not reliable



(k)



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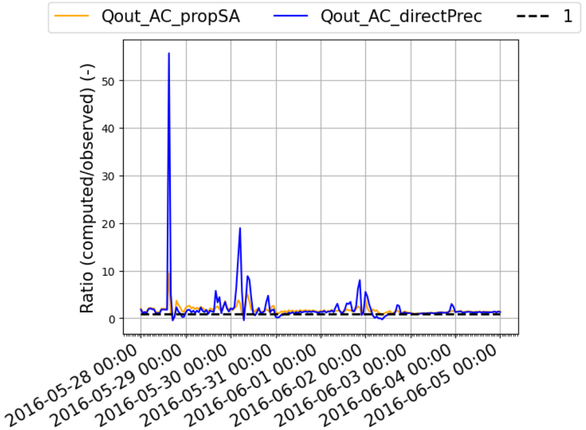

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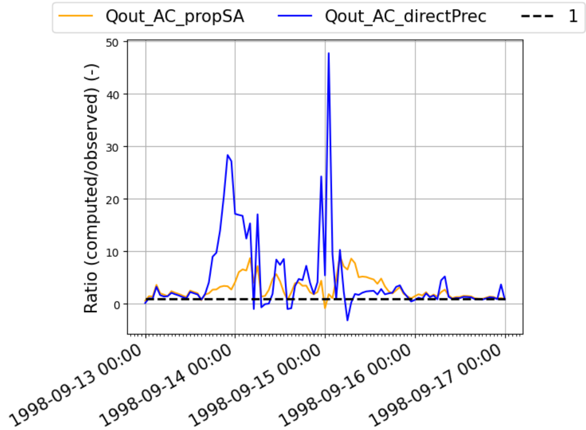

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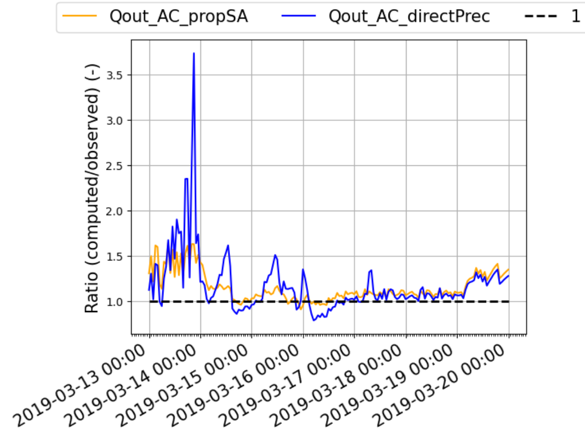

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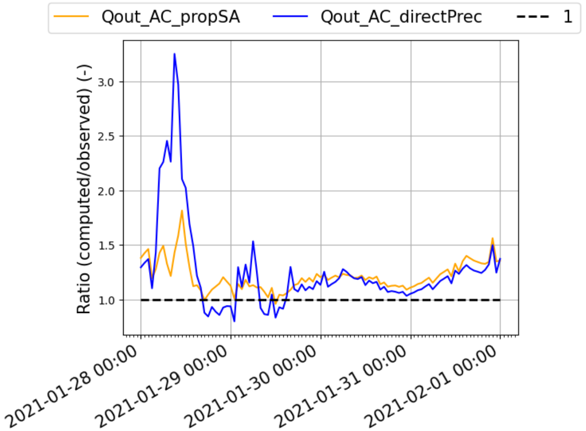

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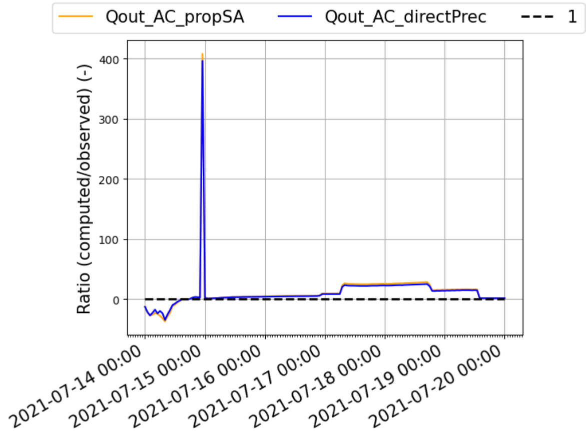

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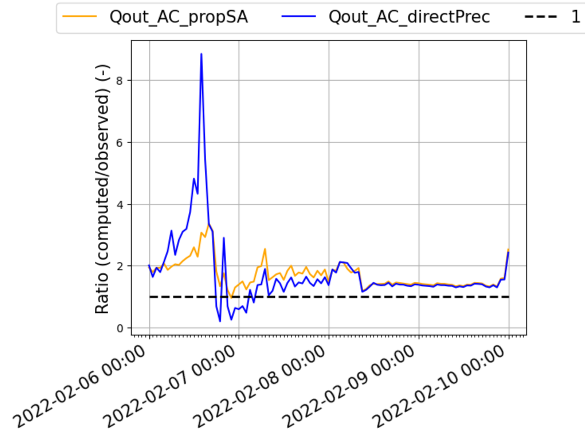
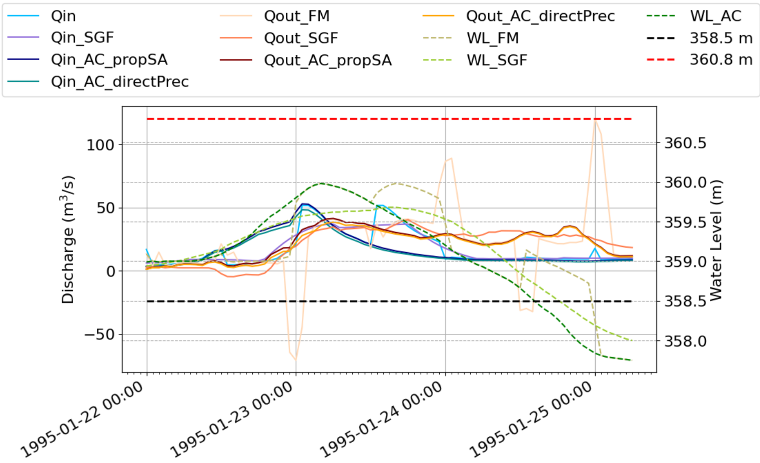


(r)

Figure A.14

A.16 Results:Graphs of inflow, outflow discharge and Water level



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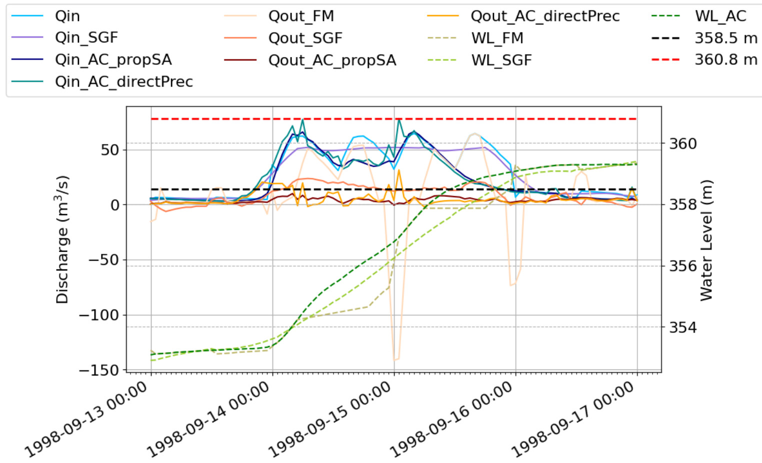

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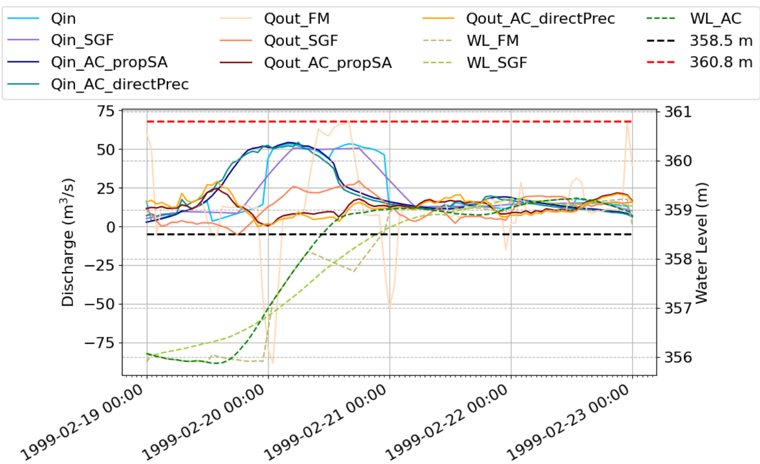

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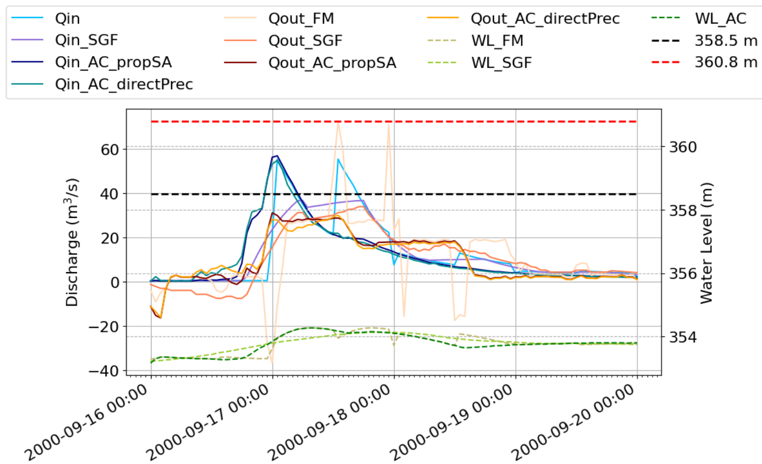

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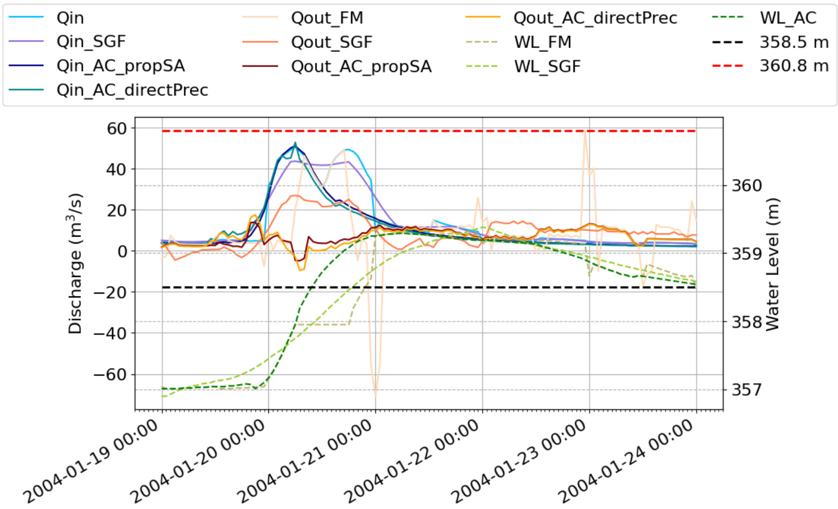

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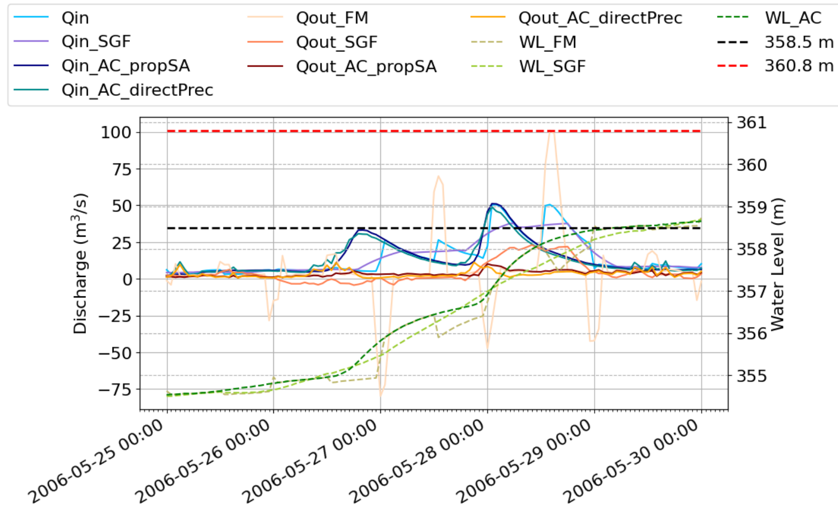
Qin_AC_propSA
Qin_AC_directPrec
Qout_FM
Qout_SGF
Qout_AC_propSA
Qout_AC_directPrec
WL_FM
WL_SGF
WL_AC
358.5 m
360.8 m
Discharge (m³/s)
Water Level (m)
60
40
20
0
−20
−40
−60
360
359
358
357
2004-01-19 00:00
2004-01-20 00:00
2004-01-21 00:00
2004-01-22 00:00
2004-01-23 00:00
2004-01-24 00:00

(e)



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Qout_SGF
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WL_FM
WL_SGF
WL_AC
358.5 m
360.8 m
Discharge (m³/s)
Water Level (m)
100
75
50
25
0
−25
−50
−75
361
360
359
358
357
356
355
2006-05-25 00:00
2006-05-26 00:00
2006-05-27 00:00
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2006-05-29 00:00
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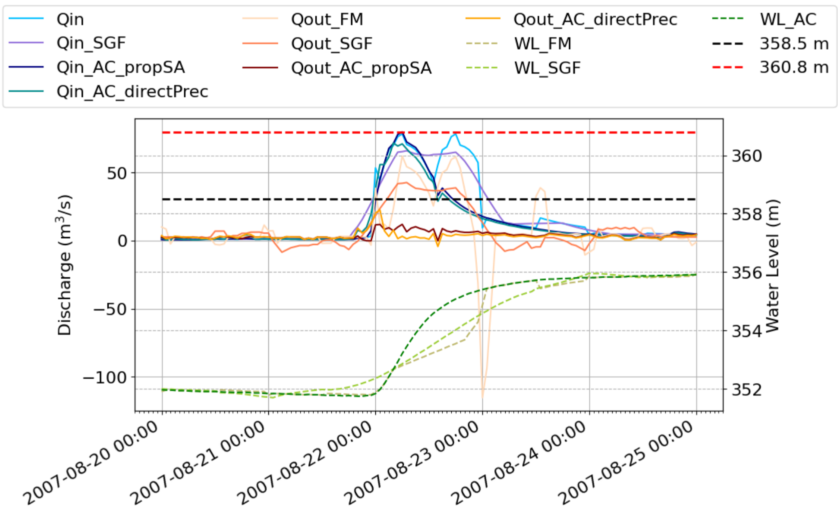
(f)



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Qout_SGF
Qout_AC_propSA
Qout_AC_directPrec
WL_FM
WL_SGF
WL_AC
358.5 m
360.8 m
Discharge (m³/s)
Water Level (m)
50
0
−50
−100
360
358
356
354
352
2007-08-20 00:00
2007-08-21 00:00
2007-08-22 00:00
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2007-08-24 00:00
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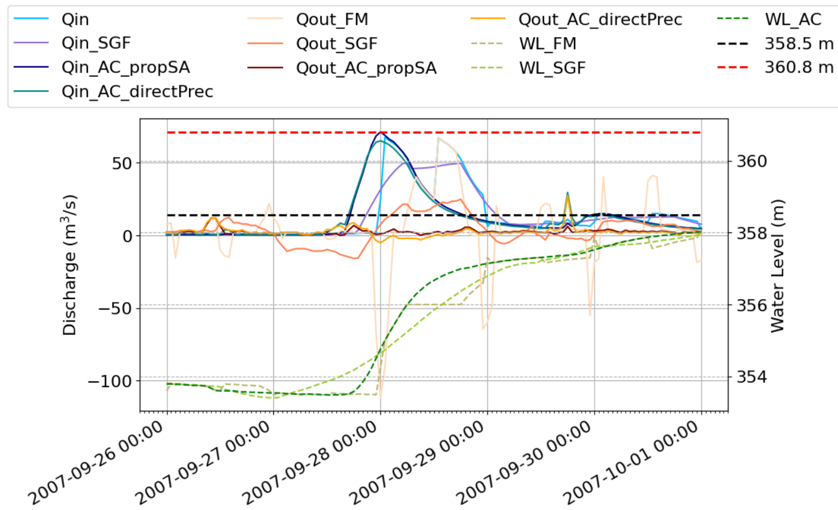
(g)



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Qout_AC_directPrec
WL_FM
WL_SGF
WL_AC
358.5 m
360.8 m
Discharge (m³/s)
Water Level (m)
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−50
−100
360
358
356
354
2007-09-26 00:00
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2007-09-28 00:00
2007-09-29 00:00
2007-09-30 00:00
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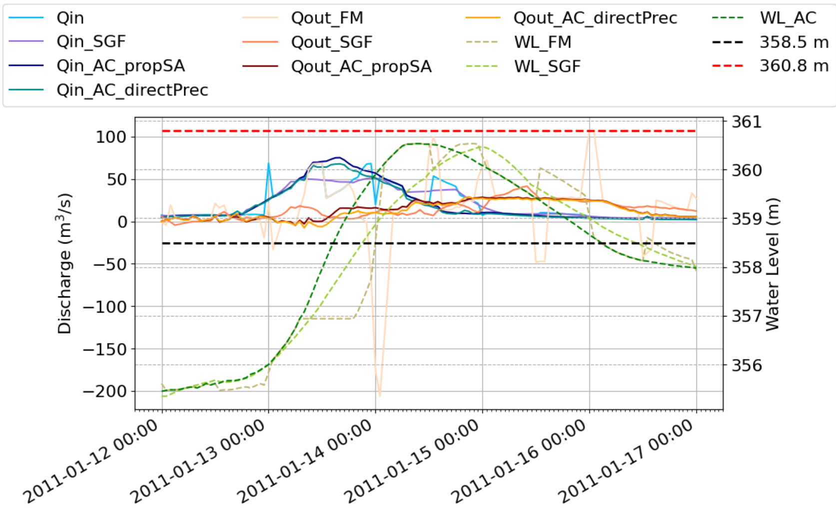
(h)



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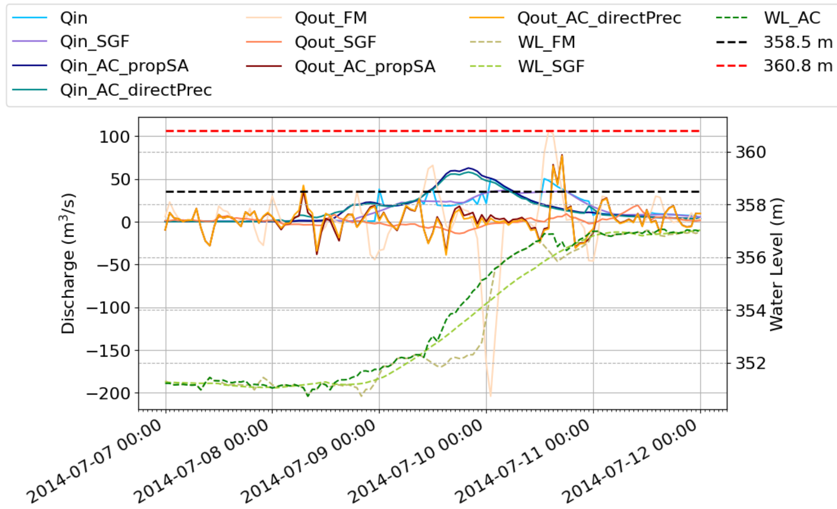

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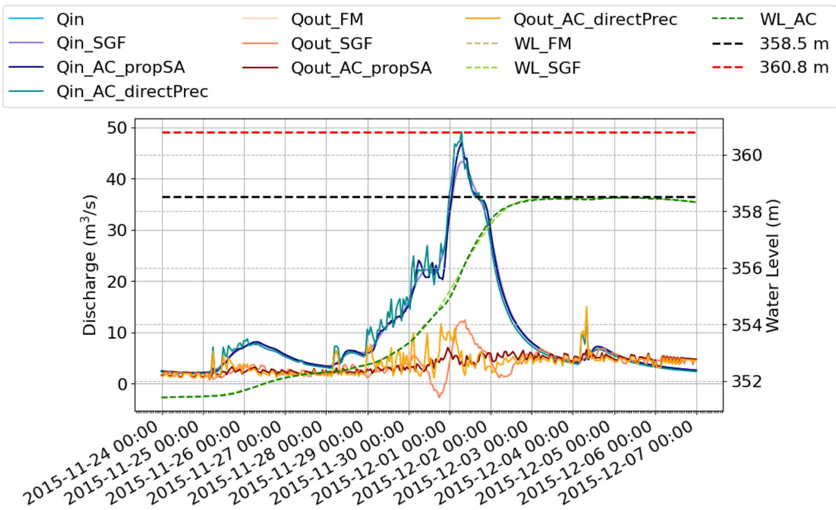

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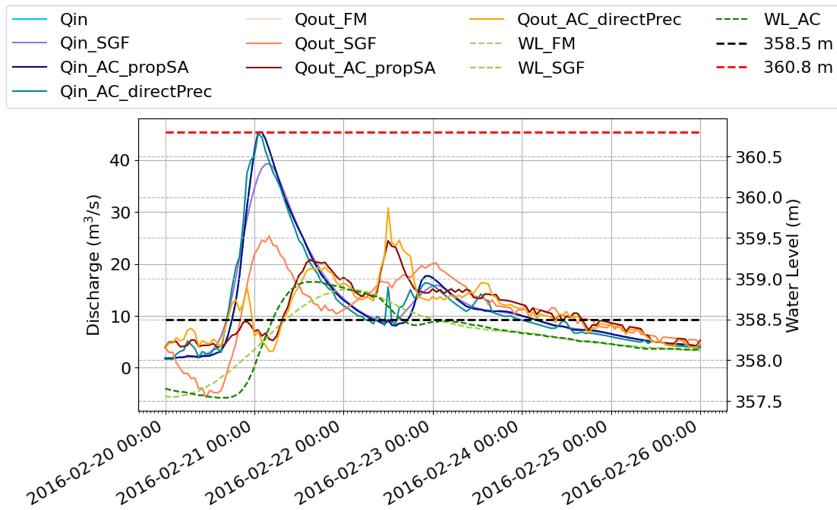

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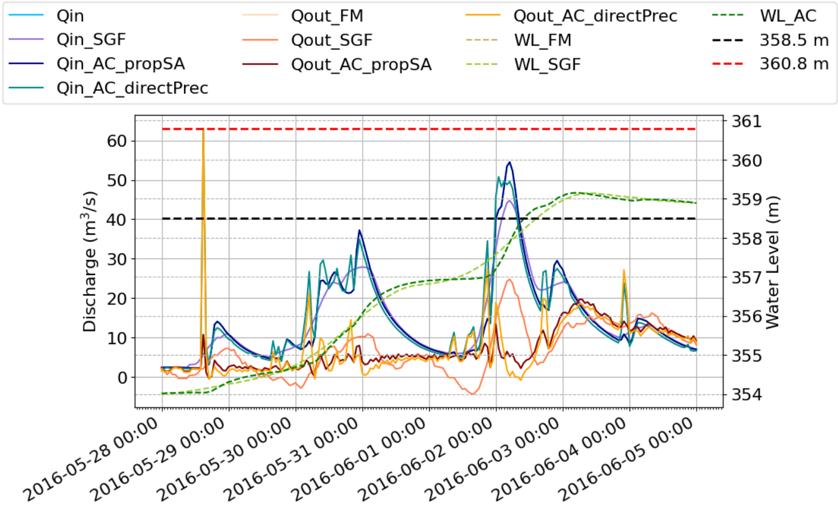
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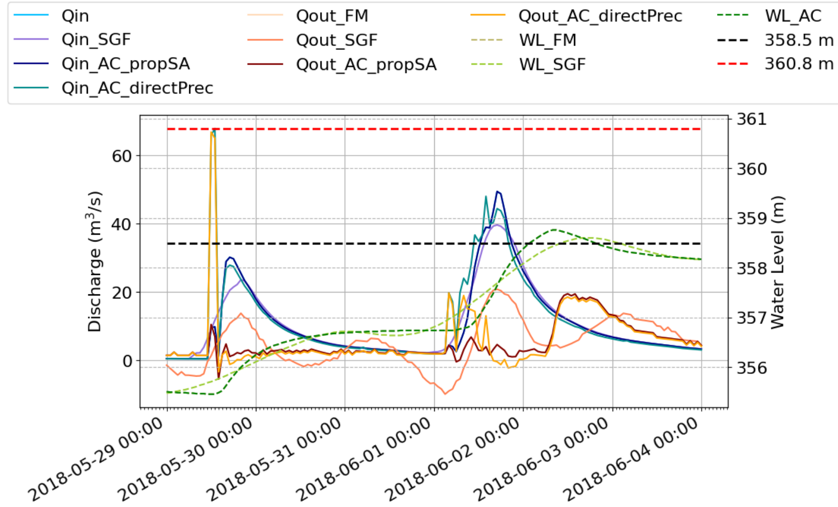
Qout_SGF
Qout_AC_propSA
Qout_AC_directPrec
WL_FM
WL_SGF
WL_AC
358.5 m
360.8 m
Discharge (m³/s)
Water Level (m)

(m)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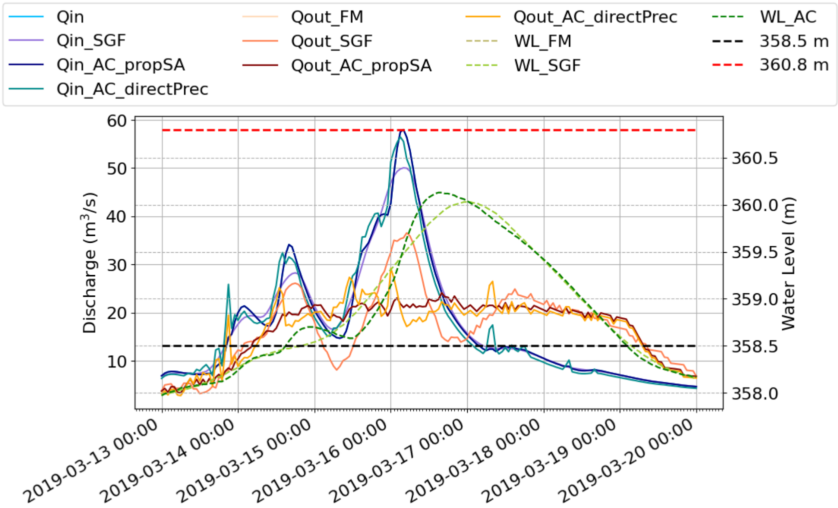
360.8 m
Discharge (m³/s)
Water Level (m)

(n)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WL_AC
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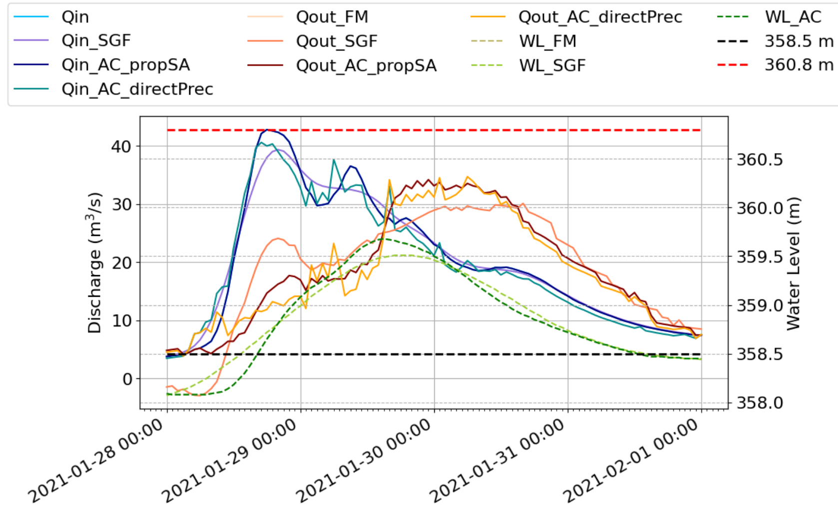
360.8 m
Discharge (m³/s)
Water Level (m)

(o)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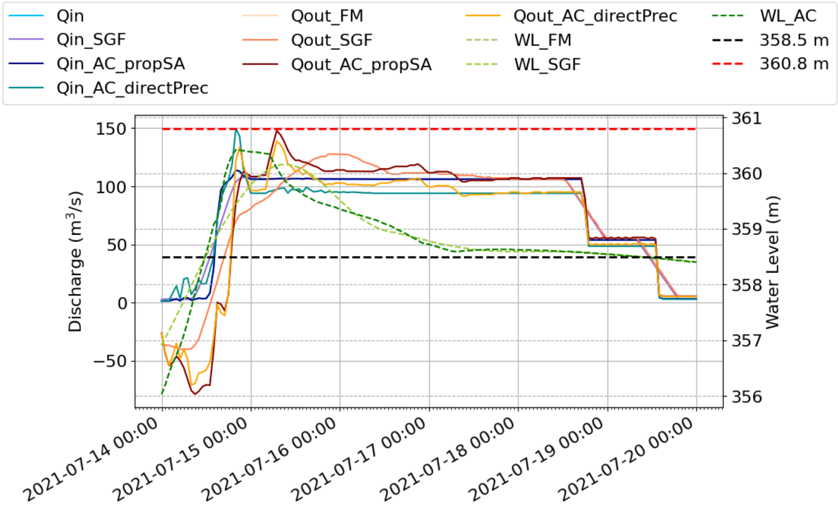
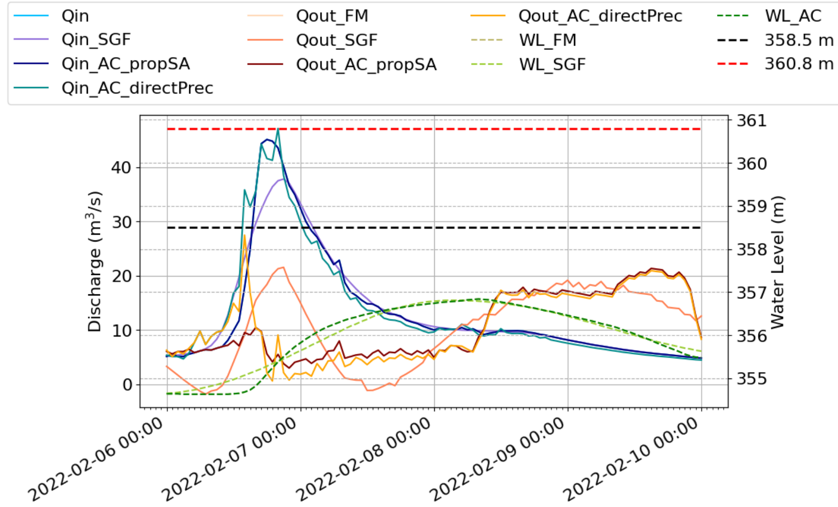
Qout_SGF
Qout_AC_propSA
Qout_AC_directPrec
WL_FM
WL_SGF
WL_AC
358.5 m
360.8 m
Discharge (m³/s)
Water Level (m)

(p)



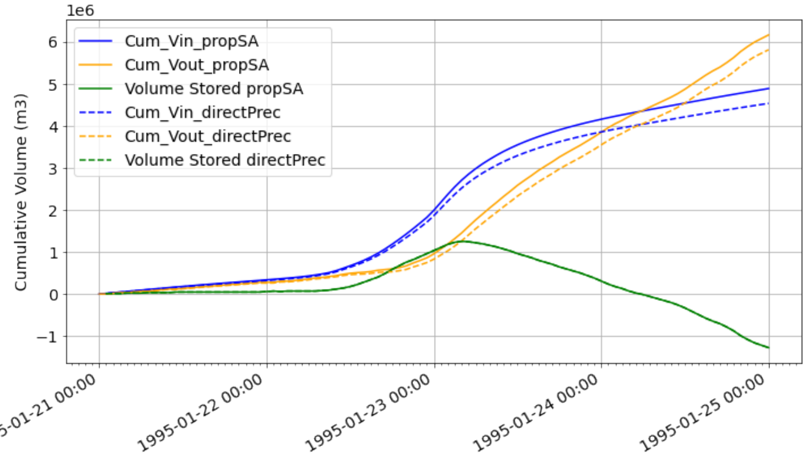
(q) Not reliable



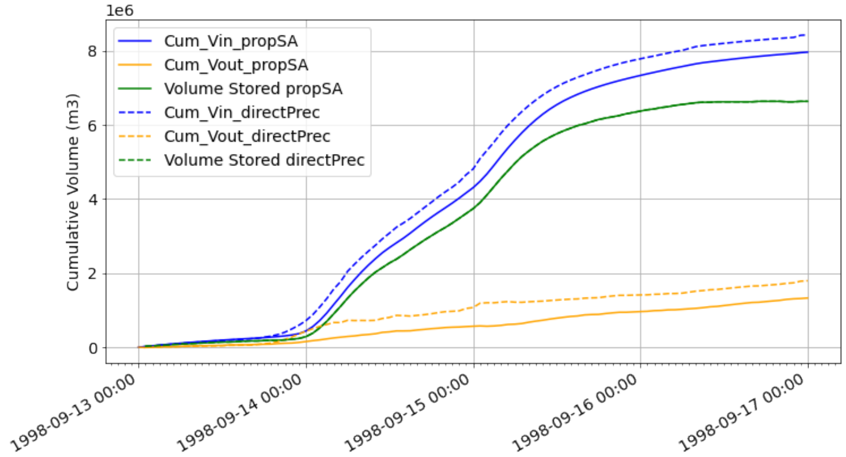
(r)

Figure A.15

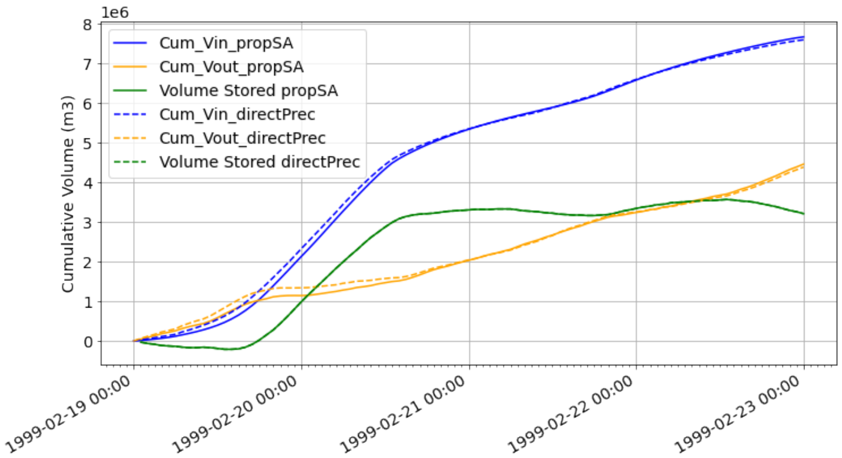
A.17 Results: Graphs of cumulative inflow and outflow volume



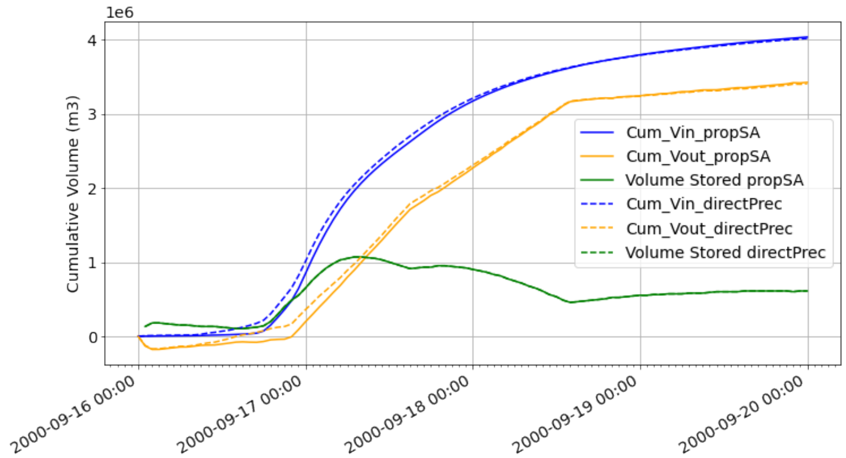
(a)



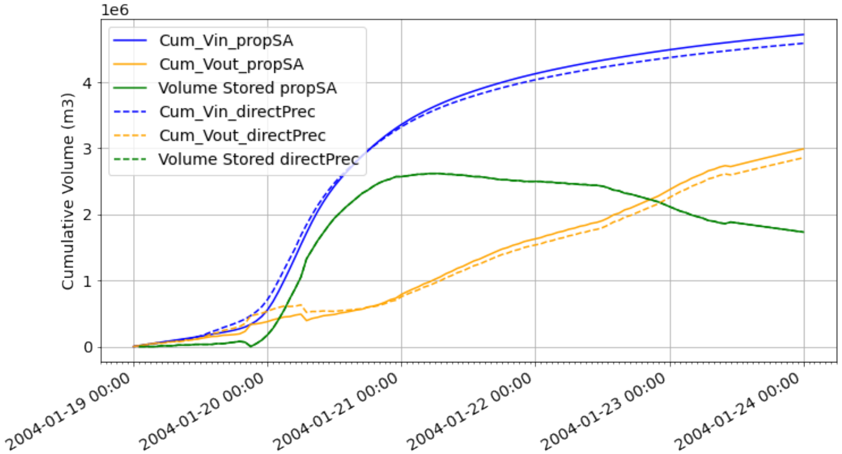
(b)



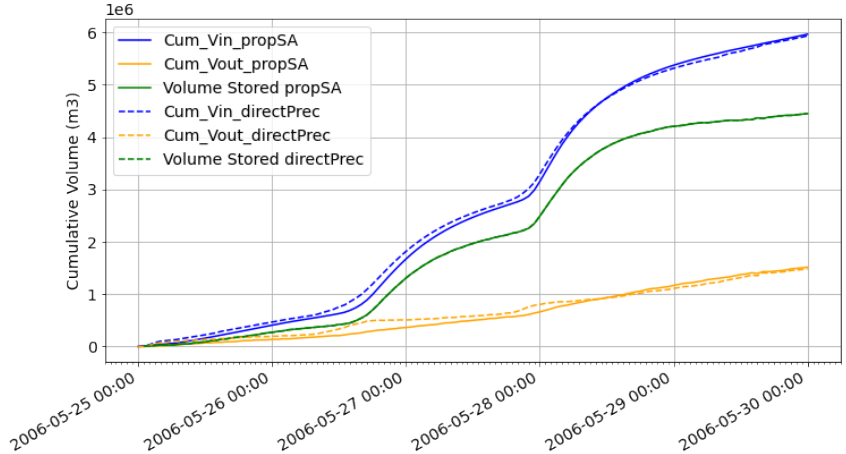
(c)



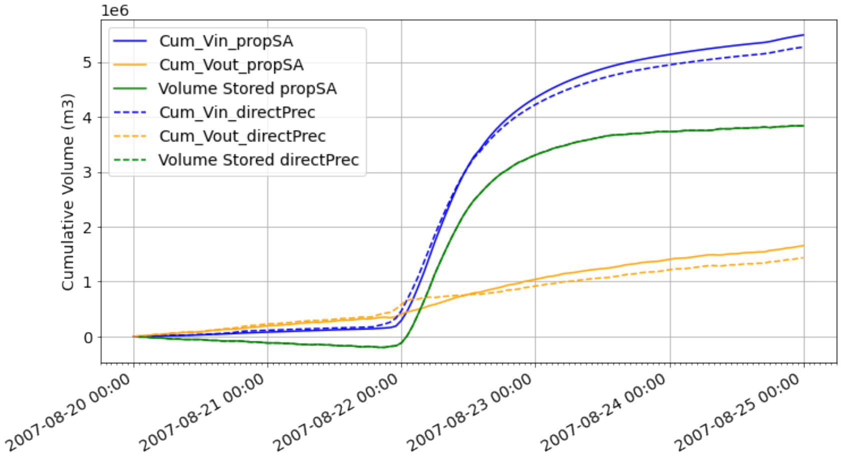
(d)


1e6
Cum_Vin_propSA
Cum_Vout_propSA
Volume Stored propSA
Cum_Vin_directPrec
Cum_Vout_directPrec
Volume Stored directPrec
Cumulative Volume (m3)
2004-01-19 00:00
2004-01-20 00:00
2004-01-21 00:00
2004-01-22 00:00
2004-01-23 00:00
2004-01-24 00:00

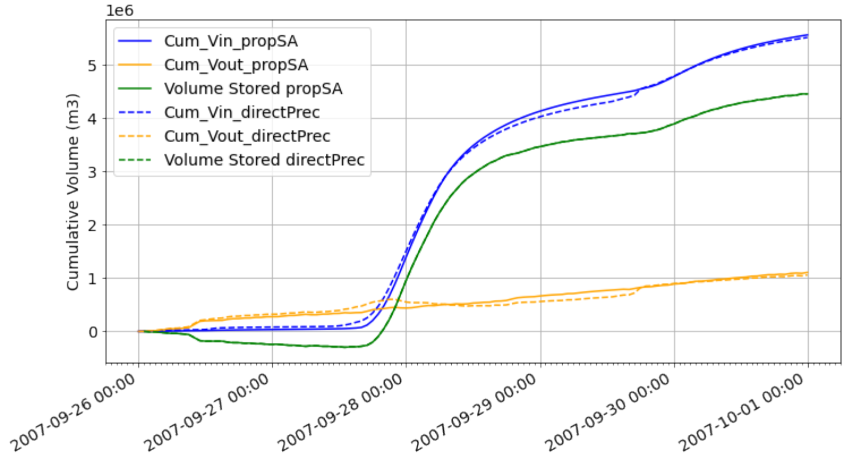
(e)


1e6
Cum_Vin_propSA
Cum_Vout_propSA
Volume Stored propSA
Cum_Vin_directPrec
Cum_Vout_directPrec
Volume Stored directPrec
Cumulative Volume (m3)
2006-05-25 00:00
2006-05-26 00:00
2006-05-27 00:00
2006-05-28 00:00
2006-05-29 00:00
2006-05-30 00:00

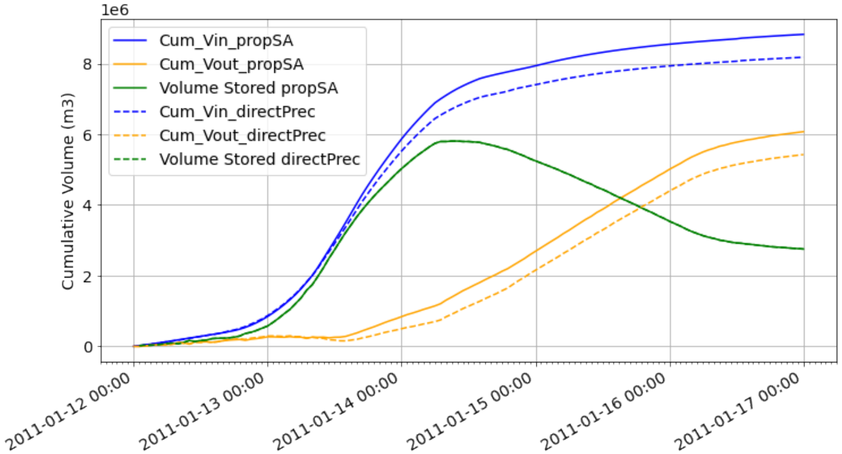
(f)


1e6
Cum_Vin_propSA
Cum_Vout_propSA
Volume Stored propSA
Cum_Vin_directPrec
Cum_Vout_directPrec
Volume Stored directPrec
Cumulative Volume (m3)
2007-08-20 00:00
2007-08-21 00:00
2007-08-22 00:00
2007-08-23 00:00
2007-08-24 00:00
2007-08-25 00:00

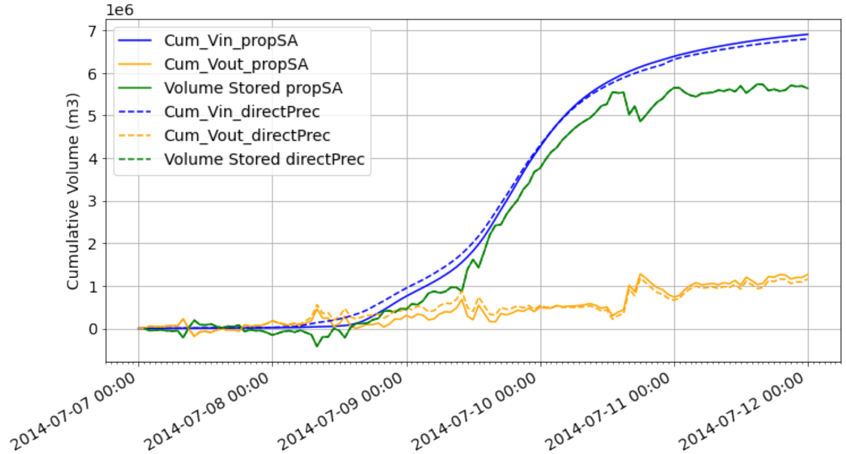
(g)


1e6
Cum_Vin_propSA
Cum_Vout_propSA
Volume Stored propSA
Cum_Vin_directPrec
Cum_Vout_directPrec
Volume Stored directPrec
Cumulative Volume (m3)
2007-09-26 00:00
2007-09-27 00:00
2007-09-28 00:00
2007-09-29 00:00
2007-09-30 00:00
2007-10-01 00:00

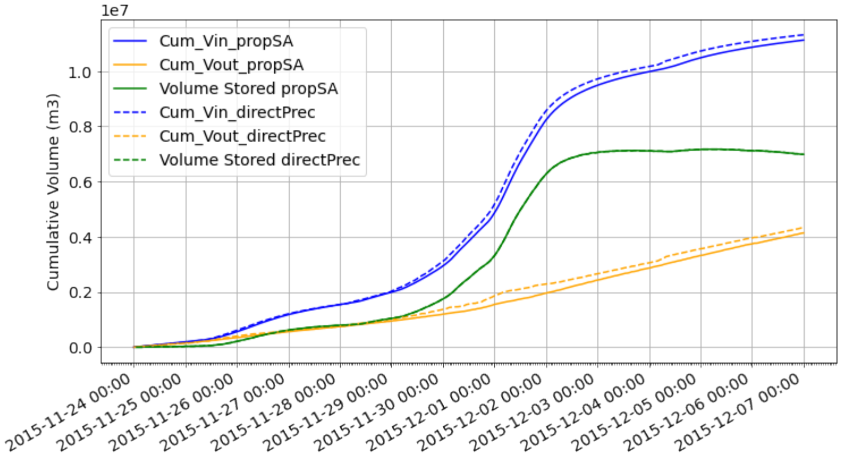
(h)



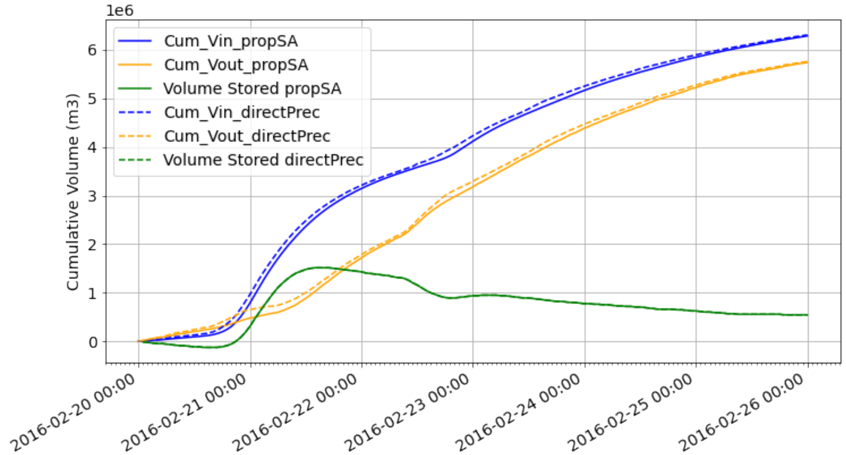
(i)



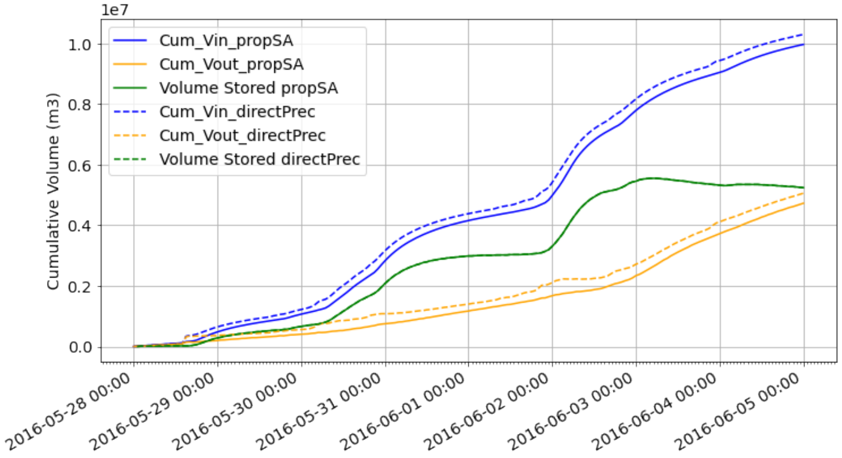
(j) Not reliable



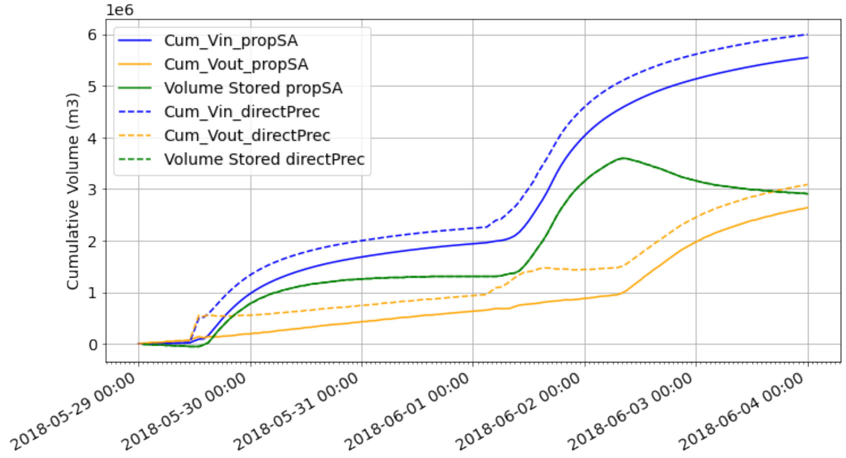
(k)



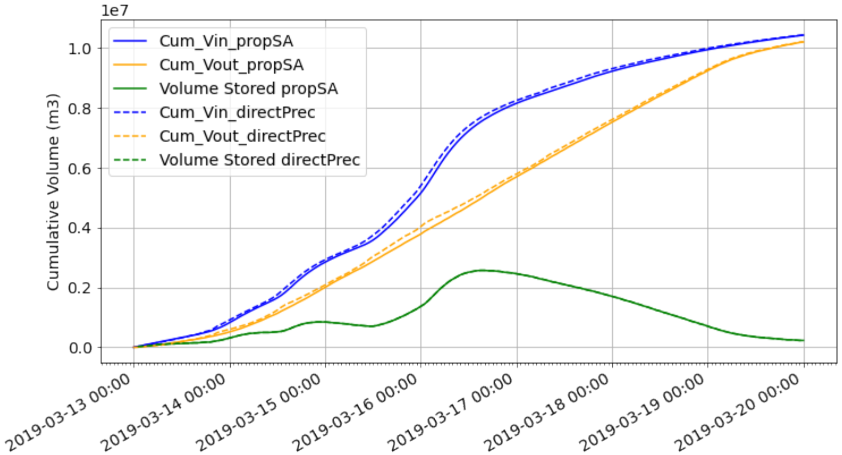
(l)


1e7
Cum_Vin_propSA
Cum_Vout_propSA
Volume Stored propSA
Cum_Vin_directPrec
Cum_Vout_directPrec
Volume Stored directPrec
Cumulative Volume (m3)
0.0
0.2
0.4
0.6
0.8
1.0
2016-05-28 00:00
2016-05-29 00:00
2016-05-30 00:00
2016-05-31 00:00
2016-06-01 00:00
2016-06-02 00:00
2016-06-03 00:00
2016-06-04 00:00
2016-06-05 00:00

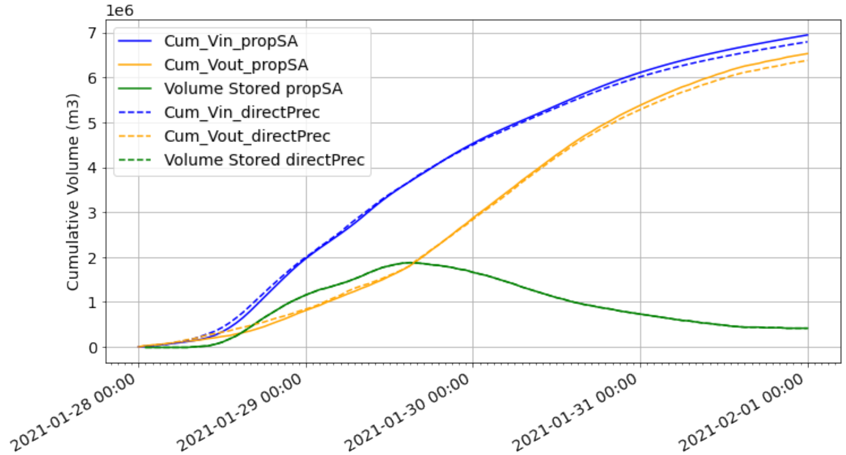
(m)


1e6
Cum_Vin_propSA
Cum_Vout_propSA
Volume Stored propSA
Cum_Vin_directPrec
Cum_Vout_directPrec
Volume Stored directPrec
Cumulative Volume (m3)
0
1
2
3
4
5
6
2018-05-29 00:00
2018-05-30 00:00
2018-05-31 00:00
2018-06-01 00:00
2018-06-02 00:00
2018-06-03 00:00
2018-06-04 00:00

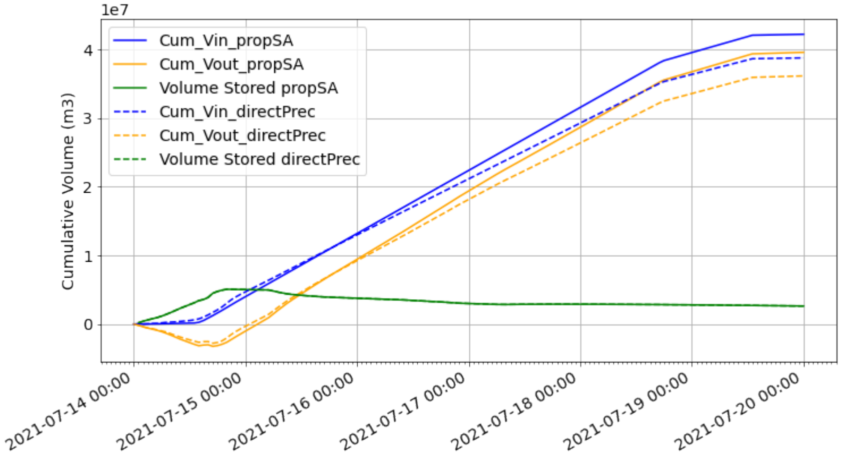
(n)


1e7
Cum_Vin_propSA
Cum_Vout_propSA
Volume Stored propSA
Cum_Vin_directPrec
Cum_Vout_directPrec
Volume Stored directPrec
Cumulative Volume (m3)
0.0
0.2
0.4
0.6
0.8
1.0
2019-03-13 00:00
2019-03-14 00:00
2019-03-15 00:00
2019-03-16 00:00
2019-03-17 00:00
2019-03-18 00:00
2019-03-19 00:00
2019-03-20 00:00

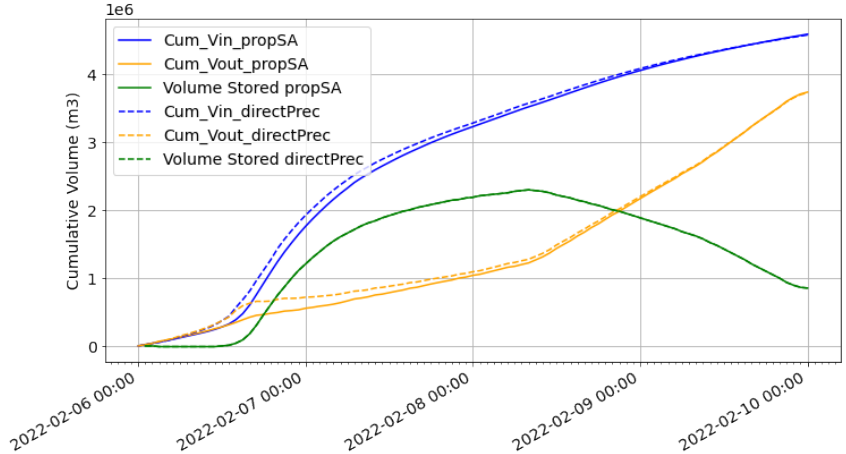
(o)


1e6
Cum_Vin_propSA
Cum_Vout_propSA
Volume Stored propSA
Cum_Vin_directPrec
Cum_Vout_directPrec
Volume Stored directPrec
Cumulative Volume (m3)
0
1
2
3
4
5
6
7
2021-01-28 00:00
2021-01-29 00:00
2021-01-30 00:00
2021-01-31 00:00
2021-02-01 00:00

(p)



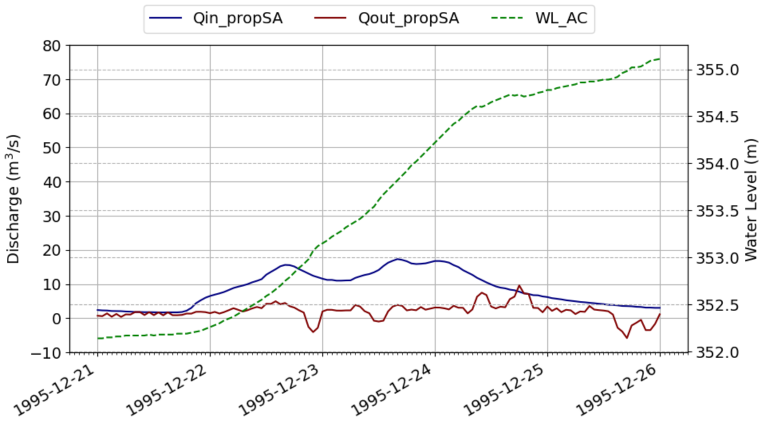
(q) Not reliable



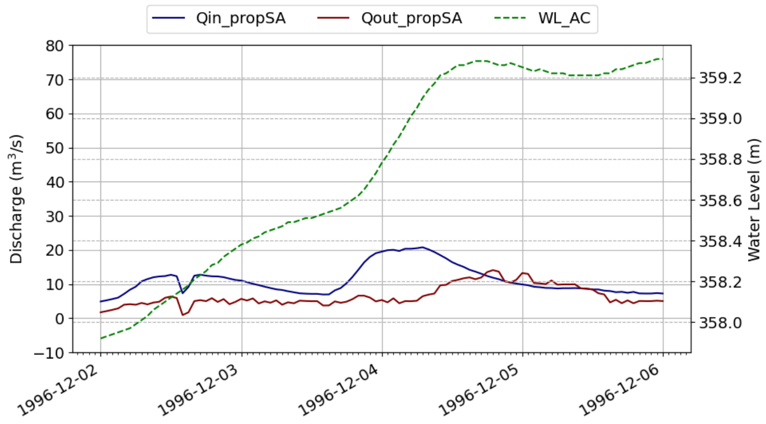
(r)

Figure A.16

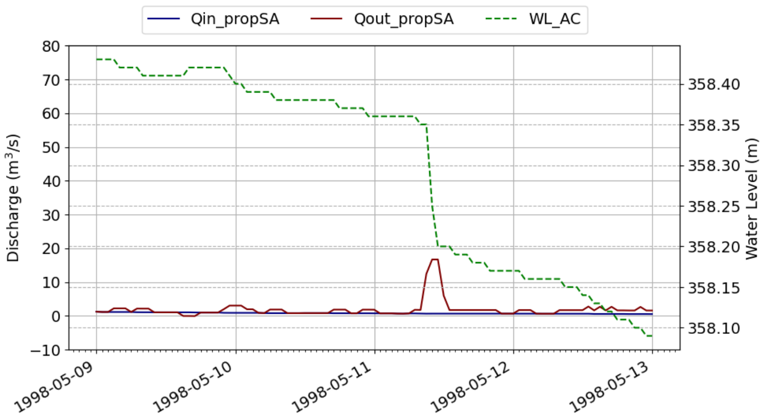
A.18 Results: Return Period - Time series of maximum annual Qout and the corresponding Qin



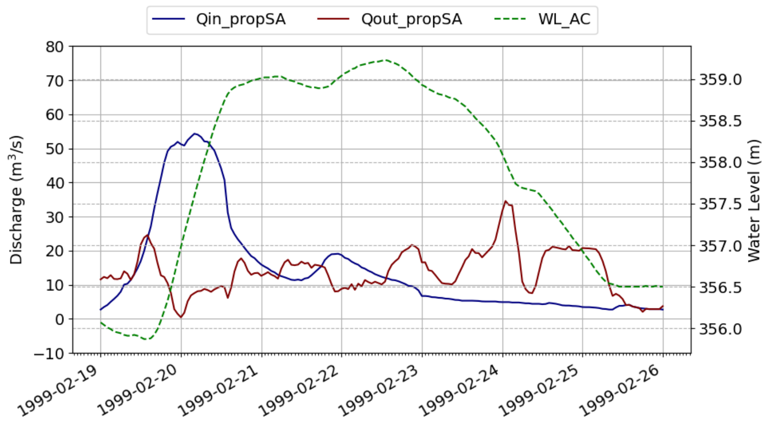
(a) 1995 - 1996



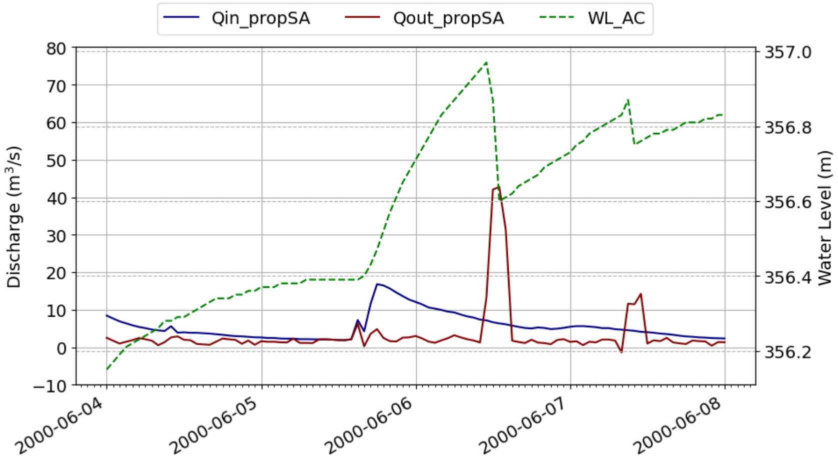
(b) 1996 - 1997



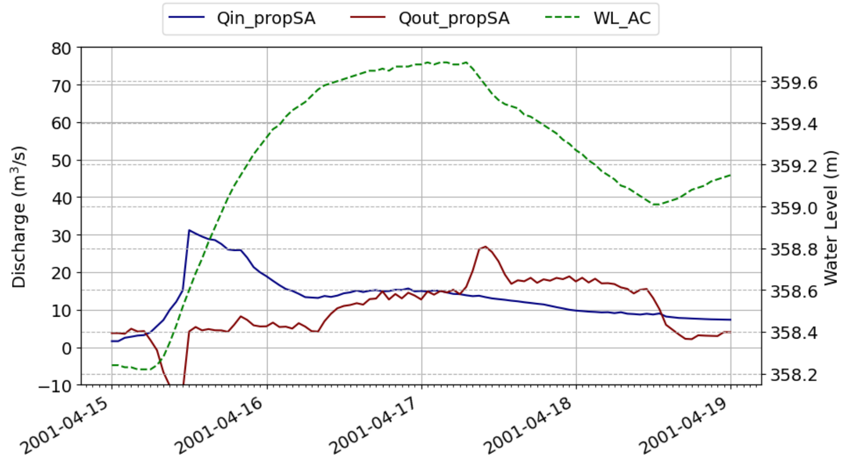
(c) 1997 - 1998



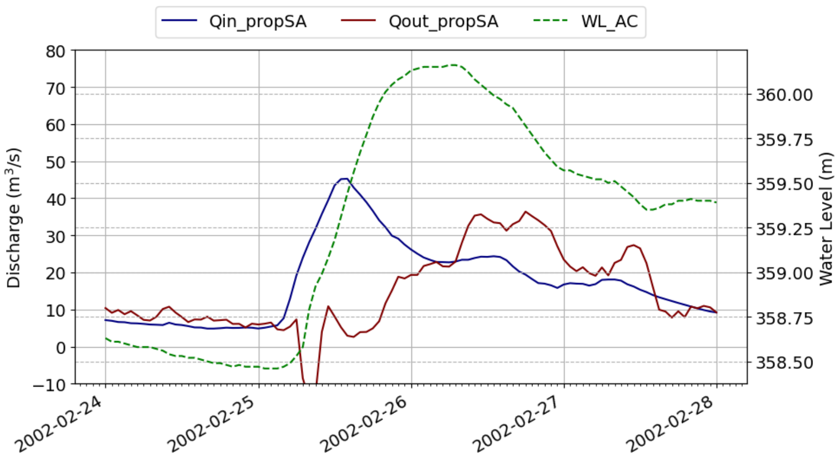
(d) 1998 - 1999



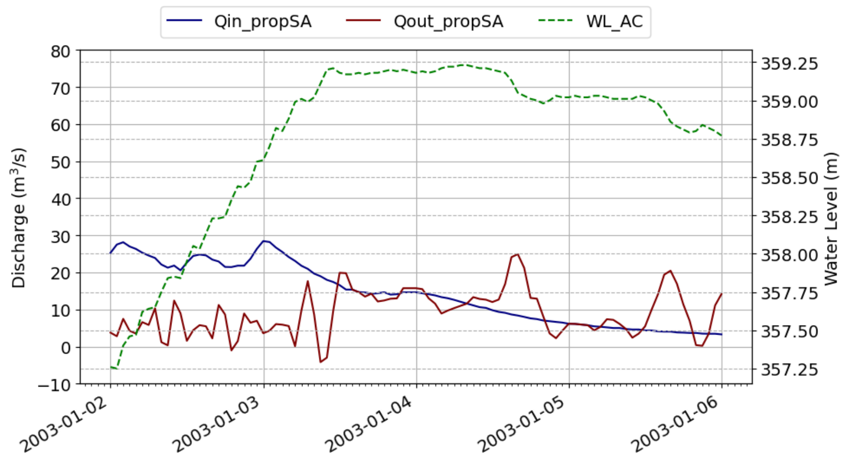
(e) 1999 - 2000



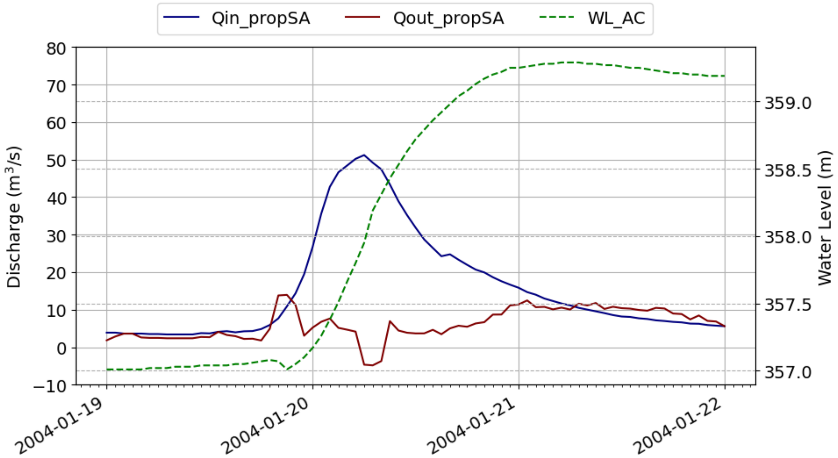
(f) 2000 - 2001



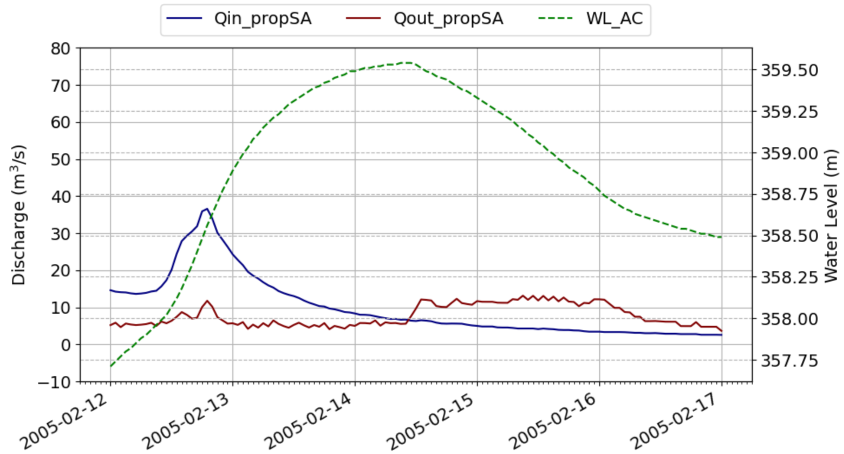
(g) 2001 - 2002



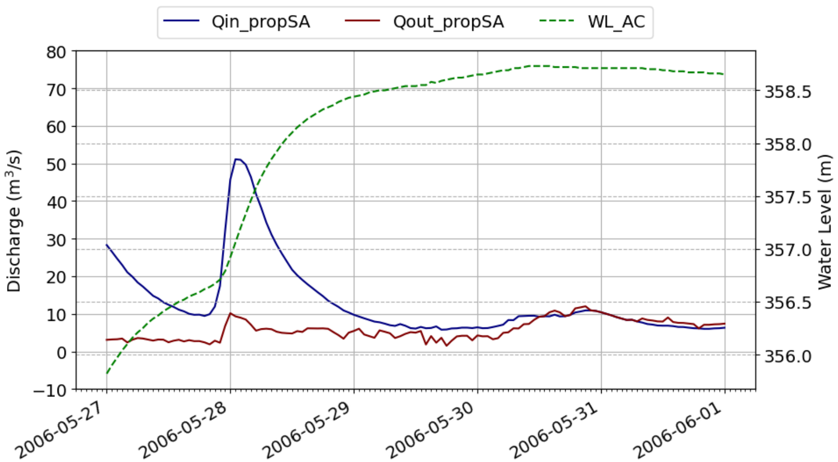
(h) 2002 - 2003



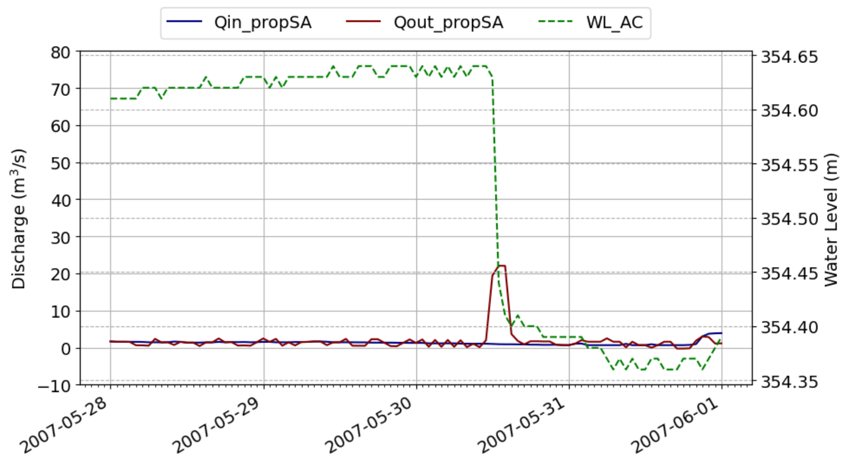
(i) 2003 - 2004



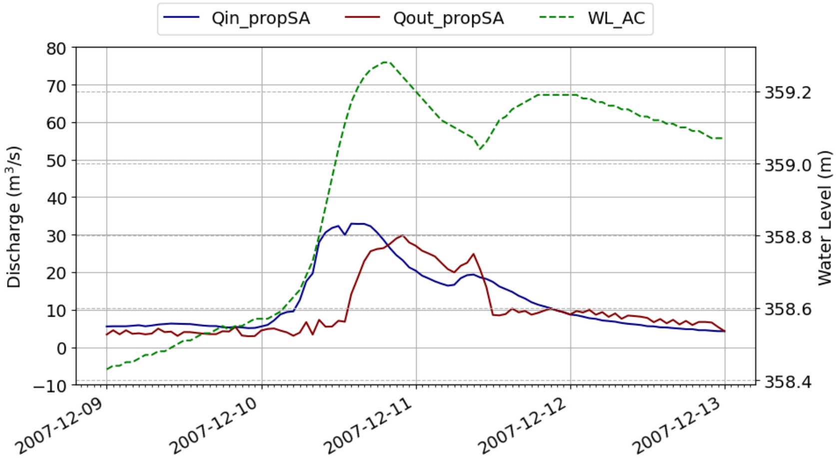
(j) 2004 - 2005



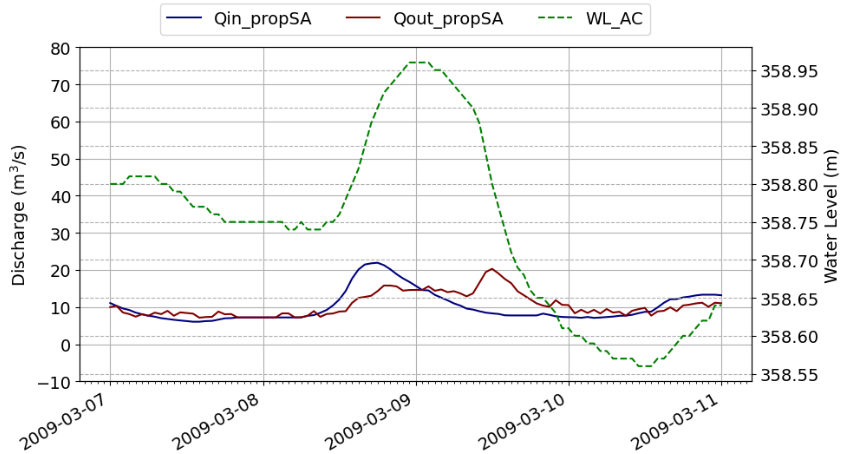
(k) 2005 - 2006



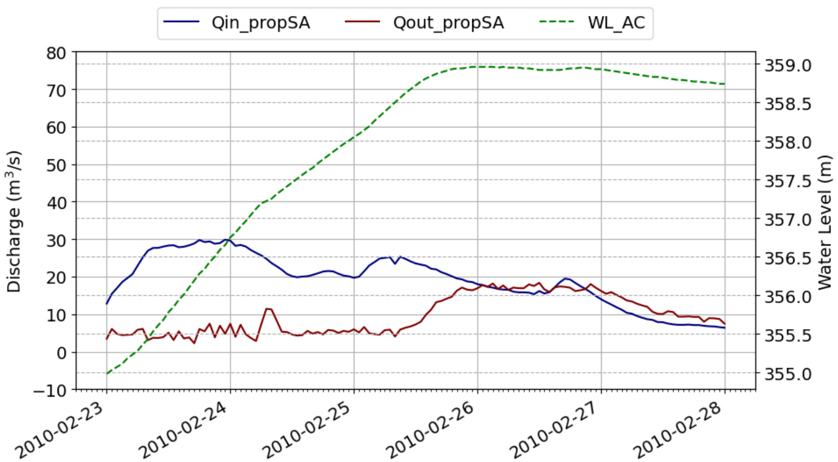
(l) 2006 - 2007



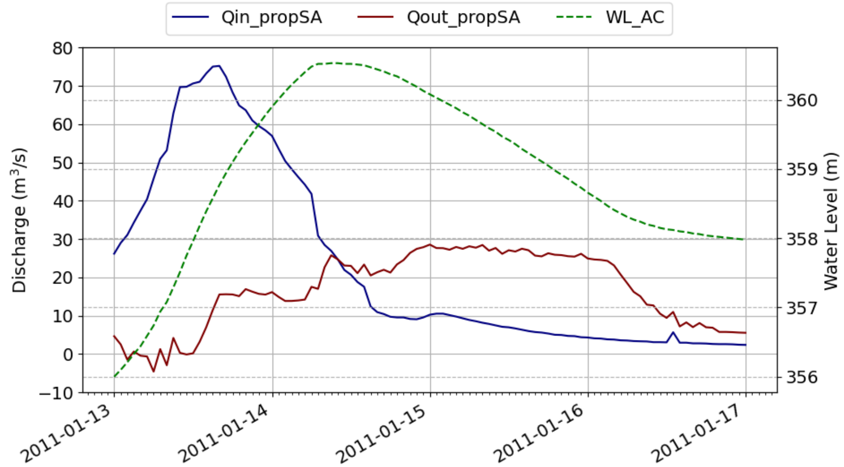
(m) 2007 - 2008



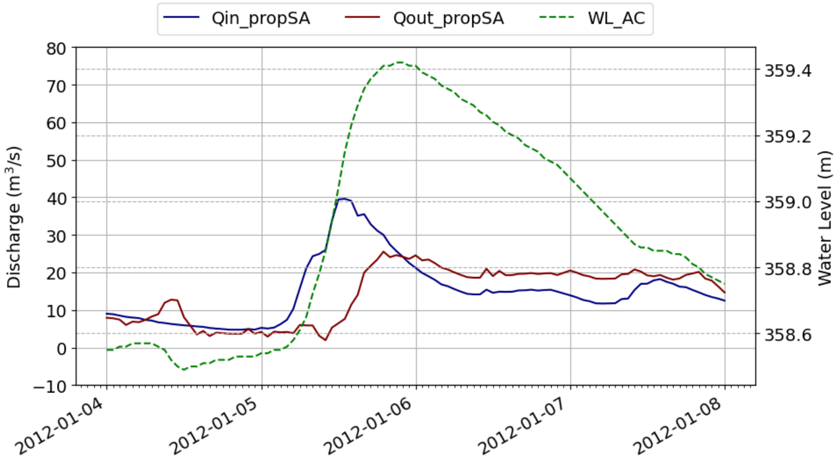
(n) 2008 - 2009



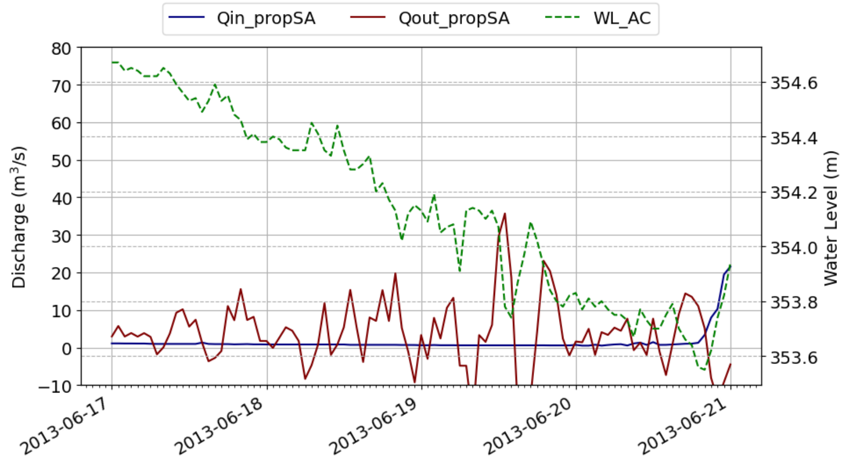
(o) 2009 - 2010



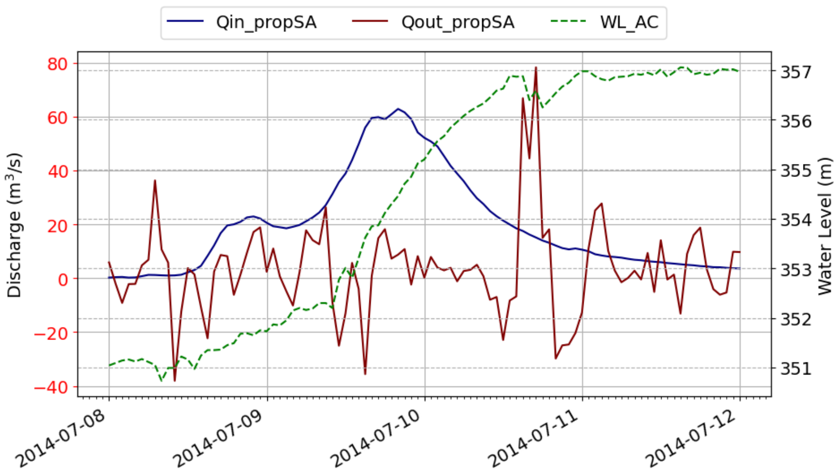
(p) 2010 - 2011



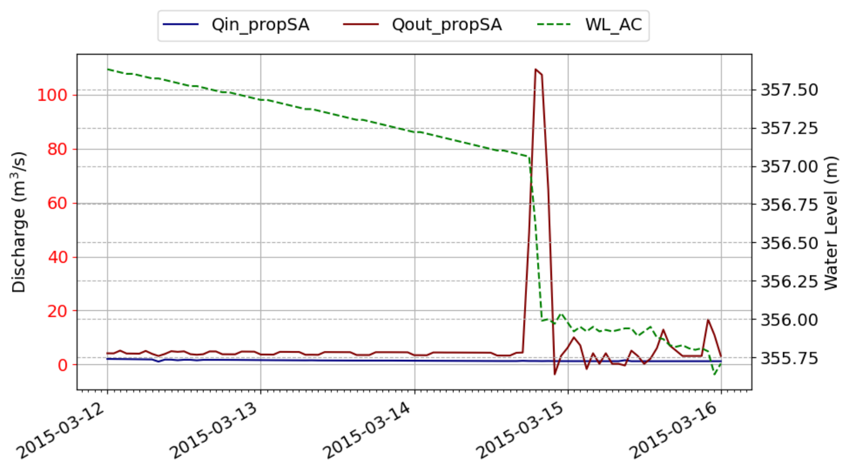
(q) 2011 - 2012



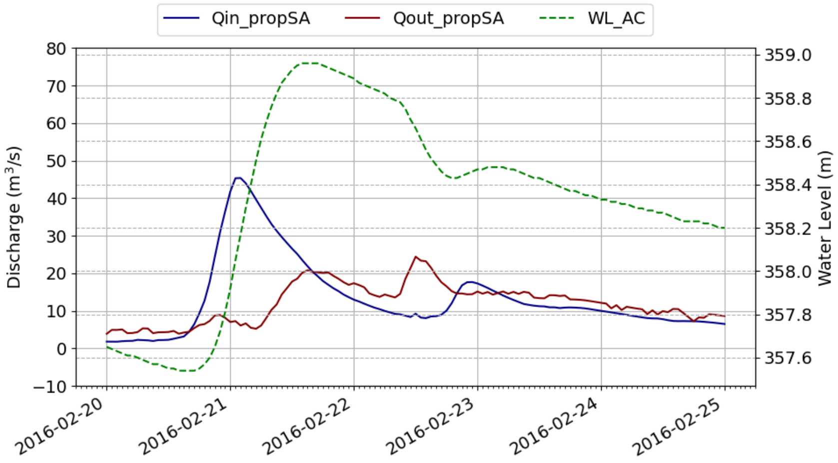
(r) 2012 - 2013



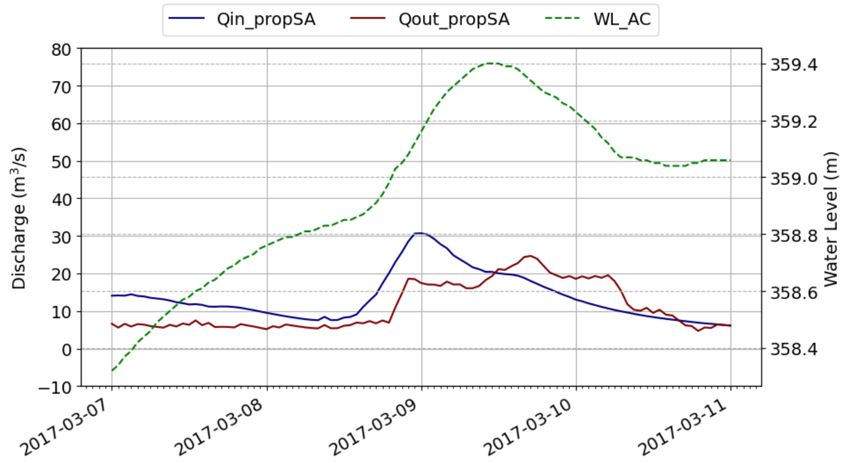
(s) 2013 - 2014 (Not reliable)



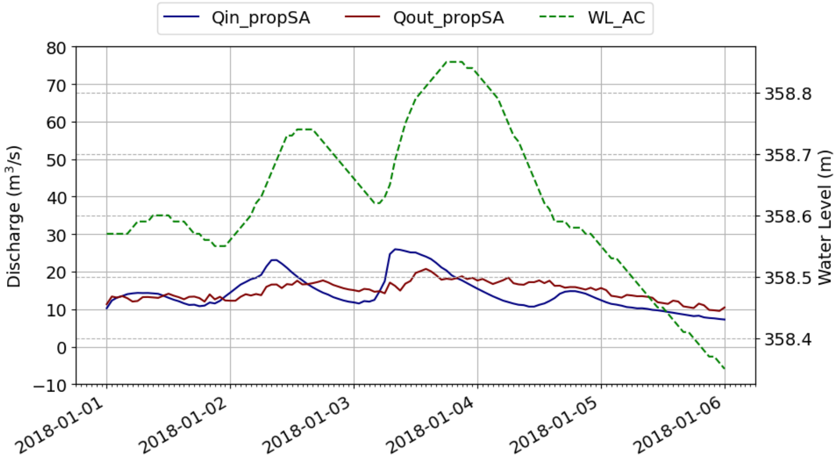
(t) 2014 - 2015 (Not reliable)



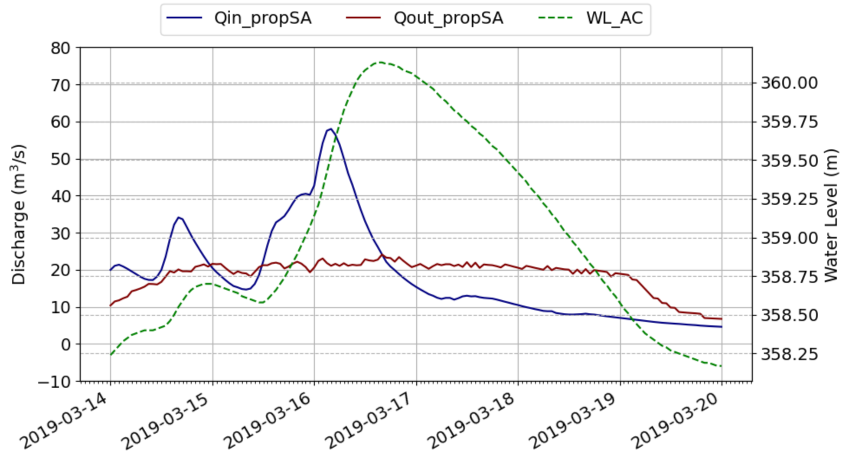
(u) 2015 - 2016



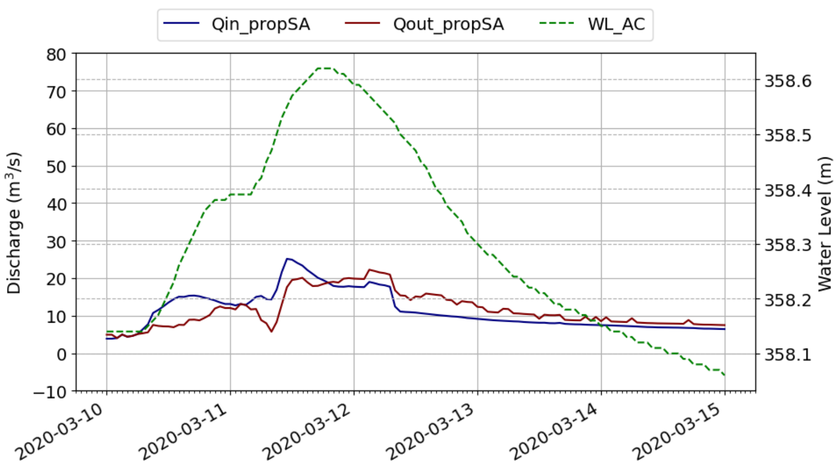
(v) 2016 - 2017



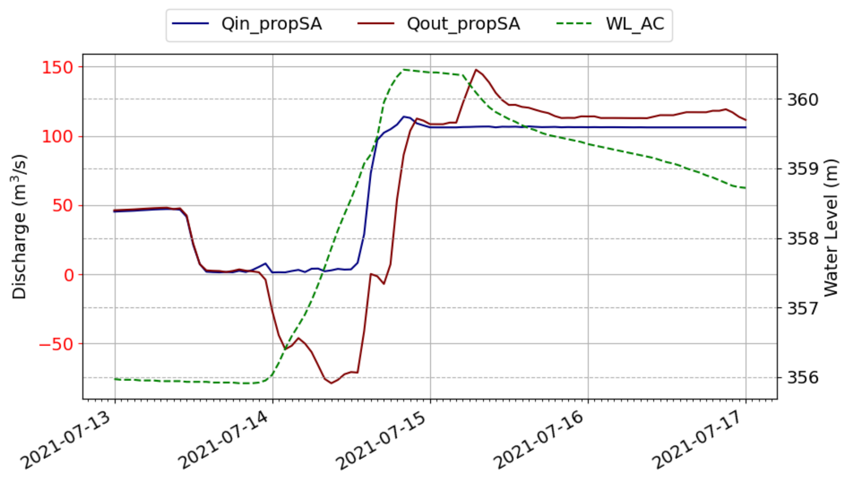
(w) 2017 - 2018



(x) 2018 - 2019



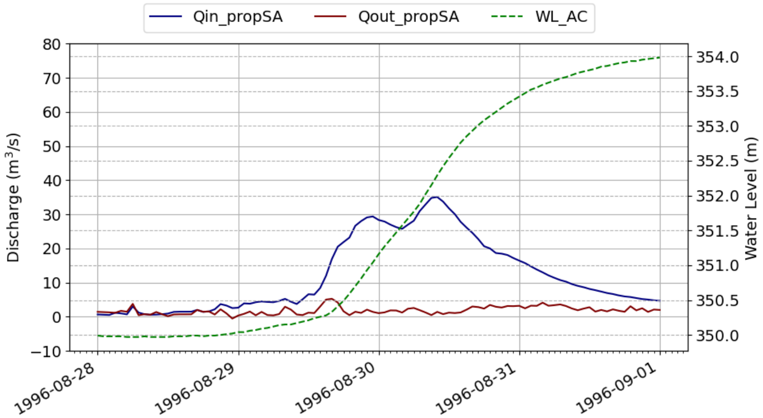
(y) 2019 - 2020



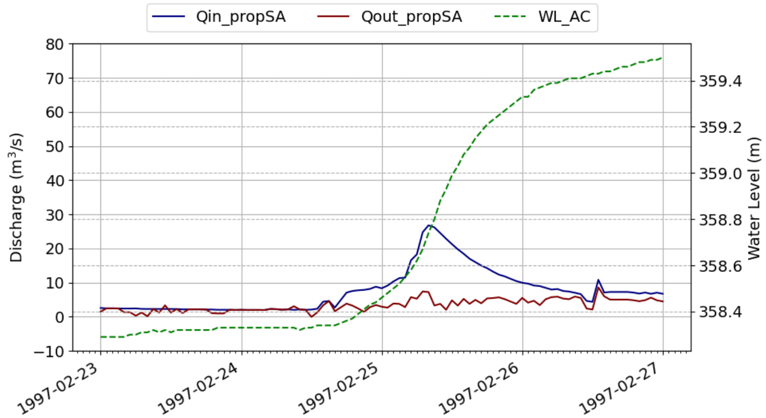
(z) 2020 - 2021 (Not reliable)

Figure A.17

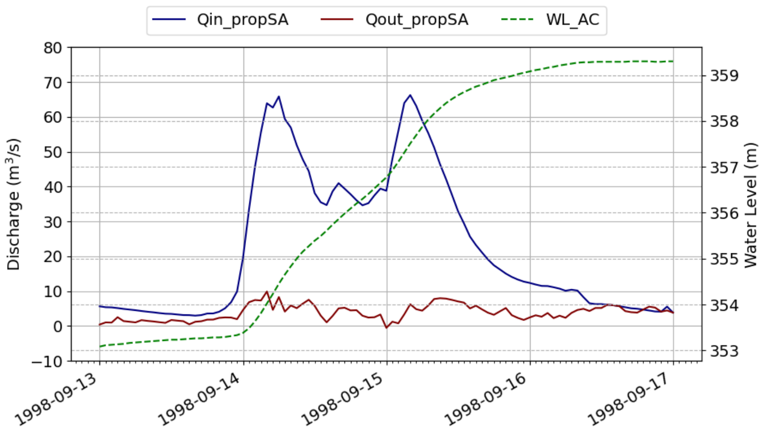
A.19 Results: Return Period - Time series of maximum annual Qin and the corresponding Qout



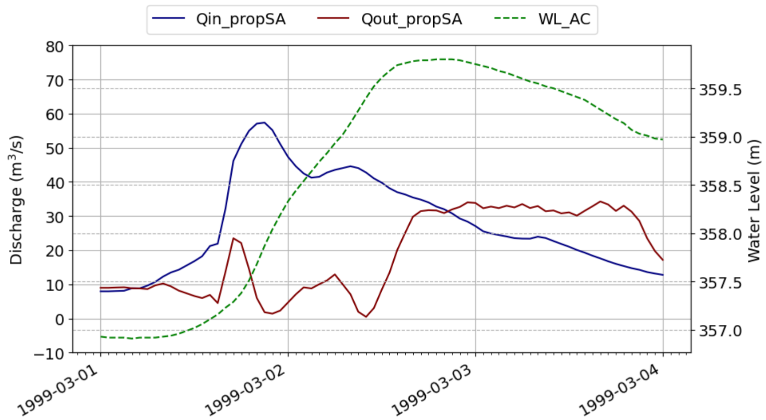
(a) 1995 - 1996



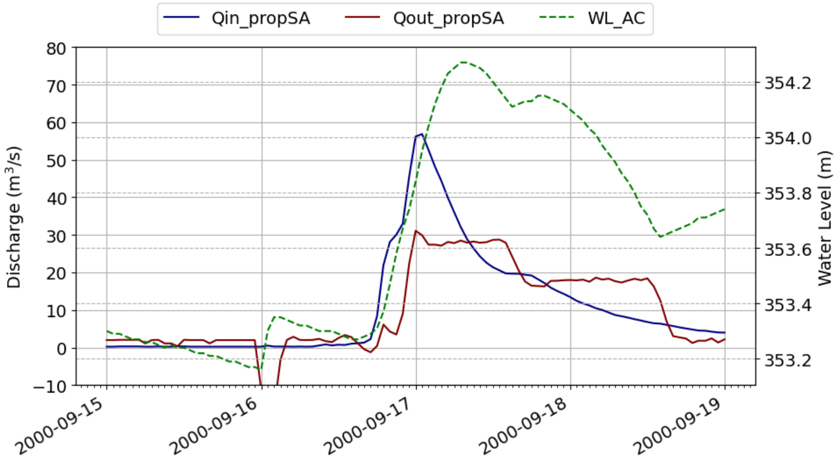
(b) 1996 - 1997



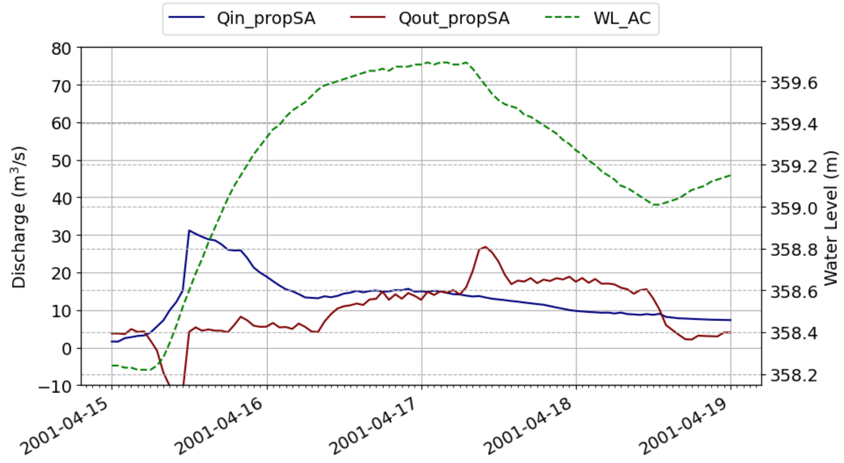
(c) 1997 - 1998



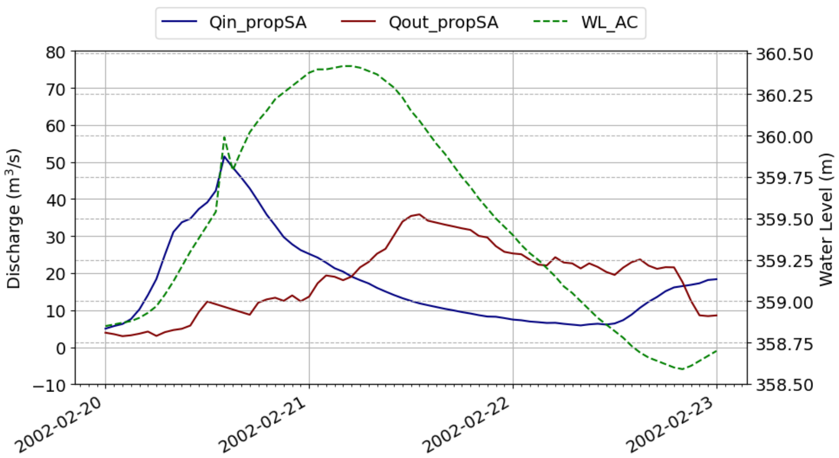
(d) 1998 - 1999



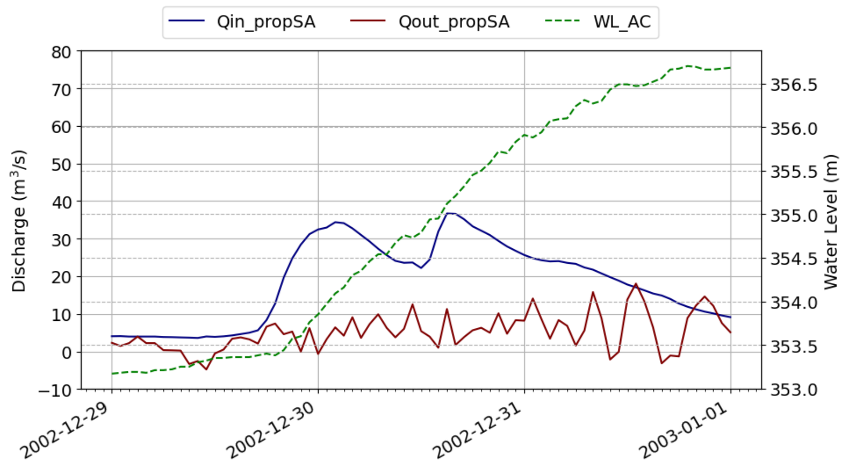
(e) 1999 - 2000



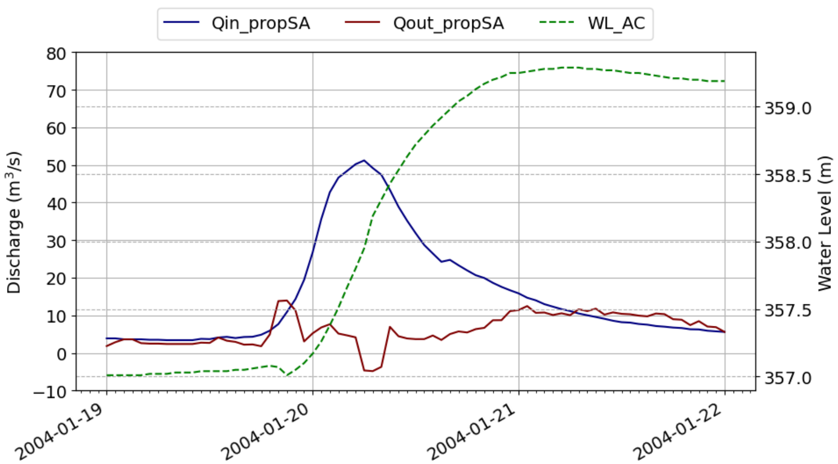
(f) 2000 - 2001



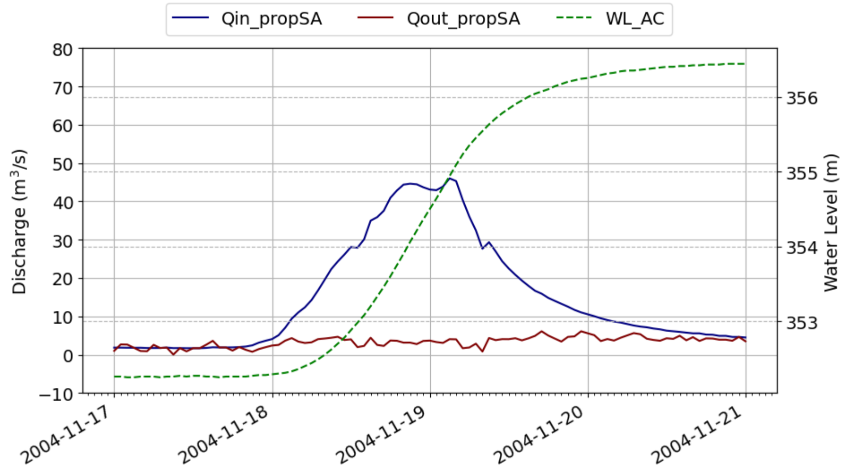
(g) 2001 - 2002



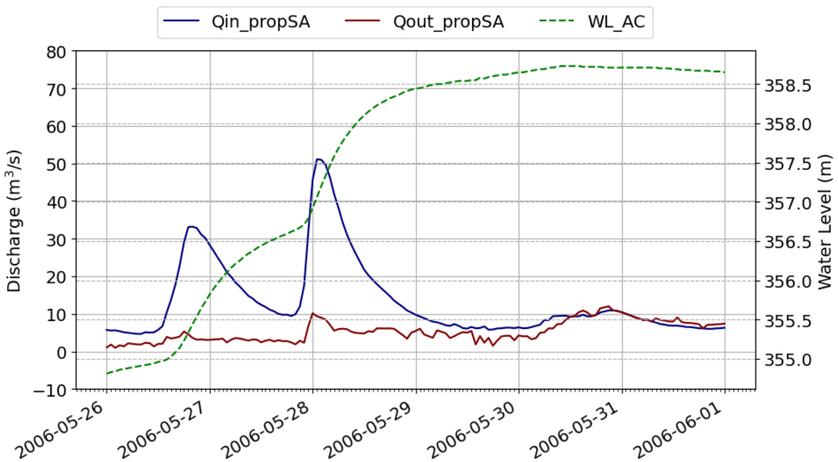
(h) 2002 - 2003



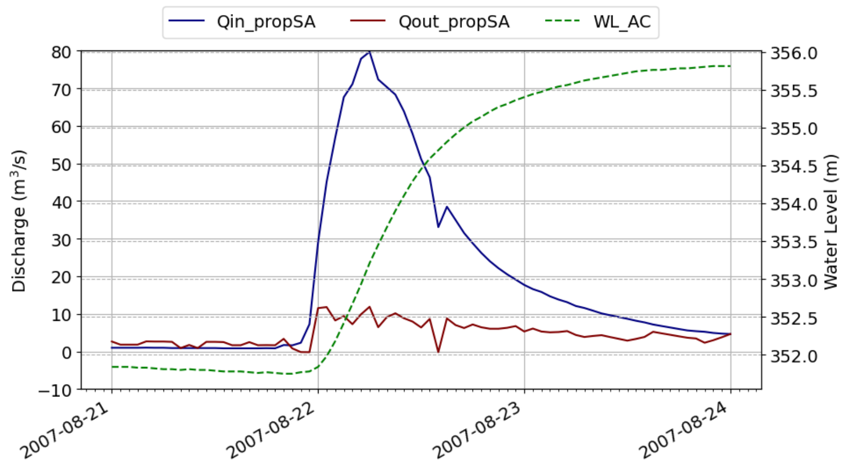
(i) 2003 - 2004



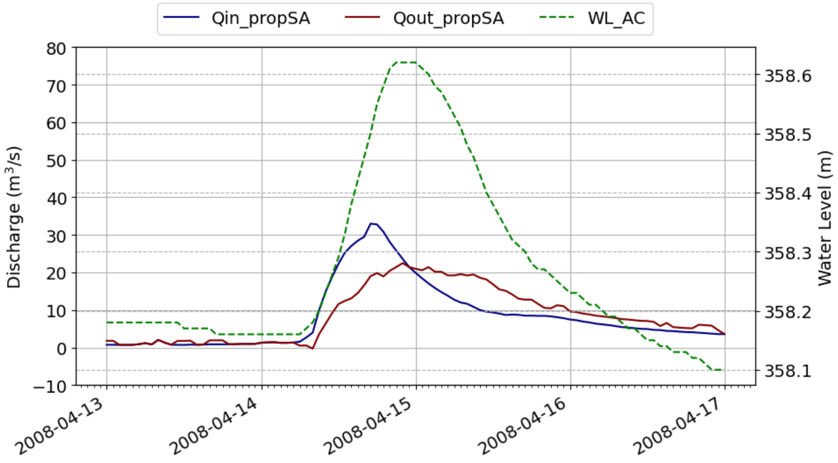
(j) 2004 - 2005



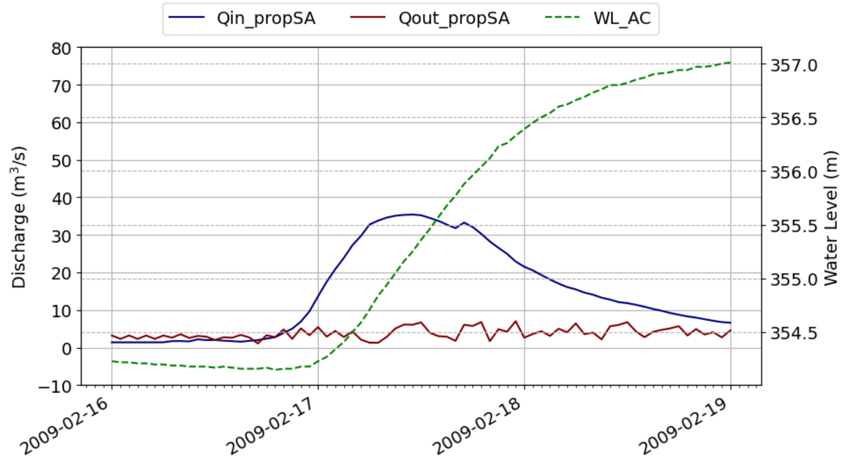
(k) 2005 - 2006



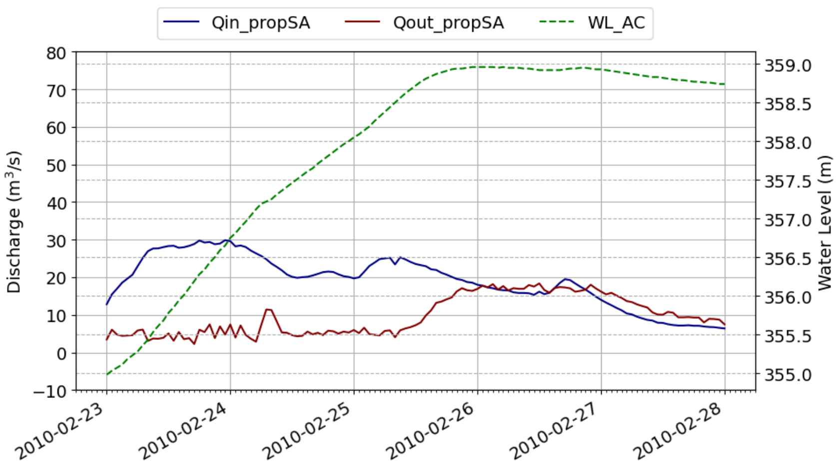
(l) 2006 - 2007



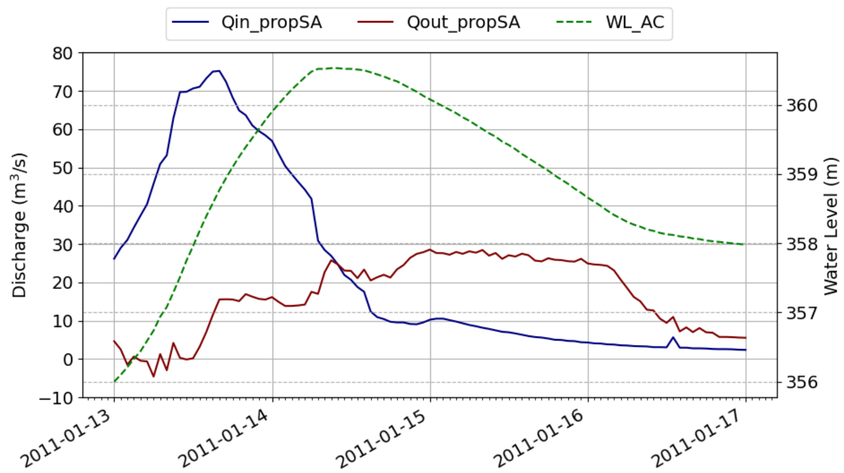
(m) 2007 - 2008



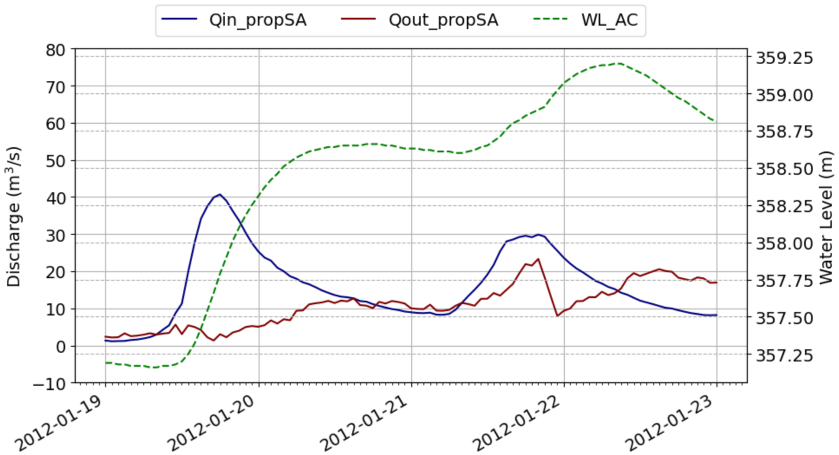
(n) 2008 - 2009



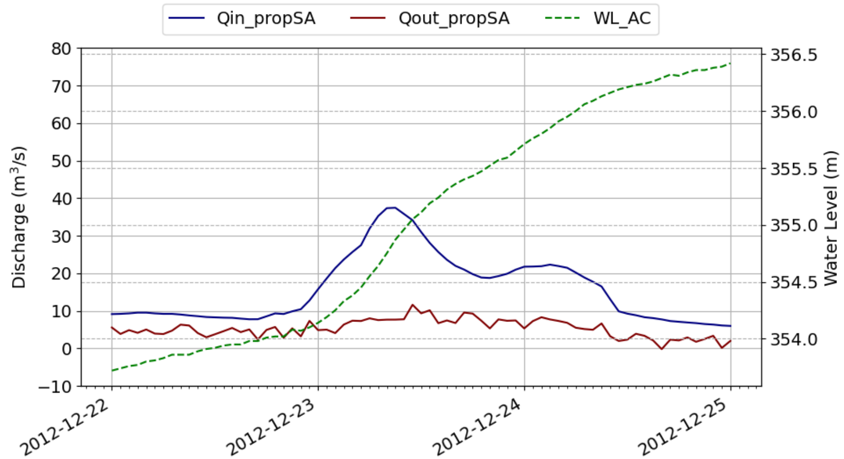
(o) 2009 - 2010



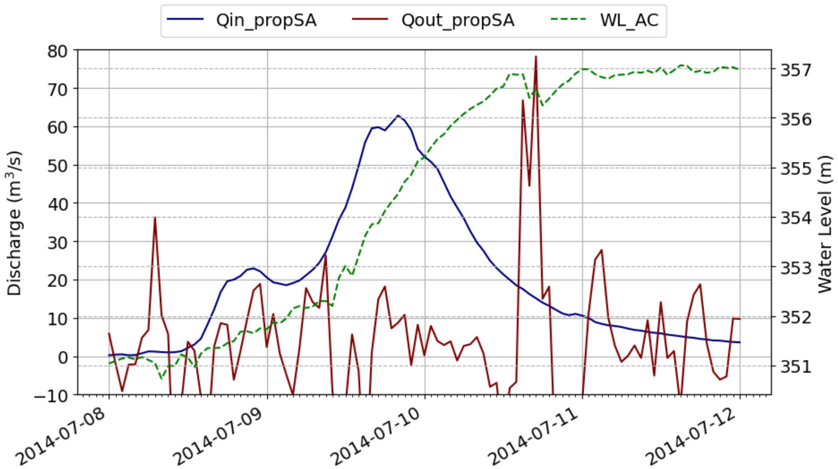
(p) 2010 - 2011



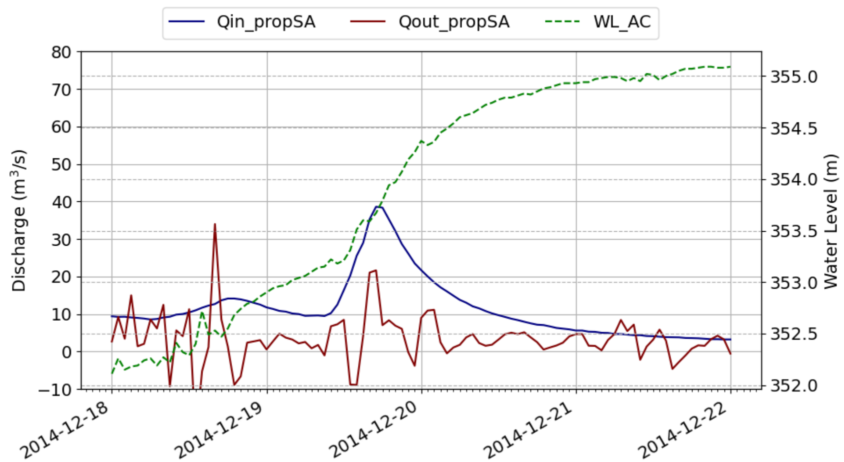
(q) 2011 - 2012



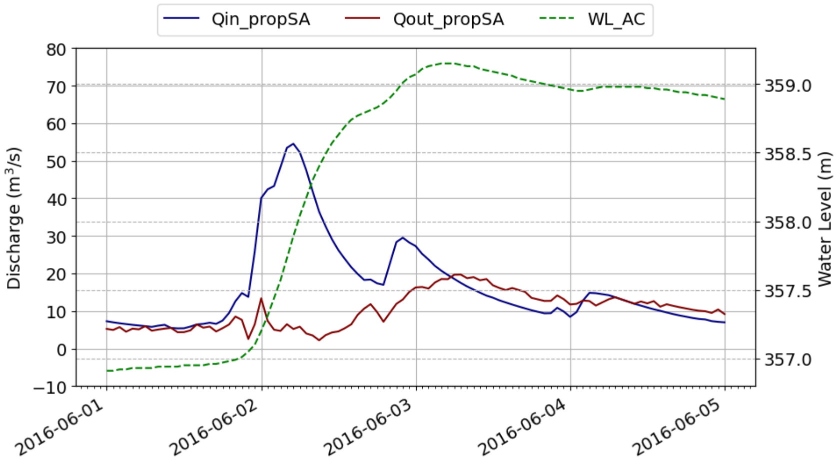
(r) 2012 - 2013



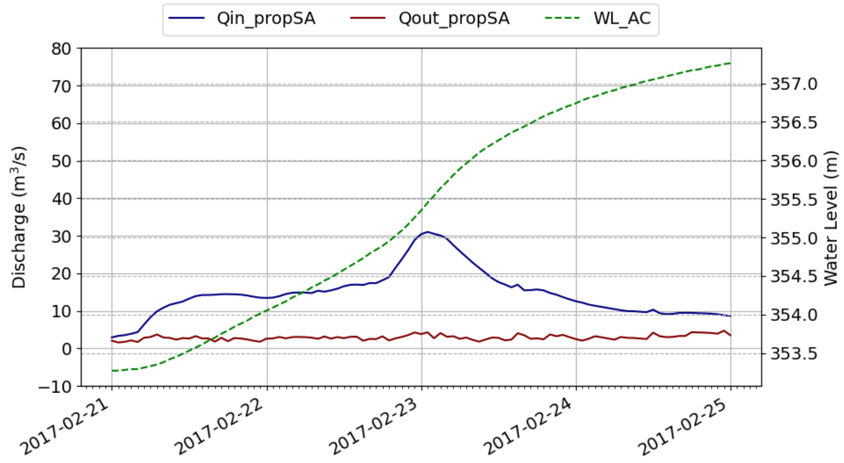
(s) 2013 - 2014 (Not reliable)



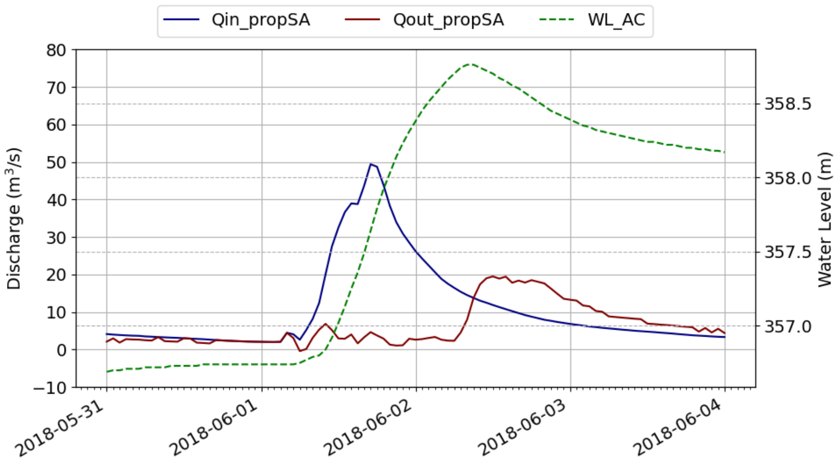
(t) 2014 - 2015 (Not reliable)



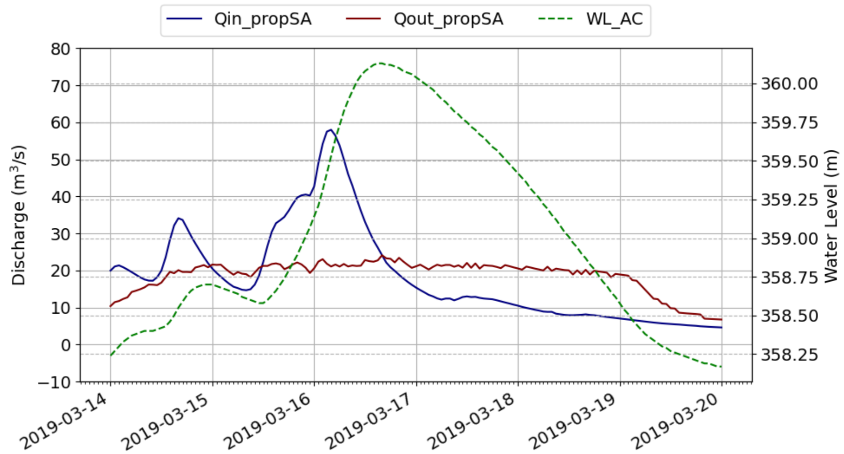
(u) 2015 - 2016



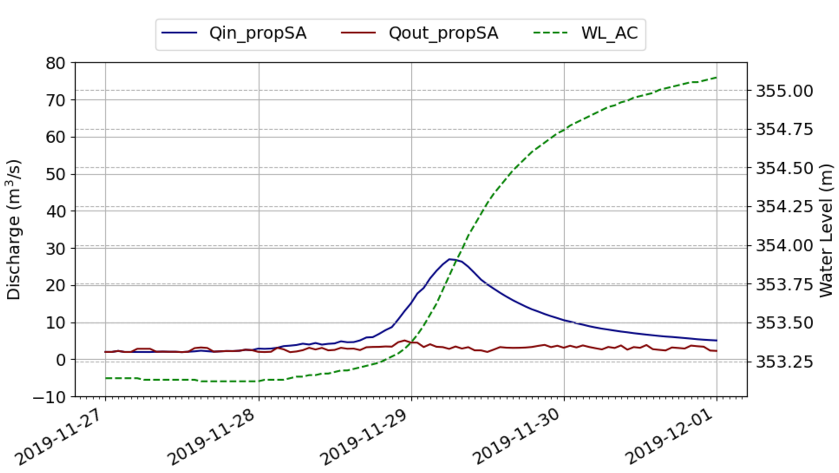
(v) 2016 - 2017



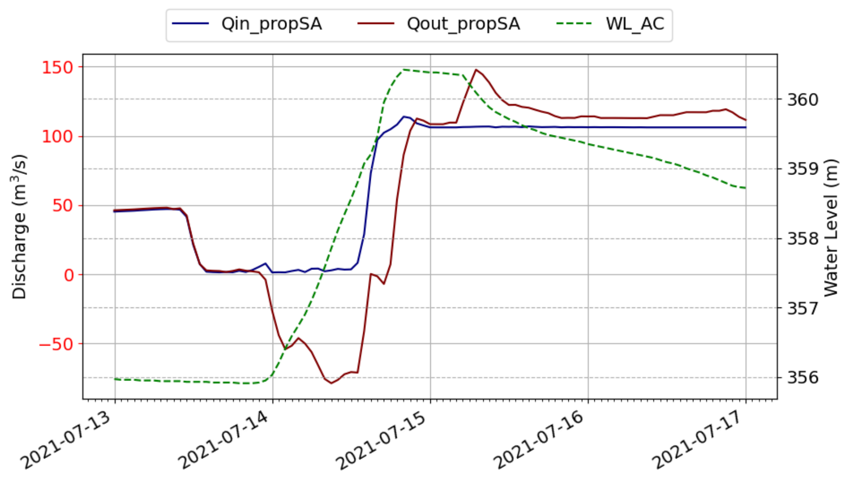
(w) 2017 - 2018



(x) 2018 - 2019



(y) 2019 - 2020



(z) 2020 - 2021 (Not reliable)

Figure A.18