Flood frequencies in places prone to ice jams, case city of Tornio

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ABSTRACT: The river Tornionjoki and the twin city of Tornio and Haparanda on the border of Finland and Sweden is known for ice jams. There have been multiple ice jam floods along the river during the last century that have caused monetary losses. Since the beginning of 2014 flood damage compensation in Finland is paid by insurance companies instead of the government. Normally damages resulting from a flood that has return period of 50 years or more are compensated. Finnish Environment Institute (SYKE) writes statements for the insurance companies about flood frequencies in unclear cases. This is not an easy task in the case of an ice jam flood because of the lack of observations and the limited resources.

There are relatively few studies on flood frequency analysis in places prone to ice jams and they have mainly focused on developing the methodology (e.g. Beltaos, 2012). This study aims to apply such methodologies in places where there is relatively much information on ice jams and ice conditions compared to other sites in Finland. With a such application it is studied, how ice jam monitoring practices should be improved during the ice jam floods and whether general national guidelines for estimating flood frequencies could be improved.

River Tornionjoki has an exceptionally long record of ice breakup dates in Finland, over 300 years. Also ice thickness measurements are more plenty than in other Finnish rivers. Analysis shows that for this location the direct method can be used for flood frequency analysis. However, because of the lack of proper data, the direct method is not an option for most of the Finnish rivers. A HEC-RAS model application shows that the location is very complicated and some key information and data is missing to trustworthily estimate frequencies with the
indirect method. To estimate the probabilities better a method utilizing GLUE (Generalized Likelihood Uncertainty Estimation) is introduced and applied. A large number of HEC-RAS model runs are performed, each run having parameters values randomly chosen from a parameter distribution. Early results show that GLUE method can bring valuable information to the frequency analysis, but more study is needed.

1. Introduction

Since the beginning of 2014 flood damage compensation in Finland is paid by insurance companies instead of the government. Normally damages resulting from floods with an annual probability of 2% or less (on average once per 50 years) are compensated. Finnish Environment Institute (SYKE) writes statements about the flood frequencies if they are not beyond dispute. In the places prone to ice jam floods the flood frequency analysis is much more difficult, contains more uncertainties and is also more laborious to do. During the ice break up the similar flood damage may be reached with a discharge significantly smaller than in open channel flow (Beltaos 2011, USACE 2011).

Basically, there are two approaches for flood frequency analysis in places prone to ice jams discussed in the literature, a direct method and indirect method (Beltaos 2010, USACE 2011). This study aims to apply both ice jam flood frequency estimation methods in River Tornionjoki, in a twin city of Tornio and Haparanda, in a place where there is relatively much information on ice jams and ice conditions compared to other sites in Finland. With a practical application it is studied, how different methods can be utilized in practice, and how ice jam monitoring practices should be improved during the ice jam floods for better understanding of flood frequencies. In addition, it is studied whether general national guidelines for estimating flood frequencies can be improved. Furthermore, a new method utilizing GLUE (Beven and Binley 1992) is tested for estimation of flood frequencies caused by ice jams.

2. Data and methods

2.1 River Tornionjoki and ice jams in the river

River Tornionjoki (Figure 1) was chosen as a case study, because a lot of observations are available and ice jam floods pose a real threat for the twin city of Tornio (Finland) and Haparanda (Sweden). This city lies on the border of Finland and Sweden. There have been multiple ice jam floods along the river during the last century that have caused monetary losses. It is estimated that in River Tornionjoki an open water (i.e. no ice) flood with a discharge probability of 1/250 years would cause dozens of apartment houses, hundreds of detached houses, shops and service stations to suffer from flooding. Damages in Tornio alone are estimated to be 9 million € (Ollila et al. 2000).

The river mouth of River Tornionjoki is at the end of the Bothnian Bay. The river is 520 km long. The basin district consists of two main rivers, River Tornionjoki flowing from Sweden and
River Muonionjoki flowing along the border between Sweden and Finland. Those two rivers connect 10 km above Pajala that is located 180 km north of the river mouth. The total area of the river basin is 40 157 km$^2$, of which 14 480 km$^2$ is in Finland, 25 393 km$^2$ in Sweden and 284 km$^2$ in Norway. Lake percentage of the basin is 4.6 % (Puro-Tahvanainen et al. 2001). There are no hydropower plants in the river and it is not regulated.

The most downstream discharge measurement station of the river is at Karunki and it is approximately 30 km upstream from the river mouth. Average flow (MQ) in Karunki is 385 m$^3$/s (1911-2013). Peak flow (HQ) is 3667 m$^3$/s, mean maximum flow (MHQ) is 2177 m$^3$/s, minimum flow (NQ) is 45 m$^3$/s and mean minimum flow (MNQ) is 76 m$^3$/s. The discharge varies significantly between seasons. Flood discharges are approximately eight times larger compared to median discharges.

There are distributary channels (largest are River Liakanjoki and Kirkkopudas) that part from the main stream after the Tornio gauging station (Figure 2). Partly for this reason, it is very challenging to build a hydraulic model for the delta area. It is not known exactly how much water and ice go to these streams in ice jam situations. According to the local information the location of the ice jam toe and the length of the ice jam is varying from year to year. The ice jam toe is usually located 1-2 kilometers downstream from the last bridge and the ice doesn’t accumulate beyond Kukkolankoski rapid, which is approximately 18 km upstream of the delta. However, there is no exact reported information available about the location and the length of the ice jam.

![Figure 1. Location and borders of the test basin.](image)
Most of the flood damages ever realized in Tornio and Haaparanda were due to ice jam flooding. The ice jam flood in 1990 caused total damages to the city of Tornio worth of € 944 000. Damages to buildings were € 260 000 and damages to personal property approximately € 450 000, respectively. The 1990 flood has been the biggest in the area of Tornio city in the observed history. The highest probabilities for ice jams exists when the river mouth of River Tornionjoki remains ice covered and the upstream part of the river has already begun to release the ice floes downstream forming an ice jam beneath the city of Tornio. A list of observed ice jam floods are listed in Table 1 (ELY 2011).

Figure 2. Map of the case area.
Nowadays, after the ice jam flood in 1990, an ice cutting machine is normally used to cut the ice cover of the estuary before the ice break-up. An embankment was also built to protect the city in 1999. The cutting has affected the formation of ice jams in the estuary, but ice jams still occur despite of the cutting (Sivonen 2002). In 2014 a deeper path was dredged through the estuary to allow a greater flow and to improve the conditions for the flowing ice to pass the city to move away from the city, closer to the river mouth. Based on observed history (1961-2014) the likelihood of ice jam formation \( P(J) \) is roughly 20\%, but recent mitigation measures have probably made ice jams more rare. The highest discharge peak comes often days to weeks after the ice break-up.

Table 1. Ice jams and ice jam floods observed in Tornio. (Modified from The preliminary flood risk assessment in Tornionjoki-Muoniojoki river basin, ELY, 2011)

<table>
<thead>
<tr>
<th>Year</th>
<th>Known damages and other information</th>
</tr>
</thead>
<tbody>
<tr>
<td>1934</td>
<td>Ice jam flood in Tornio-Haparanda</td>
</tr>
<tr>
<td>1944</td>
<td>Ice jam flood in Tornio-Haparanda</td>
</tr>
<tr>
<td>1971</td>
<td>Ice jam flood in Tornio-Haparanda</td>
</tr>
<tr>
<td>1984</td>
<td>Ice jam flood in Tornio-Haparanda. Damages all together in Enontekiö, Kolari, Pello, Ylittornio and Tornio 7,214,210 €</td>
</tr>
<tr>
<td>1985</td>
<td>Ice jam flood in Tornio-Haparanda. Damages 714,770€ (all together in Kolari,Pello, Ylittornio and Tornio)</td>
</tr>
<tr>
<td>1986</td>
<td>Ice jam flood in Tornio-Haparanda. Water level rose over 8 m in Matkakoski. Damages: 180,300 € (all together in Muonio, Kolari, Pello, Ylittornio and Tornio)</td>
</tr>
<tr>
<td>1990</td>
<td>Ice jam flood in Tornio-Haparanda. Damages to city of Tornio 944,000 €, the highest observed water level in Suensaari N2000 + 5,01m (30.4.1990)</td>
</tr>
<tr>
<td>2002</td>
<td>Water level rose couple of meters above normal situation. Applied damages approx. 146,000€</td>
</tr>
<tr>
<td>2004</td>
<td>Ice jam in Hellelä close to Tornio-Haparanda. No considerable damages.</td>
</tr>
<tr>
<td>2009</td>
<td>Ice jam in Hellelä close to Tornio-Haparanda. No considerable damages.</td>
</tr>
<tr>
<td>2011</td>
<td>Ice jam in Hellelä close to Tornio-Haparanda. No considerable damages.</td>
</tr>
</tbody>
</table>

### 2.2 Direct method

Direct method (USACE 2011) for estimating ice-affected stage frequency was used for the of Tornio water level observation station. Both mixed and combined populations are tested. In a mixed population frequency analysis, the annual peak stages are ranked and exceedance probability \( P \) is calculated using a plotting position formula (1):

\[
P = \frac{(m - a)}{(N + b)} \tag{1}
\]

where \( P = \) exceedance probability corresponding to the \( m^{th} \) ranked peak stage and \( a \) and \( b \) are coefficients that range from 0 to 1, depending on the desired probability distribution. In combined direct method peak stages are divided into independent open water and ice affected subpopulations. Both have their own frequency curves that can be then combined. The general equation for combining multiple frequency curves is:
\[ P_c = 1 - (1 - P_1)(1 - P_2) \ldots (1 - P_n) \]  

[2]

where \( P_c \) is the exceedance probability of the combined frequency curve for a given stage and \( P_1, P_2, \ldots, P_n \) are the exceedance probabilities for subpopulations for the same stage. If only two curves are to be combined, like in this case, the equation simplifies to:

\[ P_c = P_1 + P_2 - P_1P_2 \]  

[3]

In this case it was estimated that ice affected the water level three days after the marking in records that all ice was gone from the observation station in the city of Tornio.

### 2.3 Indirect method

With the indirect method ice-affected peak stages may be studied with a hydraulic model, e.g. HEC-RAS or with theoretical means (USACE 2011). A hydraulic model usually needs input data which is in whole or partially based on observations. This is the case when trying to replicate the ice jam event as well. During the ice jam phase it is difficult or even dangerous to get observations about the circumstances in the river. Water level observation stations may be far away from the ice jam location and ice may affect harmfully to the water levels and especially to discharge values derived from the water level. The ice can also damage the equipment in extreme situations. The length of the ice jam may also rest on an observer and individual ice thickness observations, if any, do not necessarily represent the whole river. Compared to open channel flow, river ice studies contain more quantities and the range of uncertainties is also wider.

The HEC-RAS model used in the calculations was constructed in an earlier project in River Tornionjoki (Persson et al. 2011). The measured cross sections were approximately 400 meters apart. For the ice modeling cross sections were interpolated every 50 meters along the area where the ice jam was allowed to form.

The amount of water flowing to the distributary channels Kirkkopudas and Liakanjoki (figure 2) was estimated. There is no knowledge of how much water and ice enters these side streams during ice jam situations. This is probably the biggest source of uncertainty. This also complicates the estimation of the ice amount in the ice jam. According to local source Kirkkopudas tributary was jammed with ice during the ice jam flood in 1990. However on an ordinary ice jam year Kirkkopudas stays open and a lot of the ice and water passes through and hence bypasses the ice jam in the main channel.

### 2.4 GLUE method

Beven and Binley (1992) discussed about the complexity of distributed hydrologic models and how the modeler usually searches for an optimal set of parameters to achieve an optimal calibration result. The method has been further developed since and discussed for example in Beven et al. (2008). They further challenged the idea of a correct combination of those parameters, as the modeler may not be sure that the chosen parameters are valid all over the model domain and that they cover the errors in the observations and in the model itself. They
presented a GLUE method (Generalized Likelihood Uncertainty Estimation) where a large number of model runs is performed, each run having parameters values randomly chosen from a parameter distribution. The range of parameters may base for example on expert opinion or observations. The distribution used in this study was uniform, but also a weighted distribution may be used.

Instead of simulating a certain, fixed set up of boundary conditions (a single discharge and downstream water elevation) and channel roughness coefficient together with an estimation about the ice jam (a single downstream location of the ice jam, Manning n for the ice cover and the ice jam, ice thickness, ice porosity and ice jam length leading to total ice volume) a set of potential ranges of the foregoing parameters were applied in the hydraulic model. To complete such an extensive modelling with hundreds of simulations, a simple user interface along with some VBA code was developed in an Excel spreadsheet. The code automatically generated parameter values over a uniform distribution and created the necessary model geometry and boundary condition files. With the extensive results (n=725) it was possible to study the effect and significance of a single parameter range to for example a water elevation in certain cross section.

The lower and upper limits of the input parameter values for the Tornionjoki test case are presented in the table 2. Based on the discharge observations at the Karunki gauging station and the markings in the records that all ice was gone from the Tornio observation station, the ice-clearing discharge at the location of town Tornio was estimated to be 2000 m$^3$/s and the upstream discharge was limited to that value. The diverting discharge to the Kirkkopudas was estimated to be varying from 10% to 20% of the total discharge. In this study it was not possible to have different Manning-n values for the solid ice cover and ice jam. For that reason a value range of n=0.025 – 0.060 was selected for both solid ice cover and ice jam. The range for the ice jam toe was allowed to form between cross sections 7 and 12 and the length of the ice jam from 500 to 3000 meters.

| Table 2. Values of the input parameter values for the Tornionjoki test case in the GLUE simulations. |
|---------------------------------------------------------------|-----------------|-----------------|
| **Parameter**                                                  | **Min value** | **Max value** |
| Manning-n, channel bed                                         | 0.025          | 0.03           |
| Manning-n for the ice jam and the ice cover                   | 0.025          | 0.06           |
| Ice Friction angle in the ice jam [degree]                    | 43             | 47             |
| Ice jam porosity                                              | 0.35           | 0.45           |
| Ice stress K1 ratio                                           | 0.30           | 0.35           |
| Max velocity under ice jam [m/s]                              | 1.25           | 10             |
| Upstream discharge Q [m$^3$/s]                                | 300            | 2000           |
| Downstream water level [m] (N2000 elevation system)           | 0              | 1.50           |
| Flow change at CS12 (flow to distributary channel) [%]        | 10 %           | 20 %           |
| Location of the ice jam toe [CS number]                       | 7              | 12             |
| Length of the ice jam [m]                                     | 500            | 3000           |
3. Results and discussion

3.1 Direct method

According to the water level observations at the Tornio gauging station most yearly peak stages are caused by open water, but the most significant ones have been due to ice jam floods. The highest peak in record 5.01 meters (in N2000 elevation system) was during an ice jam flood in 1990. The 1990 peak value was momentary, while the rest are daily averages. Figure 3 illustrates open water peaks and ice affected peaks exceedance probabilities from years 1961-1995. The figure clearly shows the significance of ice jam floods in the extreme events. Combined and mixed probabilities are almost the same. All used water level values are from the old (lower) observation station (see Fig. 2). The new observation station is located about 800 m upstream. Water level values in the Figures 4-11 are from the location of the new (upper) water level observation station.

Figure 3. Exceedance probabilities for open water and ice affected water level subpopulations from 1961-1994 in Tornio at the location of the old (lower) observation station. Also combined and mixed probabilities are presented (a=0.25, b=0.5).

3.2 Indirect method

The direct method results were planned to be compared with the results from the indirect method (USACE 2011). For the indirect method a HEC-RAS model was used. However there were too many unknown variables to define the probabilities with indirect method trustworthily. For that
reason the GLUE method was used and the HEC-RAS model which was composed for the indirect method was used in the GLUE simulations

3.2 GLUE method

To tackle the parameter and boundary condition uncertainties the GLUE method was applied and 725 separate HEC-RAS runs were performed. Calculated ice jam and water level profile for one random selected calculation option is presented in Figure 4. The allowed location of the ice jam toe is also presented in the figure.

Figures 5-10 illustrate how water elevation in a certain cross section (located at the site of the new (upper) observation station see Fig. 2) compares to Manning n for ice cover and channel, ice volume in the ice jam, upstream discharge, downstream water elevation and ice jam length (as defined in HEC-RAS prior the simulation) by using the GLUE method. Figures 6, 8 and 10 contain also the corresponding values for open water situation.

Pictures represent the variation in the water level with relation to the before mentioned parameters, although the variation of every parameter is included in the results. For example with an upstream discharge around 1000 m³/s and the given parameter range (Table 2) the water elevations varied 2.7 meters in an ice jam situation, ranging from 2.95 to 5.65 meters. In an open water situation the water elevation range was from 1.85 to 2.17 meters with the same discharge. Similarly, with an ice volume less than 1 Mm³ the water elevations varied from 1.58 to 5.49 meters averaging 3.10 meter. With ice volumes from 1 to 2 Mm³ the water elevations varied from 2.05 to 7.09 meters with an average elevation of 4.48 meters.

With the method we can clearly see that for example sea level has little or no correlation with the water level in Tornio (figure 10) for ice jams. Whereas discharge clearly shows strong correlation with water level as do the ice volume in the ice jam (figures 8 and 5).

![Figure 4. Ice jam profile for a randomly selected calculation option. The total number of calculated profiles was 725.](image-url)
Figures 5-10. The relation of water elevation with Manning n for ice cover and channel, ice volume in the ice jam, upstream discharge, downstream water elevation and ice jam length by using the GLUE method (n=725).

It was impossible to estimate the effect of single ice jam parameter (porosity, maximum under ice velocity, friction angle, ice stress K1 ratio) and its range in this study. Either the range of
each parameter was too narrow or they simply do not have a significant effect on the water elevations as for example the discharge or ice volume has.

Figure 11 represents a histogram of the water elevation results from the GLUE analysis. When the study goes further and parameter ranges are based on non-uniform distributions, a histogram may be used in flood probability analysis as the single water elevations are being handled as a yearly ice jam situation.

![Histogram of water elevation results from the GLUE analysis](image)

4. Conclusions

The estimation of ice jam flood frequencies is challenging. Even on a location that has a fair amount of observations, like River Tornionjoki at Tornio, it turned out to be difficult and error margins are large. For this location a direct method may be used, because water level observations are good enough and the ice jam years are known quite well. This is not the case in most Finnish rivers.

The indirect method utilizing HEC-RAS was found laborious. This attempt to successfully estimate the ice jam flood frequency in Tornio with the indirect method failed. The amount of uncertainties and unknown variables affecting the water flow through the city were too big. With substantial efforts on data gathering there would be a possibility to gather enough data for indirect method, but this will not usually be the situation. The object was also to find out if the indirect method is possible to implement in practice with little data gathering and small resources. This is not the case.
To understand the uncertainties better a HEC-RAS script was developed that runs hundreds of scenarios within a randomly combined input parameter and boundary conditions generated from predefined ranges. This gave better understanding on what parameters contribute to the water level most. It also contributes to developing better monitoring and documentation guidelines. The benefit of having hundreds of randomized calculations can be very useful. With HEC-RAS simulations there is, at least in theory, hundreds of synthesized ice jam events. In this early test all the values were equally distributed, which is not the case in real world. But with further development it could be possible to make ice jam flood frequency analysis with a better understanding about the uncertainties. The benefit of this method is also that all the ice jam events can be based on the latest bathymetry. Often with historical peak data there is the problem that the river has changed drastically in time due to for example dredging and embankments.

When analyzing ice jams there will always be a lot of unknowns that affect the outcome. With GLUE method we can identify parameters that do not affect the outcome at all or very little. This enables a better allocation of resources invested in hydrological observation activities. There are still challenges in applying the GLUE method with ice jams. During the automated HEC-RAS simulations it is not for example possible to find and filter out model runs that did not find a proper solution within the maximum amount of 100 ice jam iterations. A method is also needed to filter out unrealistic ice jam volumes, as HEC-RAS the parameters, their ranges and distributions need more work and the method should be tested in other rivers and for several locations of individual rivers. The authors however see the GLUE method as a promising tool in river ice hydraulics.

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6. References


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