CGU HS Committee on River Ice Processes and the Environment
19th Workshop on the Hydraulics of Ice Covered Rivers
Whitehorse, Yukon, Canada, July 9-12, 2017.

Incorporating ice effects in environmental flow indices

Knut Alfredsen
Department of Civil and Environmental Engineering, Norwegian University of Science and Technology 7491 Trondheim, Norway
Knut.Alfredsen@ntnu.no

Using hydrological indices in the assessment of regulation impacts on flow is becoming common, and such indices is also used in flow regime classification and in the development of environmental flow regimes. With very few exceptions, ice effects on flow regimes are neglected from such indices which can lead to wrong results during winter in cold regions. An exception is the work by Peters et al. (2014) who extends the Index of Hydrologic Alteration (Richter, et al. 1996) to handle some effects of ice formation and breakup. Recent work by several researchers has documented the effect of ice formation on flow in smaller streams, and this is information that could be important to further enhance the indices for hydrologic alteration used in impact evaluation and environmental flow assessment. Such information is also important in the ongoing work to classify river flow regimes within the European Framework Directive or for the ongoing hydropower relicensing in Norway. Here, the current strategies used for hydrologic variability analysis in Norway is discussed, and extensions to handle ice induced effects during freeze-up, stable winter conditions and breakup are proposed. Based on data from a number of Norwegian rivers examples on how ice modified indices can enhance the understanding of flow regimes during winter is described. A lack of data is the main hurdle in developing this methodology, and uncertainties due to this and methods to remediate this situation is discussed.

1. Introduction

With an increased interest in hydro power regulation as a renewable energy source in the transition to a fossil-free energy system, the process on defining environmental flows will be increasingly important. Norway produces nearly all energy from hydro power, and with a large storage capacity in the hydropower system there is also a potential for exporting energy to Europe. In addition, processes related to the implementation of the European Union Water Framework Directive and the relicensing of existing hydropower systems drives the need for better information of regulation impacts and improved methods to design mitigation measures. There is a large body of work on evaluating effects on river regulations on the environment in the international literature, and tools and methods for quantifying effects and devising methods for environmental management are developed and applied in practice. One approach that has been used is the computation hydrological indexes that describes elements of the flow hydrograph that constitutes the natural flow regime (Poff et al. 1997). The various indexes can then be linked to environmental performance, and effects of changes in flow on the environment can be assessed. Applying these indexes for an evaluation before and after flow changes provides a measure of change and a foundation for finding mitigation, and a basis for further and more detailed analysis of impacts. Richter et al. (1996) describes the Index of Hydrological Alteration, a total of 33 indexes describing the flow regime using measures of magnitude, frequency, duration, timing and rate of change. This method has gained popularity, and is used as a part of the environmental design methodology recently developed in Norway (Forseth and Harby 2014) and in the methodology for hydrological assessment for the water framework directive (Bakken et al. 2017).

One issue relevant for assessment in cold regions is that the common hydrological indexes e.g. (Richter et al. 1996; Olden and Poff 2003) does not consider any effects of river ice, which in cold climates could provide significant effects on flow during winter. These effects will be lost in an analysis of open water conditions alone and as an example, omitting ice would eliminate effects like ice induced flooding during freeze up, flooding during break up, duration of the ice-covered period, ice induced low flows during freeze up which is known to appear during the winter period in cold climates. To remediate some of this, Peters et al. (2014) describes a revised set of indexes that contains measures of ice effects on the flow regime using the Mackenzie river as a case study. The revised indexes include the following ice related indexes:

Table 1. Ice related hydrological indexes developed by Peters et a. (2014).

Index type	Ice index
Timing	Date of freeze-up, Date of break-up, Date of ice induced 1 day maximum, Date of ice induced 1 day minimum, Date of peak water level during ice influenced period.
Magnitude	Magnitude of flow at freeze-up, Magnitude of flow at break-up, 1-day maximum ice influenced flow magnitude, 1-day minimum ice influenced flow magnitude, Peak water level during ice influenced water level. Flow magnitude on the day of the ice influenced period.
Duration	Duration of ice influenced period

A challenge with indexes similar to the ones shown in Table 1 is the quality of the data available during the winter season. Peters et al. (2014) used data from Environment Canada that flagged the dates when the measured data are influenced by ice. If available, this is very relevant data for an assessment as described above. In Norway, data is not flagged in the discharge database and as shown by Gebre and Alfredsen (2011) the available ice data is restricted to few rivers and also uncertain for many of these rivers. On the other hand, ice corrections on a daily time scale are carried out and stored in the national database.

In this paper effects of ice on discharge is analyzed with the goal of describing indexes of hydrological variation covering ice effects for Norwegian rivers. Further, we will describe how new indexes can improve the understanding of flow regimes during winter. Availability of data to assess ice effects can be a challenge, and this is also discussed in relation to assessment strategies and uncertainty in the analysis.

2. Ice effects and hydrologic indexes

For rivers of the typical size found in Norway, recent research has improved the understanding of processes and how ice influences flow and related hydraulic parameters (Stickler et al. 2010; Turcotte and Morse 2011; Turcotte et al. 2013; Lind et al. 2016). Stickler et al. (2010) showed how formation of anchor ice dams in the river Sokna transform the hydraulic conditions and thereby available habitat under relatively constant discharge conditions. The shallow fast riffle type habitat was transformed to a succession of deeper pools. Similar results were found by (Turcotte et al. 2013), who also described methods to quantify the ice development with an energy balance model. Lind et al. (2016) describes spatial development of ice in 25 river-reaches in Sweden, and applied a statistical modelling approach to relate ice development to parameters easily obtained from geographical and meteorological information. The latter modelling approaches could be important in describing the spatial heterogeneity of ice formation in rivers which is a challenge in devising hydrological indexes.

Ice has both direct and indirect impacts on the environment which should be incorporated in an environmental assessment. It is therefore important to relate these effects to the relevant hydrological indexes to find relevant effects. Summaries of ecological impacts can be found in recent literature reviews (Huusko et al. 2007; Brown et al. 2011; Heggenes et al. 2016). Formation of ice may also influence the terrestrial environment on adjacent floodplains that is important in the assessment of environmental flows. Lind and Nilsson (2015) found a higher diversity of riparian plants in rivers with flooding related to anchor ice formation, and also a difference in aquatic plants where anchor ice formed. Lesack and Marsh (2010) shows the relationship between flood peaks and water renewal in adjacent lakes on the Mackenzie delta, and how ice jams during the spring flood influences this process.

Ice induced high flows can be a problem, but also a disturbance that has beneficial effects. Looking at the seasonal measures using e.g. the Index of Hydrologic Alteration (IHA), analysis on ice reduced data would underestimate winter flooding, and using uncorrected data ice driven flooding would bias computation of winter low flow and duration of low flow periods. The occurrence of winter floods are addressed by Peters et al. (2014) by timing and magnitude. In addition, an index describing the frequency and duration of such episodes is needed, particularly in regulated or other rivers with unstable ice cover. The index proposed here is either computed by comparing raw data with ice corrected data identifying periods were the raw data exceeds the corrected data, or by identifying rises in flow in periods where the air temperature falls below a threshold that should eliminate floods by winter rainfall.

During freeze-up, periods of low flow can be experienced as ice stores water upstream as ice and in temporary ice dams (Prowse 2000). This effect is also identified by Peters et al. (2014) and indexes for magnitude and timing are described. Here indexes for frequency and duration is added. As for the high flow events, ice induced low flows are mainly estimated using raw and corrected data, and in cases where these are not available air temperature and changes in the gradient of the recession hydrograph is used. For small streams the rate of change of the water level related to such low flows can be significant, and the maximum rate of change is computed following similar procedures as for hydropeaking analysis (Casas-Mulet et al. 2014).

Freeze-up and break-up indices are taken from Peters et al. (2014). For many Norwegian rivers, this is a difficult parameter to compute since data for ice formation and breakup is not available. An alternative method is to use the zero isotherm using the method described in Gebre and Alfredsen (2014). There are significant uncertainties in this approach which must be considered when data is used.

For many practical applications related to river regulation, the stability of the ice cover could be an important parameter for assessing ecological impacts (Finstad et al. 2004). Effects on ice cover stability is a complex interaction between winter flow, climate and water temperature, and would need a more comprehensive assessment procedure than the other ice related indexes. But some indications on this can be derived from the number of ice induced high flows during the winter period.

3. Study sites and data

Flow data is collected from the HYDRA II database at the Norwegian Water Resources and Energy Directorate (NVE). Specific dates for ice on and ice off is lacking for all the gauges used in this study, but NVE have ice adjusted the daily data for the gauge. By combining the ice adjusted data with the raw unadjusted data, ice effects on the flow can be derived and indexes computed. Only daily data have the ice correction, and in the cases where hourly data are analyzed, they are combined with daily corrected data to identify ice controlled events. The flow data is collected from the gauges at Hugdal Bru in Sokna (10.24°E, 62.99°N), Syrstad in Orkla (9.73°E,63.03°N) and Eggafoss in Gaula (11.18°E, 62.89°N). The winter period used in all analysis is defined from 1st of October until the 31st of March. Data for air temperature is collected from the Norwegian Meteorological Institute.

4. Examples of use

Figure 1 shows the ice reduced discharge in blue and the raw data with ice effects in red for the winter 2010-11. Several episodes where ice formation that lead to rises in observed discharge are shown. These episodes would lead to significant raises in water level, increases in water covered area and thereby changes in environmental conditions as shown by Stickler et al. (2010). Key indexes computed for are marked on the figure and summarized in table 2. Another important issue observed is the frequency of the peaks, due to the regulation of Orkla, no stable ice situation is established in the river and anchor ice events happen through the winter. This is also observed in modelling the ice regime for different degrees of regulation at the same site (Timalsina et al. 2013).

Figure 2 shows low flow events caused by ice formation in the river Gaula at Eggafoss during the freeze-up. The events start in late evening as anchor ice forms in the river and releases in the morning leading to a small water level rise above the recessing ice reduced natural discharge. This is an indication of the start of the ice period in the river, and such events can lead to a significant drop in water level over a short time period (16 and 28 cm respectively in the example in Figure 2).

The 1-day maximum computed from open water conditions is compared to the 1-day maximum computed from the data influenced by ice in Figure 3. The maximum value for ice covered conditions is presented both with an hourly and daily time resolution, illustrating the difference the time resolution has on the results. Note that the high value for open water 1-day maximum in 2011-12 was caused by an early spring flood.

The ice indexes were computed for the Orkla river (Syrstad gauge) for a period before the river was regulated, winters 1970/71 to 1975/76, and for the regulated period for the winters 2010/11 to 2015/16 using data with a daily time resolution. Figure 4 show the 1-day peak discharge for both periods. There is a significant difference ($p<0.05$) between the peak sizes before the regulation and after the regulation, with higher ice induced peaks after the regulation. The results show that ice induced peaks also occurred before the regulation, but that they also appeared earlier in the winter than after the regulation. The duration of the ice induced peaks are not significantly changed after the regulation. In Figure 5, the rate of change ($m^3/s/day$) for rises and drops is shown. There is a significant change both in drops and rises after the regulation, with larger drops and larger rises after the regulation.

5. Discussion

The work on hydrological indexes that is presented here can be a useful addition to previous work by Richter et al. (1996) and the extensions by (Peters et al. 2014). The measures of dynamics in flooding and low flows are important for the assessment in rivers regulated for hydropower. As shown e.g. in Figure 1 and 2 important in-stream changes is captured in this analysis which would be lost if only open water indexes where applied, and this could then be relevant for assessing ice effects on the environmental conditions in the river.

The derivation of indexes from temperature and ice corrected data can increase the use of the indexes since it can work were no ice observations are found in the meta data of the discharge series. For the indexes related to winter stability and ice cover formation, data needs may exceed what is available for many sites. The results from this work shows that for many small rivers, data on hourly resolution captures more of the dynamics of the river and for some sites sub-daily time resolution could be needed. Comparing the data in Figure 1 and Figure 4 shows that a number of short duration rises are lost or reduced when the data is aggregated to a daily time step. This is similar to the loss of accuracy in analyzing hydropeaking data, e.g. Bevelhimer et al. (2014) found that a sub-daily resolution is necessary to capture the dynamics of the peaking process. A drawback is that hourly data is mostly available for the latest decades, and such data is not typically available for older series which often is needed to define the pre-regulation period.

A source of uncertainty that comes up in an assessment of hydrologic variability using indexes based on a single gauge site as presented here is if this catches the spatial heterogeneity of the ice formation and the distributed flow dynamics caused by the freeze-up. Observed ice induced low flows in a river probably mean that there is extensive ice formation and possibly also ice induced flooding somewhere else in the same river reach. This can be remedied by measuring discharge and water level at several locations, but at least in Norway there are few rivers with this detail in the measurement network. The energy balance model presented by Turcotte et al. (2013) could be an option to better describe the ice processes over the river reach, but this increases the data needs and requires climatic and morphological data with a spatial resolution that might not be available. Another option is the statistical model described by Lind et al. (2016), and this could be further integrated into a spatial modelling strategy similar to the method described by Lindenschmidt and Chun (2014). But a more detailed modelling approach with larger data needs and more complex operation is substantially more time consuming than the standard hydrological index method, and loses the wanted simplicity of that method. Another option that could be worth exploring is to connect the hydrologic ice indexes presented here to the conceptual ice model developed by Turcotte and Morse (2013). This could then be used to group the index methods to specific river reaches and better understand the uncertainty of the method.

In the recent measures for hydro-morphological effects made for the water framework directive (Bakken et al. 2017) ice effects is categorized on a scale from natural to severely modified based on changes in ice cover and/or anchor ice formation. From a management perspective, the indexes presented here could be used to evaluate the categories in this classification. Particularly the measure based on anchor ice formation can be a complicated index to measure, and a suggestion is that the frequency and size of ice induced peaks could be used as a proxy for direct observations of anchor ice formation in the river.

The use of hydrological indexes presented here is mainly focused on river regulations where we have a situation where we need to compare a situation before and after the regulation. The method is also applicable to other types of studies where changes in the hydrology is needed, e.g. land use and climate (Bin Ashraf et al. 2016).

6. Conclusion

Ice is an important factor in the river environment in cold climates, and effects of ice should be included in any assessment of environmental flow in these areas.

- Ice modifies flow during freeze-up and break-up in a way that cannot be captured by open water hydrology. It is therefore necessary to use ice related indexes to analyze these periods.
- The analysis must be done on raw data from gauges, either measured against ice corrected data or against air temperature. Using ice corrected measurements alone removes important hydrological effects. The quality of data is highly important.
- The spatial variability of the ice formation in smaller streams may not be properly covered by a single station analysis – methods to extend the method to cover the

variability is needed, but the current approach may still give an initial understaning of the ice effects compared to open water hydrology.

- Combining the indexes devised by Peters et al. (2014) with the measures presented here should capture effects both in small and large rivers.

Acknowledgments

The author wishes to thank Tor Haakon Bakken for providing access to the preliminary results from the work on the hydro-morphological indexes for the water framework directive in Norway.

References

Bakken, T. H., T. Forseth and A. Harby(2017).Assessment of hydro-morphological state and reference conditions in regulated riversSINTEF Energy

Bevelhimer, M., R. McManamay and B. O´Connor (2014). Characterising sub-daily flow regimes: implications of hydrologic resolution on ecohydrology. River research and applications.10.1002/rra.2781

Bin Ashraf, F., A. Haghighi, H. Marttila and B. Kløve (2016). Assessing impacts of climate change and river regulation on flow regimes in cold climate: A study of a pristine and a regulated river in the sub-arctic setting of Northern Europe. Journal of Hydrology **542**: 410-422

Brown, R., W. Hubert and S. Daly (2011). A Primer on Winter, Ice, and Fish: What Fisheries Biologists Should Know about Winter Ice Processes and Stream-Dwelling Fish. Fisheries **36**(1): 8-26

Casas-Mulet, R., K. Alfredsen, B. Hamududu and N. P. Timalsina (2014). The effects of hydropeaking on hyporheic interactions based on field experiments. Hydrological Processes.10.1002/hyp.10264

Finstad, A., T. Forseth, T. Faenstad and O. Ugedal (2004). The importance of ice cover for energy turnover in juvenile Atlantic salmon. . Journal of Animal Ecology **73**(5): 959-966.10.1111/j.0021-8790.2004.00871.x

Forseth, T. and A. Harby, Eds. (2014). Handbook for environmental design in regulated salmon rivers. NINA Special Report. Trondheim, NINA.

Gebre, S. and K. Alfredsen (2011). Investigation of river ice regimes in some Norwegian water courses. 16th Workshop on the Hydraulics of Ice Covered Rivers, Winnipeg, Manitoba, Committee on River Ice Processes and the Environment.1-20

Gebre, S. B. and K. Alfredsen (2014). Contemporary trends and future changes in freshwater ice conditions: inference from temperature indices. Hydrology Research: 24.http://dx.doi.org10.2166/nh.2013.213

Heggenes, J., K. Alfredsen, A. Bustos and A. Huusko(2016).Be cool: hydro-physical changes and sh responses in winter in hydropower-regulated northern streamsUniversity College of Southeast Norway1

Huusko, A., L. Greenberg, M. Stickler, T. Linnansaari, M. Nykänen, T. Vehanen, S. Koljonen, P. Louhi and K. Alfredsen (2007). Life in the ice lane:The winter ecology of stream salmonids. River research and applications **23**: 469-491

Lesack, L. and P. Marsh (2010). River-to-lake connectivities, water renewal, and aquatic habitat diversity in the Mackenzie River Delta. Water Resources Research **46**: 16

Lind, L., K. Alfredsen, L. Kuglerova and C. Nilsson (2016). Hydrological and thermal controls of ice formation in 25 boreal stream reaches. Journal of Hydrology **540**: 797 - 811

Lind, L. and C. Nilsson (2015). Vegetation patterns in small boreal streams relate toice and winter floods. Journal of Ecology **103**: 431-440

Lindenschmidt, K.-E. and K. P. Chun (2014). Geospatial modelling to determine the behaviour of ice cover formation during freeze-up of the Dauphin River in Manitoba. Hydrology Research.doi:10.2166/nh.2013.193

Olden, J. and N. Poff (2003). REDUNDANCY AND THE CHOICE OF HYDROLOGIC INDICES FORCHARACTERIZING STREAMFLOW REGIMES. River research and applications **19**: 101-121

Peters, D., W. Monk and D. Baird (2014). Cold-regions Hydrological Indicators of Change (CHIC) for Ecological Flow Needs Assessment. Hydrological Sciences Journal **59**(3-4): 502-516.10.1080/02626667.2013.835489

Poff, N., J. Allan, M. Bain, J. Karr, K. Prestegaard, B. Richter, R. Sparks and J. Stromberg (1997). The natural flow regime. BioScience **47**: 769-784

Prowse, T. (2000). River Ice Ecology, National Water Research Institute, Environment Canada.

Richter, B., J. Baumgartner, J. Powell and D. Braun (1996). A Method for Assessing Hydrologic Alteration within Ecosystems. Conservation Biology **10**(4): 1163-1174

Stickler, M., K. Alfredsen, T. Linnansaari and H.-P. Fjeldstad (2010). The influence of dynamic ice formation on hydraulic heterogeneity in steep streams. River research and applications **26**(9): 1187-1197

Timalsina, N., j. Charmasson and K. Alfredsen (2013). Simulation of the ice regime in a Norwegian regulated river. Cold Regions Science and Technology **94**: 61-73.10.1016/j.coldregions.2013.06.010

Turcotte, B. and B. Morse (2011). Ice processes in a steep river basin. Cold Regions Science and Technology **67**: 146-156

Turcotte, B. and B. Morse (2013). A global river ice classification model. Journal of Hydrology **507**: 134-148

Turcotte, B., B. Morse, M. Dube and F. Anctil (2013). Quantifying steep channel freezeup processes. Cold Regions Science and Technology **94**: 21-36

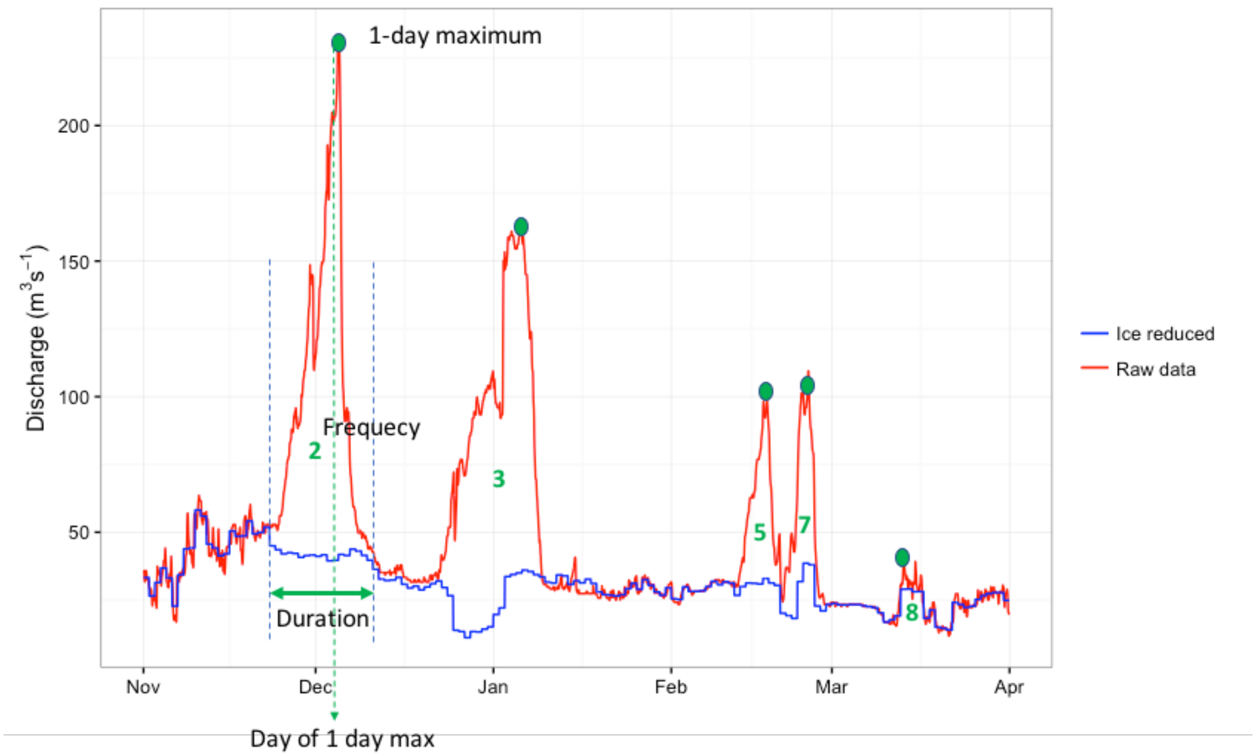

Figure 1. Ice induced high flow at the Syrstad gauge for the winter 2010-11 with characteristic measures, duration, maximum and frequency. The red curve is uncorrected observations in hourly format, the blue curve is ice reduced daily data.

Table 2. Characteristic data of the events in figure 1. Only events with a duration over 2 hours are shown in the table.

Event #	Start Date	Date of peak	Peak value (m^3/s)	Duration (hours)	Max drop $m^3/s/hour$	Max rise $m^3/s/hour$
1	2010-11-08 16:00:00	2010-11-08 17:00:00	57.04	3	3.01	0.28
2	2010-11-09 20:00:00	2010-11-09 21:00:00	56.77	4	0.68	1.76
3	2010-11-24 16:00:00	2010-12-04 21:00:00	232.35	322	22.54	12.81
4	2010-12-23 00:00:00	2011-01-05 00:00:00	162.58	413	10.19	24.00
5	2011-02-13 17:00:00	2011-02-17 16:00:00	98.49	129	4.53	4.43
6	2011-02-19 13:00:00	2011-02-19 21:00:00	49.35	14	4.67	1.73
7	2011-02-20 17:00:00	2011-02-24 21:00:00	109.45	139	7.51	4.34
8	2011-03-13 13:00:00	2011-03-13 13:00:00	39.68	2	1.53	0.00

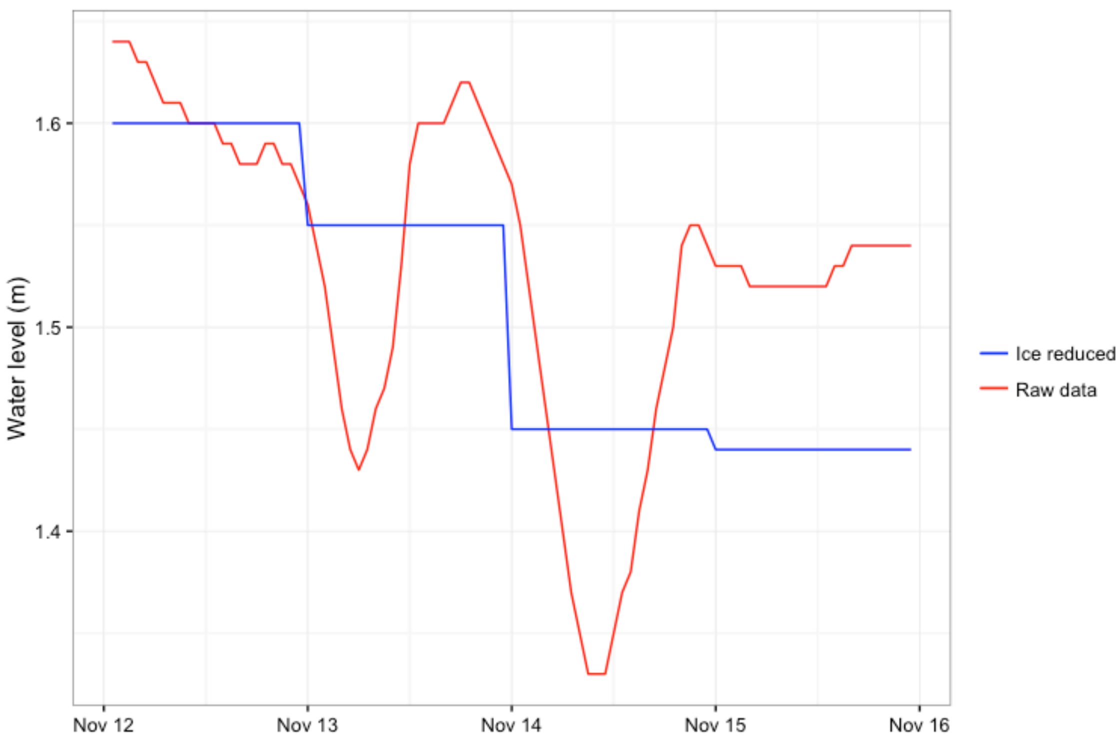

Figure 2. Example of water level drops at the Eggafoss gauge during freeze-up in the winter of 2016-17. The red line is raw data with hourly resolution, the blue line is ice corrected daily values. Characteristic parameters are similar to those in figure 1, except here we find 1-day minimum and max rate of change (reduction in water level).

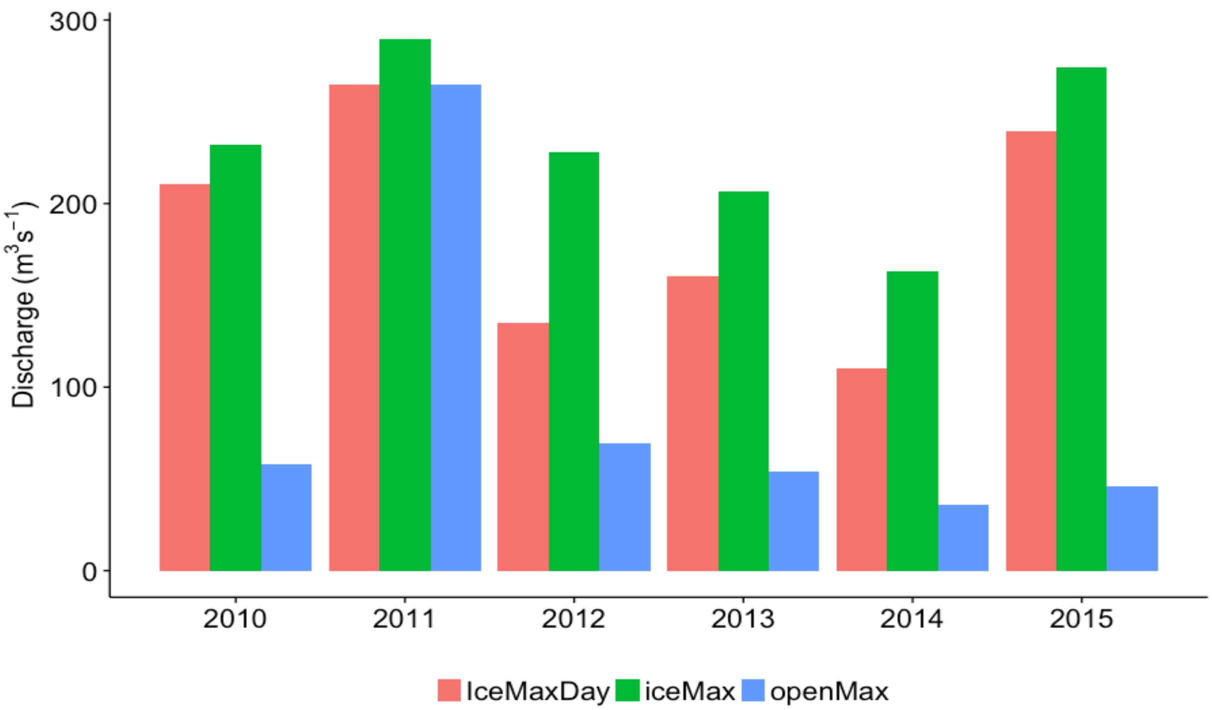

Figure 3. Comparison of the winter 1-day maximum (openMax) computed for open water conditions (ice corrected data – daily values) and the 1-day maximum (iceMax) computed from raw data with ice with an hourly resolution and the corresponding 1-day maximum (iceMaxDay) with ice with daily resolution. Note that the high value for 1-day maximum for open water in 2011-12 is due to an early spring flood.

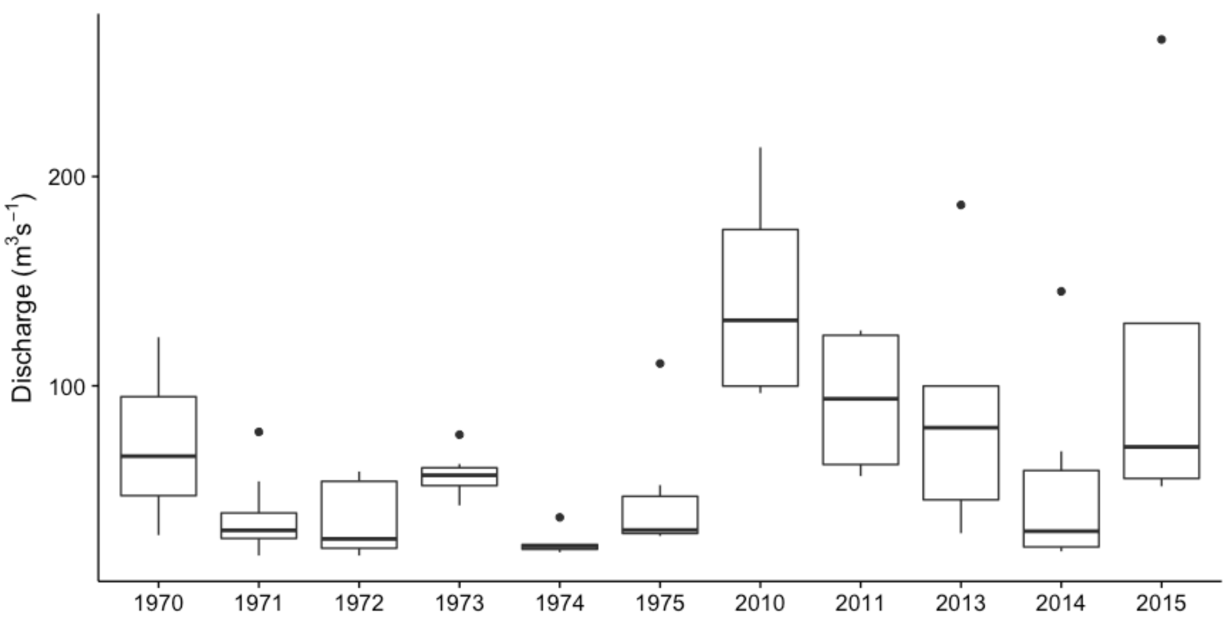

Figure 4. Example of comparison of ice induced peak discharge in the pre-regulation period (1970-75) and the regulated period (2010-2015). Bold line is the mean, box shows interquartile range and whiskers 1.5*interquartile range.

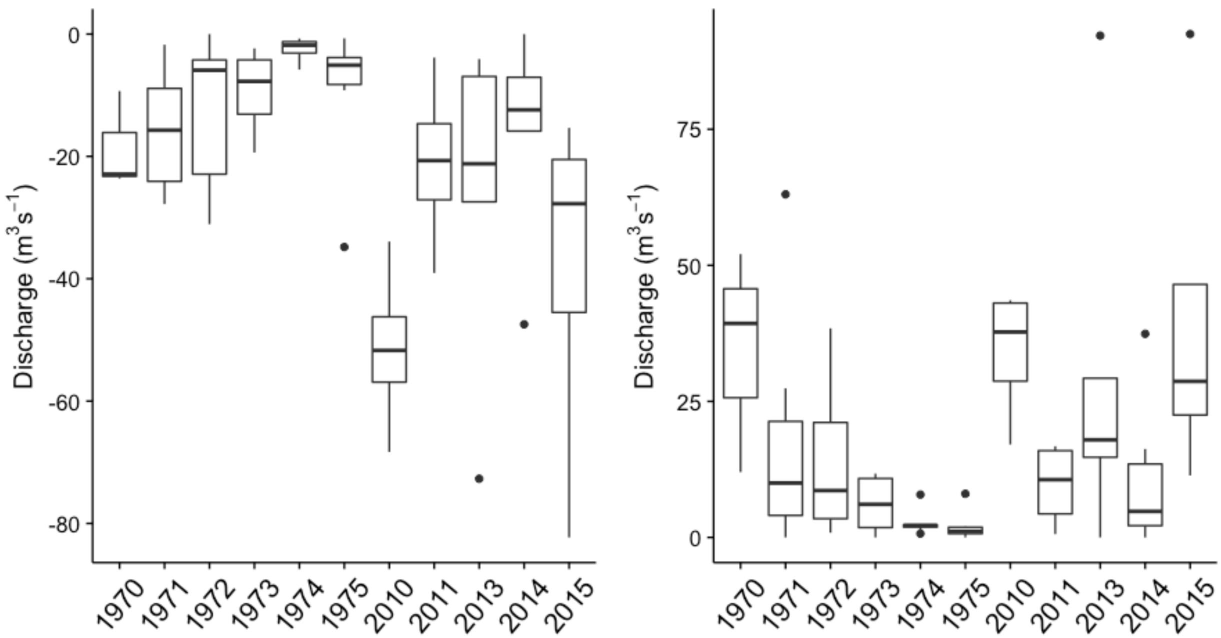

Figure 5. Daily rises (right) and drops (left) in the pre-regulation period (1970-75) and the regulated period (2010-2015).