Development of an inflow controlled environmental flow regime for a Norwegian river

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ABSTRACT: Hydropower produces 99% of the electricity in Norway and a large number of rivers are regulated. Currently static minimum flow regimes are used as a mitigation measure for most of these developments, usually having fixed values for winter and summer flow. Improved knowledge on the importance of variability in flow regimes has lead to research on alternative solutions to the static minimum flow regimes. This paper describes the development of an environmental flow regime that is designed to follow the variation in natural inflow. The flow regime is designed using an adaptation of the Building Block Methodology, and linked to high, normal and low natural flow conditions. The work is focused on the river Daleelva in western Norway which were Atlantic salmon is the key species. The paper also describes how the variable environmental flow regime can be implemented in practice in light of current Norwegian legislation.

KEYWORDS: Hydropower, Environmental flow, Building Block Methodology, Atlantic salmon

Introduction

Current environmental flow practices in Norway are dominated by static flow regimes, which often define a constant minimum flow value for winter and higher constant value for summer. Recent international research shows a need for a more flexible flow regime which takes account of the variability found in the natural hydrological regime to meet the demands of the ecosystem functions (Enders et al., 2009, Arthington et al., 2010, Poff et al., 2010). These findings are in contrast to the common practice in Norway, and the Norwegian Water Resources and Energy Directorate instigated a research programme to improve Norwegian environmental flow practices (Brittain, 2002). The project reported here is a part of this programme and has the objective to develop a method for designing an environmental flow regime that follows the natural variation in inflow to the river in question. To our knowledge there are currently few examples of environmental flow regimes operationally linked to natural inflow. (Gravem et al., 2006) described a trial regime in the river Suldalslågen that releases a fixed amount of water plus an addition based on the average of the last five days. Internationally, the Australian transparent dam methodology (Gippel, 2001) has similarity with the objective of this project. (Jacobson & Galat, 2008) described a flow regime developed for the lower Missouri river that have some similarities with the regime described in this paper, but with a greater focus on historical data in the planning of environmental releases. A methodology for defining environmental flow similar to the one used in this project have been outlined for British rivers by (Acreman et al., 2009), and their paper also discusses potential methods of handling the natural variability in flow in the environmental flow regime.

Our objective has been to develop a flexible environmental flow regime that has three levels, low, medium and high flow using a approach similar to the building block methodology (King, 2000). The three environmental flow scenarios are then linked to the same categories of natural inflow, shifting scenario depending on the natural inflow value. In contrast to some designs suggested in the literature (Gravem et al., 2006), we wanted to avoid a environmental flow regime based on a direct scaling of the natural inflow by some percentage factor, since the resulting flow of such scaling may not have any ecological significance. The project also evaluated how the new regime could be implemented in the current Norwegian legislation and how a more flexible regime can be adapted to the current hydropower operation. An important restriction put on the project work from the environmental flows programme was that only data already available should be used, and no new data collection should be carried out. This had a significant influence on how the work was done.

Materials and Methods

Study site

Daleelva is located in the Sognefjord area in western Norway (figure 1). The catchment area is 172 km^2 and the river system is heavily regulated for hydropower. The study site is defined from the outlet of hydropower K2 to the sea, but the power plant K5, with outlet directly in the fjord, also influences the study site by collecting several tributaries from the west side of the catchment and at times releases far more water into the fjord than the river. The analysis is based on a planned upgrading of K2, with a production release of 12-16 m^3/s and a minimum flow regime specifying a winter discharge of 1.5 m^3/s and a summer discharge of 6 m^3/s. Since the study site is downstream of the hydropower outlet, most of the released water will pass through the turbine. This ensures little loss of production due to releases of environmental flow, but a changed timing of releases can influence the economy of the power plant. Even with the regulation in place, large floods are not uncommon in the river (Traae et al., 2001). The river has a population of Atlantic salmon (*salmo salar*) and brown trout (*salmo trutta*), and fish can migrate a few hundred meters past the outlet of the K2 power plant until they meet a natural migration barrier.

Flow regime design and implementation

To design the flow regime we used a simplified version of the Building Block Methodology (King, 2000). The method relies on expert knowledge and is based on workshops where experts identify interest groups and their water needs. Each defined need then constitutes a building block for the flow regime. By adding the blocks together the total flow regime can be identified. In this project interest groups and building blocks were identified by the project team and water needs were allocated based on available literature. Each block is defined as a flow range with both a potential minimum and maximum, which would later be used to design the variability of the regime related to the natural flow. In accordance with project requirements, a possible monitoring program was also assigned to each block to evaluate the function of the environmental flow regime. Data from monitoring could also be used for modifying the blocks and improving the flow regime in the future (Acreman et al., 2009). Several possible approaches were identified to link the flow regime to the natural inflow: (1) using historical data, (2) using predictions of future inflow and (3) measurement in unregulated catchments.

Data

Data availability in the area is generally sparse. For discharge we have used production data from power plants K2 and K5, and inflow from the unregulated areas are determined by scaling the data series from Sogndalsvatn (a neighbouring catchment) based on catchment area and specific runoff. Temperature data is available for the years 2005-2007 measured by the Norwegian Water and Energy Directorate. For evaluating environmental issues and issues related to river use we have also used earlier studies on ecology and hydropower impacts for this river (Lund et al., 2006, Skurdal et al., 2001).

Flow regime design

We defined a flow regime with three different levels based on flow percentiles: low < 25%, high > 75% and normal between 25% and 75%. This is assumed to represent a dry, normal and wet year. Each identified block will have a value (maximum, minimum or both) for each of the three situations, and we will switch between them based on the magnitude of the natural flow. The main fish species in Daleelva is Atlantic salmon, and the defined blocks focus on meeting flow needs for spawning, hatching, swim-up, rearing juveniles, outmigration of smolts, adult migration and recreational salmon fishing. The building blocks are designed as follows:

Spawning – discharge and timing

Spawning in Atlantic salmon is mainly controlled by temperature, and discharge seems to have little effect on the timing or occurrence of spawning (Heggberget, 1988). On the other hand, high discharge at the time of spawning may lead to spawning in areas that dry out at low flows. The spawning block therefore introduces a cap on discharge during the spawning period which is not much above the minimum winter flow. The morphology of Daleelva is such that relatively large areas are submerged already at a discharge of 1 m^3/s and thus suitable areas for spawning should be available already at that discharge. An increase from 1 to 3 m^3/s lead to an increase in water covered area of only 9% (Fjeldstad unpublished data), and the cap could therefore be set around the winter minimum with little drying of redds as a consequence.

Based on data from (Heggberget, 1988), a temperature of 5 degree is defined as the start of spawning. This occurs during weeks 43 to 47 for both Atlantic salmon and trout, but due to variation of temperature between years it is suggested that the cap-flow period should be flexible and controlled by real time water temperature measurements.

Winter discharge

High winter discharge increases the wetted area and thus increases the opportunities for fish to find suitable daytime cover. An increase in winter discharge has also been shown to increase smolt production in other rivers (Hvidsten & Johnsen, 1993, Gibson & Myers, 1988). When autumn water temperature falls below 8˚ C (Rimmer et al., 1985), rapid varying flows should be avoided. The period of rapid temperature decline in autumn has been recognized as a period when juvenile salmonids are likely to be displaced because the period is energetically difficult for acclimatization. The winter discharge in each block is therefore set at a level which maintains the wetted area. It is also recommended to maintain as stable flow as possible during the temperature decline in autumn.

Hatching

Hatching was calculated based on different spawning date scenarios (Table 1). High flows during the period when alevins are in the gravel may increases mortality, therefore there is a contradiction between possibly lowered survival of alevins if flow is increased for increased survival of smolts during their migration (see below). In nature, these events coincide as well, so it appears adaptive to favour an increased flow regime in spring over the potential problem of slightly reduced incubation success. The smolt migration block therefore takes precedence over discharge controls for hatching.

Smolt migration

Temperature and discharge both play a role for initiating the smolt migration. Synchronization of smolt migration into one large movement and a high water event during the migration may increase survival by reducing the probability of predation (Hvidsten & Johnsen, 1993, Finstad & Jonsson, 2001, Hvidsten & Hansen, 1988). The bulk of the migration is estimated to occur between river temperatures of 5 – 9˚ C, although migration already starts at lower temperatures (Hvidsten et al., 1995, Hvidsten et al., 1998, Saltveit, 1998, Jonsson & Ruud-Hansen, 1985, Arnekleiv et al., 2007). Another factor found important in Norway is a sea temperature above 8ºC when the smolt migrate to sea (Hvidsten et al., 1998).

Just two years of river temperatures and no sea temperature are available for Daleelva which makes it impossible to analyze variability in possible migration timing. However, based on the cited literature, mid-May is assumed to be the time where the bulk of the smoltification occurs in Daleelva. A smolt block with a high water event with increasing magnitude and duration for each of the three flow situations is therefore placed in mid May. The quantity of water is based on the knowledge that the water release must be large enough relative to winter to trigger the migration. In a normal and wet year it is suggested that the reduction after the trigger release (latter half of May) would follow a "natural" recession pattern which should facilitate further migration. In addition, the natural run-off from the catchment is likely to be at highest at the end of May, which will further allow opportunities for smolt migration. However, the releases to trigger smolt migration must end before the swim-up (see below).

Swim-up

The discharge at the time of swim-up should be kept stable, as the high discharge during the first week after swim-up increases mortality (Jensen & Johnsen, 1999). The swim-up in Daleelva is likely to occur during the month of June (Table 1), but there is uncertainty in this estimation due to limited temperature data and a lack of observations on swim-up. It is suggested to keep the flow during June at low level by a cap-flow with absolutely no room for peaking or other rapid flow changes during the swim up period. According to the statistics, catches of adult salmon are insignificant during June, which lends further support to a stable low flow during the swim-up period (i.e. no conflicting interests for more water due to fishing considerations).

Summer discharge

Increased discharge in comparison to winter conditions will ensure increased production areas, and will thus enhance growth at the population level. Increased water flow will also maximize the production areas for macroinvertebrates, essential food organisms for the salmon. Fishing opportunities and other possible recreational uses are also improved by higher flows. Higher minimum flow in summer relative to winter can be considered good for stocking practices since there will be more space available which will help the fish to find and establish territories and reduce intra specific competition.

A summer block is defined as a base flow value with a number of low flow periods and high flow periods over the summer. The proposed low flow periods saves water for the hydropower company during the summer season, and water is then traded for a number of summer high flow periods that function as an attraction for migration (see below). It should be ensured that the low flow period still will provide ample water covered area. The timing of high and low flow periods is not fixed, and can be adjusted yearly depending on natural inflow and conditions prior to the summer.

There are indications that the brown trout run is later than Atlantic salmon (Lund et al., 2006), it is therefore recommended that one of the attraction flows is released late in the summer season. This is also obtained by keeping the base flow for September and October above the winter minimum. The higher autumn flow is also considered to aid in distributing the spawners in the river. However, at the time of spawning flows should not exceed the cap flow for spawning as discussed previously.

Migration flows

Attraction flows are suggested in summer to attract the salmon and trout to Daleelva instead of going to the outlet of hydro power plant K5 as is observed today. The recent catches of adults has been used as an indication of the timing of salmon entry to Daleelva (Lund et al. 2005), and the timing of attraction flows has been adjusted accordingly. The timing of the attraction flows should occur when the fish are motivated to migrate (i.e. during the main migration phase, (Økland et al., 2001)), and such releases have been shown to have only minor effect later in the fall (Thorstad & Heggberget, 1998). As is the case for spawning period, the timing of the freshets should not be fixed, but should rather coincide with a natural increase in flow producing a stronger effect. There is likely no need to adjust the timing in regard to water temperature, since there are no migration barriers in the river which requires high temperature for passing. However, the first peak should not occur very early in the summer season, since there is uncertainty when the swim-up will be completed, and in years with very cold spring (and if the spawning occurred late the previous fall) there may be a chance of swim up as late as early July. If it is known (e.g. from monitoring the timing of spawning and possibly swim-up) that the swim-up has occurred in June, another attraction peak could be provided in early July during a wet year.

The flow should be large enough to overcome the effect of production releases from K5, where the fish are currently attracted to. Therefore, it is likely that the energy production should be coordinated between K5 and K2, so that the production from K5 should be lowered or stopped before the increase at K2 to get a maximum effect for salmon attraction to Daleelva. The peak release can be produced relatively fast, after which the pattern should simulate a natural spate hydrograph recession, since the upstream migration occurs most freely during the recession period (Hendry et al., 2003). The releases should be repeated if the quantity of water allows (i.e. wet year) as not all adult fish enter the fjord simultaneously.

The efficacy of attraction flows is not self-evident and is questioned in larger river systems (Thorstad et al., 2003). In smaller rivers the effect of attraction releases will be larger due to less attenuation of the peak, and the release will impact a longer length of river.

Channel maintenance

Even after the regulation Daleelva experience large floods with a high degree of mass transport. Substrate mapping (Fjeldstad, unpublished data) shows cobbles as the dominating substrate and very little fine material in the substrate pore spaces, providing adequate shelter for juveniles. A flushing flood is therefore not included as a part of the flow regime.

Stocking

Stocking of salmon parr is carried out as a mitigation measure in Daleelva. It must be ensured that the stocking takes place during normal summer flows, and not during the attraction flow periods, where fish can be displaced or during the low flows where predation on the freshly stocked fish may be high.

The defined blocks are combined into a flow regime for the high, low and normal inflow conditions, and the proposed flow regime is shown in Figure 2. The yearly volumes for the new flow regimes and the existing flow regime are shown in table 2, which indicates that there is an additional cost of water for the power producer for the normal and high flow situations, and water is saved in the dry year compared to the present minimum flow regime.

Implementation of flow regime

The current Norwegian legislation contains a transparency rule regarding environmental flow releases. This requires the hydropower company to document that the correct amount of water is released at any time both to the public and to governmental controlling bodies. This will have implications on the method selected to link the environmental flow regimes to a measure of natural inflow since a regime with more variability will be more complex to communicate, particularly to interested parties among user groups in the river. Usually the control is done by placing a discharge gauge in the minimum flow reach to measure the minimum or environmental flow. In all our analyses we have assumed that the magnitude of environmental flow is measured at a location in Daleelva just downstream from the outlet from hydropower plant K2. We evaluated three different approaches for selecting and releasing environmental flow based on the designed flow scenarios.

Norwegian hydro power companies usually run 10-day inflow forecasts for their systems once a day for production planning, and one option would be to select the environmental flow value based on those forecasts. This would ensure real time changes in environmental flow and a maximum utilization of residual flow in the catchment. A problem with this approach is that there is a probability for errors in the forecasts and the predictions changes from day to day depending on the weather forecast. This would increase the need for documentation of the Forecasts for government control and there are no clear methods for working out disagreements between the regulator and controller in the case of differences in forecasts and release pattern. An even more important drawback is the lack of simple methods to communicate the forecasts to the public and to explain how errors in forecasts will influence the environmental flow released to the river.

The second option is to base the release of environmental flows on an average of the last five to seven days observed discharge in the system. This will create a delay in the release compared to the variability in natural inflow, and will not utilize the residual flow in the best possible way. On the other hand it will be easy to document and control both for public and governmental organizations.

The third option, one that we recommend, is to establish a gauge in an unregulated tributary and then use this to decide if we have a dry, normal or wet period and select the environmental flow release accordingly. This will give us close to real time changes in environmental flow, it will utilize residual flow from the catchment and it will provide simple control mechanisms for public and governmental organizations.

Discussion

As has been mentioned in the description of the building blocks there are a number of uncertainties related both to lack of data for Daleelva for performing analyses and to some extent by lack of knowledge of central ecological processes in the river. Lack of good discharge and temperature data prevents the application of recent developments in environmental flow assessment (Poff et al., 2010, Olden & Naiman, 2010), which would have been useful for planning several of the blocks in Daleelva. Among the identified uncertainties, of particular importance is the timing of spawning which should be verified both for adjusting the spawning block, but also since this influences hatching and swim-up and thereby also the magnitude and timing of the smolt migration block. There is also a need to follow up the attraction flows for migration and their effect on getting fish to enter the river. Currently the K5 plant attracts returning adults, and there is more work needed to understand the synchronization of increased releases from K2 and reduced flow through K5. Another issue is related to invertebrate communities in the river for which no data exists. It has been assumed that providing ample flow year round would also benefit invertebrates, but very little concrete analysis have been possible. A monitoring program to follow up the performance of each block with biological surveys is proposed as a part of the project, and this should be able to provide some information on some of the uncertain issues in the current flow regime over time. On the other hand, the work carried out in this project does probably reflect the situation which many Norwegian projects will face in the future when a large number of rivers are to be evaluated for ecological status and possible environmental mitigation measures as a part of the implementation of the European Water Framework Directive (Iversen, 2010). It is highly unlikely that all such projects will have the funding to perform thorough hydrological and biological surveys before environmental flows are defined, so simplified methods will have to be applied.

The building block methodology is defined as a holistic approach that should cover all ecological and physical processes in the river, and the current study may have breached some of the intent with the method with its strong focus on Atlantic salmon. However, the method provides a framework for analysis and identification of important features that are both intuitive and communicable. The quality of an application of BBM such as the one carried out for Daleelva strongly depends on the project group's ability to identify all possible key species, interest group and processes and also on the ability to handle conflicting demands properly.

New approaches to setting environmental flow regimes, particularly the focus on a stronger variation of flow with time, are challenging in relation to the current legislation and practices used in monitoring minimum flow in Norwegian rivers. Methods in which environmental flow is linked to forecasted inflow proved to be too difficult to integrate in current legislative practices. A particular problem is the need to properly document the flow for public inspection. The proposed method uses a gauge in an unregulated tributary to determine the was therefore proposed to The variability of the proposed environmental flow regime was also restricted to three levels which further improved the integration with current legislation.

In the current case the issue was solved by proposing the flow regime related to a gauge in an unregulated tributary, while any trials to include this into the operational practices of the hydropower companies provided unsuccessful.

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Table 1: Calculation of likely hatching (Crisp, 1981) and swim-up (Crisp, 1988) dates in Daleelva as a function of water temperature and possible spawning dates.

Spawning date		20 Oct	30 Oct	05-nov	10-nov	20-nov
Hatching date	2005-06	28 Mar.	14 Apr	24 Apr	2 May	10 May
	2006-07	20 Feb	22 Mar	02 Apr	11 Apr	22 Apr
Swim up date	2005-06	07 Jun	13 Jun	16 Jun	19 Jun	24 Jun
	2006-07	29 May	10 Jun	14 Jun	18 Jun	23 Jun

Table 2: Total annual water volume (mill m^3) for the different environmental flow releases and the total inflow to hydropower plant K2. Note that most of the environmental flow releases will run through the plant and will not be a "loss" for the power company.

Low inflow	Normal inflow	High inflow	Current regime Week 19-40: 6 m^3/s Rest of year: 1.5 m^3/s	Total inflow K2
101	119	141	107	222

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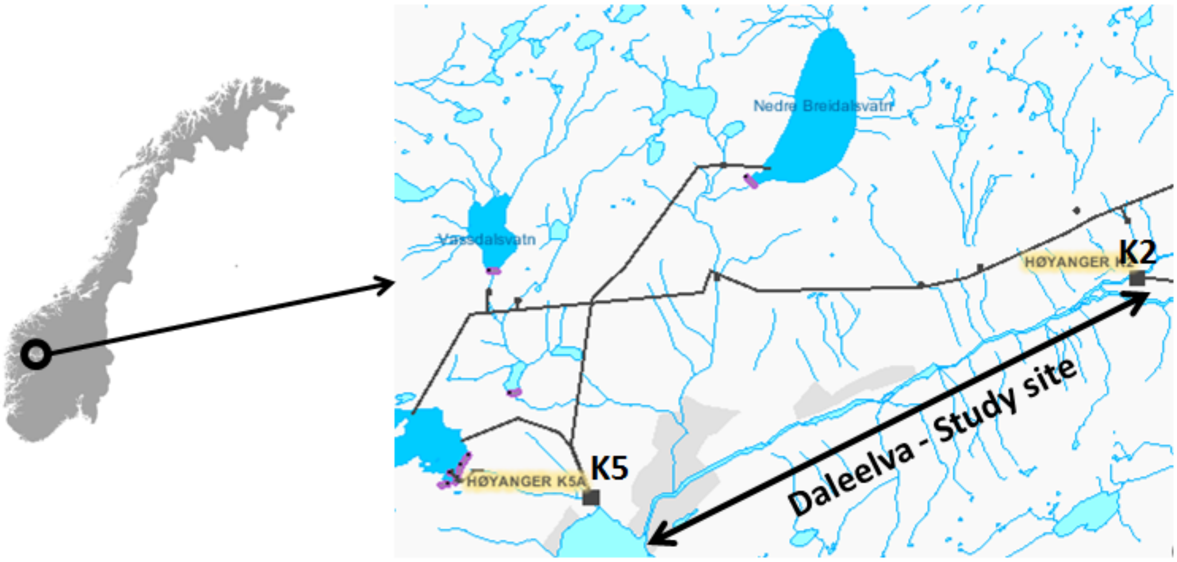

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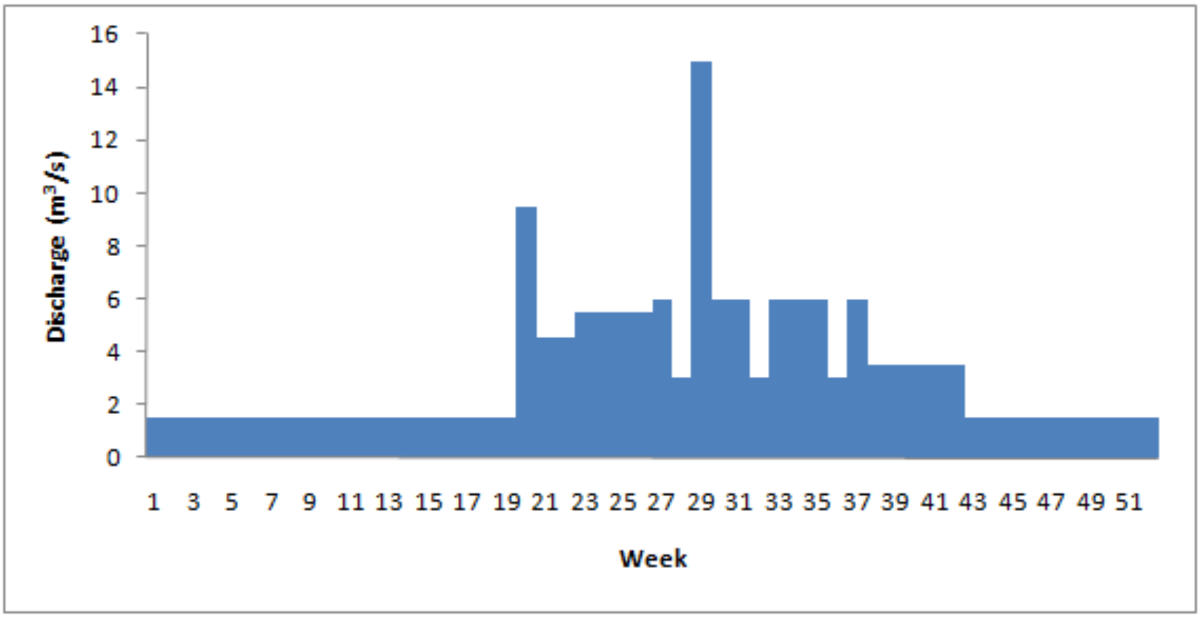
Vassdalsvatn
HØYANGER K2
K2
HØYANGER K5A
K5
Daleelva - Study site


Discharge (m^3/s)
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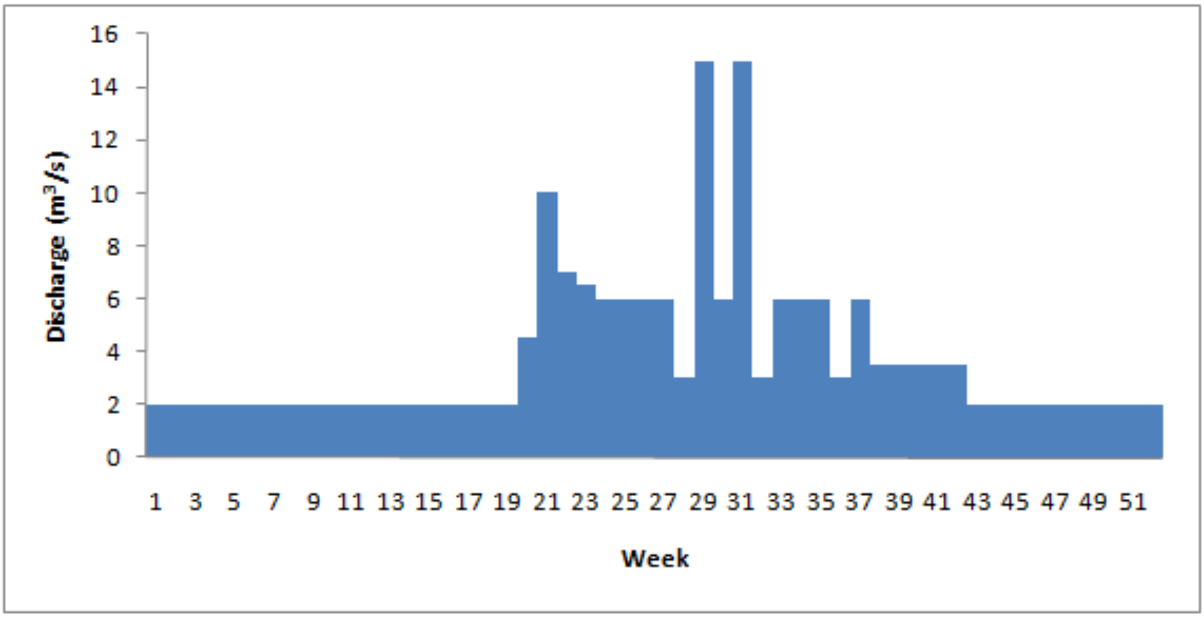
Week


Discharge (m^3/s)
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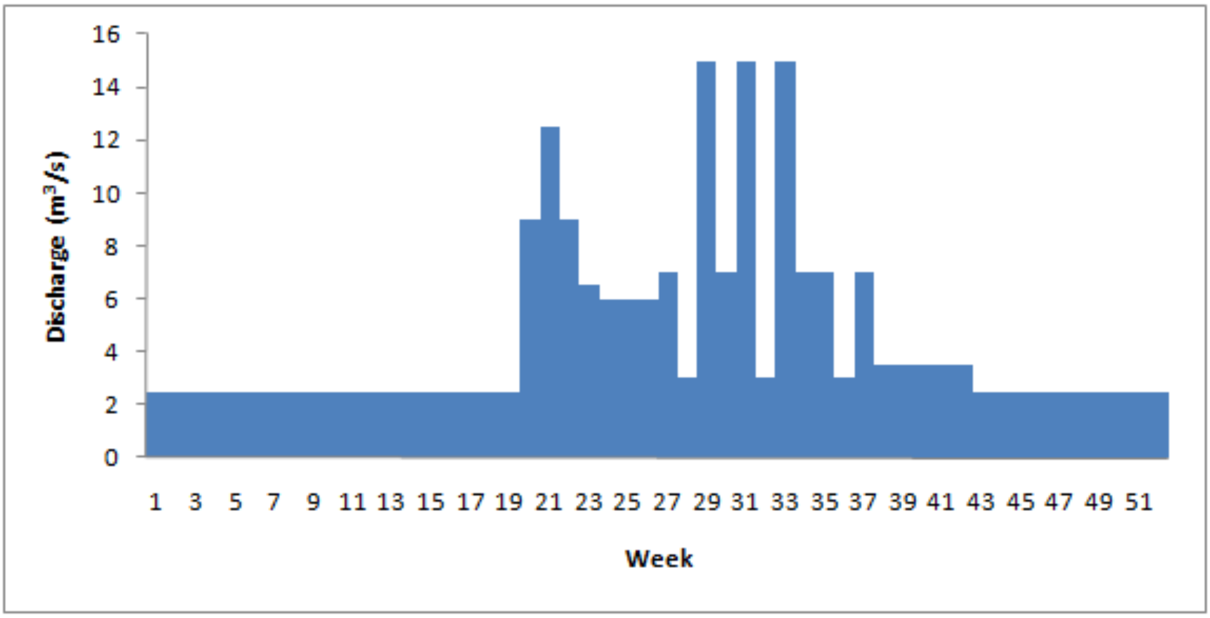
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Week