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Let it flow: Modeling ecological benefits and hydropower production impacts of banning zero-flow events in a large regulated river system

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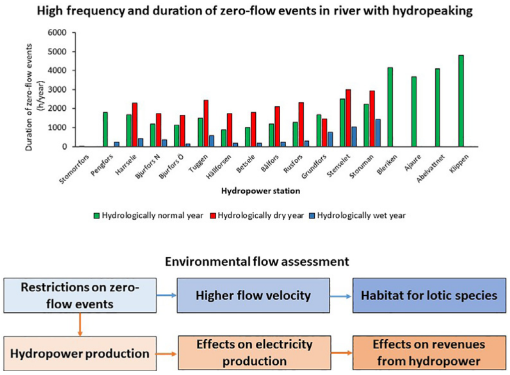
HIGHLIGHTS

- High frequency and duration of zero-flow events were documented in the regulated Ume River System.
- The hydropower stations stand still between 9—55% of the time a hydrologically normal year, resulting in periods of stagnant water.
- Introducing minimum discharge equivalent to mean annual low flow would create 240 ha of permanent lotic habitat.
- Another 107 ha of similar lotic habitat could be created after structural rehabilitation of the streambed along river reaches.
- Introducing minimum discharge in the river system would result in 0.5% loss of hydropower production annually.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydropeaking, defined as rapid and frequent changes in flow to optimize hydropower production, is an increasingly common procedure negatively affecting lotic habitats in riverine ecosystems. An important aspect of hydropeaking is zero-flow events, occurring when hydropower stations are stopped due to low energy demand or low electricity prices. We quantified the ecological benefits and consequences for hydropower production of restricting zero-flow events. The 19 major hydropower stations in the Ume River system in northern Sweden stand still with no discharge 9% to 55% of the time a hydrologically normal year, transforming lotic habitat to stagnant water. The duration of zero-flow events is exacerbated in dry years, with no discharge for 28% of the time in a typical station, to be compared with 7% in a wet year. Zero-flow events affect the behavior of fish, altering the fish community, and potentially result in low oxygen levels and low food supply to filter-feeding macroinvertebrates. We modelled the consequences of restricting zero-flow events by introducing minimum flows equaling mean annual low flow or higher for the entire Ume River catchment. The measure would result in an additional 240 ha of shallow lotic habitat with gravel to boulder streambeds having flow velocity exceeding 0.1 m/s, i.e. suitable for lotic species such as grayling *Thymallus thymallus*. In addition, the measure would enable creating another 107 ha of similar habitat after structural rehabilitation of river reaches. All measures would result in a mean loss of hydropower production of 0.5% per year for the entire river system, 98% of which would occur

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between May and October when the demand for electricity is lower. Hydropower production would also be partly moved from daytime to nighttime. As zero-flow events are common in several other river systems, restrictions on their frequency and duration could be implemented in many areas.

1. Introduction

To increase the environmental sustainability of hydropower production, future management of regulated rivers needs to balance increasing demands for renewable electricity production and legal requirements to ensure better protection of riverine ecosystems (Renöfält et al., 2010; Zhang et al., 2014; Winemiller et al., 2016; Adeva Bustos et al., 2017). Hydropower is presently the largest contributor of renewable electricity (REN21, 2019) and does not emit greenhouse gases except for under certain conditions (St. Louis et al., 2000). Hydropower also has a key function in the electricity production system of many regions in its ability to rapidly vary production output. This means that hydropower is likely to be increasingly important in the future, balancing variation in wind and solar power production to ensure that electricity demands are met and the frequency in the electricity grid remains stable (Riml et al., 2018). Hydropower can increase or decrease production within minutes by adjusting flow at hydropower stations (Sauterleute and Charmasson, 2014), a practice called hydropeaking (Moog, 1993).

Hydropeaking entails rapid shifts in flow and water levels, as well as periods of no discharge, resulting in stagnant water in impoundments and parts of reaches downstream of dams sometimes intermittently laid dry. Downstream of hydropower stations, hydropeaking results in abrupt changes between droughts and flushing flows, causing erosion, clogging of stream-bed sediment and rapid water-temperature shifts (Bruno et al., 2010; Toffolon et al., 2010; Charmasson and Zinke, 2011; Bruder et al., 2016; Tonolla et al., 2016; Moreira et al., 2019; Judes et al., 2020). Fish are at risk of being stranded or drift downstream (Holzapfel et al., 2017). Upstream of hydropower stations, hydropeaking results in fast water-level drawdowns caused by start of the turbines (Bejarano et al., 2018). Hydropeaking affects roe and juvenile fish negatively since they are sensitive to alterations in flow and water levels (Moreira et al., 2019). Brown trout *Salmo trutta* and grayling *Thymallus thymallus* can show behavioral changes related to hydropeaking caused by increased stress (Vehanen et al., 2005; Sloman et al., 2002; Flodmark et al., 2002). Further, hydropeaking causes decreased abundance and species richness of macroinvertebrates (Englund and Malmqvist, 1996). For example, Englund et al. (1997) found fewer species and lower total abundance of caddisflies (order Trichoptera) at sites with reduced flow, and the occurrence of zero-flow events stood out as the most important factor. Erosion and frequent water-level fluctuations associated with hydropeaking result in loss of cover and species richness of riparian vegetation along impounded reaches (Jansson et al., 2000; Bejarano et al., 2018). On the other hand, hydropeaking may mitigate against natural drought conditions which occur for example in Mediterranean rivers (Alexandre et al., 2016).

Effects of stagnant water (zero-flow in a normally lotic reach) are less well studied, and many regulated rivers globally have rules mandating minimum flows. However, in Sweden such rules are rare. In rivers with cascades of impoundments, habitats of lotic species are transformed into lake-like ecosystems, thus favoring generalist and lake species (Vehanen et al., 2005). Periods with stagnant water in lotic reaches will alter riverine processes such as oxygenation, sedimentation, ice-formation, thermal regimes and hyporheic exchange (Renöfält et al., 2010). With zero-flow events, species adapted to lotic environments such as drift-feeding young salmonids must frequently change habitat and feeding behavior. Kalleberg (1958) showed in experiments that instead of keeping a sheltered feeding position close to the bottom waiting for drifting insects, young brown trout and Atlantic salmon (*Salmo salar*) left their territories and began shoaling in midwater when the flow ceased. When the flow was resumed these fish had to re-establish feeding territories. Much energy is spent on shifting habitat and behavior, resulting in an increased risk of predation (Kraft, 1972). Also larger individuals are affected and spawning riverine fish are sensitive to zero-flow events with stagnant water (Grabowski and Isely, 2007) causing low oxygen levels and increasing predation from piscivores (Friedland et al., 2017).

Negative environmental effects of hydropeaking can be mitigated by structural restoration and/or by changing hydropower operational rules to implement environmental flow options (Moog, 1993; Person et al., 2014; Bruder et al., 2016). Structural measures imply diverting peak flows to parallel channels or water bodies (Brunner and Rey, 2014), building structures to retain water (Bruder et al., 2016), as well as rehabilitating degraded stream channels to increase morphological diversity. Operational measures aim to reduce the hydrological effects of hydropeaking by reducing the extremes of discharge and water levels (Niu and Insley, 2013; Person et al., 2014) to better resemble flow patterns that sustain native freshwater and estuarine ecosystems and the ecosystem services they provide (Acreman et al., 2014).

Most large river systems in northern Sweden were developed for hydropower production in the 1950-ies and 1960-ies under the water law of 1918 (SFS 1918), with little consideration of environmental consequences. In 2019, Sweden launched a national plan for relicensing of hydropower permits to meet both modern environmental requirements and provision of hydropower (Swedish Energy Agency, 2019). Almost 2000 hydropower plants will be assessed and measures to provide ecological benefits will be considered, such as minimum flow release in bypassed reaches or passages to enhance connectivity. However, a national plan for balancing the needs for hydropower production and environmental concerns (Swedish Energy Agency, 2016) recommends a maximum annual loss of hydropower production of 2.3% nationally to biodiversity improvement, compared to present conditions.

To accomplish a balance between environmental benefits and potential loss of electricity production (Saarinen et al., 2015), the water needs of ecosystems should be considered and be fully integrated in river management (Richter and Thomas, 2007). In Sweden, environmental assessments will be done in river systems where hydropower stations and dams already exist. Hence, the question to be addressed is: How much water do hydropower operators have to refrain from in order to maintain or rehabilitate riverine ecosystems (Poff et al., 2016)? Answering this requires the ability to predict and measure ecological benefits as well as losses in electricity production at the catchment scale.

Here, we model the ecological and power-production consequences of implementing simple hydropower operation rules mandating continuous flow, equivalent of at least the unregulated mean annual low flow in the Ume River catchment in northern Sweden. This environmental flow measure is intended to mitigate stress and disturbance caused by zero-flow events. Almost all lotic habitat in the main stem has been lost, since most fall height is utilized for hydroelectric production (Fig. 1 a-c). Damming and regulation have resulted in biodiversity loss (Nilsson et al., 1991; Englund and Malmqvist, 1996; Jansson et al., 2000), with notable declines in the number and abundance of populations of salmonid fish species, such as brown trout (Heggenes et al., 1996; Saltveit et al., 2001) and grayling (Andersson, 1978a, 1978b; Linløkken, 1993). Brown trout is more or less gone from the main

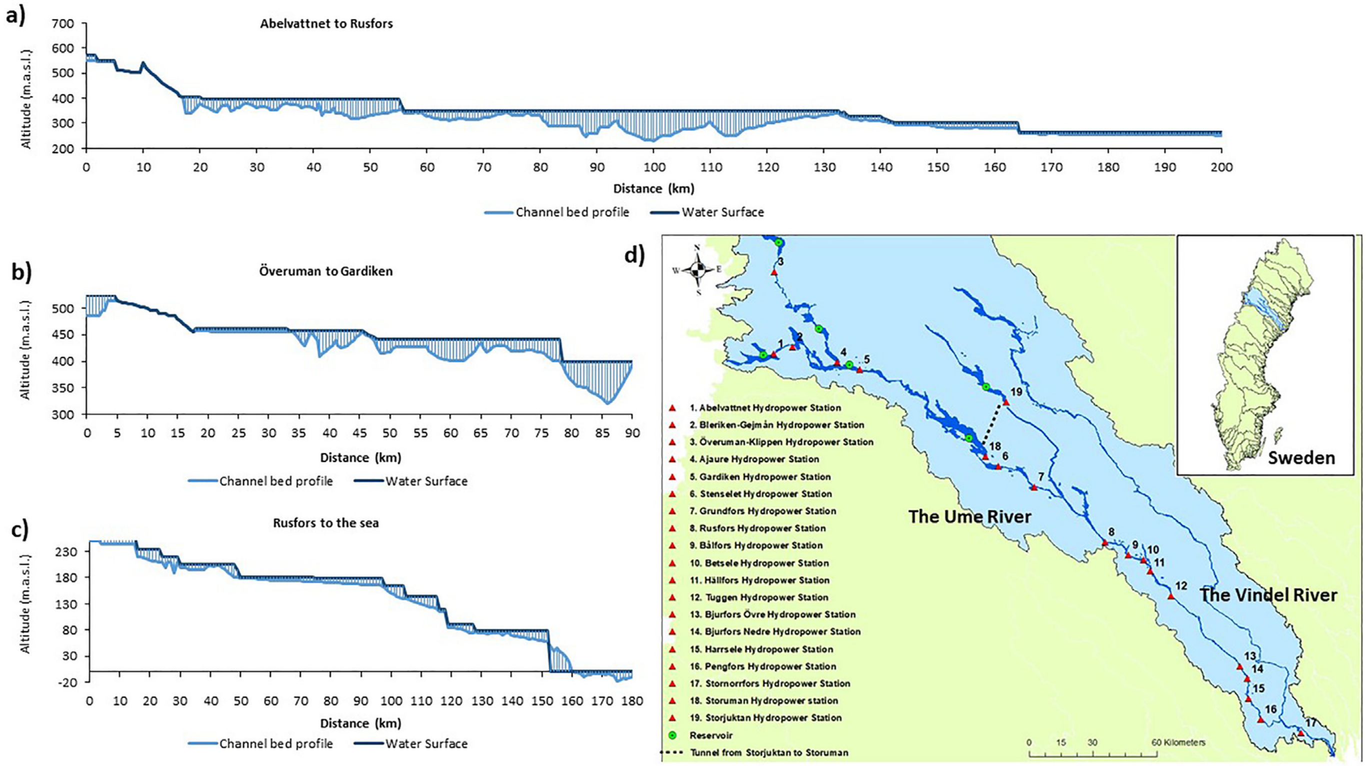

Fig. 1. Longitudinal profile of the Ume River from headwater to mouth (a-c) and map of the catchment. Channel bed (light blue) and water surface (dark blue) profiles for (a) the reach Abelvattnet to Rusfors, (b) the reach Överuman to Gardiken, (c) the reach Rusfors to the mouth of the river. (d) Map showing the Ume River cathment. Names of hydropower stations are also used for the impoundment/reservoir affected by the dam at the station throughout the paper. Inset map shows the major catchments in Sweden with the Ume River in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

stem, while there are remnant grayling populations making the latter a suitable target species for restoration efforts.

The aim of introducing minimum flow targets would be to increase the area and quality of habitat for lotic species. Continuous discharge at all power stations implies avoiding periods of stagnant water. In addition, minimum discharge requirements mean that stress and disturbance associated with starts and stops of the turbines are avoided (Greimel et al., 2018). Evaluation of the costs and benefits of environmental flow measures requires a method to quantify the predicted ecological benefits and the associated costs in terms of losses in hydropower production. In previous environmental flow assessments, some studies have assessed the projected benefits for specific species or groups of species (e.g., Esselman and Opperman, 2010; Lessard et al., 2013; Razurel et al., 2016), some studies have assessed costs in the form of reductions in hydropower production (e.g., Morrison and Stone, 2015; Nyatsanza et al., 2015) at the basin scale, but few studies have done both (but see Casas-Mulet et al., 2014; Adeva Bustos et al., 2017). The reason for the rarity of such studies is that they require large-scale inventories of habitat quality combined with knowledge of habitat requirements of target species or ecosystem functions. Finally, assessing the consequences for hydropower production requires collaboration with hydropower operators, and obtaining information about technical and legal constraints and conditions, electricity prices, flow records, and water allocation strategies among reservoirs and hydropower stations.

Here, we (1) quantify the frequency and duration of zero-flow events in the Ume River catchment, (2) quantify the projected environmental benefits of introducing requirements for minimum discharge equivalent of mean annual low discharge to improve habitat quality and area for riverine species adapted to lotic habitats, and (3) analyze effects of implementing the measure on hydropower production in the catchment. To the best of our knowledge, this is the first study to assess the frequency and magnitude of zero-flow events in a regulated catchment, and one of few to assess both the ecological benefits and impact on hydropower production of implementing an environmental flow measure in a large catchment.

2. Study area

The Ume River runs from the Scandinavian mountain range and empties in the Bothnian Bay (Fig. 1). The river is 467 km long, with a catchment area of 26,800 km^2. The Vindel River is the largest tributary, and remains free-flowing, but empties into the Stornorrfors impoundment, the last impoundment in the main stem before the sea. The mean annual discharge of the Ume River is 242 m^3/s above the confluence with the Vindel River. The river system is regulated by 19 hydropower stations, six of which are associated with large storage reservoirs and the remaining 13 with run-of-river impoundments (Fig. 1). The mean annual electric production in the Ume River is 7.7 TWh (1962–2008).

All hydrological analyses were done for all hydropower stations in the catchment, but will be exemplified by three stations: (1) Storuman, a reservoir with storage function, (2) Tuggen, representative of the run-of-river impoundments in the river, and (3) Stornorrfors, the run-of-river impoundment closest to the mouth, having limited degrees of freedom to regulate as it receives the flow from the free-flowing Vindel River (Fig. 2a-f). Comparisons of regulated flow conditions with modelled unregulated flows using mean weekly flow data for the years 1962–2008 demonstrate large changes as a result of regulation (Fig. 2a-c). The Storuman storage reservoir is filled during snowmelt in spring/early summer, with water being released the following fall and winter, resulting in altered timing and magnitude of water-level variation compared to unregulated conditions (Fig. 2a, d). In the run-of-river impoundments (Fig. 2b-c, e-f), seasonal flow variation is replaced by daily and weekly variation in discharge and water levels as a result of hydropeaking to meet variation in electricity demand,

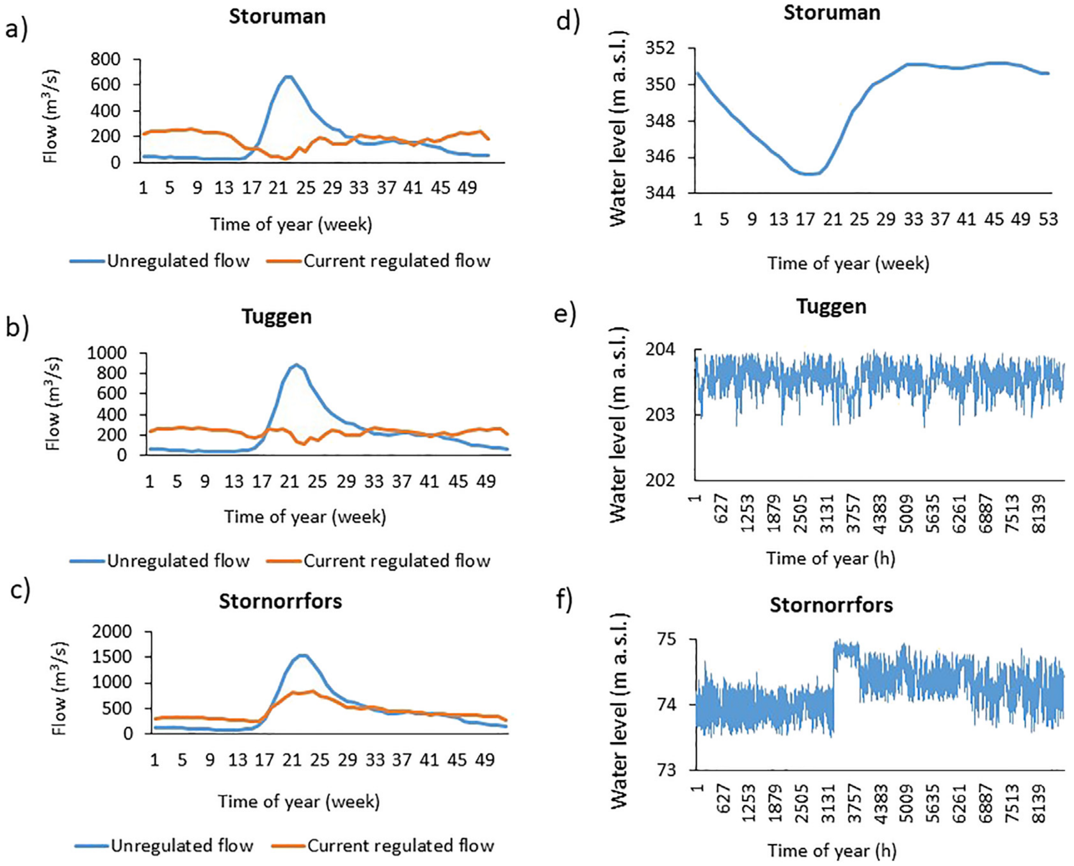

Fig. 2. Hydrographs of (a) the Storuman hydropower station situated at a storage reservoir, (b) the Tuggen hydropower station functioning as a run-of-river station with hydropeaking, (c) the Stornorrfors hydropower station functioning as a run-of-river station with limited possibilities for hydropeaking. Data are means from 1962 to 2008. (d) Weekly water-level data from the Storuman storage reservoir. (e) Water-level variation in the Tuggen run-of-river impoundment using hourly data. (f) Water-level variation in the Stornorrfors impoundment using hourly data. All water-level data are from the hydrologically normal year 2010.

although a spring-flood peak remains in Stornorrfors as a result of discharge from the free-flowing Vindel River. Water levels and flows are decoupled in all run-of-river impoundments as a consequence of hydropeaking being coordinated among the consecutive impoundments. This entails that discharge can increase while water levels decrease and vice versa. Basic technical and operational data about the hydropower stations were used to determine minimum discharge and to set hydropower operational rules (HOR) used in the flow scenarios. Turbine capacity is the flow interval used to produce electricity, ranging from the lowest possible flow through turbines without risking turbine damage (Q_{min}) to the maximum capacity (Q_{max}).

3. Methods

3.1. Calculating the frequency and duration of zero-flow events

Hourly flow data (m^3/s) was obtained from the hydropower operators to calculate the number of zero-flow events, when they occurred, and their duration, for a hydrological wet year (2012), a normal year (2010) and a dry year (2003), with hourly data as the highest resolution in time. Calculations were made for all hydropower stations in the Ume River system. In addition, we analyzed water-level changes with hourly resolution for the corresponding years.

3.2. New hydropower operational rules to avoid zero-flow events

We modelled the ecological benefits and consequences of introducing new hydropower operational rules (Person et al., 2014) mandating minimum flow at all hydropower stations below the storage reservoir Storuman to avoid extended periods of zero-flow (Table 1). We decided that the minimum discharge passing each hydropower station either through turbines or the spill gates should be equal to the unregulated mean annual low flow based on run-off 1999–2012 (data from the Swedish Meteorological and Hydrological Institute) or alternatively, the minimum flow that can be released through turbines (Q_{min}). The aim was that discharge should primarily go through the turbines, thus minimizing hydropower production losses. When the unregulated mean annual low flow was lower than Q_{min} of the turbines, the minimum discharge was increased to match Q_{min} to avoid spill. If Q_{min} substantially exceeded the mean annual low flow, water was allocated to spill gates instead of turbines. However, in cases where there were bypassed reaches, i.e. dry river beds downstream of dams, or in cases where we identified a potential for building fishways, spill water was allocated to these.

3.3. Assessment of the expected environmental benefits

The most important ecological benefits of the proposed rules would be to (1) to increase water flow velocity and avoid stagnant water in the impoundments and downstream of hydropower stations, (2) reducing the adjustable flow interval, thus decreasing the potential for hydropeaking intensity, (3) reduce the frequency of abrupt starts and stops in flow causing erosion and stress to fish and aquatic invertebrates. All assessments of environmental benefits and loss of electricity production were done at the catchment scale. The potential environmental benefits of introducing minimum flows were assessed in three ways:

1. First, we modelled the expected mean water flow velocity that would result from the mandated minimum discharge at varying distances downstream of hydropower stations (Table 2).

Table 1
Data on minimum flows for hydropower stations in the Ume River system. The minimum flow through turbines is the minimum flow that will not risk damaging the turbines (Q_{min}).

Hydropower station	Type of reservoir[a] and turbine[b]	Minimum flow (Q_{min}) through turbines (m^3/s)	Mean annual unregulated low flow (m^3/s)	Minimum discharge used as a hydropower operational rule (m^3/s)	Hydropeaking interval before measure (m^3/s)	Reduction in hydropeaking interval (%)	Flow path of minimum discharge at the hydro-power station
Abelvattnet	S-K	n/a	1.6	No	0–24	n/a	n/a
Bleriken-Gejmån	S-F	21	1.7	No	0–29	n/a	n/a
Överuman-Klippen	S-K	20	3.8	No	0–50	n/a	n/a
Gardiken	S-F	45	9.3	No	0–170	n/a	n/a
Ajaure	S-K	30	13.3	No	0–170	n/a	n/a
Storjuktan	S-F	n/a	5.7	No	0–50	n/a	n/a
Storuman	S-K	50	21.4	50	0–330	15	Turbines
Stensele	R-K	90	23.6	24	0–310	8	Spill gates[c]
Grundfors	R-K	40	24.6	40	0–330	12	Spill gates[c]
Rusfors	R-F	120	37.5	37	0–450	8	Spill gates[c]
Bålforsen	R-K	50	40.5	50	0–305	16	Turbines
Betsele	R-K	50	40.7	50	0–320	16	Turbines
Hällforsen	R-K	50	41.9	50	0–320	16	Turbines
Tuggen	R-K	55	39.6	55	0–480	11	Turbines
Bjurfors Övre	R-K	50	44.1	50	0–450	11	Turbines
Bjurfors Nedre	R-K	50	44.2	50	0–450	11	Turbines
Harrsele	R-K	85	45.3	45	0–450	10	Spill gates[c]
Pengfors	R-K	30	42.3	50	0–450	11	Turbines
Stornorrfors	R-K	80	80.0	72	0–1045	7	Turbines

[a] S = Storage reservoir, R = run-of-river impoundment.
[b] K = Kaplan turbine, F = Francis turbine.
[c] Through spill gates when the turbines are not in operation.

2. Second, we assessed the channel area with channel-bed substrate consisting of sand, gravel, pebbles, cobbles or boulders estimated to have flow velocities exceeding 0.1 m/s after introducing minimum discharge requirements. These habitat conditions were assumed to benefit lotic fish such as grayling and macroinvertebrate communities. Estimation of areas was based on surveys of water depths (<1.5 m) and bottom substrates consisting of sand, gravel and pebbles without accumulation of silt. Note that since discharge and flow are decoupled, we can assume that flow velocity will increase without any concomitant changes in depth.
3. Third, we estimated the area of new potential high-velocity habitat that could be gained by structural modification of outlet channels downstream hydropower stations. These areas would have a variation of water depths and flow velocities creating a mosaic of micro and *meso* habitats corresponding to the demands of grayling at different life stages.

3.4. Background to the choice of grayling as a target species for restoration

Large regulated rivers in northern Sweden can harbor sustainable grayling populations with reproduction in outlet channels and other reaches with high flow velocity provided important structural components in the channels are still remaining (Persson and Isaksson, 2015; Stridsman, County board of Norrbotten, 2017, personal communication). This implies structural restoration of reaches that have the potential of becoming suitable grayling habitat. We assessed potential areas suitable for different life stages of grayling based on hydrology, channel substrate composition and depth. Habitat preferences for grayling vary

Table 2
River cross sections where flow velocity calculations were performed. Habitat was defined according to flow velocity at minimum low flow into slow, medium and fast.

Section number	Reach (upstream and downstream hydropower station)	Distance from upstream hydropower station (km)	The cross-sectional area of the ground column perpendicular to the flow (m^2)	Minimum annual low flow(m^3/s)	Estimated flow velocity (m/s)	Habitat type based on flow velocity[a]
1, 2	Storuman/Stensele	6.0	300	21.4	0.07	Medium
3	Stensele/Grundfors	2.0	290	23.6	0.08	Medium
4	Stensele/Grundfors	7.0	275	23.6	0.09	Medium
5	Stensele/Grundfors	15.0	5225	23.6	0.01	Slow
6	Grundfors/Rusfors	4.0	210	24.6	0.12	Fast
7	Grundfors/Rusfors	8.0	1005	24.6	0.02	Slow
8	Rusfors/Bålforsen	1.5	326	37.5	0.11	Fast
9	Rusfors/Bålforsen	9.0	795	37.5	0.05	Medium
10	Bålforsen/Betsele	2.5	810	40.5	0.05	Medium
11	Bålforsen/Betsele	5.0	2700	40.5	0.01	Slow
12	Betsele/Hällforsen	2.5	203	40.7	0.20	Fast
13	Betsele/Hällforsen	5.0	1356	40.7	0.03	Slow
14	Hällforsen/Tuggen	3.0	1100	44.0	0.04	Slow
15	Tuggen/Bjurfors Ö	5.0	421	39.6	0.09	Medium
16	Tuggen/Bjurfors Ö	14.0	820	39.6	0.05	Medium
17	Bjurfors Ö/Bjurfors N	0.5	320	44.1	0.14	Fast
18	Bjurfors Ö/Bjurfors N	4.0	2700	44.1	0.02	Slow
19	Bjurfors N/Harrsele	1.0	160	44.2	0.28	Fast
20	Bjurfors N/Harrsele	3.0	720	44.2	0.06	Medium
21	Harrsele/Pengfors	2.0	530	45.3	0.08	Medium
22	Harrsele/Pengfors	5.0	1260	45.3	0.03	Slow
23	Pengfors/Stornorrfors	7.0	215	42.3	0.20	Fast
24	Stornorrfors/Sea	2.0	810	72.3	0.09	Medium

[a] Fast = mean velocity > 0.1 m/s, medium = mean velocity < 0.1 to >0.05 m/s, slow = mean velocity < 0.05 m/s.

depending on season, life stage, water depth, bottom substrate and water flow velocity (Gonczi, 1985; Crisp, 1996; Heggenes et al., 1996; Nykänen and Huusko, 2003; Nykänen, 2004; Nykänen et al., 2004a, 2004b). For example, during spring, grayling larvae (17–21 mm long) prefer a water depth of 10–30 cm, with sand as bottom substrate and a water velocity < 0.1 m/s. In contrast, spawning grayling prefers a water depth of 30–50 cm with gravel and a water velocity of 0.1–0.5 m/s.

3.5. Flow velocity projections

To assess the projected minimum flow velocities at varying distances from hydropower stations by implementing restrictions against zero-flow events, we made projections of expected flow velocity at 24 sections along the Ume River assuming minimum discharge requirements had been implemented. Flow velocity (m/s) was calculated for the mean annual low discharge below each power station (Table 2). When the turbines are started and stopped, swells occur that may last up to several hours. The swells may give rise to water-level differences of several centimeters and these differences are often many times greater than the friction losses that are the starting point for flow calculations with Manning's equation. For this reason, we calculated flow velocity using the eq. $V = Q / A$, where velocity V is a function of mean annual low flow Q (m^3/s) divided by the cross-sectional area A of the ground column perpendicular to the flow (m^2). For each section, A was calculated in ArcGIS Version 10 (ESRI 2011) with depth data obtained from the hydropower company Vattenfall AB. Median water levels were used in the calculations. We used flows for 2010, a hydrologically normal year, and calculated flow velocities at each section using the above equation. Based on the flow velocity measurements, we classified each section as being characterized by fast (mean $>$ 0.1 m/s), medium (mean 0.05–0.1 m/s) and slow (mean < 0.05) flow velocity. The aim was to relate the expected flow velocities at minimum flow to habitat conditions for lotic organisms, with specific focus on habitat demands of grayling (see Section 3.4).

3.6. Potential gain in area of high flow velocity in shallow reaches of impoundments

The impoundments were inventoried by boat by two persons visually inspecting bottom conditions during the summers of 2012–2014. Channel areas being less than 1.5 m deep with flow velocities estimated to exceed 0.1 m/s at minimum flow, having coarser bottom substrates (sand, gravel, pebbles, cobbles or boulders) and lacking deposits of silt and finer sediment, were quantified in all run-of-river impoundments, and the summed area per impoundment is displayed in Fig. 3. These areas were deemed to become suitable for organisms adapted to lotic habitat, such as grayling, if rules for minimum discharge would be implemented.

3.7. New habitat area downstream hydropower plant in outlet channels

Outlet channels immediately downstream of hydropower stations represent one of the few remaining types of river reaches with high flow velocity in the regulated Ume River (Fig. 3a-c), although this is true only when turbines are producing electricity. Outlet channels are often deep (3–10 m) and narrow with dredged or blasted beds, making conditions unsuitable to most aquatic macro-species. However, outlet channels where structural features such as boulders remain in the channel bed can harbor self-sustainable populations of grayling (Persson and Isaksson, 2015). We assume that with structural modification of the channel, these reaches could serve as habitat for lotic species, i.e. riverine species adapted to habitat with high flow velocities. Since any measures in the outlet channel that would lower its capacity for discharging water from the power station would affect hydropower production and

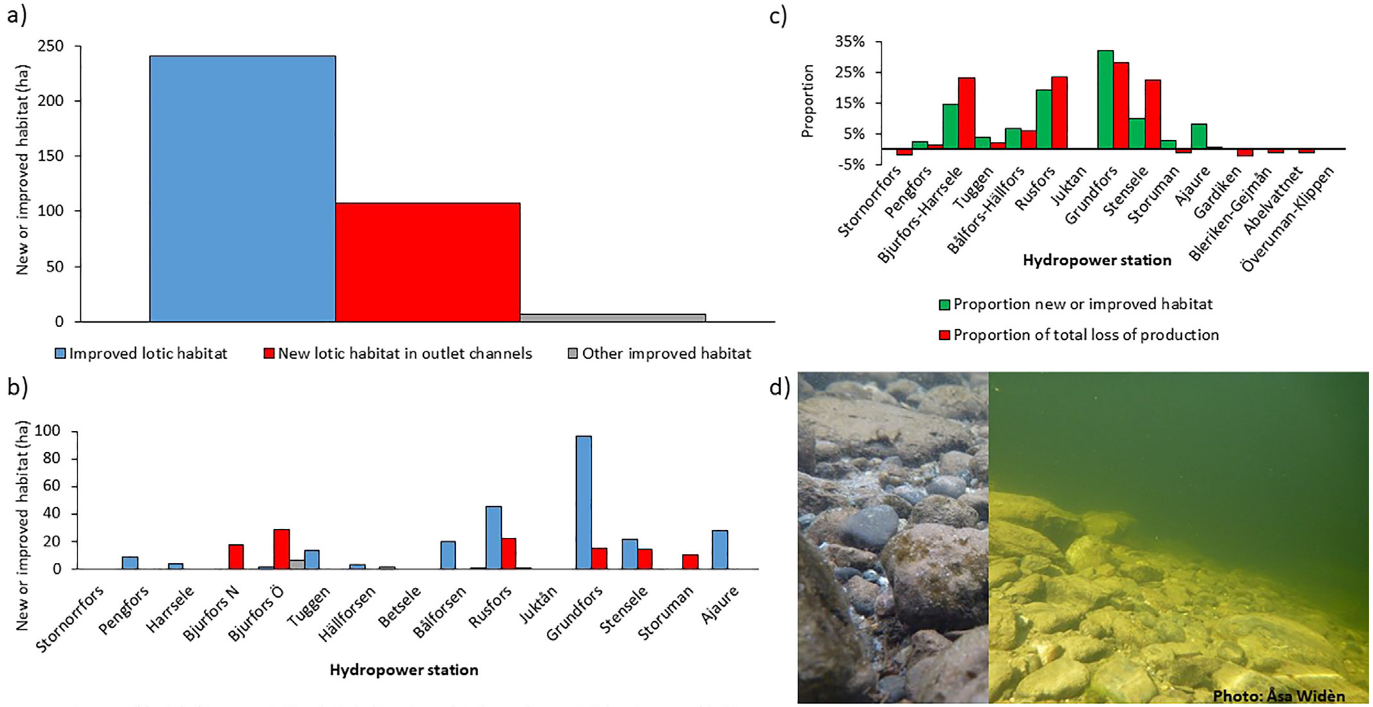

Fig. 3. Projected gains in the area and distribution of lotic habitat, defined as shallow areas with gravel, pebble, cobble or boulder channel bed substrate with flow velocity exceeding 0.1 m/s, created by introducing requirements on minimum discharge. (a) Estimated gain in area of improved and new shallow lotic habitat along the Ume River after introducing minimum discharge. (b) Same as in (a) but for each impoundment/reservoir. Gardiken, Bleriken-Gejmån, Abelvattnet and Överuman-Klippen lacked environmental benefits. (c) Estimated proportional gain in area of lotic habitat per impoundment (green bars) and proportional of annual change in electricity production per hydropower station (red bars). Bjurfors Ö, Bjurfors N and Harrsele are merged, as are Bålforsen, Betsele and Hällforsen. (d) Photos of shallow bottom substrate with pebbles and cobbles deemed as potential lotic habitat. Left: Stenselet impoundment. Right: Tuggen impoundment. Photographs: Åsa Widén. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

safety negatively, restoration work was assumed to occur by widening the channel. At all outlet channels, we assumed the construction of an "ecological shelf", i.e. a widening of the channel with depths and velocity accommodating habitat requirements at different life stages of grayling (Supplementary information, Fig. S1). This corresponds to water depths from 10 to 400 cm and flow velocities between <0.10 and 1.1 m/s (Gonczi, 1985; Nykänen and Huusko, 2003; Nykänen, 2004; Nykänen et al., 2004a, 2004b). The shallow areas would also have boulders, contributing to increased roughness and heterogeneity of hydraulic conditions.

3.8. Effects on hydropower production

We calculated the estimated loss of hydropower production at all power stations using the software ProdRisk (SINTEF, Trondheim, Norway). We used weekly flow data for the years 1962–2007, and electricity price prognoses for the period 2014–2024 by permission of Vattenfall AB. The aim of the simulations was to mimic how hydropower production is planned with the aim of maximizing hydropower production and revenues by running the hydropower system as presently with the addition of our proposed new environmental flow requirements, implemented as additional hydropower operational rules in the model runs.

ProdRisk is developed by SINTEF, Norway (www.sintef.no) and in operational use by many of the largest hydropower companies on the Nordic power market. The program was run in a market mode with energy prices given exogenously. The simulations were performed in collaboration with Vattenfall AB. The output of the analyses included estimates of electricity production, described as differences in production between the current and environmental flow modes of operation per week, water storage and flow for each of the 46 years used in the scenarios for each hydropower station in the river. To validate the model, and to ensure that our hydrological data was correct, we ran the models with current hydropower operational rules and adjusted for possible deviations compared to logged regulated flow until the model results were close to observed (mean deviation per year 0.2 GWh, equivalent to a 2.9×10^{-6}%). In the analyses, we used five price ranges, reflecting differences in the price paid for electricity depending on demand and availability on the NordPool exchange market, encompassing the Nordic and Baltic countries. The five price ranges are approximations of actual prices, and roughly correspond to two ranges having the highest prices and mainly occurring during daytime (generally about 20% higher than during night), two ranges occurring during night (having the lowest prices) and one range (10 h per week) which can occur whenever the prices are high during a week. The model runs in ProdRisk are based on equations for the production at each hydropower station based on e.g., gross head, the gravitational constant, turbine efficiency, and flow per time unit. Algorithms are then used to make decisions on where and when to allocate flow to hydropower stations in the river system to maximize hydropower production and revenues. ProdRisk finds this solution using stochastic dual dynamic programming. This means combining system simulation and strategy computation to find an optimal strategy. This is achieved by dividing the overall problem into smaller optimization problems, which are solved by using linear programming and coordinated by using the principle of Benders decomposition. The models were run with the ProdRisk license owned by Vattenfall AB.

We took no account of effects on balancing and regulating power in the simulations, i.e. the fact that production has to balance demand at each moment to keep the frequency in the electric grid stable (at 50 Hz). To analyze the extent to which the timing of hydropower production would be changed, and when potential losses would occur, we compared differences in the amount of hydropower produced at different times of the year and different times of the day between the current and environmental flow modes of operation.

4. Results

4.1. Frequency and duration of zero-flow events

There were long durations of zero-flow events in almost all the hydropower stations, especially during dry years (Fig. 4a), with individual zero-flow events lasting days or weeks. On average 84% of the zero-flow events occurred during night (between 10.00 p.m. and 06.00 a.m.). The mean duration of zero-flow events during a year with average discharge ("normal year") was 2047 h or 23% of the time, varying from almost no zero-flow events at Stornorrfors (9 h) to 10% of the time (1014 h) in Hällforsen, to 29% of the time (2518 h) in Stensele and to 48% of the time (4163 h) in Bleriken-Gejmån (Fig. 3). Klippen had the longest duration of zero-flows (4797 h or 55% of the time a normal year), but has a mandated minimum discharge of 5.5% of mean annual discharge (mean 0.94 m^3/s) released into the bypassed 6 km long channel, to be compared with the suggested 3.8 m^3/s (Table 1).

The variation in the frequency and duration of zero-flow events between dry and wet years was large (Fig. 4a). For example, the Tuggen power station stood still with no discharge 28% of the time (2442 h) during the dry year of 2003, to be compared with only 7% of the time (573 h) during the wet year of 2012. Stornorrfors was an outlier, as zero-flow events were infrequent and of short total duration (Fig. 4) because the free-flowing Vindel River empties into the impoundment thus hindering zero-flow events during a hydrologically normal year.

The frequency and timing of zero-flow events differed between storage reservoirs (mean duration 47.8% of a hydrologically normal year) and run-of-river impoundments (mean duration 17.2% of a hydrologically normal year). In Fig. 4b, the storage reservoirs are represented by Storuman, having few but long-lasting zero-flow events. For example, in 2010, one event in May lasted 563 h and one in June lasted 168 h. During the remaining year, zero-flow events were of short duration. Storuman had 168 zero-flow events during 2010, 103 in 2012 and 233 during 2003. In contrast, Tuggen, representing a run-of-river impoundment, had long-lasting zero-flow events occurring all months, except for January (Fig. 3c). The Tuggen hydropower station had 215 zero-flow events in 2010, and 104 and 295 events during the years of 2012 and 2003, respectively.

Flow duration curves for Storuman and Tuggen show that zero-flow events lasted between 32% of the year (2003, a dry year) to 15% (2012, a wet year) in Storuman, compared to between 26% (dry year) and 6% (wet year) in Tuggen. The flow duration curves show that the discharge at Storuman was close to the maximum turbine capacity for longer time spans compared to Tuggen (Fig. 4d-e).

4.2. Effects of introducing minimum discharge on flow velocity

Introducing rules mandating minimum flow discharge to eliminate zero-flow events would increase minimum flow velocity in the river, according to our projections. Since the turbines never would be turned off, stagnant water is avoided. Comparing the flow velocity at the suggested minimum discharge with calculated values of flow velocity at the actual discharge during 2010, we found large differences between reaches. Six reaches were projected to be fast flowing (velocity > 0.1 m/s), ten were projected to have medium velocity (velocity 0.05 to 0.09 m/s) and six were slow flowing (velocity < 0.05 m/s; Table 2). For river Sections 1 and 2, situated below the Storuman hydropower station, introducing a mandated minimum discharge would result in avoiding 2929 h of stagnant water conditions, occurring mainly from March to November (Fig. 5a). Introducing minimum discharge corresponding to 21.4 m^3/s (Table 2) would imply a minimum flow velocity > 0.7 m/s (Fig. 5a). In the two sections below the Tuggen station (Fig. 5b,c), flow velocity was estimated to vary between 0 and 1.3 m/s (Section 15, Fig. 5b,e), and between 0 and 0.6 m/s (Section 16, Fig. 5c,e, respectively). Here, a minimum discharge corresponding to 50 m^3/s would result in a

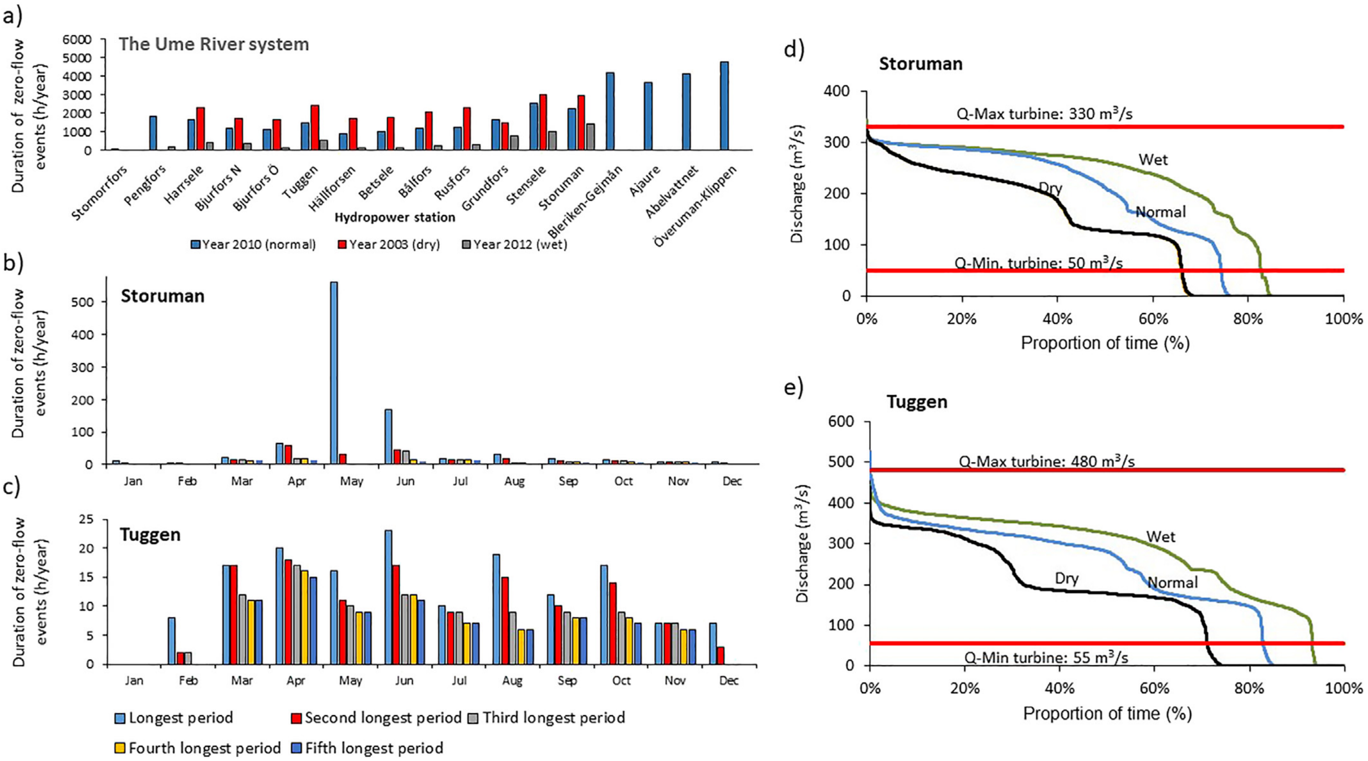

Fig. 4. (a) Duration of zero flow events during 2010 (a hydrologically normal year), 2003 (a dry year) and 2012 (a wet year) for all hydropower stations in the Ume River system except for Gardiken. Pengfors lacked reported data for the year 2010 and 2003. Bleriken-Gejmån, Ajaure, Abelvattnet and Överuman-Klippen lacked data for the year 2010 and 2003. (b) Storuman hydropower station and storage reservoir. Periods with zero-flow presented per month for 2010. (c) Tuggen hydropower station with a run-of-river impoundment. Periods with zero-flow presented per month for 2010. (d) Storuman hydropower station. Flow duration curve for the hydrologically normal year 2010, the wet year 2012 and the dry year 2003. (e) Tuggen hydropower station. Flow duration curve for the hydrologically normal year 2010, the wet year 2012 and the dry year 2003.

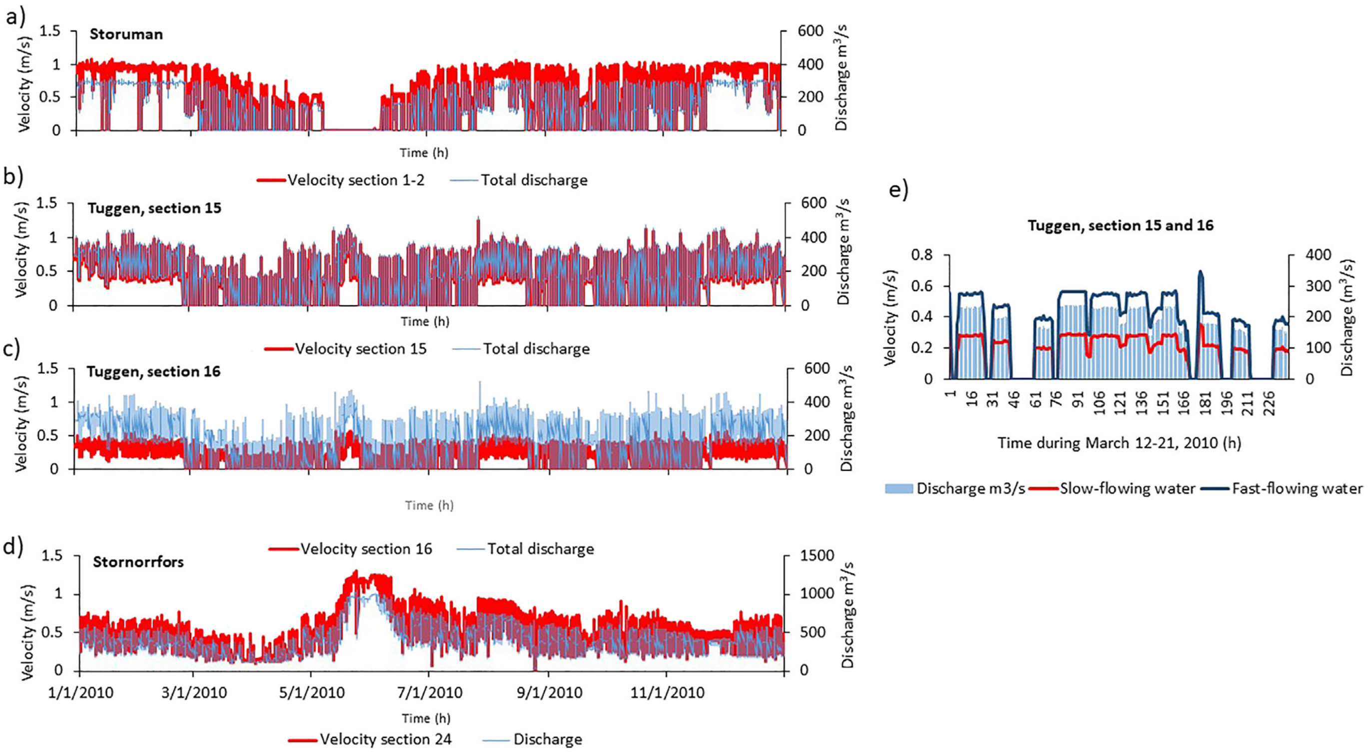

Fig. 5. Variation in water flow velocity at a number of river sections using the actual variation in discharge for 2010 compared with estimated water flow velocity at minimum discharge, based on hourly logged data. (a). Sections 1 and, 6 km downstream of Storuman hydropower station in the Stensele impoundment receiving flow from Storuman. (b) Section 15, 5 km downstream the Tuggen hydropower station in the Bjurfors Övre impoundment. (c) Section 16, 14 km downstream Tuggen hydropower station in the Bjurfors Övre impoundment receiving flow from Tuggen. (d) Sections in reach 24 receiving flow from the Stornorrfors hydropower station. (e) Water flow velocity at Tuggen during March 12 to 21, 2010. The fast-flowing section 15 is situated 5 km downstream of the power station. The slow flowing section 16 is situated 15 km downstream the power station where the channel is wider.

minimum water flow velocity > 0.1 m/s. For the reach below Stornorrfors hydropower station, implementing a rule mandating minimum discharge of 50 m^3/s would not give any effect on flow velocity, since flow exceeds this magnitude almost all the time. Flow velocity downstream of Stornorrfors was estimated to vary between 1.3 m/s and 0.1 m/s (Fig. 5d).

4.3. Projections of increases in the area and quality of lotic habitat created by minimum discharge requirements

The total area of shallow lotic habitat (having flow velocity exceeding the minimum limit of 0.1 m^3/s at all times) that would benefit from introducing a mandated minimum discharge was estimated to be 372 ha, which equals 15% of the wetted area of the run-of-river impoundments downstream of Storuman. Of this area, 240 ha consists of shallow areas with sand, gravel, pebble, cobble or boulder substrate (Fig. 3a-d), suitable for lotic species. In addition, introduction of a minimum discharge would allow creation of 107 ha of new lotic habitat in outlet channels. This can be achieved after widening (“ecological shelves”) and restoring the reaches to create shallow areas, with coarser bottom substrates suitable to lotic species, such as grayling. The area of improved and newly created lotic habitat was unequally distributed along the river with peaks in the Grundfors and Rusfors impoundments (Fig. 3b), and covaried with the estimated loss of electricity production ($r = 0.91$, $P < 0.0001$, $n = 15$, Spearman rank correlation test, assuming power stations were random samples).

4.4. Consequences for electricity production

Introducing restrictions on zero-flow events would result in a mean loss in electricity production of 39 GWh per year for the Ume River, equivalent to 0.5% of current production calculated for the period 1962–2008. This would amount to 15 MSEK per year in lost revenues, or equivalent to 0.7% of current values (Table 3). However, hydropower production as well as the predicted production loss due to flow restrictions vary among years (Fig. 6a-b). Modelled hydropower production during 1962–2007 varied between 5.4 TWh (in 1970) and 10.1 TWh (in 2001) (Fig. 6a). Effects on electricity production varied from a loss of 0.11 TWh (1.6%, 2006), to a gain of 0.025 TWh (0.3%, 1975) (Fig. 6b).

Zero-flow events generally start in February, and with rules set for continuous discharge, electricity production in the model is forced to increase during such periods (net gain in February, April and December (Table 3). In addition, minimum discharge would lead to increasing production during night (low prices) at the expense of daytime production (high demand and prices). The night and weekend production thus increased at the expense of the better-paid daytime production (Fig. 5c). Having continuous flow through power stations would also affect when during the year electricity is produced. Losses in electricity production occurred primarily from May to October (on average 98% of the loss or 38.5 GWh), whereas the remaining part of the year (January to March and November to December) only accounted for 2% of the loss or 0.5 GWh (Table 3). Electricity production losses occurred at all hydropower stations except five, which instead increased net production (Table 3). All five of these stations except Stornorrfors were situated at storage reservoirs. All run-of-river impoundments except Stornorrfors lost in annual electricity production, but gained in production from December to June. Most losses occurred during the summer season (Table 3). Loss of electricity production in Stensele, Grundfors and Rusfors was caused by spill since the minimum capacity of turbines (Q_{min}) was too large in relation to the mean annual low flow used as a benchmark for setting minimum discharge. This spill water could potentially serve other environmental mitigation measures, such as being released in fishways or bypassed river reaches. The losses in Harrsele and Tuggen were mainly caused by loss of turbine efficiency due to production occurring at lower efficiency of the turbines.

5. Discussion

Our study shows that there are opportunities to improve ecosystem health in the Ume River with mitigation measures that entail only small losses in electricity production. This is in line with the argument by Poff et al. (2016), that “a lot can be done with little water”. We would like to add “and with small losses in electricity production”, given that river management is analyzed from both ecological and engineering

Table 3
Change in electricity of production (GWh) per month and hydropower station caused by introducing demands on minimum discharge at each hydropower station. Blue color indicates net loss, light green indicates no impact and green color net gain in electricity production. Columns to the far right show change in annual revenue from electricity production and the proportional change in annual electricity production.

	January	February	March	April	May	June	July	August	September	October	November	December	Annual	Annual change in revenue (MSEK)	Pro-portional change in production (%)
Abelvattnet	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.1	0.1	0.0	0.0	0.0	**0.0**	**0.0**	**-0.2**
Gejmån	-0.8	-0.7	-0.8	0.1	0.3	-0.2	-0.7	0.8	1.0	0.7	0.3	0.5	**0.5**	**0.0**	**0.1**
Överuman-Klippen	0.4	0.2	-0.1	0.0	0.2	0.1	0.0	-0.3	0.2	0.0	0.0	0.3	**-0.2**	**0.0**	**0.0**
Ajaure	0.3	0.3	0.0	-0.2	-0.2	0.0	-0.2	-0.2	0.2	-0.2	0.2	-0.3	**-0.2**	**0.0**	**0.0**
Gardiken	-0.5	0.5	0.3	0.2	0.3	0.0	-0.3	0.0	0.0	0.0	0.3	0.0	**0.8**	**0.1**	**0.1**
Juktan	0.2	0.0	0.1	0.4	0.1	0.3	-0.3	-0.2	0.0	-0.7	0.0	0.0	**-0.1**	**0.0**	**0.1**
Storuman	0.2	0.3	0.2	0.5	0.2	0.2	0.2	-0.8	-0.3	-0.2	0.0	0.2	**0.5**	**0.1**	**0.1**
Stensele	-0.2	0.0	-0.3	-0.5	-2.2	-1.4	-1.2	-1.0	-0.8	-0.8	-0.3	0.0	**-8.8**	**-2.7**	**-3.6**
Grundfors	0.2	-0.2	-0.2	-0.8	-2.9	-1.8	-1.7	-1.3	-0.7	-1.2	-0.5	0.0	**-11.1**	**-3.4**	**-2.4**
Rusfors	-0.5	-0.3	-0.5	-1.0	-1.1	-1.4	-1.2	-1.0	-0.3	-1.0	-0.7	-0.2	**-9.2**	**-2.6**	**-4.5**
Bålforsen-Hällforsen	0.2	0.2	0.3	0.7	-0.2	0.2	-0.7	-1.5	-1.0	-0.3	-0.3	0.2	**-2.4**	**-1.2**	**-0.6**
Tuggen	-0.2	0.2	0.2	0.5	0.2	0.2	-0.2	-0.7	-0.3	-0.5	-0.2	0.0	**-0.8**	**-0.8**	**-0.6**
Bjurfors Övre-Harrsele	-0.3	-0.3	-0.2	1.0	-0.3	0.0	-1.2	-3.0	-1.8	-1.3	-1.2	-0.3	**-9.1**	**-4.2**	**-1.0**
Pengfors	-0.2	0.0	0.2	0.2	0.2	0.0	0.0	-0.5	-0.2	-0.2	-0.2	0.2	**-0.5**	**-0.4**	**-0.5**
Stornorrfors	0.2	0.5	0.5	1.7	0.2	0.7	-0.2	-2.0	-0.8	0.0	-0.3	0.3	**0.7**	**-0.1**	**0.0**
Total	**-1.0**	**0.7**	**-0.3**	**2.8**	**-5.2**	**-3.1**	**-7.8**	**-11.6**	**-4.7**	**-5.7**	**-2.9**	**0.9**	**-39.9**	**-15.2**	**-0.7**

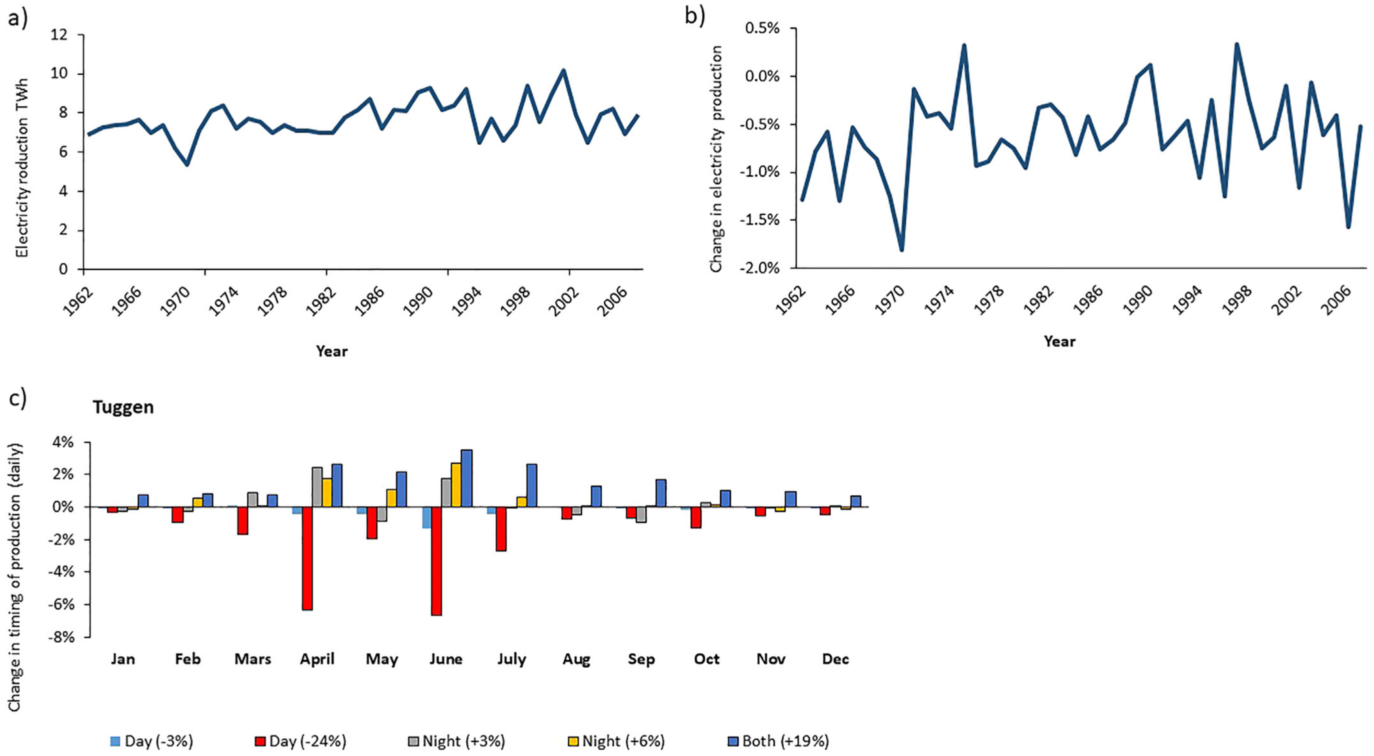

Fig. 6. (a) Total modelled annual electricity production in the Ume River 1962–2008. (b) Proportional change in annual modelled electricity production caused by introducing demands on minimum discharge, compared to annual production with current hydropower operation rules. (c) Proportional change in production per month in Tuggen occurring in different price ranges caused by introducing demands on minimum discharge, compared to annual production with current hydropower operation rules. Proportion of change presented as mean change in timing (1962–2008) per price range.

perspectives. This is probably true for many regulated rivers around the world and certainly in Scandinavia. An environmental flow assessment cannot be considered cost-effective based simply on low cost for implementation, but should be based on robust models of ecological benefits and consequences for the energy system. Here, we estimated the consequences of introducing rules mandating continuous flow through hydropower stations to improve habitat conditions for aquatic organisms adapted to lotic conditions by calculating the gains in area with conditions suitable for lotic species such as grayling, as well as changes in hydropower production and revenues. Below we discuss the main methodological challenges and implications of the results.

5.1. Ecosystem benefits of minimum flow

Effects of hydropeaking can be mitigated with rules of mandated minimum discharge, but to quantify and predict the environmental benefits this might bring is challenging (Bruder et al., 2016). We started out by identifying the lack of lotic habitat with permanently flowing water (with flow velocity meeting the requirements of lotic taxa) as a major problem in the Ume River, and hence decided to focus on the potential gain in area of lotic habitat meeting specific requirements of flow velocity and channel bed substrate conditions for the target species grayling, acting as an “umbrella” species (Roberge and Angelstam, 2004). If implemented, the minimum-flow measure would likely provide multiple benefits for riverine ecosystems that we have not tried to quantify, associated with less rapid changes in discharge going from stagnant water to high flow velocities. For example, avoiding periods of stagnant water would promote hyporheic flow, reducing the risk for critically low levels of dissolved oxygen leading to egg mortality and failed incubation in salmonids (Malcolm et al., 2003; Calles et al., 2007). Continuous reservoir release would also help avoid stagnant water resulting in high temperatures (Olden and Naiman, 2010) having negative effects e.g., on the number of egg-bearing grayling females (Wedekind and Kung, 2010). Frequent starts and stops of turbines also increase disturbance from displacement of ice and sediment (Ettema and Zabilansky, 2004; Turcotte et al., 2011; Prowse and Culp, 2003), constituting a stress for young brown trout (Watz et al., 2015) and riparian vegetation (Bejarano et al., 2018). Finally, having rules for minimum discharge through turbines would decrease the available hydropeaking interval, i.e. the range of flows available for hydropeaking, with more than 10%, since the range of discharge from zero-flow up to minimum low flow would not be allowed (Table 1). As a consequence, hydropeaking intensity would decrease, potentially also reducing water-level fluctuations. Minimum discharge could however increase the rate-of-change or flashiness of flow variation in small impoundments and hydropower stations with turbines with large capacity in relation to the mean discharge. This means that the impoundment can be filled up or emptied within a short time period. Thus, in these situations, lowering the available hydropeaking interval could increase the stress and disturbance on ecosystems. In such situations, the minimum discharge should be combined with rules on the maximum rate of change in flow or water levels. To detect such cases, flow data with high time resolution (e.g. hourly data) is needed. This helps both developing new hydropower operational rules and is essential when analyzing historical records of flow and water levels. However, we did not use hourly data in calculating how implementing environmental flows would affect electricity production since this would not match how hydropower operators plan hydropower production.

We quantified environmental benefits of introducing minimum flows as changes in suitable habitat, based on flow velocity, channel bed substrate composition and water depth, for species adapted to running waters. In doing so, there are multiple biotic interactions not taken into consideration in our study, as exemplified by the grayling. It is sensitive to competition from brown trout (Degerman et al., 2000; Goble et al., 2018), but is rarely exposed to predation from Northern pike *Esox lucius* (Sandlund et al., 2016) in their natural habitat. With increasing water flow velocity, Northern pike will have less effect on salmonids in running water. Factors affecting salmonid food availability, such as drift of invertebrates, are also affected by discharge and velocity (Naman et al., 2016) and may be positively affected by a mandated minimum discharge.

Calculating the potential benefits of environmental flow measures can be done in multiple ways, including (1) projecting their effect on processes deemed important for ecosystem functions, (2) estimating the area of habitat created or maintained by the measure, or (3) calculating the effect on the population abundance of key species (Heggenes et al., 1996; Vehanen et al., 2003; Capra et al., 2017). The three methods go from low to high precision in making projections for a target organism, and we primarily opted for the second strategy since the measure would potentially benefit multiple species, for which we have limited information, making estimates of population responses infeasible. At the same time, we employed strategy (1), assessing the effect on flow velocity since this is a key hydrological process affecting sediment redistribution, oxygenation and habitat conditions for focal species, and can be modelled quantitatively.

5.2. Catchment area perspective

Despite that ownership of hydropower stations in the Ume River system is divided among multiple hydropower companies, water management is highly integrated across the catchment. This means that estimating the consequences of introducing minimum discharge for hydropower production as well as assessing the environmental benefits had to be done at the catchment level. Our models show that restriction of zero-flow events would result in both gains and losses in production throughout the system (Table 3). In addition, the gains in habitat area would not always be located at the impoundment and hydropower station in focus. This is because a change at a specific hydropower station may force concomitant changes in operation of other stations. For example, the rule of minimum discharge through turbines was applied to all hydropower stations downstream of Storuman, but the electricity production would be affected in all upstream stations, since the flow restriction would force them to release water.

5.3. Potential synergistic effects of multiple rehabilitation measures

Although not an environmental benefit per se, introducing requirements for minimum discharge can facilitate introducing additional environmental flow measures. In hydropower stations where the minimum capacity of turbines is too large to set rules for a minimum flow equivalent of mean annual low discharge, water would be released through spill gates. However, the spill water should not be considered “lost water”, since it can be used for subsequent environmental measures, such as discharge to fishways or bypassed reaches, providing additional ecosystem benefits.

Hydropeaking intensity is modulated by river morphology (Person et al., 2014). More complex river morphology, such as meanders, islands, braided shallow sections, can attenuate flow and increase hydraulic roughness, thus reducing flow velocity variation (Hauer et al., 2013). In Norway, it is common for environmental flow measures to be combined with structural rehabilitation measures (Adeva Bustos et al., 2017; Casas-Mulet et al., 2014). Halleraker et al. (2007) concluded that a combination of habitat improvement, decreased flow ramping, and environmental flow measures would be necessary to enhance conditions for Atlantic salmon *Salmo salar*.

When calculating the total area of gained habitat for grayling and other lotic species, we assumed that environmental flow measures would be combined with structural rehabilitation of stream channels (Whipple and Viers, 2019). Measures to improve stream channel morphology, especially in-stream structures, are often needed to create the range of habitats used by species over their entire life cycle. For example, structural modification of the streambed may increase roughness helping to buffer against hydropeaking effects (Hauer et al., 2013; Casas-Mulet et al., 2014). We assumed that outlet channels below hydropower stations, having high flow velocities, could be modified to meet the requirements of grayling and similar species. This would be done by widening the channel to include shallow areas with suitable depths and flow velocity for grayling along one bank, an ecological shelf. Such measures have not yet been implemented, but there are regulated river reaches in the region with hydropeaking having self-sustaining populations of grayling in outlet channels, and these are characterized by high sediment heterogeneity, including large boulders (Persson and Isaksson, 2015). Since there is almost no remaining fall height, the structural measures are dependent on restricting zero-flow events in order to avoid stagnant water.

5.4. Loss of electricity production in relation to environmental benefits

All hydropower stations in the Ume River are scheduled to undergo a relicensing process to adapt the legal requirements to meet modern environmental demands (Swedish Energy Agency, 2019). Our results show that restricting zero-flow events in the Ume River would cause a mean loss equivalent of 39 GWh or 0.5% of current hydropower production per year (Fig. 6b), which can be compared to the range of variation among years, being 4.8 TWh for the period 1962–2008 (Fig. 6a). The fact that this between-year variation can be accommodated and managed successfully suggests that a 0.5% loss of electricity production can be considered manageable for the energy system. The maximum loss in hydropower production in the Ume River system envisioned in the Swedish National Strategy for hydropower and mitigation of riverine ecosystems (Swedish Energy Agency, 2019) was preliminarily set to 1.9% or 139 GWh of current annual production (information from the Swedish Energy Agency, the Swedish Agency for Marine and Water Management, and Svenska Kraftnät), and introducing mandates for minimum discharge would thus be well below the limit.

The fact that minimum flows would primarily run through turbines minimized production losses, so that the main impact is to change the timing rather than the magnitude of hydropower production. This means that hydropower companies are forced to produce electricity during periods of less demand and lower revenues. Given that electricity must be consumed at the same time as it is produced, changing the timing of production is potentially problematic. Hydropower plays a complex role in the electricity system, providing base power that vary between seasons and with time of day. In addition, hydropower balances short-term variation in electricity demand as well as variation in the production of other renewables like wind and solar power. The projected increases in the installed capacity of wind and solar power will likely make the ability of hydropower to balance other renewables even more valuable, with potential for increasing revenues. Despite this, there are also arguments for why the reduction in the capacity of hydropower to provide balancing power would be small. First, the largest changes in the seasonal and daily timing of production by implementing minimum flows would occur during April to August (Table 3), when the total demand for electricity is at its annual lowest and balancing capacity is high. Second, consumption patterns are likely to change in the future, with increased use of devices such as electric vehicles, that will require overnight charging. Daily patterns of consumption can also be changed by economic incentives, e.g. to move consumption from day to night (Bartusch et al., 2011). In fact, current consumption patterns put strain on the capacity of electricity grids during peak demand (Koliou et al., 2015; Öhrlund et al., 2019). In this context, moving electricity consumption from times of the day with high demand to times with lower demand would serve both environmental benefits and reduce the strain on the electricity grid, thus “killing two birds with one stone”.

If we conclude that the consequences of implementing minimum flows are manageable for the energy system, what are the reasons to believe hydropower operators will adopt the scheme, considering they would lose 0.7% of their revenues a normal year? First, a decision on implementation needs to consider alternative means of electricity production or a reduction in consumption, but these considerations are beyond the scope of this study. Second, hydropower operators are under pressure to increase environmental considerations in the process of relicensing hydropower permits. As mentioned above, a national strategy has set an upper limit of 2.3% loss of annual hydropower production for this process (1.9% for the Ume River system, preliminarily), but which actions that will be prioritized will ultimately be determined by decisions taken by the Swedish Land and Environmental Court. Given that we are involved in pilot projects in the river systems first up for re-licensing, where the aim is to identify the environmental flow actions providing the most ecological benefits with minimum impacts on hydropower production, we know that the scheme presented here will at least be among the actions considered.

5.5. Conclusions and future prospects

Climate change and electrification of society increase the demand for renewable energy sources such as hydropower, which can result in further degradation of freshwater ecosystems. Our work in the Ume River catchment is one of few examples of an assessment of catchment-scale consequences of introducing environmental flow measures where both the potential benefits for riverine ecosystems and the effects on hydropower production are quantified. The estimated consequences on hydropower production were small in relation to natural between-year variation in electricity production, and changes in the timing of production would be manageable by society. Although the results are not directly transferrable to other river systems, there is an urgent need for similar assessments in order to reduce impacts of electricity production that can be avoided, and make management of freshwater ecosystems more sustainable. Future studies should investigate direct effects of zero-flow events on riverine organisms and ecosystem processes in order to facilitate development of mitigation measures.

CRediT authorship contribution statement

Åsa Widén: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **Birgitta Malm Renöfält:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Erik Degerman:** Investigation, Methodology, Writing – review & editing. **Dag Wisaeus:** Investigation, Methodology. **Roland Jansson:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Acreman, M., Arthington, A.H., Colloff, M.J., Couch, C., Crossman, N.D., Dyer, F., Overton, I., Pollino, C.A., Stewardson, M.J., Young, W., 2014. Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. Front. Ecol. Environ. 12, 466–473. https://doi.org/10.1890/130134.

Adeva Bustos, A., Hedger, R.D., Fjeldstad, H.-P., Alfredsen, K., Sundt, H., Barton, D.N., 2017. Modeling the effects of alternative mitigation measures on Atlantic salmon production in a regulated river. Water Resources and Economics 17, 32–41. https://doi.org/10.1016/j.wre.2017.02.003.

Alexandre, C.M., Almeida, P.R., Neves, T., Mateus, C.S., Costa, J.L., Quintella, B.R., 2016. Effects of flow regulation on the movement patterns and habitat use of a potamodromous cyprinid species. Ecohydrology 9, 326–340. https://doi.org/10.1002/eco.1638.

Andersson, T., 1978a. Förändringar av fiske och fiskbestånd i Umeälven under senare decennier med särskild hänsyn till vattenkraftutbyggnaden. Del 1. Sjöarna. Inf. från Sötvattenslaboratoriet, Drottningholm, nr 2, 172 pages. (Swedish).

Andersson, T., 1978b. Förändringar av fiske och fiskbestånd i Umeälven under senare decennier med särskild hänsyn till vattenkraftutbyggnaden. Del 2 Älven. mellan Storuman och Stornorrfors. Inf. från Sötvattenslaboratoriet, Drottningholm, nr 2, 172 pages. (Swedish).

Bartusch, C., Wallin, F., Odlare, M., Vassileva, I., Wester, L., 2011. Introducing a demand-based electricity distribution tariff in the residential sector: demand response and customer perception. Energy Policy 39, 5008–5025. https://doi.org/10.1016/j.enpol.2011.06.013.

Bejarano, M.D., Jansson, R., Nilsson, C., 2018. The effects of hydropeaking on riverine plants: a review. Biol. Rev. 93, 658–673. https://doi.org/10.1111/brv.12362.

Bruder, A., Tonolla, D., Schweizer, S.P., Vollenweider, S., Langhans, S.D., Wuest, A., 2016. A conceptual framework for hydropeaking mitigation. Sci. Total Environ. 568, 1204–1212. https://doi.org/10.1016/j.scitotenv.2016.05.032.

Brunner and Rey (2014). Hydropeaking and fish migration-consequences and possible mitigation measures at the Schiffinen dam. Swiss Competence in River Engineering and Restoration., 2014, p.173–179. ISBN: 978–1–138-02676-6.

Bruno, C.M., Maiolini, B., Carolli, M., Silveri, L., 2010. Short time-scale impacts of hydropeaking on benthic invertebrates in an Alpine stream (Trentino, Italy). Limnologica 40, 281–290. https://doi.org/10.1016/j.limno.2009.11.012.

Calles, O., Nyberg, L., Greenberg, L., 2007. Temporal and spatial variation in quality of hyporheic water in one unregulated and two regulated boreal rivers. River Res. Appl. 23, 829–842. https://doi.org/10.1002/rra.

Capra, H., Plichard, L., Bergé, J., Pella, H., Ovidio, M., McNeil, E., Lamouroux, N., 2017. Fish habitat selection in a large hydropeaking river: strong individual and temporal variations revealed by telemetry. Sci. Total Environ. 578, 109–120. https://doi.org/10.1016/j.scitotenv.2016.10.155.

Casas-Mulet, R., Alfredsen, K., Killingtveit, A., 2014. Modelling of environmental flow options for optimal Atlantic salmon, *Salmo salar*, embryo survival during hydropeaking. Fish. Manag. Ecol. 21, 480–490. https://doi.org/10.1111/fme.12097.

Charmasson, J., Zinke, P., 2011. Mitigation Measures against Hydropeaking Effects. Report, Sintef Energy AS.

Crisp, D.T., 1996. Environmental requirements of common riverine European salmonid fish species in fresh water with particular reference to physical and chemical aspects. Hydrobiologia 323, 201–221. https://doi.org/10.1007/BF00007847.

Degerman, E., Näslund, I., Sers, B., 2000. Stream habitat use and diet of juvenile (0+) brown trout and grayling in sympatry. Ecol. Freshw. Fish 9, 191–201. https://doi.org/10.1111/j.1600-0633.2000.eff090401.x.

Englund, G., Malmqvist, B., 1996. Effects of flow regulation, habitat area and isolation on the macroinvertebrate fauna of rapids in north Swedish rivers. Regulated Rivers: Research & Management 12, 433–445. https://doi.org/10.1002/(SICI)1099-1646(199607)12:4/5<433::AID-RRR415>3.0.CO;2-6.

Englund, G., Malmqvist, B., Zhang, Y., 1997. Using predictive models to estimate effects of flow regulation on net-spinning caddis larvae in north Swedish rivers. Freshw. Biol. 37, 687–697. https://doi.org/10.1046/j.1365-2427.1997.00178.x.

Esselman, P.C., Opperman, J.J., 2010. Overcoming information limitations for the prescription of an environmental flow regime for a central american river. Ecol. Soc. 15 (doi:6).

Ettema, R., Zabilansky, L., 2004. Ice influences on channel stability: insights from Missouri's fort peck reach. J. Hydraul. Eng. 130, 279–292. doi:10.1061/(ASCE)0733-9429(2004)130:4(279).

Flodmark, L.E.W., Urke, H.A., Halleraker, J.H., Arnekleiv, J. V., Vøllestad, L.A., Poléo, A.B.S., 2002. Cortisol and glucose responses in juvenile brown trout subjected to a fluctuating flow regime in an artificial stream. J. Fish Biol. 60, 238–248. doi:https://doi.org/10.1006/jfbi.2001.1845.

Friedland, K.D., Dannewitz, J., Romakkaniemi, A., Palm, S., Pulkkinen, H., Pakarinen, T., Oeberst, R., 2017. Post-smolt survival of Baltic salmon in context to changing environmental conditions and predators. ICES J. Mar. Sci. 74, 1344–1355. https://doi.org/10.1093/icesjms/fsw178.

Goble, C.W., Auer, N.A., Huckins, C.J., Danhoff, B.M., Holtgren, J.M., Ogren, S.A., 2018. Fish distributions and habitat associations in Manistee River, Michigan, tributaries: implications for Arctic grayling restoration. N. Am. J. Fish Manag. 38, 469–486. https://doi.org/10.1002/nafm.10049.

Gonczi, A.P., 1985. A study of physical parameters at the spawning sites of the European grayling (*Thymallus thymallus*). Regulated Rivers: Research & Management 3, 221–224.

Grabowski, T., Isely, J., 2007. Life history and color variants in a matriline of Oklahoma salamander (*Eurycea tynerensis*). Southeast. Nat. 6, 727–736. https://doi.org/10.1656/1528-7092(2007)6.

Greimel, F., Schülting, L., Graf, W., Bondar-Kunze, E., Auer, S., Zeiringer, B., Hauer, C., 2018. Hydropeaking impacts and mitigation. Riverine ecosystem management, 91–110 https://doi.org/10.1007/978-3-319-73250-3_5.

Halleraker, J.H., Sundt, H., Alfredsen, K.T., Dangelmaier, G., 2007. Application of multiscale environmental flow methodologies as tools for optimized management of a Norwegian regulated national salmon watercourse. River Res. Appl. 510, 493–510. doi: https://doi.org/10.1002/rra.

Hauer, C., Schober, B., Habersack, H., 2013. Impact analysis of river morphology and roughness variability on hydropeaking based on numerical modelling. Hydrol. Process. 2224, 2209–2224. https://doi.org/10.1002/hyp.9519.

Heggenes, J., Saltveit, S.J., Lingaas, O., 1996. Predicting fish habitat use to changes in water flow: modelling critical minimum flows for Atlantic salmon, *Salmo salar*, and brown trout, *S. trutta*. Regul. Rivers: Res. Manage. 12, 331–344. https://doi.org/10.1002/(SICI)1099-1646(199603)12:2/3<331::AID-RRR399>3.0.CO;2-E.

Holzapfel, P., Leitner, P., Habersack, H., Graf, W., Hauer, C., 2017. Evaluation of hydropeaking impacts on the food web in alpine streams based on modelling of fish- and macroinvertebrate habitats. Sci. Total Environ. 575, 1489–1502. https://doi.org/10.1016/j.scitotenv.2016.10.016.

Jansson, R., Nilsson, C., Dynesius, M., 2000. Effects of river-regulation on river margin vegetation : a comparison of eight boreal rivers. Ecol. Appl. 10, 203–224. https://doi.org/10.1890/1051-0761(2000)010[0203:EORROR]2.0.CO;2.

Judes, C., Gouraud, V., Capra, H., Maire, A., Barillier, A., Lamouroux, N., 2020. Consistent but secondary influence of hydropeaking on stream fish assemblages in space and time. Journal of Ecohydraulics. https://doi.org/10.1080/24705357.2020.1790047.

Kalleberg, H.,1958. Observations in a stream tank of territoriality and competition in juvenile salmon and trout (*Salmo salar* L. and *S. trutta L.*).Rep. Inst. Freshwater Res., Drottningholm vol. 39 55–98.

Koliou, E., Bartusch, C., Picciariello, A., Eklund, T., Söder, L., Hakvoort, R.A., 2015. Quantifying distribution-system operators' economic incentives to promote residential demand response. Util. Policy 35, 28–40. https://doi.org/10.1016/j.jup.2015.07.001.

Kraft, M.E. 1972. Effects of controlled flow reduction on a trout stream. J. Fish. Res. Board Can. 29:1405–1411.doi:https://doi.org/10.1139/f72-218 doi:https://doi.org/10.1139/f72-218.

Lessard, J., Murray Hicks, D., Snelder, T.H., Arscott, D.B., Larned, S.T., Booker, D., Suren, A.M., 2013. Dam design can impede adaptive management of environmental flows: a case study from the Opuha Dam, New Zealand. Environ. Manag. 51, 459–473. https://doi.org/10.1007/s00267-012-9971-x.

Linløkken, A., 1993. Efficiency of fishways and impact of dams on the migration of grayling and brown trout in the Glomma river system, south-eastern Norway. Regulated Rivers: Research & Management 8, 145–153. https://doi.org/10.1002/rrr.3450080117.

Malcolm, I.A., Youngson, A.F., Soulsby, C., 2003. Survival of salmonid eggs in a degraded gravel-bed stream: effects of groundwater-surface water interactions. River Res. Appl. 19, 303–316. https://doi.org/10.1002/rra.706.

Moog, O., 1993. Quantification of daily peak hydropower effects on aquatic fauna and minimize environmental impacts. Regulated Rivers: Research & Management 8, 5–14. https://doi.org/10.1002/rrr.3450080105.

Moreira, M., Hayes, D.S., Boavida, I., Schletterer, M., Schmutz, S., Pinheiro, A., 2019. Ecologically-based criteria for hydropeaking mitigation: a review. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2018.12.107.

Morrison, R.R., Stone, M.C., 2015. Evaluating the impacts of environmental flow alternatives on reservoir and recreational operations using system dynamics modeling. J. Am. Water Resour. Assoc. 51, 33–46. https://doi.org/10.1111/jawr.12231.

Naman, S.M., Rosenfeld, J.S., Richardson, J.S., 2016. Causes and consequences of invertebrate drift in running waters: from individuals to populations and trophic fluxes. Can. J. Fish. Aquat. Sci. 1305, 1292–1305. https://doi.org/10.1139/cjfas-2015-0363.

Nilsson, C., Ekblad, A., Gardfjell, M., Carlberg, B., 1991. Long-term effects of river regulation on river margin vegetation. J. Appl. Ecol. 28, 963–987. https://www.jstor.org/stable/2404220.

Niu, S., Insley, M., 2013. On the economics of ramping rate restrictions at hydro power plants: balancing profitability and environmental costs. Energy Econ. 39, 39–52. https://doi.org/10.1016/j.eneco.2013.04.002.

Nyatsanza, F.F., Graas, S., van der Zaag, P., 2015. The impact of dynamic environmental flow releases on hydropower production in the Zambezi river basin. J. Am. Water Resour. Assoc. 51, 1029–1042. https://doi.org/10.1111/jawr.12280.

Nykänen, M., 2004. Habitat Selection by Riverine Grayling, *Thymallus thymallus* L. University of Jyväskylä https://jyx.jyu.fi/dspace/handle/123456789/13129.

Nykänen, M., Huusko, A., 2003. Size-related changes in habitat selection by larval grayling (*Thymallus thymallus* L.). Ecol. Freshw. Fish 12, 127–133. https://doi.org/10.1034/j.1600-0633.2003.00013.x.

Nykänen, Marie, Huusko, A., Lahti, M., 2004a. Changes in movement, range and habitat preferences of adult grayling from late summer to early winter. J. Fish Biol. 64, 1386–1398. https://doi.org/10.1111/j.0022-1112.2004.00403.x.

Nykänen, Marie, Huusko, A., Lahti, M., 2004b. Movements and habitat preferences of adult grayling (*Thymallus thymallus L.*) from late winter to summer in a boreal river. Arch. Hydrobiol. 161, 417–432. https://doi.org/10.1127/0003-9136/2004/0161-0417.

Öhrlund, I., Schultzberg, M., Bartusch, C., 2019. Identifying and estimating the effects of a mandatory billing demand charge. Appl. Energy 237, 885–895. https://doi.org/10.1016/j.apenergy.2019.01.028.

Olden, J.D., Naiman, R.J., 2010. Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. Freshw. Biol. 55, 86–107. https://doi.org/10.1111/j.1365-2427.2009.02179.x.

Person, E., Bieri, M., Peter, A., Schleiss, A.J., 2014. Mitigation measures for fish habitat improvement in Alpine rivers affected by hydropower operations. Ecohydrology 7, 580–599. https://doi.org/10.1002/eco.1380.

Persson, B.-G., Isaksson, M., 2015. Inventering av Skellefteåälvens älvsmagasin med biflöden - sträckan mynningen till Rengård. Skellefteå community. Unpublished report. In Swedish.

Poff, N. LeRoy, Schmidt, J.C., Kumar, A., Zarfl, C., Winemiller, K.O., Poff, N.L., Arthington, A.H., Kennedy, T.A., Naiman, R.J., Olden, J.D., Kiernan, J.D., Pittock, J., Hartmann, J., Estrin, J., Jager, H.I., Poff, N.L., 2016. How dams can go with the flow. Science 353, 161–1100. https://doi.org/10.1126/science.aah4926.

Prowse, T., Culp, J., 2003. Ice breakup: a neglected factor in river ecology. Canadian Journal Civil Engineering. 30, 30, 128–144. https://doi.org/10.1139/L02-040.

Razurel, P., Gorla, L., Crouzy, B., Perona, P., 2016. Non-proportional repartition rules optimize environmental flows and energy production. Water Resour. Manag. 30, 207–223. https://doi.org/10.1007/s11269-015-1156-y.

REN21, 2019. Renewables 2019 Global Status Report. (Paris: REN21 Secretariat). ISBN 978-3-9818911-7-1.

Renöfält, B.M., Jansson, R., Nilsson, C., 2010. Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems. Freshw. Biol. 55, 49–67. https://doi.org/10.1111/j.1365-2427.2009.02241.x.

Richter, B.D., Thomas, G.A., 2007. Restoring environmental flows by modifying dam operations. Ecol. Soc. 12, 12. http://www.ecologyandsociety.org/vol12/iss1/art12/.

Riml, J., Kløve, B., Marttila, H., Ashraf, F. Bin, Haghighi, A.T., Koskela, J.J., Alfredsen, K., 2018. Changes in short term river flow regulation and hydropeaking in Nordic rivers. Sci. Rep. 8, 1–12. https://doi.org/10.1038/s41598-018-35406-3.

Roberge, J.-M., Angelstam, P.K., 2004. Usefulness of the umbrella species concept as a conservation tool. Conserv. Biol. 18 (1), 76–85. https://doi.org/10.1111/j.1523-1739.2004.00450.x.

Saarinen, L., Dahlbäck, N., Lundin, U., 2015. Power system flexibility need induced by wind and solar power intermittency on time scales of 1–14 days. Renew. Energy 83, 339–344. https://doi.org/10.1016/j.renene.2015.04.048.

Saltveit, S.J., Halleraker, J.H., Arnekleiv, J.V., Harby, A., 2001. Field experiments on stranding in juvenile Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) during rapid flow decreases caused byhydropeaking. Regul. Rivers: Res. Manage. 17, 609–622. https://doi.org/10.1002/rrr.652.

Sandlund, O.T., Museth, J., Øistad, S., 2016. Migration, growth patterns, and diet of pike (*Esox lucius*) in a river reservoir and its inflowing river. Fish. Res. 173, 53–60. https://doi.org/10.1016/j.fishres.2015.08.010.

Sauterleute, J.F., Charmasson, J., 2014. A computational tool for the characterisation of rapid fluctuations in flow and stage in rivers caused by hydropeaking. Environ. Model. Softw. 55, 266–278. https://doi.org/10.1016/j.envsoft.2014.02.004.

Sloman, K.A., Wilson, L., Freel, J.A., Taylor, A.C., Metcalfe, N.B., Gilmour, K.M., 2002. The effects of increased flow rates on linear dominance hierarchies and physiological function in brown trout, *Salmo trutta*. Can. J. Zool. 80, 1221–1227. https://doi.org/10.1139/z02-105.

St. Louis, V., Kelly, C., Duchemin, E., Rudd, J., Rosenberg, D., 2000. Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate. Biosience 50 (9), 766–775. https://doi.org/10.1641/0006-3568(2000)050.

Swedish Energy Agency, 2016. Nationell strategi för hållbar vattenkraft. Report. In Swedish.

Swedish Energy Agency, 2019. Förslag till nationell plan för omprövning av vattenkraft. Report. In Swedish.

Toffolon, M., Siviglia, A., Zolezzi, G., 2010. Thermal wave dynamics in rivers affected by hydropeaking. Water Resour. Res. 46, 1–34. https://doi.org/10.1029/2009WR008234.

Tonolla, D., Schmutz, S., Auer, S., Zeiringer, B., Führer, S., 2016. Effects of river bank heterogeneity and time of day on drift and stranding of juvenile European grayling (T*hymallus thymallus* L.) caused by hydropeaking. Sci. Total Environ. 575, 1515–1521. https://doi.org/10.1016/j.scitotenv.2016.10.029.

Turcotte, B., Morse, B., Bergeron, N.E., Roy, A.G., 2011. Sediment transport in ice-affected rivers. J. Hydrol. 409, 561–577. https://doi.org/10.1016/j.jhydrol.2011.08.009.

Vehanen, T., Huusko, A., Yrjänä, T., Lahti, M., Mäki-Petäys, A., 2003. Habitat preference by grayling (*Thymallus thymallus*) in an artificially modified, hydropeaking riverbed: a contribution to understand the effectiveness of habitat enhancement measures. J. Appl. Ichthyol. 19, 15–20. https://doi.org/10.1046/j.1439-0426.2003.00354.x.

Vehanen, T., Jurvelius, J., Lahti, M., 2005. Habitat utilisation by fish community in a short-term regulated river reservoir. Hydrobiologia 545, 257–270. https://doi.org/10.1007/s10750-005-3318-z.

Watz, J., Bergman, E., Calles, O., Enefalk, A., Gustafsson, S., Hagelin, A., Nilsson, P.A., Norrgård, J.R., Nyqvist, D., Österling, E.M., Piccolo, J.J., Schneider, L.D., Greenberg, L., Jonsson, B., 2015. Ice cover alters the behavior and stress level of brown trout *Salmo trutta*. Behav. Ecol. 26, 820–827. https://doi.org/10.1093/beheco/arv019.

Wedekind, C., Kung, C., 2010. Shift of spawning season and effects of climate warming on developmental stages of a grayling (Salmonidae) 24, 1418–1423. doi:https://doi.org/10.1111/j.1523-1739.2010.01534.x.

Whipple, A.A., Viers, J.H., 2019. Coupling landscapes and river flows to restore highly modified rivers. Water Resour. Res. 55, 4512–4532. https://doi.org/10.1029/2018WR022783.

Winemiller, K.O., McIntyre, P.B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., Baird, I.G., Darwall, W., Lujan, N.K., Harrison, I., Stiassny, M.L.J., Silvano, R.A.M., Fitzgerald, D.B., Pelicice, F.M., Agostinho, A.A., Gomes, L.C., Albert, J.S., Baran, E., Petrere, M., Zarfl, C., Mulligan, M., Sullivan, J.P., Arantes, C.C., Sousa, L.M., Koning, A.A., Hoeinghaus, D.J., Sabaj, M., Lundberg, J.G., Armbruster, J., Thieme, M.L., Petry, P., Zuanon, J., Vilara, G.T., Snoeks, J., Ou, C., Rainboth, W., Pavanelli, C.S., Akama, A., Soesbergen, A. v, Saenz, L., 2016. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. Science 351, 128–129. https://doi.org/10.1126/science.aac7082.

Zhang, J., Xu, L., Yu, B., Li, X., 2014. Environmentally feasible potential for hydropower development regarding environmental constraints. Energy Policy 73, 552–562. https://doi.org/10.1016/j.enpol.2014.04.040.

Web reference

SINTEF, d. Norwegian software developerhttps://www.sintef.no/en/software/prodrisk/(2020-11-11.

SMHI. Swedish metrological and hydrological institute. https://www.smhi.se/data/hydrologi/vattenwebb (2015-11-05).