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Special Section:
Advancing process representation in hydrologic models: Integrating new concepts, knowledge, and data

Environmental Flow Scenarios for a Regulated River System: Projecting Catchment-Wide Ecosystem Benefits and Consequences for Hydroelectric Production

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Key Points:

- We made an environmental flow assessment of a regulated river system, quantifying the ecological benefits and effects on energy production
- We calculated the benefits of implementing environmental flows by estimating gain in habitat for target organisms across the catchment
- We used optimization software to project the catchment-level effects of implementing environmental flows on electric production and revenues

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

To enable prioritization among measures for ecological restoration, knowing the expected benefits and consequences of implementation is imperative but rarely explicitly quantified. We developed a novel method to prioritize among environmental flow measures to rehabilitate ecosystems in the Ume River catchment in northern Sweden, a river system heavily regulated for hydropower production. Our strategy was to identify measures with minimal impact on hydropower production while providing substantial environmental benefits. Based on field surveys of remaining natural values and potential for ecological rehabilitation, we quantified the projected gain in habitat area of implementing environmental flows for target organism groups, for example, lotic fish species and riparian vegetation, along the whole river length. We quantified the consequences for hydropower production by identifying a set of hydropower operational rules reflecting the constraints added by environmental flows. We then used production optimization software to calculate changes in hydropower production and revenues. Implementing restrictions on zero-flow events by mandating minimum discharge at all run-of-river hydropower stations and allocating 1%–12% of mean annual discharge to bypassed reaches in the entire catchment would result in a 2.1% loss of annual electricity production. Adding flow to fishways would increase the loss to 3.1% per year. With implementation of more natural water-level fluctuations in run-of-river impoundments, the loss increases to 3.8%. These actions would increase the habitat for lotic species like the grayling *Thymallus* more than threefold and increase the area of riparian vegetation by about 66%. Our method forms a basis for ongoing implementation of nationwide environmental rehabilitation schemes.

Plain Language Summary

Developing river systems to produce hydropower results in impoverished riverine ecosystems. Legal demands to strike a balance between the provision of renewable electricity and consideration of the value of riverine ecosystems have led to calls for ecological rehabilitation of river systems to conserve their natural values. To achieve this, environmental rehabilitation actions are needed, including quantifying environmental benefits and consequences for hydropower production at the catchment level. We developed a novel methodology for the "cost-benefit analyses" needed and made an environmental flow assessment of the heavily regulated Ume River system in Sweden. We surveyed remaining natural values and potential for rehabilitation, which we quantified as the projected gain of habitat area for target organisms, summed for the entire catchment. We then calculated the expected consequences on hydropower production of implementing a set of environmental flow scenarios, using software used by hydropower operators for planning electricity production. We found that it would be possible to introduce environmental flow options that would lead to substantial gains in the area of habitat for lotic species and riparian plants, while keeping the costs in terms of losses of hydropower production within the limits outlined in a strategy for increased environmental consideration of hydropower permits in Sweden.

1. Introduction

Hydropower is considered a green and renewable source of electricity, and the ability to store water in reservoirs enables matching electricity production minute-by-minute to variation in demand (Poff & Schmidt, 2016). However, hydropower production entails modifying rivers with large infrastructure such as dams and diversion canals. As a consequence, riverine ecosystems belong to the ecosystem types that are most degraded globally (Dudgeon et al., 2006). Freshwater is a limited resource with multiple users claiming their right to water required

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for hydropower, irrigation, industrial, and recreational needs (Davis, 2007). To avoid conflicts, and to protect biodiversity and ecosystem functions as well as generating electricity, integrated water resource management of regulated river basins is required (Davis, 2007). In rivers regulated for hydropower, this often implies reoperating reservoirs to meet environmental goals in addition to the electricity production that motivated dam building (Poff et al., 2003).

Environmental flows (EF) can be defined as "the quantity and timing of water flows required to maintain the components, functions, processes and resilience of aquatic ecosystems and sustain the goods and services they provide to people" (The Nature Conservancy, 2020). Environmental flow measures are based on the assumptions that making the flow regime more similar to pristine, unregulated conditions will benefit native species and ecosystem functions (Lytle & Poff, 2004) and that any deviation from natural flow patterns will alter ecosystems (Armanini et al., 2014; Arntzen et al., 2006; Carlisle et al., 2016; Caruso, 2013; Harrison et al., 2016; Poff & Zimmerman, 2010; Quadroni et al., 2017). To integrate environmental flows into water management, there is a need to identify and quantify the ecological benefits they provide as well as the consequences they carry, for example, in terms of changed electricity production. Without such assessments, refraining from optimized electricity production can be hard to motivate (Campbell, 2016). A methodology that allows to prioritize among environmental flow measures facilitating ecosystem functions and biodiversity while continuing to provide benefits provided by dams and regulated flows is therefore needed (Arthington, Bhaduri, et al., 2018; Arthington, Kennen, et al., 2018; Gawne et al., 2018; Poff, 2018; Stoffels et al., 2018; Webb et al., 2018). The ambition of environmental flow measures can vary from implementing flows to fully resemble the natural flow regime to small changes in timing or magnitude targeting a specific environmental objective (Acreman, Arthington, et al., 2014; Bakken et al., 2012). To be able to predict and evaluate the response to environmental flow actions (Poff et al., 2010; Poff & Zimmerman, 2010), the expected benefits can be linked (a) to key ecological and fluvial processes, such as hydraulic conditions (Rivaes et al., 2015), thermal regimes (Olden & Naiman, 2010), or water quality (Nilsson & Renöfält, 2008), (b) to projections of habitat provision (Casas-Mulet et al., 2014), or (c) to estimates of population abundance of target organisms (Poff, 2018). Assessment of projections of the habitat area with suitable conditions or abundance of target organisms provided by a specific environmental flow option is needed, but rarely done except for single species at small spatial scales (Ayllon et al., 2009).

Currently, there are no catchment-scale assessments of the consequences of introducing environmental flows in river systems developed for hydropower. The catchment scale is crucial, given that in river systems with multiple dams and hydropower stations, changing operation at one dam or station will affect flow at dams both upstream and downstream. Thus, hydropower operators use optimization algorithms to determine flow at each station in the system to optimize production in relation to electricity demand and prices (Hammid et al., 2020; Labadie, 2004). To evaluate the consequences of introducing environmental flows necessitates using hydropower optimization algorithms to correctly evaluate their consequences. In addition, projections of environmental benefits made at the catchment scale are needed. Presently, such projections are often limited to presenting hydrographs with and without environmental flows with little information on catchment-scale consequences for riverine species.

Here, we present a novel environmental flow assessment made at the basin scale of the regulated Ume River in the north of Sweden with (a) quantitative projections of the expected gain in the area of ecosystem types important for target riverine organisms, along with (b) calculations of the projected impacts on hydropower production. The Ume River was developed for hydropower in the 1950 and 1960s with little environmental consideration, and the general view has been that implementing environmental flow measures would entail considerable loss of electricity production (Government bill, 1977/78:57, 1977). By running a range of scenarios, we enabled prioritization among environmental-flow options, balancing environmental benefits against electricity production losses (Adeqva Bustos et al., 2017; Bejarano et al., 2019; Poff et al., 2003). Assessing catchment-wide ecosystem responses to implementing environmental flows entails shifting spatial scale from catchment-level projections of gained area of different ecosystem types to more precise, reach-scale analyses linking changes in hydrologically driven processes to projected biotic responses. The project was made possible by collaboration among representatives of hydropower operators, Umeå University, regional authorities, and local communities involved in a trust-building process striving toward a shared perception of the main water management alternatives (Arthington, Kennen, et al., 2018).

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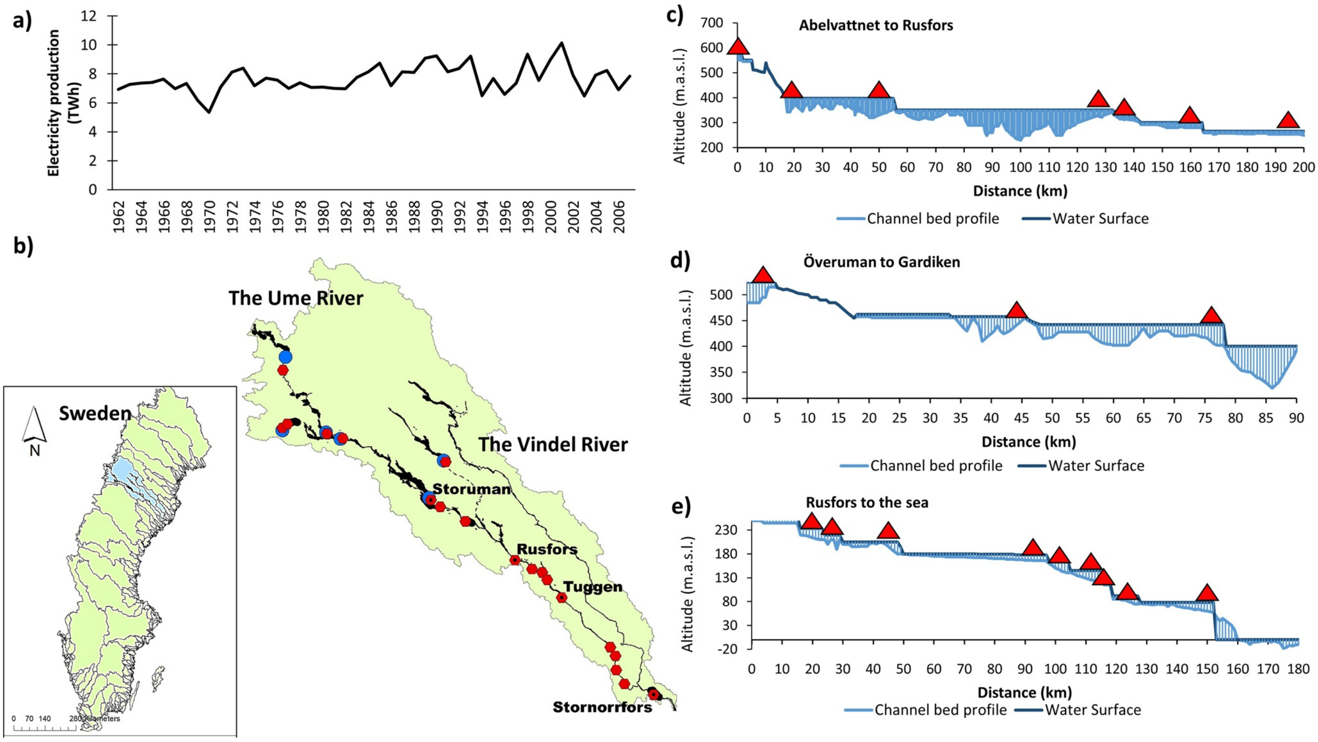

Figure 1. Annual hydroelectric production and study area. (a) Annual hydroelectric production (1962–2008) of the Ume River system. (b) Map showing the position of dams and hydropower stations in the Ume River catchment. (c–e) Longitudinal profiles of the Ume River from headwater to mouth.

2. Study Area

The regulated Ume River is situated in the north of Sweden and runs from the Scandinavian mountain range eastward to the Bothnian Bay, part of the Baltic Sea (Figure 1b). Before onset of regulation, the channel was confined, running on crystalline bedrock consisting on gneiss and granite along most of its length with sediment deposited by inland ice (Bedrock 1:1 million, Geological Survey of Sweden, 2021). Active floodplains were rare, and sediment transport was relatively low. With a mean annual electricity production of 7.7 TWh (during the period 1962–2007; Figure 1a), the river system is the third largest hydropower producer in Sweden. The Ume River was regulated during the 1950 and 1960s with 19 dams and hydropower stations. Six of these are storage reservoirs, and the remaining 13 are run-of-river impoundments in cascade with potential for hydropeaking operation. All available fall height has been utilized for electricity production (Figures 1c–1e), resulting in altered flow regimes and loss of connectivity due to dams (Widén et al., 2016). Only 1% of the reaches remain fast flowing or turbulent (i.e., having >0.1% stream gradient, equivalent to about 140 ha based on river length and mean width), compared to 39% before onset of regulation. Regulation has also altered the fish (Henricson & Müller, 1979) and macroinvertebrate fauna (Englund & Malmqvist, 1996) as well as reduced the diversity and cover of riparian vegetation (Jansson et al., 2000; Nilsson et al., 1991) compared to free-flowing rivers. The area of riparian vegetation along the Ume River is only 12% compared to pristine conditions based on comparisons with the free-flowing Vindel River (reduction in the width and cover of herbs and dwarf shrubs in riparian zones using data from Nilsson et al., 1991).

Many reaches have been bypassed, with flow diverted from the main channel, leaving it dry, with stagnant water or with reduced discharge. Seven of these bypassed reaches (Storuman, 6-km long; Nysele, 2 km; Grundfors, 3 km; Gardiken, <1 km; Abelvattnet, <1 km; Harrsele <1 km; Pengfors <1 km) were left dry after regulation, whereas four have a static minimum discharge of 0.5%–12% of the mean annual flow (Klippen, 24-km long and 0.94 m^3/s; Gejmån, 8-km long and 0.057 m^3/s; Juktån, 60-km long and 3.9 m^3/s; and Stornorrfors with a mean flow of 23 m^3/s from 16 May to end of September; Table S1). Flow regulation is the main environmental pressure on ecosystems in the river system, but historically the Ume River has been transformed for timber floating activities (Huusko & Yrjänä, 1995; Nilsson et al., 2005), and there is ongoing mining and forestry in the catchment.

The Ume River was developed for hydropower production in accordance with the Swedish water law of 1918 (Swedish Code of Statues, 1918 nr 523, 1918) with little or no consideration of ecological consequences. Compensation measures for lost lotic habitat and wild fish mandate the release of hatched salmon (*Salmo salar*), brown trout (*Salmo trutta*), grayling (*Thymallus thymallus*), and Arctic char (*Salvelinus alpinus*) (Table 1). A single fishway is built in the system, situated at Stornorrfors, enabling migration to the free-flowing tributary Vindel River (Figure 1b). In 2019, Sweden implemented legislative changes to renegotiate hydropower permits both to consider environmental rehabilitation and to ensure national supply of hydropower. Hence, all hydropower plants will undergo relicensing to obtain new permits. The measures that may be considered for enhancing the environmental conditions are, for example, environmental flows, fishways, and structural restoration of bypassed reaches such as dry channels and blocked side channels.

Throughout this study, the regulated flow regimes of the river system are exemplified by four hydropower stations: The Storuman hydropower station (Figure 2a) is situated at the dam of a large storage reservoir, where water from the spring flood is stored to be released during autumn and winter to meet ambient electricity demand (Figures 2a and 2e). Downstream from Storuman follows a cascade of 13 run-of-river impoundments, making Storuman a regulating tap for all downstream impoundments. The Rusfors dam (Figures 2b and 2f) has a function for both seasonal storage and as a run-of-river impoundment, with subdaily to weekly variations in water levels following variation in demand for hydropower production, and a drop in water levels in spring as stored water is released. The Tuggen hydropower station and dam (Figures 2c and 2g) represents a typical run-of-river impoundment with frequent hydropeaking, exhibiting subdaily to weekly variation in water levels and flow throughout the year (Figure 2g). The Stornorrfors hydropower station is unique as it receives the flow from the free-flowing Vindel River (Figure 1b). The impoundment of Stornorrfors, thus, exhibits short-term variation caused by hydropeaking (Figure 2h) as well as seasonal variation reflecting the unregulated flow of the Vindel River (Figure 2d).

3. Methods

The work to meet our objectives proceeded in multiple steps, and collaboration among stakeholders was crucial at several of them as illustrated in Figure 3. We started out formulating the visions and goals, preceding the inventories and modeling required. After extensive field work, costs and benefits of restoration measures were assessed, and a joint evaluation of the potential risks and uncertainties of implementing the measures was done. All this forms the basis for prioritization and implementation of rehabilitation measures, but these later steps were beyond the scope of the present study. However, Sweden implemented legislative changes to renegotiate hydropower permits in 2019 and the environmental flow assessments performed will assist in the relicensing process where increased consideration of environmental remediation is required.

3.1. Collaboration and Management

A "Ume River project" was initiated in 2012 by local communities along the river, working in collaboration with authorities, nature conservation organizations, and hydropower operators, with the aim to rehabilitate riverine ecosystems in accordance with the Water Framework Directive (EU 2000/66) (Widén et al., 2016). This collaboration permeated the entire project (Figure 3), and the management method used was similar to the "Strategic Adaptive Management" described by Kingsford and Biggs (2012). The collaboration was later formalized by forming the association "Föreningen Samverkan Umeälven" (The Association for Collaboration along the Ume River) where municipalities, local fishery management associations, local nature conservation associations, and Umeå University are represented. The association collaborates with hydropower operators and water management authorities and coordinates several ongoing ecological rehabilitation projects in the river system.

3.2. Visions and Objectives for River Ecosystems With Hydropower Production

The vision for the work, determined in collaboration (Figure 3), was to make riverine ecosystems resemble conditions in free-flowing rivers, except for unavoidable consequences of continued hydropower production. Based on previous analyses of which habitats and ecosystem functions are most negatively affected by regulation (Widén et al., 2016), we focused on increasing the area of (a) aquatic lotic habitat (reaches with high flow velocity, compensating for the loss of rapids), (b) riparian vegetation (contributing to biodiversity and stabilizing riverbanks), and (c) enhancing connectivity enabling fish migration. Field surveys of the potential for gains in these habitat

10.1029/2021WR030297

Table 1
Dry Channels and Nature-Like-Channels Related to Hydropower Stations in the Ume River, Blue Shading

Hydropower station	Length (km) nature like channel (n) or dry channel (d)	Release of farmed salmon (Quantity)	Release of farmed grayling (Quantity)	Release of farmed brown trout (Quantity)	Release of farmed Arctic char (kg)	Ranking of fishway	Downstream river length (Ld, km)	Upstream river length (Lu, km)	Downstream river length with lotic habitat, (Ld, km)	Upstream river length with lotic habitat, (Lu, km)	Salmon fish factor	Brown trout fish factor	Grayling fish factor	Arctic char fish factor	Whitefish, pike, perch, burbot, eel and fresh-water pearl mussel Fish factor	Sum fish factor
Stornorrfors	8.0 (d)	94000	20000	22000	0	(1)	24	470	*	**	13192	3958	6156	***	25549	48855
Pengfors	0.1 (d)	14000	750	0	0	(11)	470	11	**	*	23	7	11	***	76	117
Harrsele	0.6 (d)	0	750	250	0	(12)	3	11	*	0.3	***	3	5	***	98	106
Bjurfors Nedre	0	0	6500	0	0	(16)	11	7	0.3	1	***	2	3	***	33	38
Bjurfors Övre	0	0	5000	0	0	(4)	7	50	1	1.5	***	3	4	***	2035	2042
Tuggen	3.2 (n)	0	3500	0	0	(14)	50	18	1.5	0.4	***	0	0	***	63	63
Hällforsen	0.3 (d)	0	2500	500	0	(9)	18	6	0.4	0.5	***	3	5	***	155	163
Betsele	0.2 (d)	0	3000	500	0	(13)	6	7	0.5	1.5	***	5	8	***	92	105
Bålforsen	0.2 (d)	0	3000	750	0	(10)	7	19	1.5	1.6	***	1	2	***	134	137
Rusfors	3.0 (n)	0	3500	2000	0	(2)	19	122	1.6	41	***	819	1274	***	4383	6476
Grundfors	2.5 (d)	0	1500	2500	0	(5)	122	64	60	41	***	31	48	***	429	508
Stensele	0	0	1500	1500	0	(15)	122	13	60	5.7	***	2	4	***	44	50
Storuman	10.0 (d)	0	0	0	0	(17)	13	6	5.7	1	***	1	1	***	26	28
Storjuktan	60.0 (d)	0	0	2000	0	(3)	6	80	1	2	***	4	6	***	4458	4468
Gardiken	0.7 (d)	0	0	0	0	(8)	80	30	2	8	***	14	22	23	164	223
Bleriken/Gejmån	8.0 (d)	0	0	0	0	(18)	30	3	8	0.5	***	1	1	5	17	24
Ajaure	0.6 (d)	0	0	10000	0	(7)	30	64	8	31.2	***	31	48	20	134	233
Överuman-Klippen	6.0 (d)	0	0	200	920	(6)	64	37	31.2	0	***	0	0	247	175	422
Abelvattnet	n/a	0	0	0	0	(19)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Note. Ranking and priorities according to Pini Prato et al. (2011) and whether channels are planned to be used as migration solutions (blue shading). Yellow shading shows statutory fish release according to water law per hydropower station in the Ume River. Columns with green shading describes river length with lotic habitat downstream and upstream hydropower plants. Fish factor (F) per salmonid species is presented per hydropower station. The last column consists of the sum of fish factors of all species included in the analyses.

*Lack of lotic habitat. **Migration to the Vindel River. ***Species never been present in the Reach.

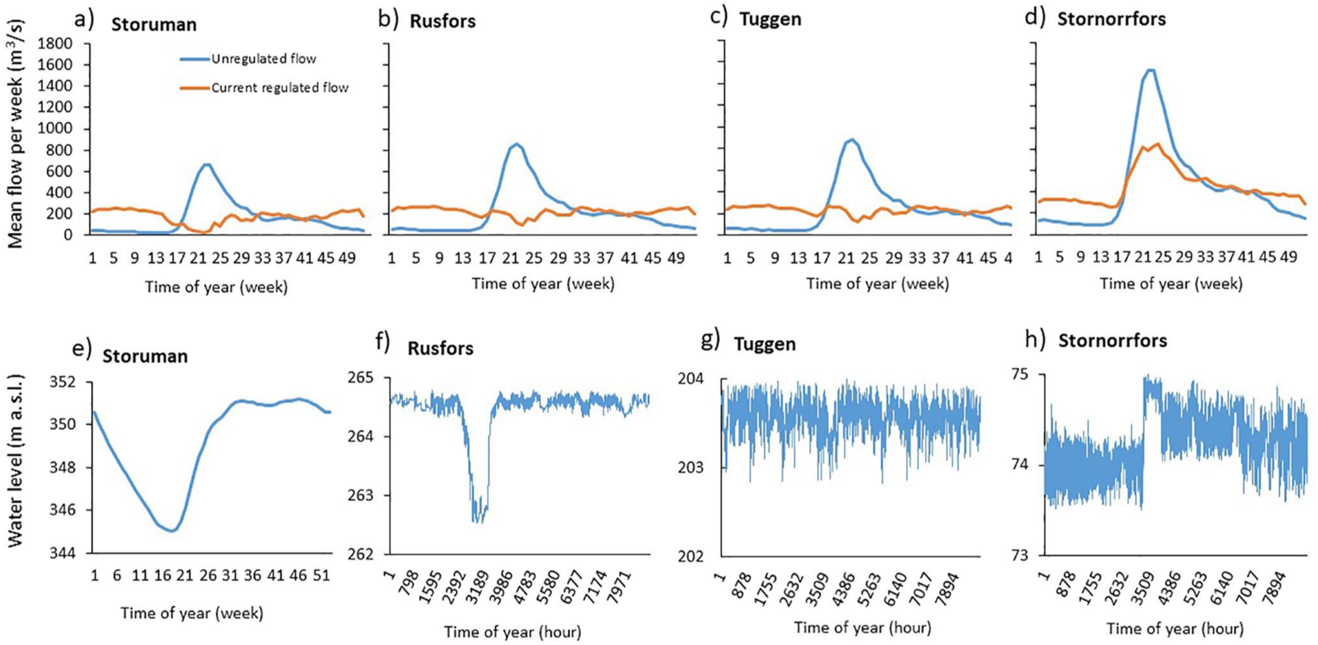

Figure 2. Variation in discharge over the year using weekly data for the period 1962–2014 for (a) the storage reservoir Storuman and the run-of-river impoundments (b) Rusfors, (c) Tuggen, and (d) Stornorrfors. In (a–d), blue lines represent modeled unregulated flow and red lines represent regulated flow. Changes in water level (m above sea level) for (e) the storage reservoir Storuman and the run-of-river impoundments (f) Rusfors, (g) Tuggen and (h) Stornorrfors. Water-level data for Storuman is based on means per week for the period 1962–2008, and for the run-of-river impoundments hourly data for the hydrologically normal year of 2010 are displayed.

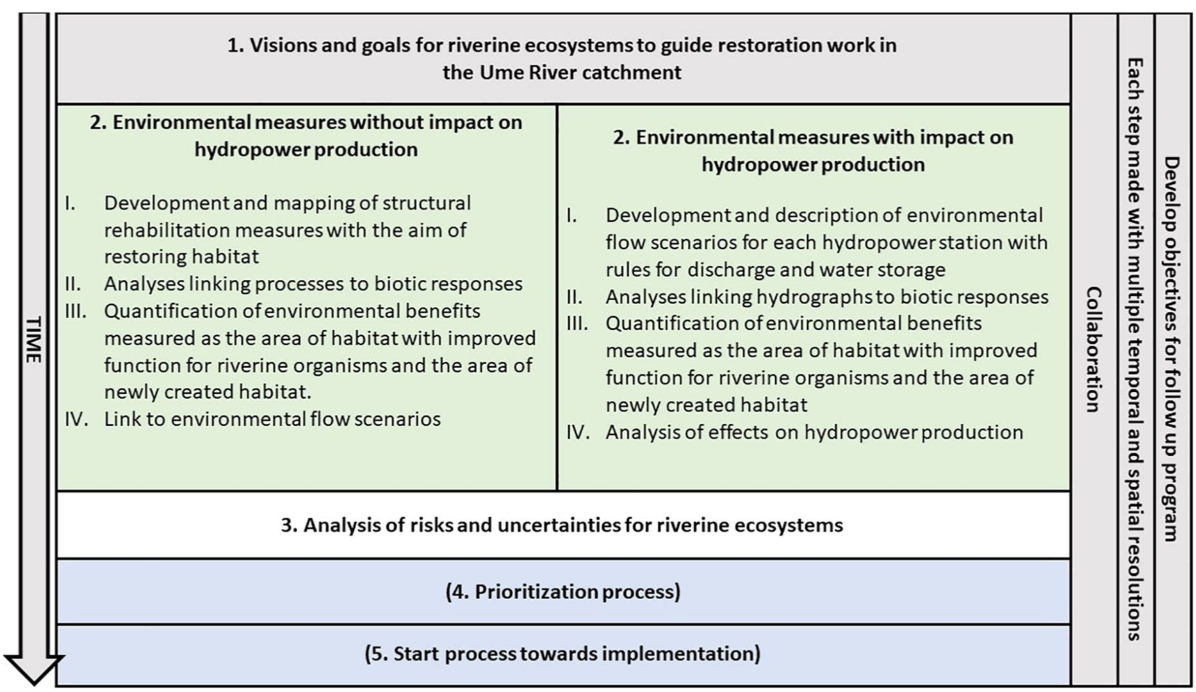

Figure 3. Schematic illustration of the process toward assessing the costs and benefits of environmental flow options for the regulated Ume River catchment. Collaboration among stakeholders was crucial for each step in the process, whereas prioritization and implementation of the measures were beyond the scope of the study.

Table 2
Environmental Flow Components Used in the Modeling With a Short Description of How They Were Implemented in Hydropower Operational Rules, and the Ecological Processes Expected to Benefit From the Action

Environmental flow component	Description of hydropower operational rules formulated per hydropower station.	Ecological processes expected to benefit from the action	Method for calculation of environmental benefits (section in main text)
A	Restrictions on zero-flow events in run-of-river impoundments between Storuman-Stornorrfors (13 hydropower stations)	Habitat for lotic organisms, flow velocity, oxygenation, sediment dynamics	II, III, IV
	Discharge through turbines exceeding MALF or Q_{min}		
B	Restrictions on zero-flow events in run-of-river impoundments along the entire river (storage impoundment included)	Habitat for lotic organisms, flow velocity, oxygenation, sediment dynamics	II, III, IV
	Discharge through turbine ≥MALF or Q_{min}		
C	More natural water-level variation (spring flood peak and lower summer levels) from May to September	Establishment of riparian vegetation	I
D	Discharge into technical fishways (throughout the year), 3% of unregulated runoff	Connectivity and dispersal of fish. Gain of new lotic habitat upstream and downstream.	VI
E	Discharge into technical fishways (throughout the year), 6% of unregulated flow	Connectivity and dispersal of fish. Gain of new lotic habitat	VI
F	Discharge into bypass channels with seasonal variation in flow (throughout the year), 1%–12% of unregulated flow	Connectivity and dispersal of fish and improved function of lotic habitat in the channel	V
G	Discharge into bypass channels with seasonal variation in flow (throughout the year), 6–20 of unregulated flow.	Connectivity and dispersal of fish and improved function of lotic habitat in the channel	V
H	Seasonal flow variation (spring %flood peak and lower winter flow)	All processes but connectivity issues remain along with slow flow velocity in reservoirs	N/A
I	Unregulated flow (mimicking the natural flow regime) with dams remaining	All processes but connectivity issues remain along with slow flow velocity in reservoirs	N/A

Note. Detailed information of flow releases to bypass channels, fishways, side channels etc. is presented in the Supporting Information S1. MALF = mean annual low flow, Q_{min} = minimum flow that can go through turbines.

types and functions were made for each individual impoundment (Hall et al., 2011). The free-flowing Vindel River was used as a reference representing a system unaffected by river regulation. The Vindel River is of similar discharge and length compared to the mainstem Ume River, and the rivers run parallel from headwaters until they join about 30 km from the mouth (Figure 1b). Available evidence suggests the rivers had similar ecosystems before the Ume River was dammed (Jansson et al., 2000; Nilsson & Jansson, 1995; Sjörs, 1973; Sjörs & Nilsson, 1976; Sundborg, 1977).

3.3. Environmental Flow Scenarios Consisting of "Building Block" Combinations

We identified environmental flow measures with the potential of promoting ecosystem functions or habitat conditions for riverine organisms called "environmental flow components" (EFC) (Table 2). Each EFC corresponds to a flow aspect, that is, a "building block" (Tharme & King, 1998) that promotes a process or condition benefitting riverine organisms (Table 2). For comparison, we included a scenario with the aim to model unregulated flow conditions. In the modeling phase, each hydropower station was theoretically run by a set of hydropower operational rules (HOR) determined by technical conditions and legal permits regulating hydropower production (Table S2). This included factors such as fall height, spillgate and turbine capacity, and turbine type and efficiency. Turbine capacity was defined as the range in discharge possible to use for electricity production. The lowest possible flow through turbines without the risk of damage was called Q_{min} and the flow equivalent to turbine maximum capacity was called Q_{max} (Table S2). Flows lower or higher than this were released through spillgates in the models. EFCs were formulated with consideration of HORs to minimize losses in electricity production (Table S2). Bypass channels were divided into reaches with reduced or ceased flow called dry channels, natural-like channels, and blocked side channels (Table S1). EFCs were combined into different environmental flow scenarios, each of them covering all 19 hydropower stations in the river system.

3.4. Calculation of Environmental Benefits

We calculated the expected environmental benefits of all EFCs as the area of newly created habitat and habitat with improved quality based on field surveys of riparian zones, composition of the channel bed, and flow velocity. We quantified the projected gains in the area of multiple types of habitat:

1. Riparian vegetation: Based on inventories of impoundment shorelines, we identified all shoreline areas with shallow slope and fine-grained soils along all run-of-river impoundments (Widén et al., 2016). We assumed that riparian vegetation would establish on these shorelines after introduction of variation in water levels mimicking natural variation from May to September. This would help stabilize banks, reduce erosion, and increase biodiversity in the riparian zone (Hubble et al., 2010; Naiman et al., 1993), and riparian vegetation is known to reduce temperature variation by shading (Bowler et al., 2012) and provide organic matter to aquatic food webs (Wallace et al., 1997), although the importance of latter benefits is poorly known in large rivers. For vegetation establishment, we assume that structural rehabilitation with large boulders protecting riparian zones from ice erosion and waves will be done at some sites. Presently, the long duration of inundation at low riparian elevations, combined with disturbance from water-level variation and ice scour, prevents vegetation establishment (Jansson et al., 2000). The methodology is described in Supporting Information S1, "Implementing more natural water-level variation to restore riparian vegetation in run-of-river impoundments."
2. Lotic habitat in outlet channels: The potential increase in the area of lotic habitat of shallow depths (<2.0 m) and flow velocity exceeding 0.8 m/s in outlet channels (tailwater reaches) below hydropower stations was assessed based on bathymetric surveys. These areas were considered new lotic habitat, given the introduction of rules for minimum discharge to allow for a minimum flow velocity at all times. Presently, there may be long periods of zero discharge (Widén et al., 2021). In calculating the area, we also assumed structural modification, such as widening the channel to create shallow areas and addition of boulders and dead wood, would be done to improve conditions for lotic species such as grayling. The methodology is described in Supporting Information S1, "Creation of lotic habitat in outlet channel at the Bjurfors Övre hydropower station."
3. Lotic habitat in impoundments: The potential to restore reaches with high flow velocity (defined as river gradient being 0.1% or higher) was inventoried and their area was estimated. The entire length of run-of-river impoundments were surveyed using a boat by two persons visually inspecting channel-bed conditions during the summers of 2012–2014. The definition of lotic habitat was water depths <2.0 m with a channel bed consisting of sand, gravel, pebbles/cobbles, or boulders without accumulation of fine sediments. This implies that flow velocities are high enough to prevent the beds to be clogged by fine sediment or that fine sediment is flushed during high-velocity events. Presently, there may be long periods of zero discharge in reaches with potentially high flow velocity, leading to stagnant water.
4. Improved ecosystem functions in bypassed reaches: We calculated the area of dry channels and blocked side channels with reduced discharge due to flow being diverted to hydropower stations, assuming these reaches would become a suitable habitat for lotic species after introduction of a mandated minimum flow suggested in some EFCs. In this, we assumed that structural modification to adapt the morphology of the channel to the minimum discharge would be carried out where needed. More information on this is found in Supporting Information S1, "Seasonal flow variation in the Jukt River."
5. Enhancing connectivity: We considered allocating discharge to fish passages in cases where passage across a dam wall would reconnect fish populations with suitable habitat upstream of the dam. We calculated the gain as both the length of river reaches made available to migrating fish and the area of lotic habitat created by the fish passage in cases where habitat would consist of side channels with a diversity of sediment sizes. The design and cost of potential passage solutions were not considered, but the purpose was to put a price tag on the water flow needed. In calculating the river length made available for migration, we assumed that barriers such as road culverts, as well as dams and weirs built for purposes other than hydropower identified in our catchment-wide inventory, would be modified to allow passage. Additionally, we calculated a Priority Index (IP_s) for the Ume River catchment hydropower stations, following Pini Prato et al. (2011). Using the equation $IPs = \left(Ld + Lu\right) \times \frac{Lu}{Ld \times H} * F$, where Ld is the length of the continuous river reach downstream the barrier (distance to the first downstream barrier), Lu is the length of the continuous river reach upstream the barrier

(distance to the first upstream barrier), and H the height of the barrier. F is a fish factor calculated based on the presence of species, represented by a conservation value (V_C) and the mobility of native migratory fish species (*Mob*) (Näslund et al., 2013). In order to weight the importance of fish populations of the examined reach, composed by i species, we used the equation $F = \sum k_i = \sum \left(Mob_i + Vc_i\right)^2$, where k_i shows the importance of connectivity for a certain fish species based on its tendency of migration and value of conservation. The fish species we considered were Arctic char (*Salvelinus alpinus*), brown trout (*Salmo trutta*), burbot (*Lota lota*), eel (*Anguilla anguilla*), grayling (*Thymallus thymallus*), perch (*Perca fluviatilis*), pike (*Esox lucius*), salmon (*Salmo salar*), whitefish (*Coregonus lavaretus*), and also the freshwater pearl mussel (*Margaritifera margaritifera*).

3.5. Consequences of e-Flows on Hydropower Operation

We ran scenarios for hydropower production for all 19 hydropower stations in the Ume River catchment simultaneously, since changing the flow at one hydropower station may result in both losses and gains at other stations, both upstream and downstream. Also, benefits of environmental flow measures at one station may have cascading effects along the river. For example, flow release at one dam could facilitate flow release further downstream. We ran all models with weekly historical hydrological data (runoff during 1962–2007) for all scenarios, except for scenarios that included EFCs requiring hourly flow data to calculate the costs. These were run using data from three years, representing a typical dry, a normal, and a wet year for the 13 run-of-river impoundments. Modeling was done using the software ProdRisk, which was developed by SINTEF, Norway, and is in operational use by many of the largest hydropower producers in the Nordic power market. The program was run in a market mode with energy prices exogenously given from the hydropower company Vattenfall. ProdRisk allows scheduling within a geographical area assuming no internal transmission grid bottlenecks. The software uses stochastic dual dynamic programming (Gjerden et al., 2015) to solve the optimization problem by combining system simulation and strategy computation to find an optimal flow release strategy. The overall problem is achieved by dividing the general problem into smaller optimization problems that are solved by using linear programming and coordinated by using the principle of Benders decomposition (Rahmaniani et al., 2017). The main inputs are inflows to the reservoirs and market prices for electricity. The outputs are scenarios for reservoir operation, hydropower production, marginal value of water in different reservoirs, and a profit distribution. The models were run in collaboration with hydropower operators in the river system.

Our models were validated against records of observed discharge and electricity production at the hydropower stations. We ran the model of the Ume River system with current hydropower operational rules and adjusted it by comparing with observed regulated flows until model results closely matched observed production (within 0.2 GWh or less than 0.0001% deviation). We then compared electricity production and flow in each scenario with current regulated conditions (called scenario 0). We analyzed the water economy of the river system by checking the volume of stored water in the large reservoirs Storuman, Gardiken, and Storjuktan. The purpose was to check the availability of water during dry years, potentially making hydropower operation rules difficult to implement. The years 1970, 1994, 1996, 2003, and 2006 were unusually dry, but all models met the HOR, even though sometimes with small margins.

We obtained results for each scenario per hydropower station in the river as impact on electricity production, effect, volume of water storage in reservoirs, and flow through turbines and spillgates for each of the 46 years run in the models. Furthermore, data were obtained to analyze changes in water-level variation and water volume in the impoundments with hourly resolution. The scenario with natural variation in water levels during the growing season was only run for the run-of-river impoundments using hourly data outside of ProdRisk. Altering water-level variation affects hydropower production by altering fall height and constraining opportunities for hydropeaking, since the available amplitude for hydropeaking during the end of summer period decreased (Widén et al., 2016). The results of these calculations are presented in Supporting Information S1, “Implementing more natural water-level variation to restore riparian vegetation in run-of-river impoundments.”

The outcomes were distributed over five different price ranges, occurring at different times during day and night, reflecting variation in demand for electricity. No account was taken of the capacity to meet variation in ambient electricity demand, but conclusions about impacts on this ability can be drawn from analyses of temporal changes in hydropower production compared to regulation with current conditions.

4. Results

We modeled different combinations of EFCs, which resulted in a total of 28 scenarios (Tables 2 and 3). The gain in habitat for riverine species varied from 64 ha (Scenario 3) to 947.9 ha (Scenarios 17 and 18). Ecological benefits for scenarios 8, 9, and 19 were not calculated. Loss of electricity production varied from 0.5% (Scenario 1) to 20.6% (Scenario 9, unregulated conditions) and loss of revenues varied from 0.7% (Scenario 1) to 23% (Scenario 9) as a mean during 1962–2007. EFC A and B constituted the base, being included in 21 scenarios (Table 3).

4.1. Environmental Benefits

Implementing restrictions against zero-flow events by introducing rules mandating a flow corresponding to, or exceeding, the minimum mean annual low flow at all hydropower stations in the catchment was estimated to result in the creation of 354.9 ha of habitat suitable for lotic species (Table 4). The area included outlet channels below hydropower stations, being areas with high flow velocity, reaches in impoundments with high flow velocity as a result of remaining fall height or narrow sections, and areas around tributary mouths (Table 4; Supporting Information S1, "Creation of lotic habitat in the outlet channel at the Bjurfors Övre hydropower station"). This area of lotic habitat would represent a more than threefold increase (from 140 to 494.9 ha), but would still only constitute 7% compared to pristine conditions (based on the preregulation river length having a gradient >0.1%). Introducing more natural timing of water-level variation in the run-of-river impoundments from May to September, better reflecting conditions in free-flowing rivers, was projected to result in the establishment of 64 ha of new riparian vegetation along the river (Table 4; Supporting Information S1, "Implementing more natural water-level variation to restore riparian vegetation in run-of-river impoundments"). This represents a 66% increase and would increase the total area of riparian vegetation along the river to be 20% of preregulated conditions. Flow release into bypassed reaches that had been laid dry, with reduced discharge and sometimes stagnant water, would result in 161.7 ha of lotic habitat in reaches with a sufficient gradient to result in turbulent flow (Table 4; Supporting Information S1, "Seasonal flow variation in the Jukt River"). The flow released into these reaches was assumed to exhibit seasonal variation mimicking natural flows.

Building fishways would potentially make 437.3 ha of lotic habitat available to migrating fish populations. Based on prioritization indices for connectivity (Table 1), we suggested the construction of passages at four hydropower stations, that is, Rusfors, Storjuktan, Bjurfors Övre, and Grundfors. At Stornorrfors hydropower station, there is an existing fishway, giving fish access to 470 km river length in the tributary Vindel River (excluded in the calculated area of 437 ha). For the remaining 12 hydropower stations, where discharge into bypassed reaches and side channels are suggested, we did not consider additional discharge for fishways, since passage solutions might take advantage of the flow already allocated. Prioritization showed that the most efficient locations for reestablishing connectivity were at the Bjurfors Övre, Rusfors, Storjuktan, and Grundfors dams (Table 1), based on the potential for enhancing dispersal and mobility of natural fish species in the Ume River.

Summing the different categories of potential environmental benefits per impoundment (Figure 4a) shows where in the catchment they would occur and the spatial co-occurrence among them, forming a basis for prioritization. The results show that Rusfors, the Jukt River, Storuman, and Storjuktan have the largest potential gains in riverine ecosystem areas in the river system. Rehabilitation of lotic habitat as a result of requirements for minimum discharge through hydropower stations (Table 4, EFC A and B) would give the largest increase in area in the Bjurfors Övre (36 ha), Rusfors (67 ha), Grundfors (112 ha), and Stensele (35 ha) impoundments (Figure 4b). Rusfors has the largest potential for new establishment of riparian vegetation (40 ha) in response to changes in water-level variation (Figure 4d; Table 4, EFC C). Finally, the potential of gaining habitat by flow release into dry and bypassed reaches and fishways (Table 4, EFC D, E, F, and G) was largest in the Rusfors (260 ha) and in the Jukt Rivers (114 ha) (Figure 4c).

4.2. Impact on Hydrology (Flow)

Hydrographs of mean weekly flows (using modeled flow data from 1962 to 2007) for the most important scenarios are presented in Figures 5a–5d. All environmental flow scenarios except the scenario with seasonal variation in flow (scenario 19) and the natural flow regime scenario representing unregulated conditions (scenario 9) resulted in relatively small hydrological changes compared to current conditions (scenario 0). The hydrographs for

10.1029/2021WR030297

Table 3

Description of the Scenarios With Various Combinations of Environmental Flow Components, and the Projected Consequences of Their Implementation Measured as the Area of Habitat Gained, and the Associated Change in Hydropower Production and Revenues

Scenario	Environmental flow components	Description and spatial distribution	Restored area (ha)	Absolute change in electricity production (GWh)	Proportional change in electricity production (%)	Proportional change in revenue from hydropower production (%)
0		Current hydropower operation rules. Mean hydropower production (1962–2008) was 7.7 TWh/year, and the mean revenue was 246.4 million euro				
1	A	Minimum discharge of at least mean annual low flow to avoid zero-flow events downstream of Storuman [a]	354.9	−39.4	0.5	0.7
2	B	Minimum discharge of at least mean annual low flow to avoid zero-flow in all hydropower stations [b]	354.9	−75.9	1.0	1.2
3	C	More natural water-level variation (spring flood peak and lower summer levels) from May to September [a]	64	−77.0	1.0	0.9
4	D	Discharge to fishways (technical or nature-like side channels; flow throughout the year). 3% of mean annual unregulated discharge [b]	275.6	−73.7	0.9	0.9
5	E	Discharge to fishways (technical or nature-like side channels; flow throughout the year). 6% of mean annual unregulated discharge [b]	275.6	−219.9	2.9	2.7
6	F	Discharge with seasonal variation into bypass channels affected by diversions (throughout the year). 1%–12% of mean annual unregulated discharge [b]	161.7	−84.9	1.1	1.1
7	G	Discharge with seasonal variation into bypass channels affected by diversions (throughout the year). 6%–20% mean annual unregulated discharge	161.7	−169.5	2.2	2.2
8	H	Seasonal flow variation (spring flood peak and lower winter flow) [b]	N/A	−415.0	5.4	7.3
9	I	Unregulated flow (mimicking the natural flow regime) with dams remaining [b]	N/A	−1586.0	20.6	23.0
10	A + C	See above for combination	510.6	−115.3	1.5	N/A
11	A + D	See above for combination	510.6	−100.2	1.3	1.4
12	A + E	See above	630.5	−150.5	2.0	2.1
13	A + F	See above	516.6	−158.0	2.1	2.2
14	A + G	See above	516.6	−297.2	3.8	4.0
15	A + D + F	See above	792.2	−240.6	3.1	2.9
16	A + E + G	See above	792.2	−410.7	5.3	5.5
17	A + C + D + F	See above	947.9	−289.7	3.8	N/A
18	A + C + E + G	See above	947.9	−487.7	6.3	N/A
19	A + H	See above	N/A	−450.0	5.8	8.0
20	B + C	See above	510.6	−152.9	2.0	N/A
21	B + D	See above	510.6	−134.0	1.7	2
22	B + E	See above	630.5	−190.0	2.4	2.7
23	B + F	See above	516.6	−190.0	2.4	2.7
24	B + G	See above	516.6	−321.0	4.1	4.3
25	B + D + F	See above	792.2	−244.4	3.2	3.4
26	B + E + G	See above	792.2	−432.2	5.6	5.8
27	B + C + D + F	See above	947.9	−321.4	4.2	N/A
28	B + C + E + G	See above	947.9	−509.2	6.6	N/A

[a]run-of-river impoundments downstream of Storuman hydropower station. [b]all hydropower stations.

Table 4
Explanation of the Projected Catchment-Level Environmental Benefits of Different Environmental Flow Options

Environmental flow measure	EFC [a]	Type of ecosystem	Explanation	Area (ha)	River length (km)	Flow path
Minimum discharge of at least mean annual low flow to avoid zero-flow events downstream of Storuman.	A, B	Lotic habitat in outlet channels	Area of outlet channels can serve as habitat for lotic species after structural modification of channel beds and restriction on zero-flow events	107.1	13.3	Turbines
		Lotic habitat in impoundments	Areas with potential for high flow velocity that can serve as habitat for lotic species with restriction on zero-flow events	240.4	14.0	Turbines
		Tributary outlets in impound-ments	Area of tributary outlets that can serve as habitat for lotic fish species if the intensity of hydropeaking is reduced as a result of minimum discharge	7.4	-	Turbines
More natural water-level variation (spring flood peak and lower summer levels) from May to September	C	Riparian vegetation	Area of impoundment shoreline deemed suitable for riparian vegetation establishment (silty-sandy soils and less than 90 degree inclination) with water-level variation that allows for plant establishment	64.0	-	Turbines
Discharge into bypassed channels (with seasonal variation in flow)	F, G	Reaches with reduced discharge due to diversion	Area of bypassed channels that could serve as habitat for lotic species following release of minimum flow discharge	161.7	104.5	Spill gates
Discharge to fishways	D, E, F, G	VII	Area of lotic habitat for migrating fish species made available by construction of fishways.	437.3	36.6	Spill gates

[a]Letters refer to Table 2.

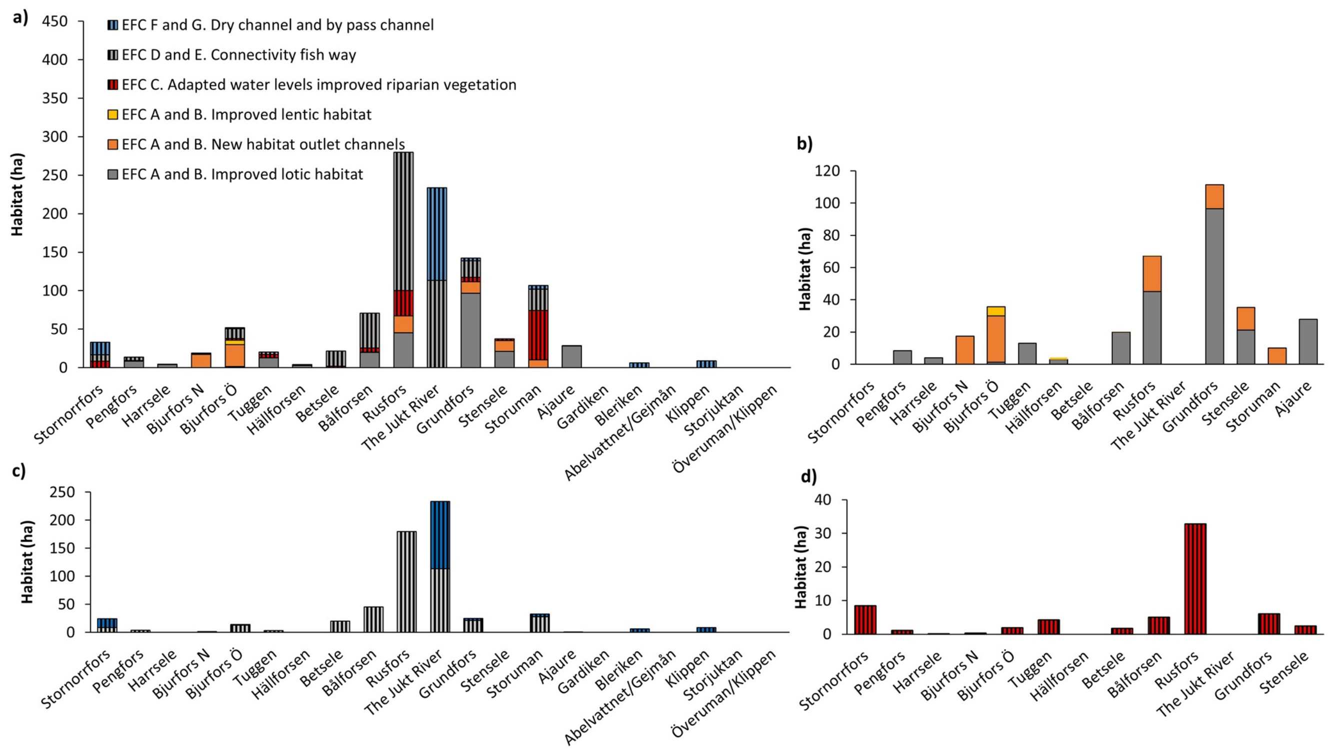

Figure 4. Projected environmental benefits from the different environmental flow components (EFC) summarized as the expected increase in area per reservoir. (a) All benefits for each EFC per impoundment summed up for the entire catchment. (b) Environmental benefits covering EFC A and B, that is, lotic habitat gained in outlet channels, impoundments and in tributary mouths in impoundments. (c) Environmental benefits covering EFC D and E, that is, area of lotic habitat made available to migrating fish by fishways and environmental benefits covering EFC F and G, that is, area made available in dry channels and by pass channels. (d) Environmental benefits from EFC C, that is, area of riparian vegetation gained by more natural variation in water levels from May to September.

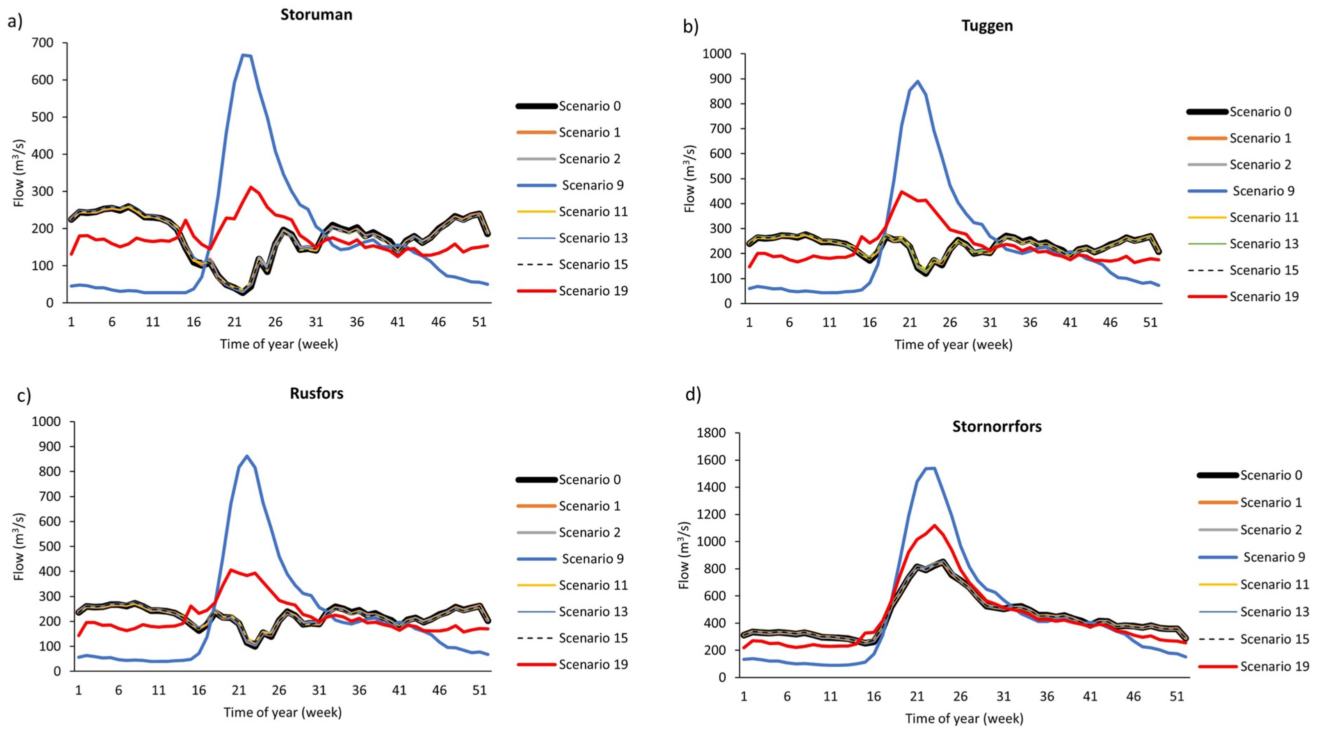

Figure 5. Hydrographs of environmental flow scenarios for (a) the Storuman. (b) The Rusfors, (c) the Tuggen and (d) the Stornorrfors hydropower stations. Hydrographs describing current conditions (scenario 0), restrictions on zero-flow events downstream of Storuman (scenario1), restrictions on zero-flow events in all hydropower stations (scenario 2), run-of-river (no storage capacity in reservoirs used; scenario 9), a combination of restrictions on zero-flow events downstream of Storuman and discharge to fishways (scenario 11), combination of restrictions on zero-flow events downstream Storuman and spill water to bypass channel (scenario 13), combination of restrictions on zero-flow events downstream of Storuman, discharge to fishways and bypass channels (scenario 15), combination of restrictions on zero-flow events downstream of Storuman and seasonal flow variation (Scenario 19) (Table 3). Flow lines in scenarios 0, 1, 2, 11, 13, 15 are highly similar and follow each other closely.

the run-of-river hydropower stations indicate that introducing restrictions against zero-flow events would result in a small spring-flood occurring in May (Figure 6c).

4.3. Impact on Electricity Production and Economic Revenues

Table 3 summarizes the results of the ProdRisk models that projected the effect of integrating environmental flow measures into hydropower operational rules on hydropower production per scenario. Introducing rules for minimum discharge at hydropower stations downstream of Storuman to avoid zero-flow events would result in a mean loss of 0.5% per year and 0.7% of the mean annual revenue from hydropower compared to current conditions (Table 3, EFC A). Implementing the same measure at all hydropower stations in the catchment would increase the mean loss to 1.0% of the production and 1.2% of the revenue, respectively (Table 3, EFC B). Introducing more natural water-level variation in all run-of-river impoundments from May to September to facilitate establishment of riparian vegetation would cost 1.0% of mean annual production (0.9% loss of revenues; Table 3, EFC C), whereas the cost for flow allocated to the prioritized fishways (3% of mean annual discharge) would be 0.9% in terms of both production and revenue (2.9% and 2.7% if flow would be increased to 6% of mean annual discharge; Table 3, EFC D, E).

Allocating flow to bypassed reaches (1%–12% of mean annual discharge) would cost 1.1% per year both in the loss of production and revenue, and these figures would increase to 2.2% per year if flows are increased to between 6% and 20% of mean annual flow (Table 3, EFC F and G). Losses in electricity production in the models are primarily caused by release of water into bypassed reaches and to fishways (thus bypassing turbines) and by forcing production to occur at low turbine efficiency. There was a tight correlation between production losses and amount of spill water (i.e., flow that do not pass turbines) per scenario ($r = 0.97$, $P < 0.001$, $n = 10$ scenarios, Pearson product-moment correlation). In all these scenarios, we assume that the environmental flow component

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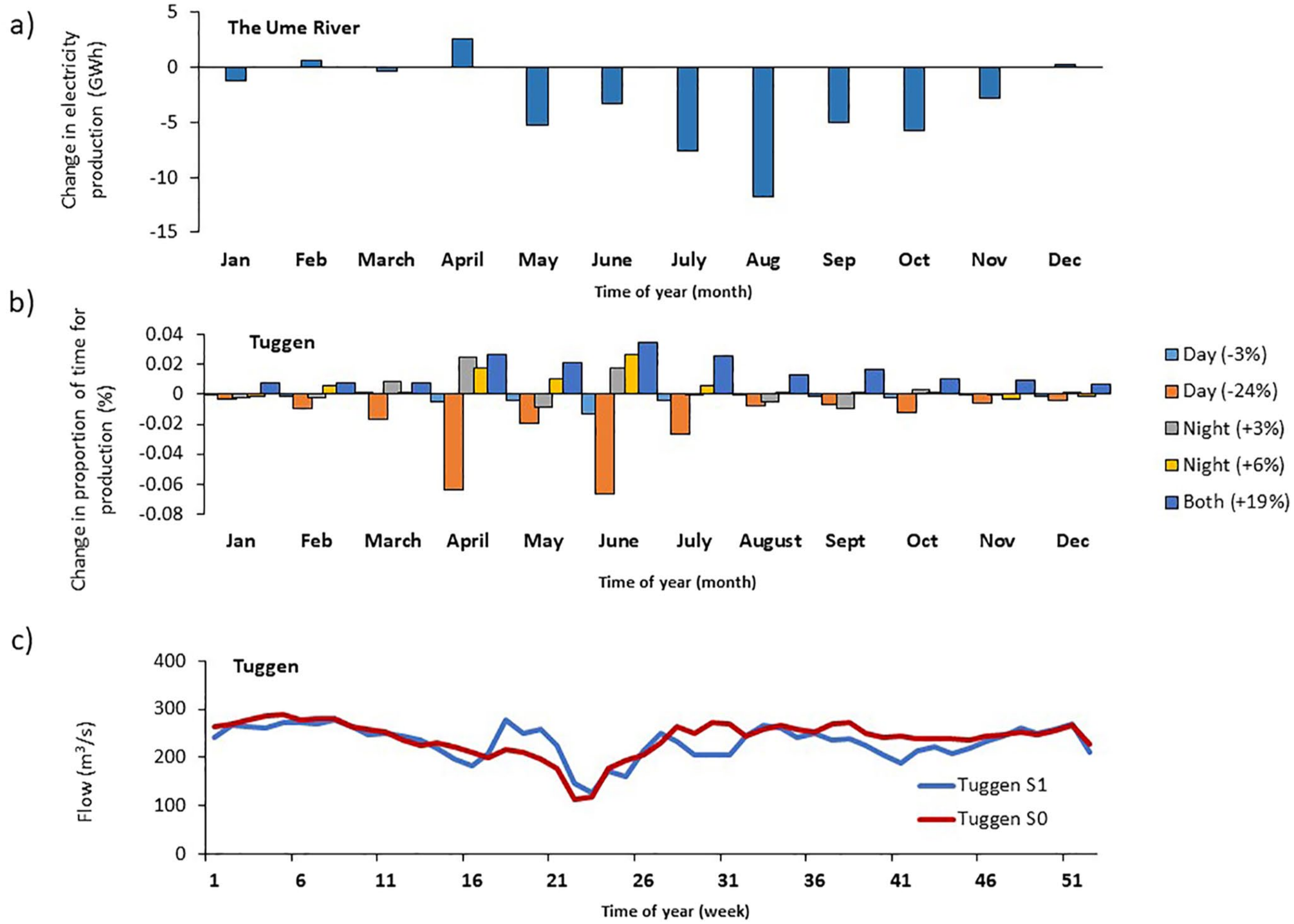

Figure 6. (a) Projected change in electricity production per month in scenario 1 compared to scenario 0 (representing current conditions) for the entire Ume River. (b) Projected proportional change in electricity production per month and in different electricity price categories largely representing the daily timing of production for the Tuggen hydropower station, comparing scenario 1 with scenario 0. (c) Modeled average flow (1962–2014) at Tuggen for scenario 0 and scenario 1.

is implemented at all sites in the catchment as described in the methods. If individual fishways or bypassed reaches would be dropped from implementation, the costs would be proportionally reduced.

We also combined different environmental flow components in scenarios to explore their combined effect on hydropower production. The combinations are found in Table 3, and we just highlight a few examples here: Having restrictions on zero-flow events by mandating minimum discharge at all hydropower stations downstream of Storuman and allocating 1%–12% of mean annual discharge to bypassed reaches in the entire catchment would result in a 2.1% loss of mean annual electricity production (scenario 13), whereas adding flow to fishways to this would increase the loss to 3.1% per year (scenario 15). Combining minimum discharge, more natural water-level fluctuations in run-of-river impoundments along with flow to fishways and bypass channels would give a yearly reduction of 3.8% of electricity production (scenario 17).

Loss of hydropower production in scenario 1 occurred mainly during May to November, with the largest losses during July and August (Figure 6a). Analyses of the timing of hydropower production using price intervals show that production was moved from daytime to nighttime (Figure 6b) in all scenarios where minimum discharge was included as an environmental flow component (Table 4). In Figure 6c, this is exemplified by the Tuggen hydropower station. Here, the hydropower station exhibited a 24% decrease in daytime production under scenario 1. In general, the proportional loss of revenues was higher than the losses in electricity production or 15% higher across scenarios (Table 4), reflecting that hydropower production was moved to time periods with lower electricity prices.

5. Discussion

Our assessment demonstrates that introducing environmental flows in one of the most heavily regulated and fragmented river systems in Europe (Nilsson & Jansson, 1995) would have the potential to lead to an extensive recovery of its riverine ecosystems. This includes actions to increase the area of aquatic habitat with high flow velocity (a threefold increase or larger depending on scenario), increase the area of riparian vegetation (66% increase), and measures to enhance migratory pathways for lotic fish species, with reductions in hydropower production that are limited to up to 3.1% per year (Table 3, scenario 15). It should be noted that the positive responses expected from the environmental flow measures are a function of the scarcity of environmental mitigation measures presently being implemented, and the lack of consideration of natural values during hydropower development of the river system. Our results indicate that environmental mitigation with continued hydropower production would also be possible in other heavily regulated river systems, although the magnitude of expected recovery to mitigation might vary depending on local conditions. Second, in the scenarios, we assume that for each environmental flow component, all prioritized actions in the catchment are implemented. In future implementation, a more restrictive prioritization may be done, for example, dropping a few fishways and bypassed reaches below dams to further reduce the cost.

5.1. Ecological Benefits of Environmental Flow Measures

Mapping environmental benefits at the catchment scale hinges on assumptions of how riverine processes affect biota and should be based on studies of cause-effect relationships (Palmer & Ruhi, 2019). Most environmental flow scenarios, except for the ones mimicking natural flow and spring flood conditions, would entail small changes in the hydrographs compared to the among-year variation in present regulated conditions (Figure 5 and Table 3). The regulated hydrology would be largely maintained with small modifications, but with changes in the daily timing of electricity production. From an ecological perspective, one might question if the projected benefits represent a significant improvement of ecosystem health? First, our suggested measures (e.g., flow in bypass channels and minimum discharge through hydropower stations) would increase the area of reaches with high flow velocity more than threefold, providing habitat for lotic species adapted to rapids and similar ecosystems. Such areas had been reduced to just 3% of preregulation levels. In addition, our environmental flow measures would facilitate fish migration and an about 66% increase in riparian vegetation establishment. We argue that these gains represent vital aspects of riverine ecosystems, and thus, support our claim that improvement of important ecosystem functions is feasible even in heavily regulated river systems (Acreman, Overton, et al., 2014).

We assumed that successful ecosystem rehabilitation, defined as the return of aspects of natural reference conditions (Bunt et al., 1999), would entail both changes in flow operation and structural mitigation measures (Adeva Bustos et al., 2017; Bakken et al., 2012; Bruder et al., 2016). Habitats of riverine organisms depend on both flow and geomorphological conditions, implying changes in flow that may require structural modifications and vice versa (Whipple & Viers, 2019). Ecological benefits may not be realized in the absence of improving structural features of channels and riparian zones. For example, flow release to maintain high and consistent flow velocity may need to be complemented by structural restoration of the river channel to provide habitat for lotic species (Adeva Bustos et al., 2017; Quadroni et al., 2017; Tuhtan et al., 2012; Vehanen et al., 2003).

The environmental flow measure with rules for minimum discharge through hydropower stations (Table 3) served to ensure minimum flow velocity in the stream channel, but will also reduce the rate of change in flow and water levels resulting from hydropeaking. Imposing limits on the speed of alteration of flow or water levels are common measures of environmental flow implementation (Poff et al., 2017). However, by restricting flow and water-level intervals, the ability to go from zero to high discharge and vice versa is also restricted as a result of the inertia of the water volume in the impoundment (Widén et al., 2021).

5.2. Visions, Objectives, and Target

The starting point and key to success in developing environmental flow measures was the collaboration process, where agreement on a vision and *leitbild* for rehabilitation was a prerequisite for further actions (Poff et al., 2010; Richter et al., 2006). Reaching consensus on this was challenging, but without an agreement on the vision being rehabilitating ecosystems to resemble aspects of pristine river ecosystems rather than developing some novel,

10.1029/2021WR030297

more lake-like ecosystem in the impoundments and reservoirs, setting objectives for ecosystem rehabilitation would have been difficult, and the process would likely have derailed.

Constructing and formulating environmental flow measures is difficult and there have been many attempts to answer the question “how much water does a river need?” (Horne et al., 2017; Richter et al., 1997). The "Range of Variability Approach" of Richter et al. (1997) is a structured, stepwise method that aims to mimic aspects of natural flow regimes, using dam operational rules and setting ecological boundaries for changes to the flow regime of the river ecosystem. We used a dual approach in the environmental flow assessment. First, we identified the measures needed to mimic the natural flow regime, which implied minimizing storage capacity in the whole river, resulting in a 20.6% loss of hydropower production (Table 3). In scenario 8 (Table 3), we modeled the introduction of a spring flood, resulting in a 5.8% loss of production. These production losses exceed the maximum set by the Swedish Government in the national strategy for hydropower and riverine environments (Swedish Energy Agency, 2016). The alternative strategy was to accept the fact that the river system will primarily be managed for hydropower production also in the future and consider environmental flow measures with less impact on hydropower production (Acreman, Arthington, et al., 2014). We based the environmental flow measures on analyses of habitat loss and degradation resulting from hydropower production, mapping of remaining natural values, focusing on actions that could be done with minor impacts on electricity production. Hence, the primary focus was on environmental flow measures that allow water to run through turbines. Even though the hydropower production may be lower as a result of production at lower efficiency of turbines and revenues may be lost by enforcing production during parts of the day with lower electricity prices, losses are minimized.

5.3. Issues of Spatial Scale and Temporal Resolution

The spatial scale of models and priorities is important to consider when developing plans for implementing environmental flow measures, and we argued for the catchment as the appropriate level for projections to be realistic, since any reach, impoundment, or reservoir in a river system is hydrologically linked to other parts of the catchment. The suggested environmental flow measures implied both losses and gains in electricity production (Figure 6a) and an environmental flow action resulting in higher production at one station (because it enforced higher discharge) sometimes resulted in production losses at stations further downstream, if the higher discharge from upstream led to spill. This can be exemplified by the Jukt River, where introducing seasonal variation in minimum discharge would result in increased spill in hydropower stations further downstream as flows would exceed turbine capacity during snow melt (Supporting Information S1, “Seasonal flow variation in the Jukt River”). Changes in mandated flows may also change the local efficiency curves, both for better or worse for electricity production.

The environmental flow components were designed to improve ecosystem functions. As long as hydropower operators abide by the operational rules set by our scenarios, the hydropower stations are free to optimize electricity production. Hence, there is a risk that implementing environmental flows using operational rules with weekly time resolution may result in increasing intensity of hydropeaking to compensate for revenue losses, which would not be detected using weekly averages of flow only. To assess this risk, the effects of environmental flow scenarios should be studied at high temporal resolution at specific sites before environmental flow implementation, along with the use of follow-up programs to detect unanticipated negative ecological effects.

Hydrological between-year variation is a complicating factor when implementing environmental flow measures, given considerable differences in the availability of water for electricity production and ecosystem function. Fixed environmental flow rules without adjusting for between-year variation may have unexpected effects and be more costly during hydrologically extreme years. However, some flow measures do not necessarily need to be performed every year and can thus be abandoned in hydrologically unsuitable years. For example, a long-term experiment of how riparian plant communities respond to changes in the frequency and duration of inundation shows that flooding once every 3.5 years was enough to maintain species-rich riparian forest communities in a free-flowing river (Ström et al., 2011), and that legacies of past flooding conditions still remained 19 years after hydrological change (Sarneel et al., 2019). Thus, mimicking spring floods to promote riparian vegetation is likely to have effects lasting several years and could be avoided during dry years to increase cost effectiveness.

In contrast to the example above, most environmental flow options cannot simply be abandoned during dry years. Moreover, unplanned release of water or water shortages could be negative for the ecosystem, electricity production, or infrastructure, as well as eroding trust in the collaboration process. Modeling the consequences of environmental flow implementation over time periods long enough to include hydrologically extreme years help anticipate problematic situations and may be complemented by analyzing historical hydrological records and projections of future conditions with nonstationary hydrological conditions (Poff, 2018). Such analyses will help in identifying conditions when there is insufficient discharge to simultaneously meet needs for hydropower production and environmental flow or runoff events necessitating spill threatening downstream structural restoration efforts to improve ecosystem function. Such knowledge will facilitate managing current and future threats impacting freshwater ecosystems (Reid et al., 2019). Since extreme weather events are expected to increase in frequency as a result of climate change, such effects are essential to consider (Adynkiewicz-Piragas & Bartlomiej, 2020). How can enough flexibility be built into environmental flow rules to be prepared for future extreme events and which magnitude of deviation should be taken into account? Operational rules legally imposing minimum discharges during dry years that end up in lack of water have to be avoided, and water-balance projections could be an important tool (Horne et al., 2017). Managing such situations is a strong argument for integrated management of environmental flows with representatives of hydropower operators, authorities, and research institutions. Despite planning, implementation will remain something of an experiment with potential for unexpected consequences. In the Jukt River, where we have worked to introduce seasonal fluctuations in minimum discharge (Supporting Information S1, "Seasonal flow variation in the Jukt River"), the Land and Environmental Court decided on a five-year probationary period with follow-up programs to ensure the ecosystem function of the new flow regime.

The free-flowing Vindel River joins mainstream Ume River in the Stornorrfors impoundment, the last one before the sea (Figure 1b). The Stornorrfors power station rarely empties water in the spillways and rarely exhibits zero flow. One aspect of this is that during high-flow events in the Vindel River, the remaining hydropower stations in the Ume River hold back discharge or even stop production to be able to run Stornorrfors with minimal spill. This results in zero-flow events in most hydropower stations downstream of Storuman, also affecting the introduction of environmental flow measures, since they generally imply having rules for continuous discharge to provide flow in fishways and bypassed reaches. This demonstrates the need for catchment-level assessments and to have rules for Stornorrfors during hydrologically extreme years (dry and wet).

One of the biggest challenges in the environmental flow assessment was reinstating aspects of natural sediment dynamics (Poff et al., 1997), given the dominance of glacial deposits of coarse sediment in the river valley and cascades of reservoirs acting as sediment traps. Even though we were unable to suggest options for reinstating sediment dynamics in general, we expect that some of the suggested environmental flow options will have positive effects on sediment redistribution. First, we expect that the increase in flow velocity as a result of mandates for minimum discharge through turbines will flush fine sediment from some gravel and pebble channel beds, but did not try to quantify the extent of this. Second, reinstating seasonal variation in flow in the Jukt River will result in increased sediment transport and flushing of fine sediment from channel beds, according to projections. In other river systems, opportunities for reintroducing sediment dynamics may be better.

5.4. Effects on Electricity Production and Revenues

The economic consequences of environmental flow measures have rarely been studied in the same context as environmental benefits for an entire catchment, but it was made possible in this study due to collaboration among relevant stakeholders. In most environmental-flow scenarios, loss of electricity production was small compared to variation in electricity production among years, going from 5.5 TWh in 1970 to 10.2 TWh in 2001 (Figure 1a) to be compared with the predicted losses in scenarios, going from 39 to 1586 GWh (Table 3). The between-year variation is manageable in the present Swedish electricity system, which indicates that at least the scenarios developed in accordance with the designer paradigm of Acreman, Arthington, et al. (2014) should be realistic to implement in the future, especially since runoff is expected to increase as a result of climate change (Andréasson et al., 2004).

Losses in hydropower production as a result of implementing environmental flows were proportionally higher measured in monetary values than measured in electricity production (Table 3). The reason for this was that our constraints force the hydropower operators to produce electricity during time periods with lower prices on the Nordic electricity exchange market NordPool (www.nordpoolgroup.com).

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If more simple rules of thumb are used to estimate effects of introducing environmental flows on hydropower production instead of our catchment-scale simulations using software as ProdRisk, the risk would be that loss of production is miscalculated. For example, we may compare our results for the Ume River with calculations of loss of hydropower production as a result of introducing environmental flows made by the Swedish Agency for Water and Marine Management (Supporting Information S1, "Comparison of methods to calculate electricity production losses"). They used a method where they calculated how much the flow allocated to fish passages, bypassed reaches, and minimum discharge in reaches with reduced discharge would cost using a simplified methodology. However, the simplified calculation led to an overestimation of annual electricity production of 717 GWh using an adjustment index of 8% compared to the actual average production per year (period 1962–2014). More importantly, the simplified procedure does not allow for calculating the consequences of environmental flow measures where the water is still used for electricity production, such as the rules mandating minimum flow through power stations. This requires an optimization program such as ProdRisk and long time series to predict how hydropower operators would respond. Thus, using only simple calculations based on water spilled from power stations would seriously limit the possibility of judging the feasibility of implementing environmental flow measures. Given that the national target for the maximum hydropower production loss due to implementation of environmental flow measures has been set to only 2.3% (1.5 TW; Swedish Energy Agency, 2016), there is a need for high accuracy of methods used to calculate loss of electricity production.

Analyses using hydrological data with hourly time resolution to map the timing of hydropower production show that when introducing minimum discharge rules, hydropower stations are forced to increase the electricity production at night at the expense of daytime production (Figure 6b). This would decrease the capacity for meeting present variation in electricity consumption. If minimum discharge requirements were implemented in all regulated rivers in Sweden, the resulting increase in nighttime hydropower production would have to be met by changes in electricity consumption, perhaps stimulated by price incentives, with lower prices during nighttime. Such changes may be on the horizon, with electrification in societ. altering consumption patterns, for example, with electric cars charging batteries during nights (Stikvoort et al., 2018). Moreover, according to projections of the future electricity system in Sweden, the national grid is expected to be unable to meet peaks in demand, meaning that efforts to move the timing of consumption of electricity to periods of less demand would offload the pressure on the grid during daytime, thus being a contribution to sustainable use of energy resources (Bartusch et al., 2011; Öhrlund et al., 2019).

6. Conclusions

Moving toward sustainable use of freshwater resources and conservation of freshwater ecosystems is becoming even more important in the light of future climate change, putting pressure on strategies for the construction and management of hydropower dams and stations (Grill et al., 2017). Central to our approach was catchment-wide assessments of ecological benefits and costs in terms of loss of hydropower production. The approach would not have been possible without collaboration among multiple stakeholders responsible for or affected by how the river is managed: hydropower operators, water management authorities, and local communities in the river basin.

Our assessment of ecological benefits of introducing environmental flows was based on inventories of both natural values and potential for ecosystem recovery from degradation caused by fragmentation and flow regulation by dams. The suggested measures would have large benefits for key organism groups characteristic of natural riverine ecosystems, including salmonid fish species, other species dependent on lotic aquatic habitats, and riparian plants. However, to enable prioritization of rehabilitation measures, projections of the area of ecosystems gained by implementing different environmental flow options need to be complemented by methods to put price tags on the alternatives. By using novel methods employing software used for planning of hydropower production, we calculated the catchment-scale costs in terms of losses in hydropower production and revenues. This showed that there are many options for implementing environmental flow measures at costs that must be considered reasonable, and in line with demands of for example, the European Union Water Framework Directive. Having realistic projections of costs as well as ecological benefits of environmental flow options will change the debate on policies for ecological rehabilitation of river systems developed for hydropower production, since the parties involved can have a common understanding of the consequences of different policy decisions. Finally, we stress the importance of evaluating and validating the catchment-scale benefits of introducing environmental flows. Partly, this can be done by experimentally testing assumptions of the relationships between flow parameters and ecological outcomes. However, validation of the long-term ecological benefits will also require practical implementation of environmental flows where the outcomes are carefully evaluated.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

In accordance with AGU's data policy, data are made accessible in DRYAD, a repository of research data (doi: 10.5061/dryad.1ns1rn8t8).

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