

## Introduced flow variability and its propagation downstream of hydropower stations in Sweden

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### ABSTRACT

Hydropower regulations may increase flow variability when compared with the natural hydrological regime, with detrimental impacts on river habitats. Attenuation of the variability improves ecological status at some distance downstream of the introduced variability, and being able to accurately estimate this distance is critical for the evaluation of ecological status. The attenuation has only been studied previously for specific rivers, and the dominant mechanisms have not been analyzed in detail. In this work, the attenuation and its important drivers are studied for regulated rivers in all of Sweden by comparing Fourier components and their attenuation based on hydrological and hydraulic models and observations, with comparisons also to lake attenuation. In many rivers, weekly flow variability is dominant among periods up to 1 month, and variability with periodicity days to months attenuates with an exponential rate that is largest for short periods. This is mainly driven by instream processes. Furthermore, regulated systems often resemble cascades with low-gradient river stretches between the dams. The associated attenuation can be described by hydrological models using a linear channel and linear reservoir. In contrast, the sometimes-used diffusion wave equation is often unable to replicate the observed attenuation here. Lakes may contribute significantly to attenuation.

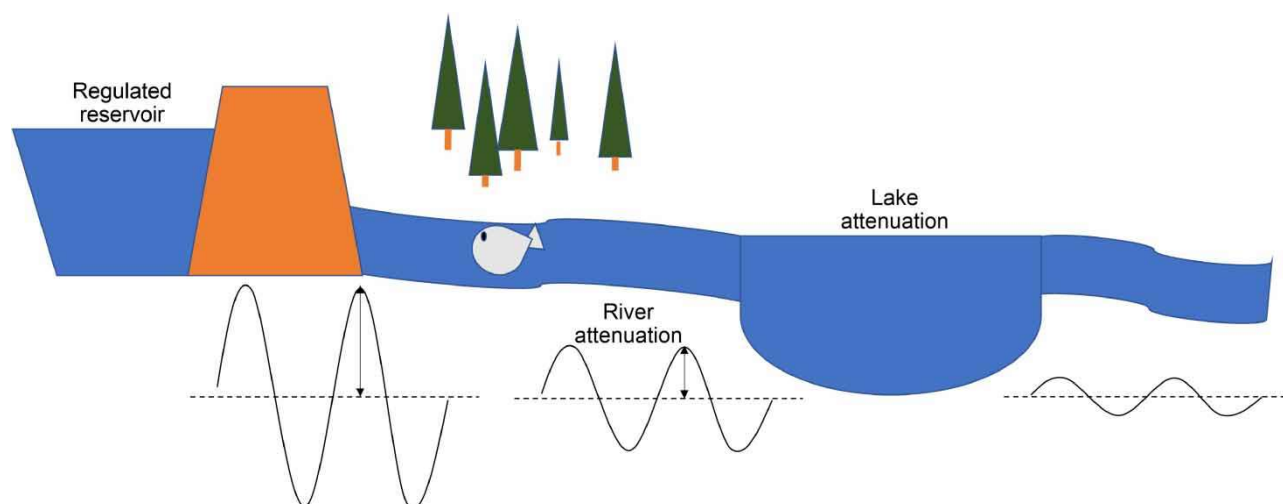
**Key words:** hydropower, river and lake attenuation, spectral analysis

### HIGHLIGHTS

- Exponential river attenuation rates are presented.
- Attenuation of variability introduced by hydropower is more efficient than what the diffusion wave equation predicts and can be described by a combined linear channel and linear reservoir.
- Undisturbed river stretches are nevertheless often not long enough for substantial attenuation.
- Lakes have a larger attenuation potential than rivers, especially at low flows.

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## GRAPHICAL ABSTRACT



## INTRODUCTION

Hydropower production contributes to 97% of the renewable electricity production worldwide (Göthe *et al.* 2019). As such, it has an immense role in the mitigation of climate change. In addition to this direct value as a source of renewable electricity, it also contributes to balancing power as needed depending on how well the production of wind and other fluctuating sources meet the energy demand. However, this might result in substantial fluctuations in streamflow downstream of power plants. These fluctuations can create zones that are wetted and dried at short time intervals, ultimately becoming lost as a habitat to most species. Macrophytes may then die, affecting also invertebrates and fish. Young fish may be stranded, and important areas for fish spawning might be lost (Tallaksen & Lanen 2004). To reduce ecological impacts, restrictions for hydropower production are enforced by regulatory frameworks, such as the Water Framework Directive in Europe. In Sweden, there will be a particular focus on the ecological impacts of hydropower regulations over the current and coming decade when all hydropower licences are being revised (Swedish Agency for Marine and Water Management *et al.* 2019).

Restrictions for hydropower production for improved ecology should consider flow fluctuations downstream of hydropower regulations and how quickly these are attenuated in the downstream direction. Because ecological impacts are expected to depend on the frequency and amplitude of flow variability, a useful measure of flow variability is obtained by using the Fourier transformation. This transformation decomposes the variability into a frequency domain characterized by periodic waves, or modes, of different frequencies with their respective amplitudes (deviations from the local average flow). The flow variability introduced by a hydropower plant will be attenuated as the water moves downstream, and by analyzing the variability in the frequency domain, the attenuation rates can be assessed separately for these different modes. Especially the modes with large amplitudes are of interest and we call the one with the highest amplitude the dominant mode. The attenuation depends on the type of disturbance. Andersson (2020) investigated the damping of perturbations caused by an upstream step-wise change in the discharge rate. Applying the Fourier transformation to observed or simulated time series, as done previously in Sweden by, e.g. Wörman *et al.* (2010), provides more information on the damping of flow perturbations of different periods caused by hydropower regulations. The same authors provided expressions for an exponential decay in the downstream direction, depending on the period (frequency) as well as on the celerity and dispersion coefficient. Even though exponential decay is reported in the literature and is the classical solution to the diffusion problem (Henderson 1966), and despite its usefulness in performing quick estimates of attenuation, we have not found verified decay rates for instream attenuation that can be applied in Swedish regulated rivers.

As opposed to the attenuation of rainfall over a watershed, which is usually dominated by processes outside individual river reaches (Rinaldo *et al.* 1991; Robinson *et al.* 1995; White *et al.* 2004), we are interested in the attenuation of hydropower-induced flow perturbations that are acting directly on river flow. It is reasonable to assume that mainly instream processes will attenuate these disturbances. In Sweden, rivers regulated for hydropower production often resemble cascades with

low-gradient river stretches of slope less than  $10^{-3}$  m/m between the dams, because most of the head difference is used for production. The question is then how efficient attenuation is in these rivers and how it is best evaluated. The hydrological rainfall-runoff model HYPE (Lindström *et al.* 2010) and the diffusion wave equation (Henderson 1966) have both been applied frequently to describe attenuation in Swedish-regulated rivers. These models consider different physical mechanisms of attenuation, and no model intercomparison study has been performed to assess which model best describes the amplitude reduction downstream of hydropower regulations. Therefore, there is a lack of understanding of the dominant processes for attenuation in Swedish-regulated rivers, which hampers the assessment of ecological impacts.

HYPE is used operationally for Sweden's national flood forecasting and drought warnings, and is also used to assist in the planning of hydropower operations, evaluate hydropower and climate impacts, and calculate the leakage of nitrogen and phosphorus (e.g. Grimvall *et al.* 2014). The instream translation and attenuation of flood waves is represented by a simple combination of a linear channel and a linear reservoir within each sub-catchment, i.e. the attenuation depends on storage effects similar to lakes, which become increasingly important at decreasing Peclet number ( $Pe$ ) in rivers (Rinaldo *et al.* 1991). The simulated flow has been carefully calibrated to observations as a continuous effort by the Swedish Meteorological and Hydrological Institute (SMHI) over the past decade (e.g. Lindström 2016), but the attenuation has not been previously evaluated in terms of the decay rates of Fourier modes along river reaches.

Henderson (1966) proposed that the hydromechanical response in rivers can be evaluated using the diffusion wave equation, and this has also been applied to describe attenuation in Swedish-regulated catchments (e.g. Wörman *et al.* 2010). This equation is sometimes called the kinematic wave equation, but we avoid this terminology because it has also been used to describe waves without dispersive effects (e.g. Maidment, 1992). The kinematic celerity is, however, used in both models. The diffusion wave equation has two parameters, the flow celerity and the dispersion coefficient. These are assumed to be approximately constant in a river if the water depth does not change much (Wörman *et al.* 2010), and in this case, the equation is linear. However, applying constant parameters also assumes that the friction slope consists mainly of the river bed slope, which according to Henderson (1966) would require bed slopes larger than  $10^{-3}$  m/m, a condition often not met in regulated rivers in Sweden. Rinaldo *et al.* (1991) found relationships between the celerity and dispersion coefficient that depend on friction properties, water depth, and the bottom slope (for perturbations from uniform flow). However, this approach underestimates the dispersion coefficient and overestimates the celerity if the bed slope is too small. Another reason the dispersion coefficient may be underestimated is that additional dispersion can occur due to channel irregularities (Henderson 1966). It is therefore uncertain how well the model from Rinaldo *et al.* (1991) will perform for the rivers considered in this study. White *et al.* (2004) and Robinson *et al.* (1995) studied the dependence of attenuation on the Horton–Strahler order and return period, both of which can be interpreted to some extent as a dependence on the overall discharge rate. They found that the hydraulic dispersion coefficient increased with increasing order and return period, i.e. with increased discharge, which is consistent with a dispersion coefficient that increases with celerity and water depth, as found by Rinaldo *et al.* (1991).

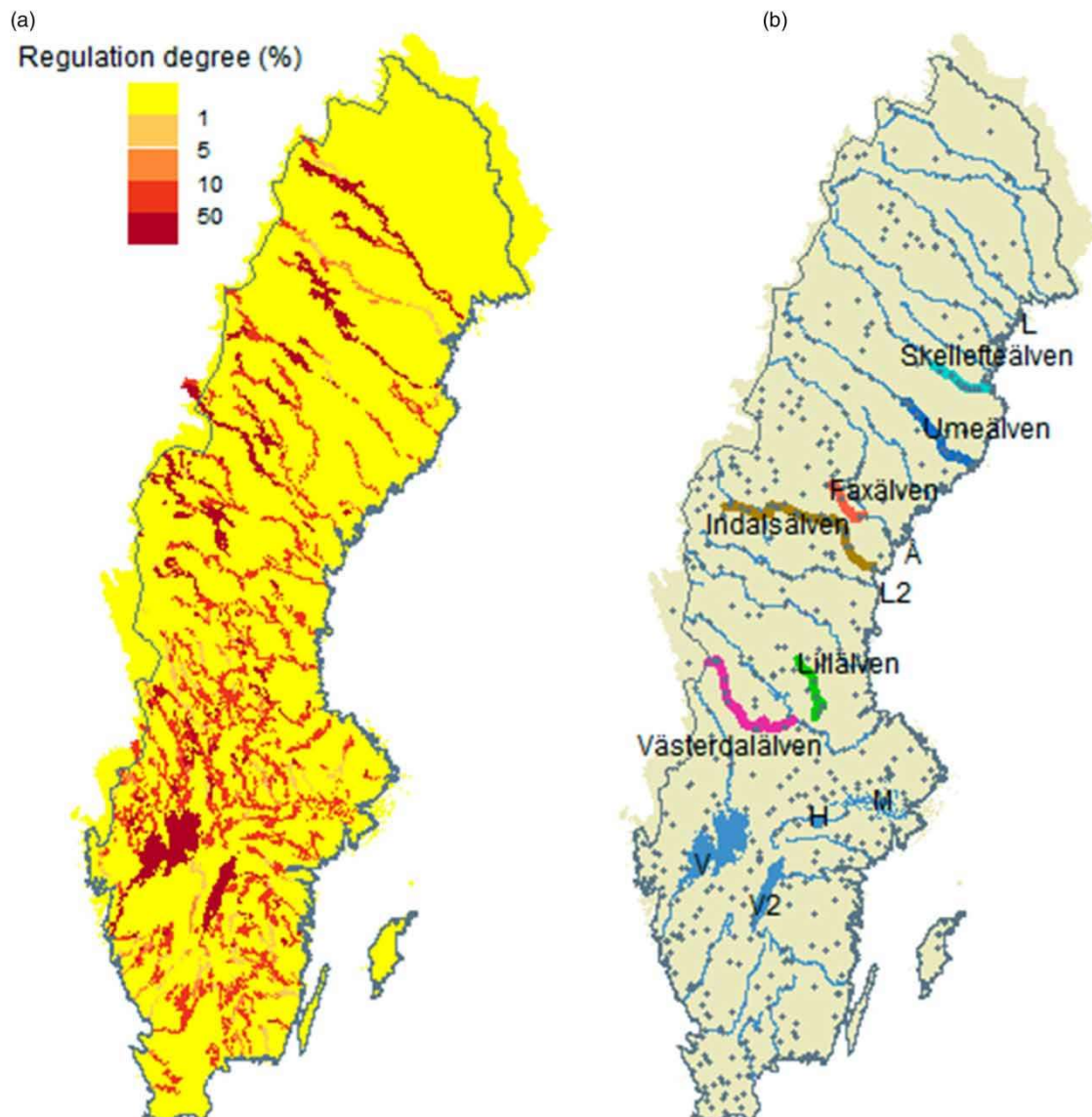
In addition to instream attenuation, Sweden has about 100,000 lakes with a surface area of more than 0.01 km<sup>2</sup>. Lakes may substantially contribute to the damping of flood waves (e.g. Quin & Destouni, 2018). As far as the authors know, there is no overview of how lakes contribute to the damping of flow variability of different frequencies, and this adds uncertainty about the total attenuation in catchments with many lakes.

The specific aims of this study are to (i) assess the flow variability caused by hydropower in all of Sweden, (ii) assess the rate at which this variability is attenuated in rivers, (iii) improve the understanding of the processes that are responsible for instream attenuation, (iv) assess what models can be used to quantify the attenuation rate, and (v) to assess the role of lakes for attenuation.

## METHODS AND DATA

### Study area

This study analyzes dominant modes and attenuation rates in all river reaches of Sweden with a regulation degree of at least 1%, defined as the percentage of the total yearly flow that can be stored in upstream lakes and dams, see Figure 1(a). The study period was 2009–2018. An additional careful examination of the simulated attenuation as compared to the observed attenuation was performed in six rivers, see Figure 1(b).



**Figure 1** | Maps of Sweden and parts of Norway and Finland that have inflow to Sweden, showing (a) the regulation degree for all rivers of Sweden and (b) six annotated and marked river stretches where the simulated attenuation was compared with the observed attenuation. This map also displays locations of discharge observations that were used to update the simulated flow (points), as well as locations of the large lakes Vänern (V), Vättern (V2), Hjälmaren (H) and Mälaren (M) and rivers Luleälven (L), Ångermanälven (Å) and Ljungan (L2), which are mentioned in Methods and Results sections.

### Observed and calculated discharge data

To meet the aims of this study, analyses were performed on discharge data obtained from various sources as shown in Table 1 and described below in further detail. The dominant mode was assessed based on observations and simulations with HYPE. Simulations without hydropower were then analyzed to separate the impact of hydropower. The attenuation was evaluated from these data complemented by other models to facilitate the understanding of important processes for attenuation, and to assess what models can provide reliable results. Specifically, HYPE simulations with only instream processes (here called  $HYPE_{riv}$ ) were performed to separate the impacts of instream processes from those of variable runoff, and HYPE results were compared to results from the diffusion wave equation to further increase the understanding of dominant attenuation processes and assess what model best describes observation data.

**Table 1** | Overview of methods used

| Method              | Type                                                                                                                                                                                                                                                                                                                                                                                 | Causes of flow variability and its attenuation                                                                                                                                                                                                                                                           |
|---------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Observation         | Discharge observation                                                                                                                                                                                                                                                                                                                                                                | The true processes                                                                                                                                                                                                                                                                                       |
| HYPE                | Hydrological rainfall–runoff model including hydropower flow regulations, discretized by sub-catchments and a daily time step. So-called station updates are used (see text). The Swedish parameterization S-HYPE was used here. It is possible to exclude the impact of hydropower regulations (the ‘HYPE-QN’ model application), in which case station updates are not used either | Variability by hydropower regulations and variable runoff production. River translation and attenuation by a linear channel coupled with a linear reservoir. Lake attenuation by physical restrictions of the outlet represented by a nonlinear rating curve                                             |
| HYPE <sub>riv</sub> | HYPE’s river translation and attenuation model alone                                                                                                                                                                                                                                                                                                                                 | Variability introduced as sinusoidal inflow at one location. River translation and attenuation as HYPE                                                                                                                                                                                                   |
| Diffusion wave      | Hydraulic model                                                                                                                                                                                                                                                                                                                                                                      | Variability introduced as sinusoidal inflow at one location. River attenuation, depending on celerity and a dispersion coefficient, was calculated in the Laplace domain and converted to time series using the inverse Laplace transform. In addition, an analytical expression of attenuation was used |

### Observed discharge

Observed discharge rates at a daily time step were collected from SMHI’s database. In six river stretches, these were used to compare the simulated and observed attenuation in rivers, see [Figure 1\(b\)](#). In addition, observations were used to update simulation results at 579 locations ([Figure 1\(b\)](#)) as explained below.

### Hydrological simulations with HYPE

Daily discharge was calculated using the hydrological model HYPE with the Swedish parameter set S-HYPE (version 2016f), whereby Sweden and surrounding inflow areas are discretized into approximately 40,000 sub-catchments. A 10-year initialization period was used. HYPE is a rainfall–runoff model that is calibrated to observations (e.g. [Lindström 2016](#)), mainly using parameters that vary by land use and soil type, sometimes (also here) with regional adjustments. Therefore, it can also be used in catchments that lack observations. The version used here has mean NSE (Nash–Sutcliffe Efficiency) of 0.80, mean KGE (Kling–Gupta Efficiency) of 0.84, and mean volume error of  $-0.9\%$ , measured over a subset of 283 stations that belong to the official SMHI network, over the calibration period 2009–2018. These statistics were obtained without using station updates to the observed flow, see below.

Each sub-catchment in HYPE may have a main river that is fed by rivers upstream, by runoff from the sub-catchment itself (via a local river and lake), and to a smaller degree by precipitation on the water surface itself. At the outlet of a sub-catchment, a lake that receives water from the main river can be modeled. Such lakes will impact the overall attenuation of the upstream flow perturbations. Additionally, a hydropower station that regulates the outflow from the lake can be introduced. The discharge may also be impacted by abstractions and releases due to, e.g. municipal use and by water transfer such as the transfer of hydropower production water to a sub-catchment further downstream. The HYPE code and parameters are described elsewhere (e.g. [Lindström et al. 2010](#); [Strömqvist et al. 2012](#)) and only the most relevant aspects for this work are presented here, i.e. the description of hydropower regulations and river and lake routing.

**Hydropower regulations:** HYPE can model the outflow from regulated lakes as a combination of hydropower production and spill ([Arheimer & Lindström 2014](#)). The production water is sometimes released further downstream. Dates with different production rates can be set, and the spill is calculated by a rating curve, in general as a nonlinear function of water depth above a threshold. Careful and incremental adjustments to the model description of Sweden’s hydropower regulations have been performed over the past decade, and seasonal regulations are now very well described. Hydropower regulations of shorter duration, such as on the weekly time scale, have not been introduced directly into the model parameterization or equations. However, most of these regulations can also be introduced directly into the model by replacing the simulated flow with the observed value for historical periods, as was performed here. In a total of 579 stations ([Figure 1\(a\)](#)), the calculated discharge was substituted by the observed discharge at every time step where available data exists, impacting the

simulation of the downstream flow. These station-updates give us a unique opportunity to study the attenuation of short-term regulations over the entire country.

*Natural regime:* Stream discharges simulated for the current regulated conditions were compared to stream discharges simulated assuming natural lake outflow, the so-called HYPE-QN model (Arheimer & Lindström 2014 and Table 1). The purpose of the regulation is to even out the flow, and store water for electricity production, primarily in the winter. In the QN version, this storage is removed, and natural flow conditions are simulated. The outflow is modeled using rating curves that describe observations prior to the building of dams, if observations from this period were available, or otherwise by rating curves that describe spill at regulated conditions. In addition, man-made diversions to hydropower plants are removed. Natural flow simulations have been verified against reconstruction calculations of natural flow performed by the hydropower industry (see e.g. Arheimer & Lindström 2014).

*River routing with a linear channel and linear reservoir:* The HYPE model accounts for translation and dispersion of the flow along the main river in each sub-catchment using a linear channel in series with a linear reservoir (cf. Chow *et al.* 1988). Pure translation takes part in the channel, while the linear reservoir is used for attenuation by storage effects. The total volume that flows out of the linear reservoir during a time step,  $V_{out}$  ( $m^3$ ), is calculated from an analytical solution to the dynamic changes in storage volume  $S(t)$  ( $m^3$ ) and outflow  $q(t)$  ( $m^3/day$ ) during the time step. (Note that we use the day as a unit of time here as the implementation in HYPE is using the time-step size as a time unit. However, in the Results section, we present discharges as  $m^3/s$  which is more intuitive.) It is assumed that the instantaneous outflow rate is proportional to the volume of the linear reservoir

$$q(t) = \frac{1}{k} S(t) \quad (1)$$

The proportionality constant  $k$  (unit days) is set such that the average time the water spends in the linear reservoir is the same as if there was pure translation also in this part of the river. Some water will arrive before and after the average time, thus attenuating the peak of a pulse. Furthermore, the continuity equation gives that

$$\frac{dS}{dt} = transq - q(t) \quad (2)$$

where  $transq$  ( $m^3/day$ ) is the inflow to the linear reservoir during the time step. HYPE uses a fixed (user determined) time-step size, and because the time-step size will usually not match the timing of the inflow to the linear reservoir, a queuing system that keeps track of the appropriate fraction of water to pass to the reservoir in a given time step, depending on the water velocity and river length is included. The expression for the total outflow from the linear reservoir,  $V_{out}$  ( $m^3$ ), during a time step, obtained from the solution to Equations (1) and (2), is

$$V_{out} = r_1 transq + r_2 S(0) \quad (3)$$

$$r_1 = \Delta t - k + k \exp\left(-\frac{\Delta t}{k}\right) \quad (4)$$

$$r_2 = 1 - \exp\left(-\frac{\Delta t}{k}\right) \quad (5)$$

Here,  $\Delta t$  (days) is the time-step size and  $S(0)$  ( $m^3$ ) is the linear reservoir storage volume before inflow this day.

*Lake routing:* The outflow from non-regulated lakes is calculated using a rating curve that is nonlinear in the general case,

$$q_L(t) = K h(t)^p \quad (6)$$

Here,  $q_L(t)$  ( $m^3/day$ ) is the lake outflow,  $h(t)$  (m) is the height above a threshold for outflow,  $K$  is a constant ( $m^{3-p}/day$ ) that will equal the outflow when the water is 1 m above the threshold, and  $p$  (–) is an exponent. The exponent has been fitted individually where observations are available (Lindström 2016). The most frequent value,  $p = 2$ , consistent with a parabolic shape of the outlet, was then used in ungauged basins.

### Simulations with only HYPE river routing

Streamflow time series were created from an artificial inflow at the upstream end of the river that was then routed through the river using HYPE's equations for river transport and attenuation (linear channel and linear reservoir) alone, without other processes such as precipitation, evaporation, or local runoff.

At the upstream end of the river, a sinusoidal inflow with a mean of  $10 \text{ m}^3/\text{s}$ , amplitude of  $1 \text{ m}^3/\text{s}$ , and with the chosen period was inserted during a simulation time corresponding to 10 such periods. The outflow at a distance downstream of this periodic inflow was calculated. Different river lengths between 1 and 20 km were tested, but as very minor differences in the attenuation rate were observed, only results from the 10-km river length are shown in the Results section.

### Calculations with the diffusion wave equation

The diffusion wave equation describes continuous translation and dispersion along rivers (Henderson 1966)

$$\frac{\partial y}{\partial t} + v \frac{\partial y}{\partial x} = D_L \frac{\partial^2 y}{\partial x^2} \quad (7)$$

Here,  $y$  (m) is the local and temporal water height of the river,  $t$  (s) is time,  $x$  (m) is location along the river,  $v$  (m/s) is celerity, and  $D_L$  ( $\text{m}^2/\text{s}$ ) is the dispersion coefficient. Note that the differential equation is valid for the perturbation in water height as well as for the actual height because the perturbation can be calculated by subtraction of the average height from the actual height. We assume that the perturbation of discharge is proportional to the perturbation of water height, such that  $y$  can represent a discharge perturbation (unit  $\text{m}^3/\text{s}$ ). This means that we assume that the change in river width when the height fluctuates is negligible compared to the mean river width, which is often a good approximation, and that the change in celerity with the perturbations is also negligible (cf. Henderson 1966). Hence, we let  $y$  be the flow perturbation of a given frequency  $\omega$  (-).

By assuming that the system is not perturbed before time zero, after which a sinusoidal perturbation of frequency  $\omega$  and size  $A_0$  ( $\text{m}^3/\text{s}$ ) is applied at  $x = 0$ , an analytical solution can be obtained in the Laplace domain as given by Equations (8) and (9). These equations were derived in Supplementary Material, Appendix B. Here, ' $\sim$ ' denotes a Laplace-transformed variable and  $s$  is the Laplace variable.

$$\tilde{y}(\omega, x, s) = \frac{A_0 \omega}{s^2 + \omega^2} \exp(r x) \quad (8)$$

$$r = \frac{v - \sqrt{v^2 + 4D_L s}}{2 D_L} \quad (9)$$

The first term (the fraction) in Equation (8) is the Laplace transform of  $A_0 \sin(\omega t)$  and the second term relates to the damping. The flow perturbation in the time domain is the inverse of the full expression, corresponding to the convolution of the inverse of the two terms. We obtained this inverse numerically for different  $\omega$ .

The celerity  $v$  (m/s) and dispersion coefficient  $D_L$  ( $\text{m}^2/\text{s}$ ) were estimated using expressions from Rinaldo *et al.* (1991)

$$v = \frac{3}{2} C \sqrt{y_0 S_0} \quad (10)$$

$$D_L = \frac{v y_0}{3 S_0} \quad (11)$$

Here,  $y_0$  is the uniform depth (m),  $C$  is Chezy's friction factor, and  $S_0$  is the bed slope. The friction factor can be estimated as (Chow *et al.* 1988)

$$C = \frac{1}{n} R^{1/6} \quad (12)$$

where  $n$  is Manning's roughness coefficient (e.g. 0.03 for bottom materials of natural straight clean rivers) and  $R$  is the hydraulic radius (cross-sectional area divided by wetted perimeter). SI units are used here. For wide rivers,  $R$  may be approximated

by  $y_0$ . This approximation was used here, and the depth was estimated from a generic dependence on discharge rate that was calibrated for Swedish rivers (Lindström *et al.* 2018)

$$y_0 = c q^f \quad (13)$$

Here,  $c = 0.56 \text{ ((m}^3/\text{s)}^{1-f})$  and  $f = 0.3405 \text{ (-)}$ .

Two additional methods were used to estimate the celerity. First, it was estimated from a previously calibrated relationship between velocity  $vel$  (m/s) and discharge in Swedish rivers (Lindström *et al.* 2018), giving

$$vel = k q^m \quad (14)$$

where  $k = 0.2141 \text{ ((m}^3/\text{s)}^{1-m})$  and  $m = 0.1988 \text{ (-)}$ . We use  $vel$  here to represent celerity although celerity could be up to about 70% larger than the velocity under the kinematic wave assumption (Miller, 1984).

Finally, celerity was estimated from peak travel times  $t_{peak}$  (s) between stations with observed discharge data at 15-min resolution, separated by distance  $x_{peak}$  (m) along rivers,

$$v = \frac{x_{peak}}{t_{peak}} \quad (15)$$

We will refer to this as the observed celerity.

### Fourier transformation of discharge data

When studying attenuation of the flow perturbations obtained from observations and simulations, we first applied the Fourier transform to convert these time series to Fourier modes of different periods  $T = 2\pi/\omega$  with their respective perturbation amplitudes  $A$ . The choice of using amplitudes (unit of flow), rather than variance, was made to facilitate intuitive interpretation of results.

We analyzed amplitudes of perturbations from time series of discharge using the Fast Fourier Transform (FFT; Cooley & Tukey 1965) implemented in R (function 'fft' in R version 3.6.3). FFT provides a very fine discretization of short periods down to the shortest period, here 2 days by the Nyquist criteria, and a much coarser discretization of long periods. This is not ideal in our context, because we wanted to compare the relative influence of modes with different periodicity, according to integer number of days. For a fairer comparison, the short periods, i.e. those where the spacing between them was less than one day, were lumped to the nearest integer day according to

$$A(T_i, x_j) = (A(T_{i1}, x_j)^2 + A(T_{i2}, x_j)^2 + \dots + A(T_{in}, x_j)^2)^{0.5} \quad (16)$$

where  $T_{ik}$  is the mode  $k$  pertaining to the nearest integer day  $i$  and  $n$  is the total number of modes pertaining to the day  $i$ .

This method preserves the variance criteria

$$\sum_i A(T_i, x_j)^2 = 2 \text{ Var}(Q(x_j)) \quad (17)$$

which is required by the definitions of variance (Var) and the Fourier transform. After applying this procedure, the dominant mode was calculated as the mode that has the largest amplitude  $A$  in a given sub-catchment. Identification of this mode, often described in terms of its period  $T$ , is a frequent task in stochastic hydrological analysis (Padmanabhan & Ramachandra Rao 1988).

We chose to disregard temporal changes of the spectra, such as seasonal variations, which could have been analyzed by, e.g. wavelet analysis (Schaeffli *et al.* 2007).

## Calculation of decay rates in rivers and lakes

### River exponential decay

The exponential growth rate,  $\sigma(T, x)$ , at a point  $x$  along a river describes the growth (positive values) or decay/attenuation (negative values) of modes when traveling downstream in the river. It is an important measure of how far into the downstream system hydropower regulations can impact the ecology. Note that we are not talking of growth or decay in terms of time-dependence here (the system is unconditionally stable), but in terms of the distance downstream from a boundary condition that is perturbed with a given spectrum. We often observe that the attenuation processes cause exponential decay in the rivers, as explained by, e.g. Wörman *et al.* (2010), but amplitudes can also increase due to increase of natural flow variability and due to new hydropower stations encountered. In the continuous case, the definition of  $\sigma$  is

$$\sigma(T, x) = \frac{dA(T, x)/dx}{A(T, x)}. \quad (18)$$

For the discrete case at outlets of sub-catchments of HYPE, it was calculated as

$$\sigma(T_i, x_j) = \frac{(A(T_i, x_j) - A(T_i, x_{j-1}))/rivlen_j}{(A(T_i, x_j) + A(T_i, x_{j-1}))/2}. \quad (19)$$

Here, *rivlen* (m) is the main river length in a sub-catchment. If water flows between the outlet of sub-catchment  $j-1$  to the outlet of sub-catchment  $j$  then it will have passed through the entire main river of sub-catchment  $j$ . The corresponding  $\sigma$  was assigned to sub-catchment  $j$ , because it represents processes occurring there. If this sub-catchment receives flow from more than one upstream sub-catchment, the one with largest overall variance was used in the definition of growth rate. This is an intuitive choice and is also consistent with the expected average amplitude, because the smaller perturbation can either add to the larger one (when they are in phase) or subtract from it (when they have opposite phase). However, we also note that if perturbations of the sub-catchments typically occur with the same phase, the overall impact might be somewhat additive instead. In cases where hydropower production water is released further downstream in a river, the simulated  $\sigma$  may have very large negative or positive values as the river enters and exits the part of the river that is bypassed by production water, and the observed  $\sigma$  that compares observation data upstream and downstream of the bypassed part of the river may be close to zero due to the absence of river attenuation processes, because the total length of the river section between comparison locations was always used in the definition.

The same method to calculate  $\sigma$  was applied to the discharge time series obtained using HYPE<sub>riv</sub> and the diffusion wave equation. In the latter case, also an analytical solution was tested in the Results section,

$$\sigma = \operatorname{Re} \left( \frac{v - \sqrt{v^2 + 4D_L i \omega}}{2 D_L} \right). \quad (20)$$

Note the similarity of this equation with Equation (9).

### Lake attenuation factor

Unregulated lakes will attenuate flow perturbations depending on the rating curve constant  $K$  and exponent  $p$  (cf. Equation (6)), the lake area  $\alpha_L$  (m<sup>2</sup>), and aspects of the inflow to the lake. In Supplementary Material, Appendix A, we show that sinusoidal lake inflow with amplitude  $A$  (m<sup>3</sup>/day), frequency  $\omega$  (1/day) and phase  $\theta$  (–) produces sinusoidal outflow with a different amplitude and a phase shift  $\varphi$  (–). Asymptotically for large times, i.e. after the impact of the initial conditions have died out, the perturbation of the outflow from its mean value  $q_m$  is

$$\hat{q}(t) = A \frac{k_L}{\sqrt{k_L^2 + \omega^2}} \sin(\omega t + \theta - \varphi), \quad \text{where} \quad (21)$$

$$k_L = \left( \frac{K}{q_m} \right)^{1/p} \frac{p q_m}{\alpha_L} \quad (22)$$

$$\varphi = \arctan\left(\frac{\omega}{k_L}\right) \quad (23)$$

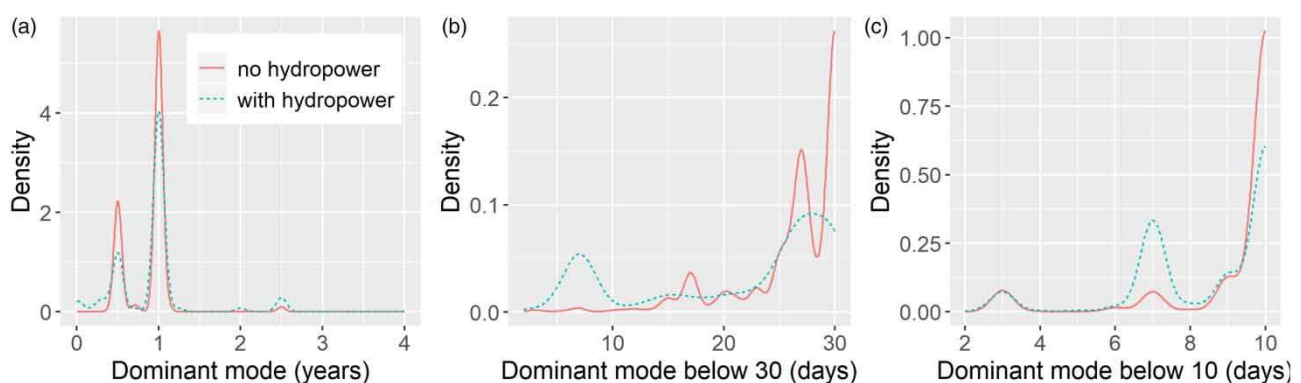
Here,  $k_L$  (1/day) is the recession coefficient of the lake at the mean flow. As Equation (21) shows, the attenuation factor over the lake is  $k_L/\sqrt{k_L^2 + \omega^2}$ , i.e. it depends on the parameters describing the rating curve as well as the lake area, in addition to the average flow and frequency of the perturbation studied. For example, perturbations of period 7 days ( $\omega = 2\pi/T = 10^{-5} \text{ s}^{-1}$ ) and mean flow  $100 \text{ m}^3/\text{s}$  in a lake with  $p = 2$ ,  $K = q_m/4$  and  $\alpha_L = 10 \text{ km}^2$  (a large lake extending, e.g.  $10 \text{ km} \times 1 \text{ km}$ ) would give  $k_L = 10^{-5} \text{ s}^{-1}$ . Then the damping factor is  $1/\sqrt{2}$ , such that about 70% of the amplitude remains after the perturbation passes the lake.

## RESULTS

Here, we first describe the dominant modes in regulated rivers of Sweden, based on the daily time series from HYPE. After this, HYPE's decay rates along a few chosen rivers are examined in more detail and compared with observations as well as with results from the diffusion wave equation. The attenuation in rivers is then presented at the national scale, followed by results on attenuation in lakes.

### Influence of regulations on dominant modes in Sweden

We are interested in the dominant mode in all of Sweden and how it is impacted by hydropower regulations. Our focus is on modes at least a few days long, since shorter modes are more difficult to represent based on a daily time resolution. Figure 2(a) shows how common different dominant modes are in the sub-catchments, as probability distribution functions. These are based on all 4,288 sub-catchments that are regulated by more than 1% (cf. Figure 1), but results are shown both with hydropower and with the natural model (no hydropower) for the same set of catchments. Although modes up to the simulation time of 10 years are obtained in the FFT, only those up to 4 years are shown for clarity. In most sub-catchments, the dominant mode is 1 year. There are also many sub-catchments that have their dominant mode at exactly the 6-month period based on the FFT results. This represents two peaks per year, rather than exactly 6 months between the peaks (the FFT assumes periodic functions), and is consistent with a combination of discharge originating from the spring snow melt and that caused by autumn rains. For comparison, Nordic regions characterized by the highest monthly flows originating from snow-melt and the second or third highest monthly flow caused by autumn rains were defined and mapped by Gottschalk *et al.* (1979) as transition regions. Fleming *et al.* (2002) also observed high amplitudes of the 6-month and 1-year modes in a catchment of Florida, mainly due to rainfall patterns. The importance of these modes in Sweden is somewhat reduced with hydropower, probably because hydropower aims to reduce the seasonality in streamflow and due to competition with other 'artificial' modes. In general, the dominant modes vary more between subcatchments if hydropower is simulated. When restricting the search for the dominant mode to modes of period up to 30 days (Figure 2(b)) or 10 days (Figure 2(c)), it is most commonly found in the larger range of the respective span. However, the 7-day mode is also dominant in many sub-



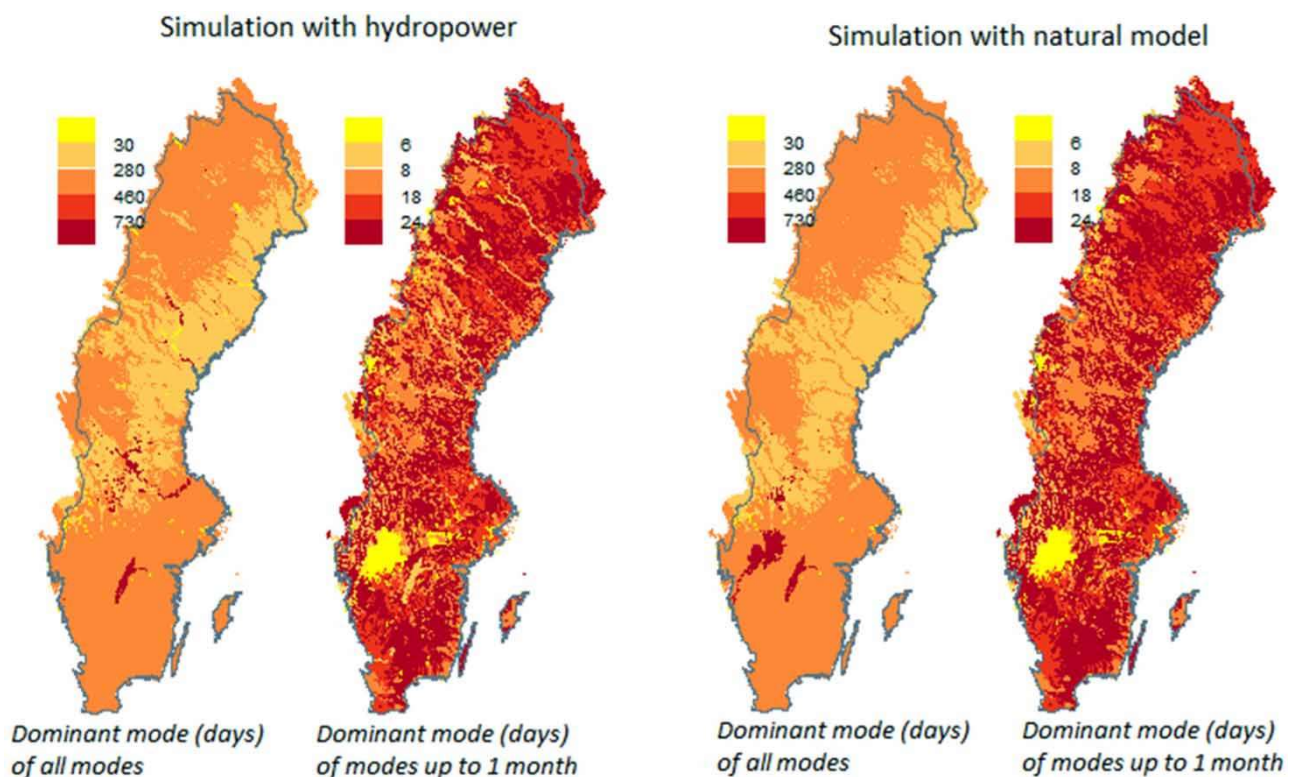
**Figure 2** | Probability density of the dominant mode of the 4,288 sub-catchments that are regulated by more than 1%, based on simulation results with hydropower and with the natural model. The dominant mode was searched for between (a) all modes, (b) all modes up to 30 days, and (c) all modes up to 10 days.

catchments, especially with hydropower. Some catchments have dominance of the 3-day mode, but results are more uncertain for very short periods. A similar analysis based on the daily time series of precipitation showed that this mode is dominant in almost all sub-catchments. However, a thorough investigation of precipitation would require higher time resolution, which is outside our scope.

Figure 3 shows the geographical patterns of the dominant mode for all sub-catchments, regardless of regulation degree. Again, the 1-year mode is dominant in most of Sweden. However, in the northeast the dominant mode is 6 months, away from large rivers. Restricted to the monthly scale, the following largely regulated rivers from north to south have dominant mode 1 week (cf. Figure 1): Luleälven, Skellefteälven, Umeälven (excluding the unregulated tributary Vindelälven), Ångermanälven, Indalsälven and Ljungan. Because these rivers are among the largest in Sweden, much of the total discharge in Sweden is dominated by weekly regulations, when the comparison is restricted to modes up to 1 month, with the possible exception of very short modes that were not studied here. As expected, in the natural model (no hydropower), there is no weekly dominance in these rivers. HYPE calculates flow between basins in the four large lakes, namely Hjälmaren, Mälaren, Vänern, and Vättern (Figure 1). This flow was not used to calculate the dominant mode (or the attenuation). Instead, dominant mode results shown in the maps also for these lakes are based on results at the outflow from the lakes, at the location of the first station-update. The regulated outflow from the large lake Vättern to river Motala ström is also dominated by weekly flow on the monthly scale, whereas the outflow from lake Vänern to river Göta älv is dominated by an even shorter mode at this time scale (3 days). Also, the natural outflow from lake Vänern has this very short dominant mode, but in this case the spectrum is quite flat (not shown), i.e. all modes up to one month have similar sizes.

### Verification of simulated attenuation towards observations

By using station updates in the hydrological simulations, flow variability due to hydropower is captured also over short time periods, only limited by the daily time step. In the river sections between these updates, the simulations typically show attenuation. In this section, the simulated attenuation, in terms of the exponential decay rate, is compared with attenuation shown by observations, focusing on regulated rivers. In regulated catchments of Sweden, it is rare to find two hydrological stations



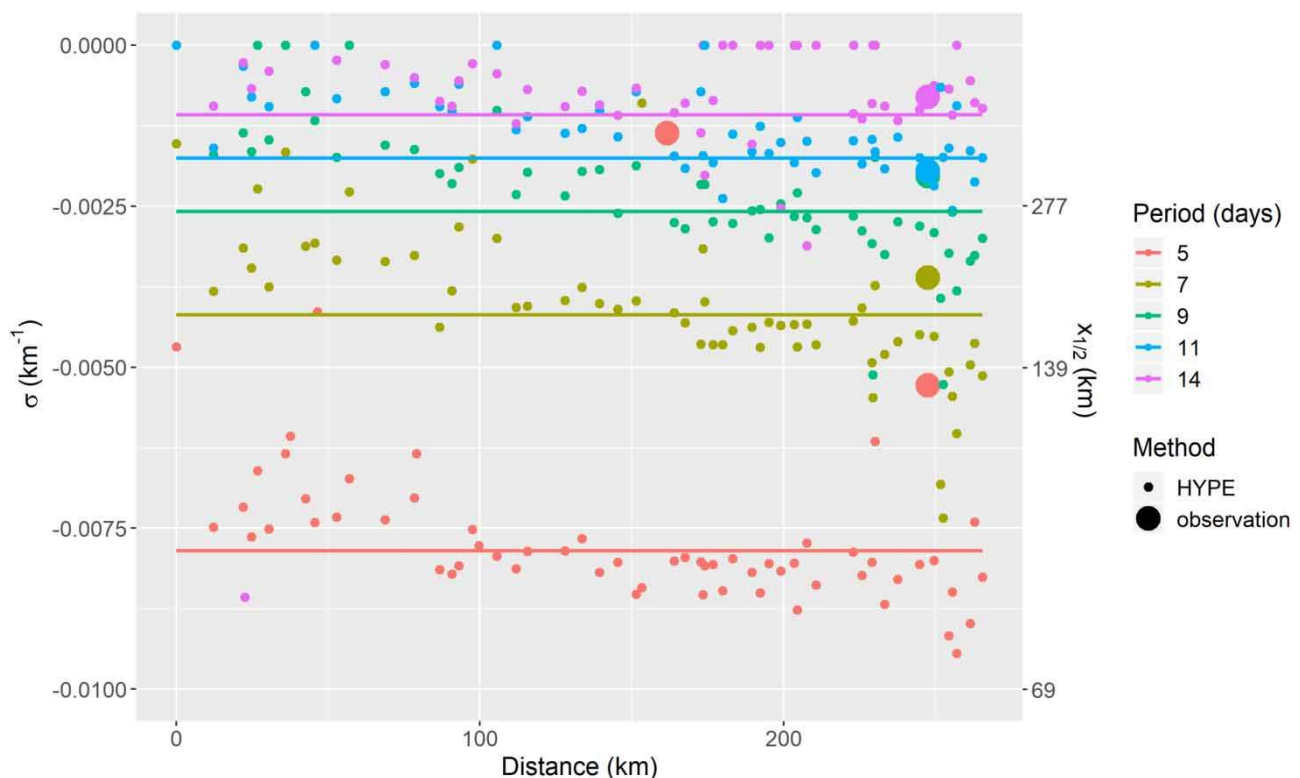
**Figure 3** | The dominant mode (days) from simulations with hydropower (the current situation) and with the natural model.

along a river with no flow regulation occurring between these stations. This makes the comparison of simulated and observed attenuation challenging. When these regulations between stations increase the perturbation amplitude (positive  $\sigma$ ), we disregard them from the comparison, since we are interested in the river attenuation. However, not all regulations perturb all periods, either by choice of the managers, by limitations caused by the available regulation volume or other restrictions.

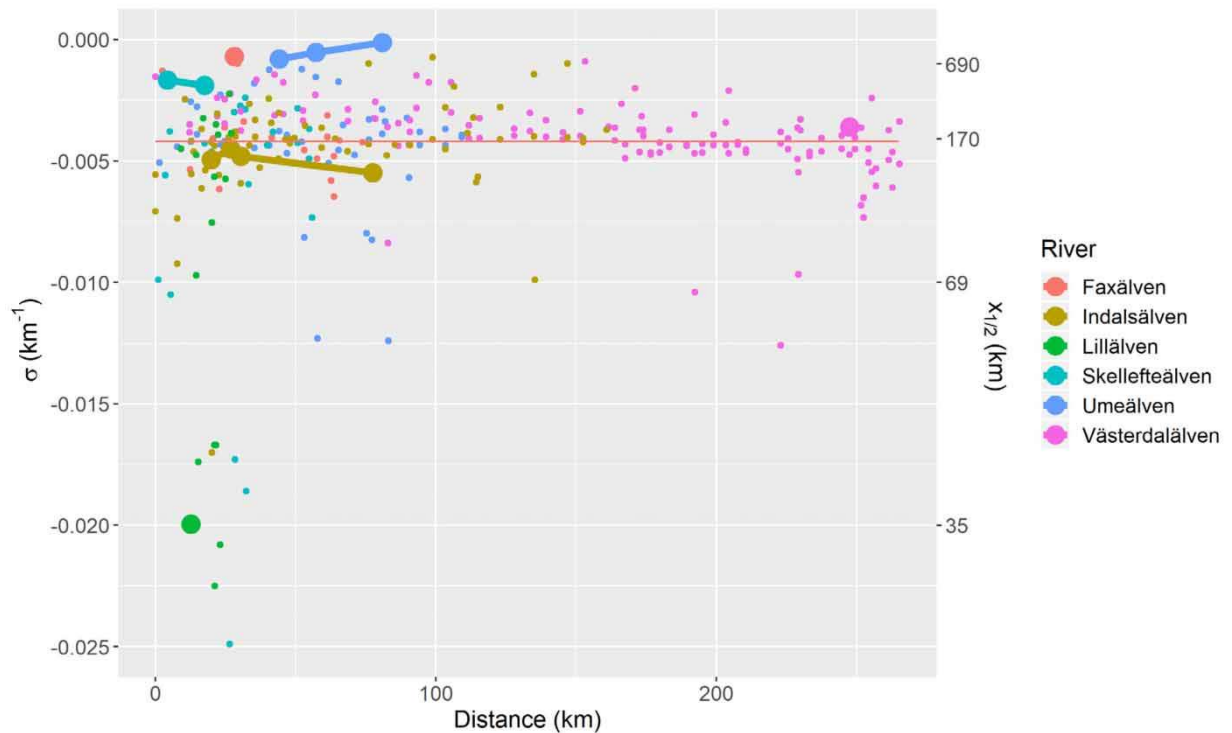
Figure 4 shows the negative growth rate along river Västerdalälven (cf. Figure 1). There are no natural lakes in this river. The average flow in the lower sections is on the order  $100 \text{ m}^3/\text{s}$ . The decay is faster for short periods. There are five stations with updates in this section. Down to the fourth station, most observed amplitudes increase overall, due to new regulations, and are therefore not shown in the figure which only shows the decay. However, at the fifth and last station, the observed amplitudes have decreased, and the rate of simulated reduction is very similar to the observed reduction for periods from 7 days and larger. For example, the observed 7-day period decay was  $-0.0036 \text{ km}^{-1}$  and the values of the full HYPE simulation vary around the similar  $\text{HYPE}_{\text{riv}}$  result of  $-0.0042 \text{ km}^{-1}$ . This indicates that the simulated attenuation is a good description of actual river attenuation for periods of size 7 days or longer. Shorter modes decay too quickly in the hydrological simulations, which is likely due to difficulties describing periods of a few days when a daily time step is used.

The  $\text{HYPE}_{\text{riv}}$  growth rates are very close to the full simulation results for periods up to 14 days, which means that the simulated river decay is indeed due to attenuation within rivers and not significantly impacted by other processes. The 15-day mode is not shown but its amplitude increases also between the last stations. On this time scale, other processes also impact the simulated attenuation.

Figure 5 shows the simulated and observed attenuation of the 7-day mode in six river stretches (see locations in Figure 1), as a function of distance along the rivers from chosen starting points. Again, only negative  $\sigma$  are shown because of the focus on attenuation processes. The examples from large river basins are from their downstream sections, in order to study the impact of upstream regulations while reducing problems with ambiguity raised by regulations in the stretch itself. There is no trend for  $\sigma$  with position in the river, which supports the assumption of exponential decay. The simulated values again often vary



**Figure 4** | A 5- to 14-day mode simulated and observed growth rate  $\sigma$  in river Västerdalälven, as a function of distance along the river downstream of the border with Norway, until the merge with river Österdalälven. Thin lines are  $\text{HYPE}_{\text{riv}}$  results. A few simulated values of  $\sigma$  less than  $-0.01 \text{ km}^{-1}$  are outside the figure axis, and positive  $\sigma$  is not shown. The right axis shows the distance  $x_{1/2}$  until perturbations are reduced by a factor of 2. Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/nh.2022.138>.



**Figure 5** | A 7-day mode simulated (small circles) and observed (large circles) growth rate  $\sigma$  in six rivers (see map in Figure 1). The half-distance is shown on the right scale. The chosen scale excludes one negative  $\sigma$  in Umeälven ( $-0.13 \text{ km}^{-1}$ ) which is due to a lake, and due to very short distance between this observation and its upstream neighbor, and positive  $\sigma$  is not shown. The thin red line shows the  $\text{HYPE}_{\text{riv}}$  result. Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/nh.2022.138>.

around the  $\text{HYPE}_{\text{riv}}$  result  $-0.0042 \text{ km}^{-1}$ , corresponding to the amplitudes being reduced by a factor of two after 170 km (the ‘half-distance’). The observed  $\sigma$  in rivers Indalsälven and Västerdalälven are aligned with common simulated values, supporting the simulated attenuation. In rivers Umeälven, Faxälven, and Skellefteälven, almost constant amplitudes (no decay) are observed, which we think is due to the additional regulations and/or bypassed river channels. The rapid decay shown for river Lillälven, is an artifact of very small amplitudes that increase and decrease insignificantly along the river.

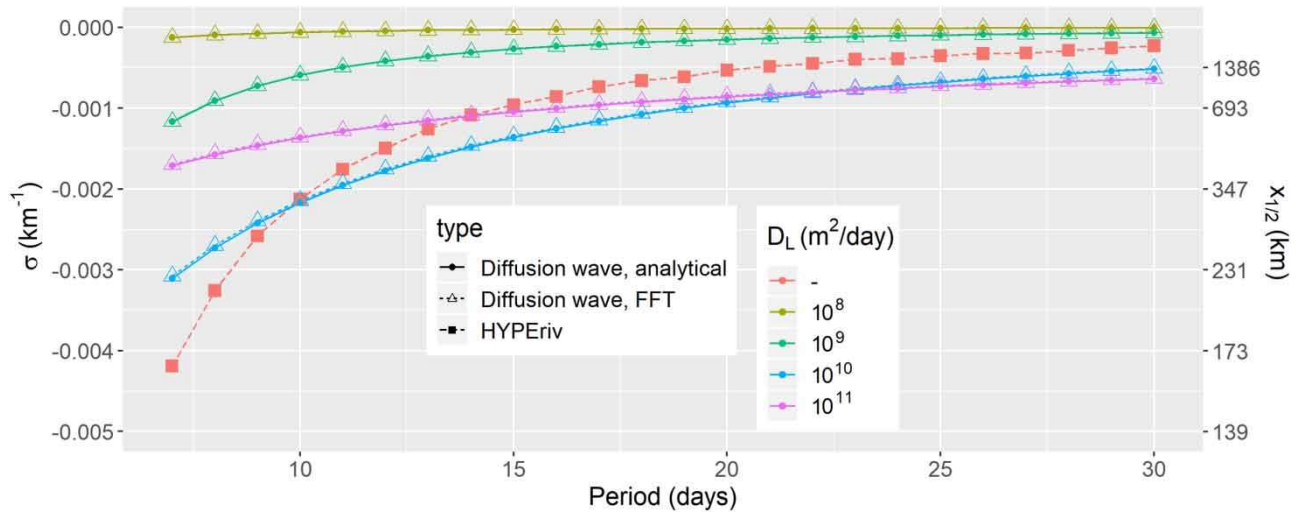
In summary, the comparison with observations shows that attenuation of periods from 7 days and larger is well described by  $\text{HYPE}_{\text{riv}}$ , that  $\sigma$  is determined by instream processes for periods up to 14 days, and that almost no attenuation could be observed in some rivers, likely due to regulations between observations and/or bypassed river channels.

### Comparison with the diffusion wave

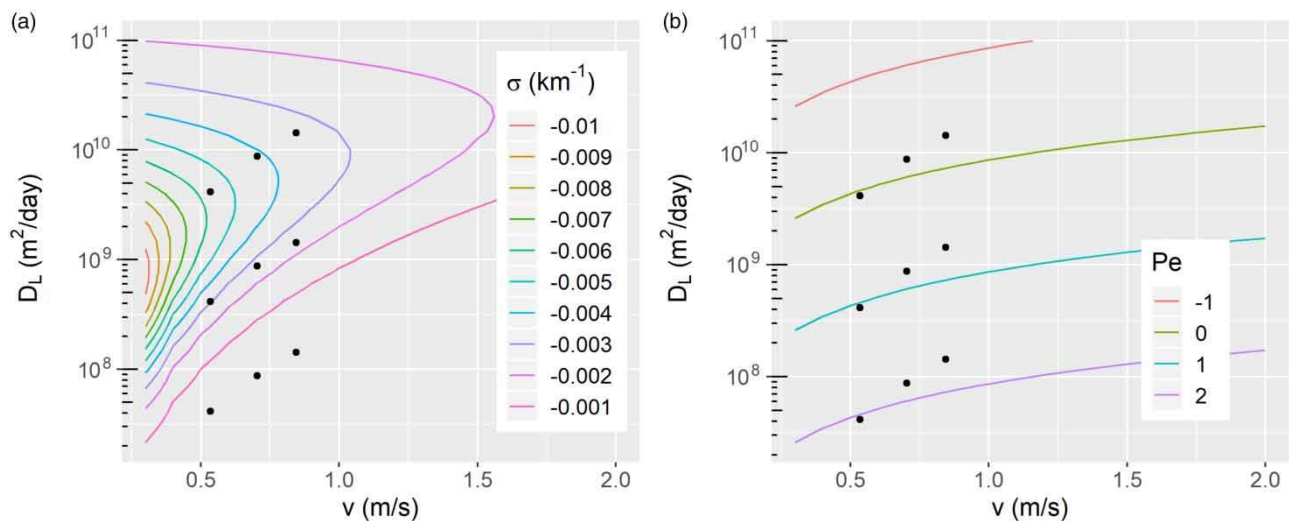
Here, the processes responsible for river decay are further analyzed by comparing the  $\text{HYPE}_{\text{riv}}$  attenuation with that of the diffusion wave (Figure 6).  $\text{HYPE}_{\text{riv}}$  results for modes larger than 14 days are potentially overestimating attenuation as discussed above. The figure again shows that attenuation is most efficient (more negative  $\sigma$ ) for periods of short duration.

Damping described by the diffusion wave is also shown in the figure, here using celerity  $v = 1 \text{ m/s}$  as a first example. To make a fair comparison with  $\text{HYPE}_{\text{riv}}$  results employing a daily time step, the FFT solution was calculated for a daily time step, however tests showed that a finer time step produced very similar results, that results were insensitive to changed river length between 1 and 100 km (10 km is used in the figure), and that the analytical solution (Equation (19)) produced very similar results. Perturbations of period less than 10 days are less attenuated with the diffusion wave compared to the verified  $\text{HYPE}_{\text{riv}}$  solution, and this applies regardless of the value of  $D_L$ , with the chosen celerity. The closest agreement between the diffusion wave results and the confirmed  $\text{HYPE}_{\text{riv}}$  results for periods 7–11 days was obtained using  $D_L$  on the order  $10^{10} \text{ m}^2/\text{day}$  ( $10^5 \text{ m}^2/\text{s}$ ).

Next, we investigate in more detail at what conditions the diffusion wave might produce the observed  $\sigma$ , focusing on the 7-day mode. Figure 7 shows contour lines of the exponential growth rate  $\sigma$  and the Peclet number  $Pe$  as functions of the



**Figure 6** | Growth rate for modes 7–30 days using HYPE<sub>riv</sub> and the numerical and analytical solutions to the diffusion wave equation with different dispersion coefficients  $D_L$  and a constant celerity  $v = 1$  m/s. Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/nh.2022.138>.



**Figure 7** | (a) Contour lines of diffusion wave  $\sigma$  when  $v$  is between 0.3 and 2 m/s (the unit m/day is used in defining  $\sigma$ ) and  $D_L$  is between  $10^8$  and  $10^{11}$  m<sup>2</sup>/day. (b)  $\log_{10}(Pe)$ . The black dots show  $(v, D_L)$  for slope  $10^{-3}$  (lowest  $D_L$ ),  $10^{-4}$  and  $10^{-5}$  m/m (highest  $D_L$ ), at discharge rates 100, 400 and 1,000 m<sup>3</sup>/s from left to right. Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/nh.2022.138>.

celerity  $v$  and dispersion coefficient  $D_L$ . Here,  $Pe = v a / D_L$  was defined using length scale  $a = 100$  km which is the order of magnitude required before the 7-day mode amplitude is reduced by a factor of two.

For each contour of  $\sigma$ , the region above the maximum celerity is not permissible, because for a given celerity  $v$ , a higher dispersion coefficient  $D_L$  should always produce more negative  $\sigma$ . The existence of a non-permissible region can also be identified directly from Equation (20) because larger  $D_L$  in the denominator will give smaller absolute value of  $\sigma$  if the impact of the denominator is larger than that of the nominator, which depends on  $v$  and  $T$ . Comparing Figure 6(a) and 6(b),  $\sigma$  is not permissible in the approximate range  $\log_{10}(Pe) < 0$ , i.e.  $Pe < 1$ , meaning when the time for diffusion is less than the time for advection. It is intuitive that the diffusion wave equation cannot be used when the dispersive effects would dominate, because the dispersion of a wave is caused by different travel times of moving water in a stream. When attenuation is due to volume storage more similar to lakes, other processes dominate.

We therefore need to find combinations of  $(v, D_L)$  that are both permissible and produce the observed  $\sigma$ . Table 2 shows example combinations and their resulting  $\sigma$  and permissibility, based on characteristics of river Västerdalälven and nine hypothetical rivers that have realistic bed slopes and discharge rates (also shown in Figure 7). Here, the celerity and water depth were first estimated based on river discharge (Equations (13) and (14)), and then Rinaldo's model (Equation (11)) was used to calculate the dispersion coefficient from the celerity, water depth and bed slope.

The choice of using a calibrated water velocity (Equation (14)) to represent wave celerity  $v$  (m/s) in Table 1 was made because it can easily be calculated for all of Sweden, and was much closer to the observed celerity (Equation (15)) than Rinaldo's celerity (Equation (11)). For example, the lower stretch of river Västerdalälven had observed celerity 0.6 m/s in a flood situation in the summer of 2010. The peak flow was approximately 400 m<sup>3</sup>/s, which gives velocity 0.7 m/s according to Equation (14), very close to the observed peak celerity. On the other hand, Rinaldo's celerity from Equation (11) with friction factor from Equation (12) gives an overestimated celerity 3 m/s, here using  $n = 0.03$ . We also made comparisons in two more rivers with the same conclusion: In May 1995, the observed celerity in river Vindelälven, a tributary to Umeälven (slope 0.001 m/m), was 1.1 m/s, as compared to nearly the same water velocity 1.0 m/s from Equation (14) but much higher celerity 5.8 m/s from Rinaldo's Equation (11). In May 2018, the observed celerity in Öre älv, south of Umeälven (slope 0.002 m/m), was 0.7 m/s, as compared with the same value for water velocity from Equation (14) but celerity 5.7 m/s from Rinaldo's Equation (11).

River Västerdalälven has larger slope ( $10^{-3}$  m/m) and river Indalsälven has smaller slope ( $10^{-5}$  m/m) than the slope  $10^{-4}$  m/m required by the diffusion wave model to obtain observed  $\sigma$  in the permissible range. Hence, damping in these rivers could not be described by the diffusion wave model. Instead, this model would predict an attenuation one order of magnitude too low for river Västerdalälven, only reaching closer to the observed value if the dispersion coefficient was increased by one order of magnitude. For the very low-gradient river Indalsälven, the diffusion wave solution is not even permissible. Hence, the slope does not predict  $\sigma$  in these rivers, contrary to what the diffusion wave equation with Rinaldo's  $D_L$  would predict.

In summary, the diffusion wave could produce observed attenuation for certain combinations of  $v$  and  $D_L$  but these combinations were not consistent with Rinaldo's celerity, which was overestimated, or dispersion coefficient, which was underestimated. This can be explained by the use of bed slope to represent the friction slope in rivers where this approximation is known to be questionable, i.e. when the bed slope is around  $10^{-3}$  m/m or less (Henderson 1966), in addition to neglecting channel irregularities in the estimate of  $D_L$ . We expect that similar results hold for other modes, albeit with other ranges of acceptable  $v$  and  $D_L$ . These ranges can be calculated for any period  $T$  by expanding terms in Equation (20).

As opposed to the above discussion, HYPE simulations were able to reproduce attenuation in rivers of both very small (Indalsälven) and larger (Västerdalälven) slope, the latter slope also being quite small due to the impact of regulations that use up much of the depth difference in regulated rivers.

### Attenuation in regulated rivers of Sweden

Here, the varying growth and decay rates of different modes in Swedish rivers is discussed based on results from HYPE simulations. The main goal is to study the decay downstream of hydropower stations, and we therefore do not present results for

**Table 2** | Desired  $\sigma$  along with the corresponding permissible range in  $v$  and  $D_L$ , followed by examples

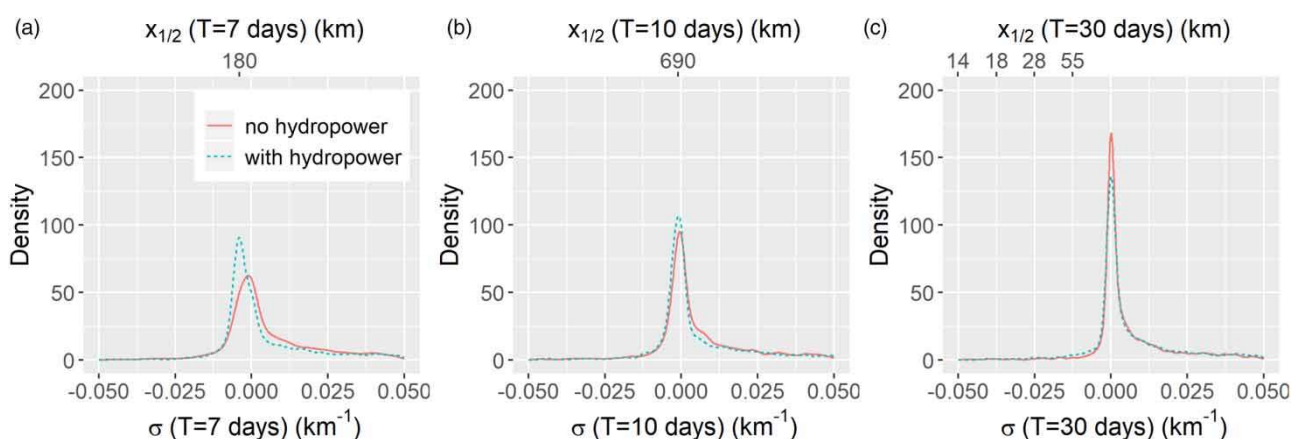
| Case                            | Permissible? | $\sigma$ (km <sup>-1</sup> ) | $y_0$ (m) (Equation (13)) | slope (m/m) | $v$ (m/s) (Equation (14)) | $D_L$ (m <sup>2</sup> /day) (Equation (11)) |
|---------------------------------|--------------|------------------------------|---------------------------|-------------|---------------------------|---------------------------------------------|
| Desired                         | Yes          | -0.004                       | -                         | -           | 0.3–0.8                   | $10^8$ – $10^{10}$                          |
| River Västerdalälven            | Yes          | -0.0004                      | 4.3                       | 0.0007      | 0.7                       | $10^8$                                      |
| Upper set of points (Figure 6)  | No           | -0.006                       | 2.7                       | 0.00001     | 0.5                       | $10^{10}$                                   |
|                                 | No           | -0.004                       | 4.3                       | 0.00001     | 0.7                       | $10^{10}$                                   |
|                                 | No           | -0.003                       | 5.9                       | 0.00001     | 0.8                       | $10^{10}$                                   |
| Middle set of points (Figure 6) | Yes          | -0.003                       | 2.7                       | 0.0001      | 0.5                       | $10^9$                                      |
|                                 | Yes          | -0.003                       | 4.3                       | 0.0001      | 0.7                       | $10^9$                                      |
|                                 | Yes          | -0.002                       | 5.9                       | 0.0001      | 0.8                       | $10^9$                                      |
| Lower set of points (Figure 6)  | Yes          | -0.0003                      | 2.7                       | 0.001       | 0.5                       | $10^8$                                      |
|                                 | Yes          | -0.0003                      | 4.3                       | 0.001       | 0.7                       | $10^8$                                      |
|                                 | Yes          | -0.0003                      | 5.9                       | 0.001       | 0.8                       | $10^8$                                      |

Note: A lower cutoff at  $v = 0.3$  m/s is used. The slopes refer to average river slopes excluding production depth differences. Equations used are given in parentheses.

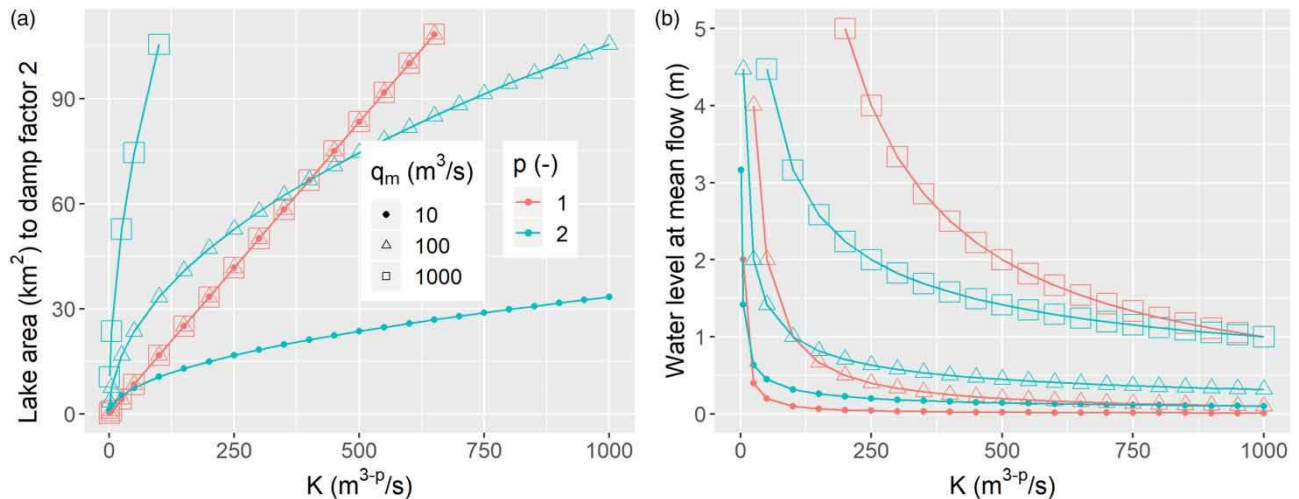
subcatchments where station updates are used (often with large growth due to new hydropower information), or with less than 1% regulation. Figure 8 shows the probability density of the exponential growth rate. Growth (positive values) is here due to natural phenomena like changed rain patterns and larger total variance with larger total flow. Values outside the presented range are excluded because they represent the effect of bypassed river channels, large tributaries, large lakes or very small river distance, as checked in several rivers for the 7-day mode. For the 7-day and 10-day modes, the most common growth rate is  $-0.0039$  and  $-0.0010 \text{ km}^{-1}$ , respectively, with hydropower, and less negative without hydropower. It is reasonable that the shortest modes decay fastest. These two growth rates (when they are consistent in a river) mean that the amplitudes would be reduced by a factor of two after about 180 and 690 km, respectively ( $x_{1/2} = \ln(1/2)/\sigma$ ). This is longer than typical distances between hydropower stations, which is, for instance, a bit over 10 km in the lower stretch of river Indalsälven. Perturbations of the natural state without hydropower decay slower, perhaps because their amplitudes are smaller and more similar to the natural addition of perturbations along the way, i.e. decay is counteracted by new perturbations. The most common growth rate of the 30-day period is positive, both with and without hydropower, and most subcatchments have positive growth of this mode.

### Lake attenuation

We have seen from the HYPE results and the observations that even rivers with small slopes require long stretches before amplitudes are significantly reduced. Here we present results from the analytical derivation of lake attenuation. We focus on the lake descriptors (the lake area as well as the coefficient  $K$  and exponent  $p$  of the rating curve), needed to introduce an amplitude reduction by a factor of two, assuming there is no active lake regulation. Figure 9(a) shows this required area of the 7-day mode. For comparison, the parameters that are calibrated for unregulated lakes in S-HYPE are often around 2 for  $p$  and are often below  $500 \text{ m}^{3-p}/\text{s}$  for  $K$ . The figure shows that the required lake area is very sensitive to the mean flow, which would vary during the year in the real case. Lakes will not contribute significantly to the attenuation of weekly flow perturbations if the average flow is on the order  $1,000 \text{ m}^3/\text{s}$  because the required area would be at least on the order of  $100 \text{ km}^2$ , unless water levels several meters above the threshold would be accepted (at small  $K$ , see Figure 9(b)). Only 0.2% of outlet lakes in S-HYPE are that large. If the mean flow is on the order  $100 \text{ m}^3/\text{s}$  and a water level up to 2 m above the threshold is acceptable, then  $K$  would need to be at least 50 for  $p = 1$  or 25 for  $p = 2$  and this would correspond to a required lake area of 8 or  $17 \text{ km}^2$ , i.e. on the order  $10 \text{ km}^2$ , which is fulfilled for 5% of outlet lakes. Similarly, for mean flow  $10 \text{ m}^3/\text{s}$ , the lake area would need to be on the order  $1 \text{ km}^2$ , which is the case for 40% of outlet lakes. In summary, lakes may contribute significantly to attenuation of the 7-day mode, but only when the flow is on the order  $100 \text{ m}^3/\text{s}$  or less. Longer modes than 7 days require larger lakes for the same amplitude reduction, but may also have smaller amplitudes, i.e. they may need less attenuation to meet ecological requirements.



**Figure 8** | Probability density of the growth rate  $\sigma$  of the (a) 7-day, (b) 10-day and (c) 30-day modes with hydropower (dashed blue) and without hydropower (solid red). The most common half-distance  $x_{1/2}$  with hydropower is marked in sub-figures (a) and (b), and a few extra values are given for illustration in sub-figure (c). Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/nh.2022.138>.



**Figure 9** | (a) Lake area required to damp the 7-day mode by a factor of two and (b) water level above threshold where outflow can commence, as functions of the coefficient  $K$  of the rating curve, and for different mean flows  $q_m$  and rating curve exponents  $p$ . Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/nh.2022.138>.

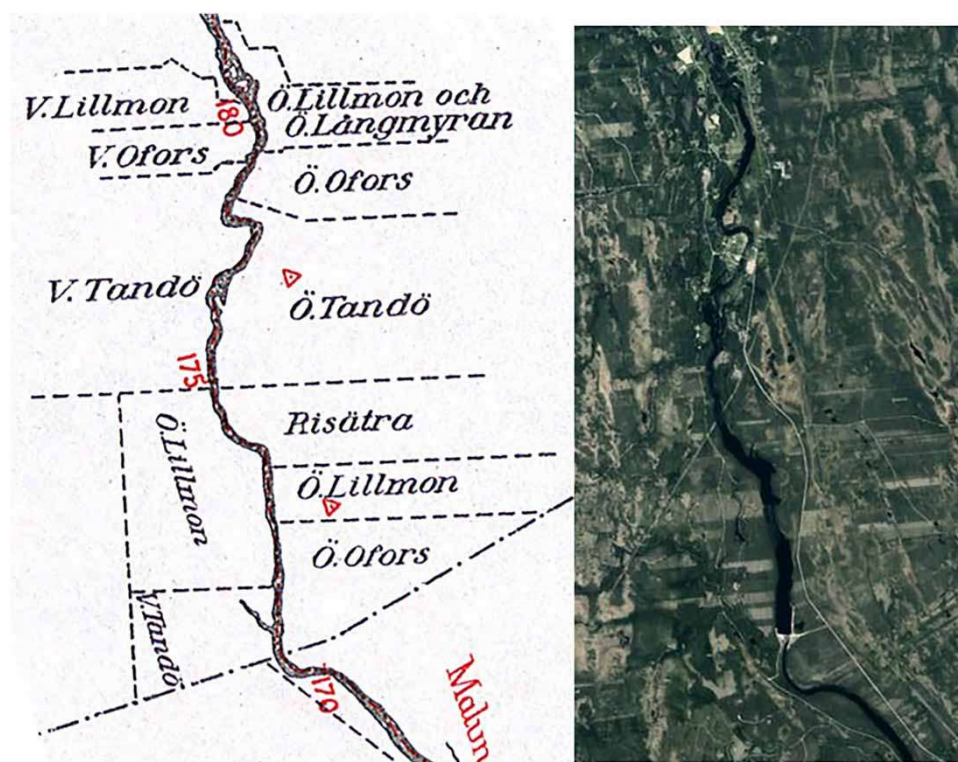
The figure or corresponding equations can be used to obtain a quick estimate of required lake area or parameters for the outflow section, whereas actual constructions would require additional consideration to lake slopes etc.

## DISCUSSION

Focusing on regulated rivers where the amplitude of studied modes is dominated by hydropower production, we found that attenuation in the downstream direction is exponential with a coefficient  $\sigma$  that has quite small variability between regulated rivers, but depends heavily on the period of the perturbation. We also found that the decay is explained very well assuming only HYPE's river attenuation for modes 7–14 days, i.e. not considering contributions from surrounding land. Furthermore, the attenuation in rivers is not easily described by the diffusion wave equation in these rivers. Regulated systems often resemble cascades with low-gradient river stretches between the dams. As [Rinaldo \*et al.\* \(1991\)](#) observed, at decreasing  $Pe$ , storage effects may dominate in rivers. This is consistent with the success of HYPE and difficulties of the diffusion wave equation for these rivers. The impact of 'lake-alike' attenuation is therefore important and it is due to volume storage in addition to possible local restrictions of the flow in rivers of varying width. One example of the difficulties in distinguishing between river and lake after regulation is given from river Västerdalälven in [Figure 10](#).

Despite rivers acting almost like lakes, attenuation is not quick enough to make much of a difference in many rivers, in relation to the short river stretches that are undisturbed. Therefore, ecological values may not increase significantly away from hydropower stations in many regulated rivers in Sweden. However, not all regulations impose perturbations of all periods. For example, in Västerdalälven, the downstream stretch has more than 100 km river length with undisturbed decay of the weekly perturbation, reducing its amplitude from about 9 to 6 m<sup>3</sup>/s. In Indalsälven downstream of the large, regulated lake Storsjön, some regulations do further impact the 7-day mode and some do not, but here the overall impact is a more or less constant amplitude of this mode.

The analysis of lakes showed that the processes governing lake attenuation are the parameters describing the outflow restrictions (rating curve) as well as the lake area, in addition to the average flow and the period of the perturbation studied. The average flow varies throughout the year. Variability during low-flow periods can be especially harmful for ecology due to very low resulting minimum flows. The lake attenuation may be of larger relative importance during these critical periods since the requirements of lake size or outflow section are reduced in these instances, related to the nonlinear shape of the rating curve. There are some existing unregulated lakes in regulated rivers, e.g. one lake in river Skellefteälven. Although these lakes have the potential to reduce variability, this may not always be desirable from an economic standpoint of downstream production. For example, a reduction of the 7-day mode would reduce flow on weekdays, when the electricity price is higher, and increase flow on weekends, when the price is lower.



**Figure 10** | River Västerdalälven by the 'Lima' hydropower regulation, before (left, Kungl. Vattenfallsstyrelsen and Statens meteorologisk-hydrografiska anstalt, 1921) and after (right, [www.eniro.se](http://www.eniro.se), 2022-04-13) construction of the dam.

## CONCLUSIONS

Our work demonstrates how a well-calibrated national hydrological model can be used to understand the dominant physical river processes and be of use for management decisions. By analyzing discharge variability and its attenuation along regulated streams from observations, HYPE simulations and the diffusion wave model, and by performing an analysis of the attenuation in lakes, we found that:

- Flow variability caused by hydropower in Swedish rivers is often dominated by regulations at a weekly time scale, when analyzing variability of time-scales from 2 days up to 1 month.
- To reduce the amplitude of these weekly perturbations in rivers by a factor of two, around 180 km of undisturbed river is required. The actual reduction factors are often smaller, due to limited distances between hydropower regulations.
- Attenuation of flow variability introduced by hydropower in the downstream direction along rivers is mainly due to instream lake-alike processes.
- The simple river routing method in HYPE using a linear channel and a linear reservoir described the flow attenuation very well, and gave much better results than the diffusion wave analogy for Swedish rivers. The reason for this is probably that the river slopes between hydropower dams is small. The difficulties in applying the diffusion wave model may also be due to neglecting the impact of channel irregularities, an effect that is difficult to parameterize.
- Lakes may contribute significantly to attenuation of the 7-day mode, but only when the flow is on the order  $100 \text{ m}^3/\text{s}$  or less. Longer modes than 7 days require larger lakes for a given amplitude reduction.

Apart from the direct use of the results for management decisions, the results presented herein can also be used to introduce short-term regulations in hydrological simulators without the need for station updates. This is needed for forecasts, such as deterministic forecasts (the 7-day mode typically has a minimum value on Sundays) or stochastic seasonal forecasts where it can improve indicators such as the number of days below or above a threshold. Another important avenue for future research is to assess sub-daily flow variability that might become increasingly important in a future energy system.

## DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories. Data from the flow gauges used for this work can be downloaded at <https://www.smhi.se/data/hydrologi/vattenwebb> and model outputs can be downloaded from <https://vattenwebb.smhi.se/archive/>.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 23 December 2021; accepted in revised form 6 October 2022. Available online 31 October 2022