Large-scale comparison of flow-variability dampening by lakes and wetlands in the landscape

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Abstract
Considering the potential of wetlands to dampen temporal variability of water flow through the landscape, they are increasingly considered as possible nature-based solutions to mitigate risks of flooding and drought. In this study, we investigate flow variability by means of a flow dampening factor and use observation data from 1984 to 2013 for 82 Swedish catchments to statistically and comparatively analyze the large-scale effects on this factor of multiple wetlands and lakes in the landscape. The results show good correlation between large-scale flow dampening and relative area of lakes and floodplain wetlands within a catchment. An increase in relative area up to around 15% for lakes and 0.5% for floodplain wetlands lowers the temporal standard deviation of runoff (R) to around 10%–15% of that for precipitation (P), compared with a common flow-variability dampening of around 35% for catchments with lake-wetland area close to zero. Further increase in these relative areas, or in those of wetland types other than floodplain wetlands, has little or no flow dampening effect. The results indicate that the large-scale flow dampening effect of lakes and floodplain wetlands is mainly due to their water-storage capacity and less due to their possible effects on the partitioning of P between R and evapotranspiration. Overall, the results emphasize the importance of accounting for the problem scale and relative water-storage capacity of wetlands when considering their large-scale efficiency as possible nature-based solutions for large-scale flow-variability regulation in whole catchments.

KEYWORDS
ecosystem service, flow-variability regulation, nature-based solution, wetlands, lakes

1 | INTRODUCTION

Inland water systems (including lakes, rivers, marshes, swamps, and floodplains) may affect the timing and magnitude of runoff through the landscape, providing an ecosystem service of flow regulation (Millennium Ecosystem Assessment, 2005a, 2005b). Hydrological ecosystem services (Brauman, Daily, Ka'eo Duarte, & Mooney, 2007) related to flow regulation that lakes and wetlands may provide, as the main water-covered landscape features, include storage of water during wet periods (Lane & D’Amico, 2010), reduction of flood peaks and stormwater retention (Acreman & Holden, 2013; Loucks, 1990; Ogawa & Male, 1986; Wang et al., 2010), groundwater recharge or discharge (Gilfedder, Frei, Hofmann, & Cartwright, 2015), and streamflow and flow variability (Golden et al., 2016; Martinez-Martinez, Nejadhashemi, Woznicki, & Love, 2014; Yao, Wang, Lu, Yu, & Li, 2014). Historically, wetlands have been lost worldwide (Davidson, 2014), because they have been seen as marginal lands available to use for agriculture, forestry, urban development, and other human
activities (Mitsch & Gosselink, 2007). More recently, associated loss and degradation of ecosystem services have been recognized, leading to proposals to restore and construct wetlands as possible nature-based solutions for managing environmental changes and related ecosystem services in the landscape (Thorslund et al., 2017).

There are, however, potential pitfalls in judging the role that wetlands can play as nature-based solutions for large-scale management of ecosystem services in the landscape. One such pitfall can be to neglect how wetland ecosystems are defined and categorized. For example, wetlands are broadly defined in the Ramsar Convention (1971) and the Millennium Ecosystem Assessment (2005b) as encompassing all temporarily and permanently flooded areas of freshwater, including lakes, as well as brackish and salt-water bodies with a depth of up to 6 m. As the Millennium Ecosystem Assessment (2005b) notes, it would be erroneous to assume that all such types of water-covered landscape features have similarly significant beneficial roles; for example, for the landscape ecosystem service of flow regulation. A global review of the role of wetlands on the terrestrial hydrological cycling concluded that wetlands may strongly affect this cycling but also warned against making generalized assumptions across various types of wetlands (Bullock & Acreman, 2003). For example, floodplain wetlands may reduce or delay flood magnitude, whereas upland, rainfed wetlands may decrease or increase it (Acreman & Holden, 2013; Bullock & Acreman, 2003). These findings highlight the need to study actual effects of different types of wetlands and lakes in and across different landscapes and parts of the world. Another potential pitfall is not considering the large-scale functions and services that may be provided by the whole spectrum of different lakes and wetlands and their spatial occurrence and distribution (Mitsch & Gosselink, 2000) over the large scales of whole catchments (Brauman et al., 2007; Thorslund et al., 2017).

One important aspect of the potential large-scale effects that lakes and wetlands may have on flow regulation is their influence on flow variability, that is, on dampening the magnitude of peaks and troughs in runoff through the landscape. In their global review of wetlands, Bullock and Acreman (2003) compiled a total of 439 published statements on the water quantity functions of wetlands; only 28 statements referred to flow variability. Of these, 12 conclude that upland wetlands increase flow variability, 10 conclude that floodplain wetlands decrease flow variability, and six conclude that there is no wetland effect on flow variability (Table 5e, Bullock & Acreman, 2003). However, nearly all of these statements refer to studies of only one or, at most, a few wetlands within only one or two catchments. Only two of the statements were based on field studies of the combined effects of multiple wetlands on the variability of large-scale water flow (runoff). One of these studies concluded that multiple floodplain wetlands (along the Okavango and Sudd rivers) reduce large-scale flow variability (Sutcliffe & Parks, 1989), whereas the other concluded that multiple upland wetlands (peat bogs on steep slopes in the United Kingdom) increase it (Burt, 1995).

In more recent studies on the effect of wetlands on hydrological services related to flow regulation, Wang et al. (2010) have modeled the effects of wetland conservation and restoration, concluding that both measures reduce peak discharge but that the effect of conservation is greater. Yao et al. (2014) found an increase in peak flows due to loss of wetlands during the last half-century in a catchment, whereas Martinez-Martinez et al. (2014) instead found that wetland restoration generally reduces streamflow but has a negligible effect on daily peak flow rates and their frequency. Parry, Holden, and Chapman (2014) reviewed ecosystem services gained from peatland restoration and reported difficulties and knowledge gaps in determining if restoration affects peak flows. Larger scale studies have considered the role of geographically isolated wetlands as elements within greater hydrological and habitat networks (Cohen et al., 2016; Evenson, Golden, Lane, & D’Amico, 2015; Golden et al., 2016; Lane & D’Amico, 2010). These studies and findings in the global review of wetland effects on the hydrological cycle by Bullock and Acreman (2003) converge with the recent meta-analysis by Thorslund et al. (2017) in highlighting the need for more large-scale studies of the function of whole wetlandscapes (defined as the landscape of an entire catchment with multiple wetlands within it).

Here, we contribute to addressing some large-scale knowledge gaps through a data-driven analysis of (a) how flow variability is affected by multiple lakes and wetlands, within and across multiple catchments; (b) possible seasonal differences in large-scale lake and wetland effects on flow variability; and (c) possible influence of longer term hydroclimatic change on the large-scale wetland effects on flow variability. Our analysis is carried out for lakes and each of the following types of wetlands: all wetlands (excluding lakes), floodplain wetlands, upland wetlands, open upland wetlands, and forested upland wetlands. The analysis is statistical, using publicly available observation data from 1984 to 2013 for 82 Swedish catchments. In these long-term data series of relevant hydroclimatic variables, we specifically look for statistical signals of large-scale effects of lakes and wetlands in dampening the temporal variability of daily runoff, relative to that of the daily precipitation input, in and across the multiple investigated catchments.

## 2 | GENERAL CONCEPTUAL AND QUANTIFICATION BASIS

Figure 1 schematically illustrates the general conceptual basis for the quantification focus of this study on large-scale flow through whole hydrological catchments and how the temporal variability of this flow is influenced by the prevalence of wetlands and/or lakes within the catchment landscape. In general, the whole landscape and its various features, including wetlands and lakes, of any hydrological catchment, filters and dampens the temporal variability of incoming precipitation (P) to a considerably smaller temporal variability in the outgoing runoff (R). The main aim of this paper is to quantify and analyze the specific effects of wetland and lake prevalence within the catchment landscape on this flow dampening, with varying total wetland and lake areas relative to catchment area among different study catchments. As a concrete, quantified example, Figure 1 illustrates this dampening of temporal variability in R relative to that in P with data from a typical catchment in the investigated Swedish region (Figure 2). This region, further described in Section 3, includes multiple hydrological catchments with data available to quantify the dampening of their flow variability from P to R and classify the catchments based on this quantification (different catchment colors, Figure 2).
In the illustrated catchment example in Figure 1, the standard deviation quantifying the temporal variability of daily \( R \) is \( \sigma_R = 0.7 \text{ mm/day} \) whereas that of the driving water flux input of daily \( P \) is \( \sigma_P = 4.3 \text{ mm/day} \) (including days with 0 mm \( P \)). We refer to the relation \( (\sigma_R/\sigma_P) \) between the standard deviation of daily \( R \) to that of daily \( P \) in a catchment as the flow dampening factor, or just dampening factor, of that catchment. We use this factor to consistently and comparatively quantify and analyze the dampening of temporal flux variability from that in \( P \) to that in \( R \) and assess how it depends on the occurrence of wetlands and lakes in and across the multiple investigated catchments (Figure 2).

For the catchment example illustrated in Figure 1, the flow dampening factor is \( \sigma_R/\sigma_P = 0.7/4.3 = 0.16 \), that is, the characteristic temporal variability in daily \( R \) is 84% lower than that in \( P \). Also, in the relative terms of coefficient of variation (CV; standard deviation normalized by the long-term average value), the CV of \( R \) is smaller than that of \( P \); for the catchment example illustrated in Figure 1, \( CV_R = 1 \) and \( CV_P = 2 \). Assessment of relative flow-variability dampening by comparing the CV of \( R \) to that of \( P \) would imply dampening factor quantification as \( (\sigma_R/\sigma_P) \) because the partitioning of long-term average \( \bar{P} \) between corresponding long-term average \( \bar{R} \) and \( ET \) implies that \( \bar{R} < \bar{P} \) and thus \( (\bar{P}/\bar{R}) > 1 \). This partitioning thus implies an additional dampening effect quantified by \( (\sigma_R/\sigma_P) \) compared with that quantified by the CV relationship \( (\sigma_R/\sigma_P) \). Because this additional dampening effect is accounted for in \( (\sigma_R/\sigma_P) \), so is also the influence of lakes and wetlands on \( P \) partitioning (van der Velde, Lyon, & Destouni, 2013) and through that on \( (\sigma_R/\sigma_P) \). The \( P \) partitioning, and through that the dampening factor \( (\sigma_R/\sigma_P) \), may also be further affected by hydrological seasonality (Verrot & Destouni, 2016), long-term changes in climate (van der Velde et al., 2014), and human land and water uses (Destouni, Jaramillo, & Prieto, 2013; Jaramillo & Destouni, 2015). In this study, we want to capture all possible influences on flow-variability dampening due to lakes and wetlands and use therefore the standard deviation relation \( (\sigma_R/\sigma_P) \) as our primary comparative flow dampening factor.

For the same Swedish Water Management Districts (WMDs) as in the present study (Figure 2), Quin, Jaramillo, and Destouni (2015) have previously studied the effects of wetlands and lakes on the large-scale retention of waterborne nutrients. Both the retention of waterborne nutrients and the dampening of flow variability are important regulatory ecosystem services that wetlands and lakes may provide (Millennium Ecosystem Assessment, 2005a, 2005b). The previous analysis of large-scale nutrient retention showed this to be large for lakes and insignificant for wetlands (Quin et al., 2015), but results for large-scale flow regulation by wetlands and lakes, which is in focus here, may differ even though both services depend on the large-scale flow through catchments. Specifically, for nutrient retention, the wetlands and lakes in a catchment can only retain a significant amount of waterborne nutrients if a significant fraction of the total water flow (runoff, \( R \)) that carries the nutrients through the catchment landscape passes through the wetlands and lakes within it. In contrast, for the flow regulation service, the water level in each wetland and lake is hydraulically (pressure-wise) connected with the water levels in surrounding subsurface and surface waters. Through this water–pressure connection, the wetland and lake prevalence may significantly affect the flow-variability regulation in the catchment landscape, even without a large flow fraction (of total \( R \)) going through the wetlands and lakes themselves. The present analysis of wetland and lake effects on large-scale flow regulation enables a valuable and unique comparison with corresponding results for large-scale waterborne nutrient retention in the same WMDs, which we address in Section 6.
The study area covers two Swedish WMDs, the North and the South Baltic Proper (Figure 2). Annual average precipitation ranges from about 600 to 900 mm/year, runoff is about 200 to 400 mm/year, and evaporation is about 400 to 500 mm/year. For all catchments, spring (starting March 15) is cold to mild, with low levels of P compared with the annual average rate but average levels of R; summer (from May 15) is mild to temperate, with high levels of P but low to average levels of R; autumn (from September 25) is mild to cold, with average levels of P but low levels of R; and winter (from December 5) is cold to freezing, with average levels of P and high levels of runoff (Figure S4). The selection of 82 catchments for this study is based on the availability of runoff data from monitoring stations with at least daily resolution over a sufficiently long time period (from 1984 to 2013) to have a relevant statistical sample of temporal flow variability and enable assessment of possible effects due to longer term hydroclimatic change (question [c], in Section 1). Thirty-two catchments are in the North Baltic WMD and 50 catchments in the South Baltic WMD. For all 82 catchments, the minimum, maximum, average, and median of the catchment area, lake area per catchment, and area for different categories of wetlands per catchment are shown in Table 1. The maximum, average, and median values for the relative area of lakes and different categories of wetlands are also shown. In the North and South Baltic WMDs there are over 11,000 lakes greater than 1 ha and many more less than this size. The number of wetlands is larger.

The catchments in the study area are relatively uniform with regard to topography, geology, and soil type. In addition to the lake and wetland coverage provided in Table 1, about 60% of the study area is forested, and about 22% is agriculture. Topographically, few areas reach heights greater than 200 m above sea level. The terrain is undulating, with raised areas interspersed by valleys, both usually only a few hundred metres to a few kilometre across. The surface of raised areas is mostly exposed bedrock or shallow moraine topsoil (0 to a few metres deep). The valleys are mostly filled with clay and silt sediments (up to tens of metres deep). Only in the southernmost part of Sweden, and around some of the largest lakes, are sediment basins more extensive and deeper. More information is available in Swedish in the management plans for each WMD (Vattenmyndigheten Norra Östersjön, 2009; Vattenmyndigheten Södra Östersjön, 2009).
TABLE 1 Selected statistical values for catchment area and the area and proportions of lakes and wetlands for all 82 study catchments (Figure 2) in the North and South WMDs

|          | Min. | Max. | Ave. | Med. | Max. | Ave. | Med. |
|----------|------|------|------|------|------|------|------|
| Area     |      |      |      |      |      |      |      |
| Catchment| 0.8  | 22,600| 967  | 261  |      |      |      |
| Lake     | 0    | 2,482| 109  | 9.9  | 0.35 | 0.062| 0.056|
| Wetland (all types) | 0   | 1,131| 57   | 9.6  | 0.17 | 0.053| 0.045|
| Floodplain wetland | 0  | 101  | 3.4  | 0.5  | 0.02 | 0.003| 0.002|
| Upland wetland | 0  | 1,029| 54   | 8.7  | 0.17 | 0.050| 0.042|
| Open upland wetland | 0  | 484  | 20   | 2.4  | 0.07 | 0.016| 0.011|
| Forested upland wetland | 0 | 545  | 34   | 6.0  | 0.14 | 0.034| 0.030|

Note. For each catchment, lake and wetland areas and proportions have been calculated using the SMD dataset (see Section 4). For wetlands, values are provided across the different wetland categories (see Section 4). SMD: Svenska Marktäckedata; WMD: Water Management District.

4 MATERIALS AND METHODS

In this study, we have compiled data on daily R and P, as well as on temperature (T), and wetland and lake occurrence in each catchment. The flow dampening factor is calculated for 82 catchments in the Swedish study region (Figure 2) and two time periods, 1999–2013 and 1984–1998. These time periods are obtained by dividing the total time length with continuous availability of daily R data, 1984–2013, into two. This is done in order to get the longest possible climate-representative time periods (of 15 years each) for the longer term hydroclimate change assessment related to question (c) in Section 1. The most recent period, 1999–2013, is the base-case period for all quantifications in the study while conditions in the preceding period, 1984–1998, are used for the hydroclimatic change assessment. For each period, we assess the relationship between the dampening factor and relative lake and wetland area in each catchment. To enable the results to be compared and checked for consistency, this catchment-wise assessment is done both separately and in combination for the two Swedish WMDs of the North and South Baltic (Figure 2).

Daily data on R (discharge normalized by the catchment area) are obtained from the Swedish Meteorological and Hydrological Institute (SMHI, 2015) for discharge measurement stations in the North and South Baltic WMDs. The availability of daily R data (compared with daily P and T data, which are available over longer time periods) determined the two longest possible climate-representative time periods of 15 years each, 1999–2013 and 1984–1998. The locations of the 82 discharge measurement stations with ≤10% missing daily R data in both of these time periods defines the catchments, with the following overlap characteristics (Figure 2): first-level catchments do not lie within any other catchment; second-level catchments lie within the first-level catchments; and third-level catchments lie within the second-level catchments. Overlapping catchments are used only to increase the statistical sample size and make full use of available discharge data. Data on daily P and T in the 82 catchments are also obtained from SMHI (2014a). Daily P rates (mm/day), which includes rainfall and snowfall, and T values (°C) are available for the whole of Sweden in a 4 × 4 km grid dataset, where the values for each grid square have been interpolated by SMHI based on the measurement data from meteorological stations.

4.1 Lakes and wetlands in the catchments

The wetland types used in this study are based on data on lake and wetland occurrence from Svenska Marktäckedata (SMD; eng. Swedish Land Cover Data), produced by Sweden’s national mapping authority (Lantmäteriet, 2005). It is a primarily satellite-based (Landsat TM) geographic information system dataset for year 2000 (±1 year) with a 25 × 25 m resolution. The SMD classification system is based on the European Environment Agency CORINE land-cover system (European Environment Agency, 1995), providing additional land-cover sub-classes and a higher resolution for many of these. SMD uses five main land-cover classes: (a) artificial surfaces, (b) agricultural areas, (c) forests and semi-natural areas, (d) wetlands, and (e) water bodies. Despite this dataset being based on data from 2000, it is reasonable to assume that the number and area of lakes and wetlands does not change significantly over the time periods analyzed in this study (see the Additional Results and Discussion in the Supporting Information).

In SMD, lakes are distinguished from wetlands, and both are mapped if they have an area of 1 ha or greater. Lakes are classified into open-water areas or areas of water with floating vegetation and are generally perennial water bodies. The SMD wetland classes are based on hydrological characteristics as well as vegetation type and cover (Lantmäteriet, 2005). Regarding the hydrological characteristics, the SMD dataset primarily consists of perennial wetlands, where the water level is close to, at or above the ground surface. (Although ephemeral wetlands are also included in SMD wetland classes, these are almost exclusively present on the limestone-bedrock islands of Gotland and Öland, not included in this study). The SMD wetland classes are found in the following two main land-cover classes of the SMD land-cover classification: (a) forests and semi-natural areas and (b) wetlands. Forest wetlands have >30% tree cover and are classified according to the type of forest overlying them. The wetlands class includes subclasses limnogenous marshes, bogs, and salt marshes. These all have <30% tree cover. In SMD, limnogenous wetlands are generally comprised of surface-water fed, floodplain wetlands, whereas bogs and forested wetlands are generally comprised of rainwater-fed, upland wetlands (Lantmäteriet, 2005). Bogs are further subdivided into ‘wet bogs,’ ‘other bogs,’ and ‘peatlands with turf extraction.’ Both SMD classes of limnogenous wetlands and bogs also include types of wetlands that can be translated as ‘fens’ and are partly groundwater-fed.
In this study, we include both SMD lake classes, ‘open-water’ and ‘vegetation-covered’ as a single lake type. The SMD wetland classes included in this study are limnogenous marshes, bogs, and forest wetlands—salt marshes are not included. For this study, we consider the SMD limnogenous wetland class as floodplain wetlands and the SMD bog and forest wetland classes as upland wetlands. We adopt the term ‘upland wetlands,’ referring to upland, rain-fed wetlands (Acreman & Holden, 2013), which distinguishes these types of wetlands from predominantly surface-water fed floodplain wetlands. In this study, the SMD wetland classes are thus grouped into the following wetland types: all wetlands (excluding lakes), floodplain wetlands, upland wetlands, open upland wetlands, and forested upland wetlands.

4.2 Asssessing lake and wetland effects on flow dampening

For each catchment, we calculate the total area of all lakes and wetlands, as well as that of the different lake and wetland types. We further normalize this area by total catchment area to obtain relative lake area ($A_{Lake}/A_{Catchment}$) and relative wetland area ($A_{Wetlands}/A_{Catchment}$). These relative lake or wetland-area measures are consistent with the area normalization of P and R data and allow direct comparison of catchments of different size (as do also the area-normalized P and R data).

For each catchment (i), the long-term average (mean) value ($\bar{R}_i$), and standard deviation ($\sigma_{R,i}$) of daily R is calculated for each period, 1999–2013 and 1984–1998. For each period and catchment (i), we also extract the daily P data from the $4 \times 4$ km grid dataset and calculate corresponding mean ($\bar{P}_i$) and standard deviation ($\sigma_{P,i}$) values. The relation of the flow dampening factor ($\sigma_{R,i}/\sigma_{P,i}$) to relative lake and wetland area is assessed for all wetlands, floodplain wetlands, upland wetlands, open upland wetlands, and forested upland wetlands for all 82 catchments in the two Swedish WMDs, the 32 catchments in the North Baltic WMD and the 50 catchments in the South Baltic WMD (Figure 2).

4.3 Assessing seasonal differences in lake and wetland effects on flow dampening

For each catchment, a seasonal flow dampening factor is calculated, in addition to the whole-year factor, to capture possible seasonal differences in lake or wetland effects on flow dampening. Such differences may exist due to winter freezing, spring snowmelt, or peak evapotranspiration (ET) in summer, for example. Season start dates are obtained from maps compiled by SMHI (2014b), displaying meteorologically defined, mean season start dates from 1961 to 1990 as isolines covering the whole of Sweden. The following start dates apply: March 15 for spring, May 15 for summer, September 25 for autumn, and December 5 for winter.

Based on these seasons, we calculate for each catchment (i) and time period mean seasonal values ($\bar{R}_{i,season}, \bar{P}_{i,season}$) and standard deviations ($\sigma_{R,i,season}, \sigma_{P,i,season}$) of daily R and P, and a corresponding seasonal dampening factor ($\sigma_{R,i,season}/\sigma_{P,i,season}$). Thereby, the relationship between seasonal dampening factor and relative lake or wetland area in and among the study catchments can be assessed. To assess how well a fitted regression function for the corresponding whole-year relationship can work as a model for the seasonal relationship conditions, we calculate the mean square error of such model results for the different seasons as

$$\text{MSE}_{season} = \frac{1}{n} \sum_{i=1}^{n} (\hat{Y}_i - Y_i)^2,$$

where $\hat{Y}_i$ is the vector of the model predictions (for the seasonal dampening factor), $Y_i$ is the vector of observed values (of relative lake/wetland area), and $n$ is the number of catchments, i.

4.4 Assessing climate-period differences in lake and wetland effects on flow dampening

To address question (c), on the possible influence of longer term hydroclimatic change on the large-scale wetland effects on flow variability, we calculate for each catchment and climate-representative periods, 1984–1998 and 1999–2013, the temporal standard deviation $\sigma_x$, long-term average value $\bar{x}$, and corresponding temporal coefficient of variation $CV_x = \sigma_x/\bar{x}$ for daily P and R. Furthermore, we calculate and compare the dampening factor ($\sigma_{R,i}/\sigma_{P,i}$) between the periods and its relation to relative lake or wetland area.

To characterize prevailing large-scale hydroclimatic conditions of P, R, and T, and quantify their differences between the two periods, we consider spatial average values of each variable over the whole North Baltic and South Baltic WMDs. Based on the nonoverlapping first-level catchments, seven in the North Baltic WMD and 26 in the South Baltic WMD (Figure 2), we calculate for each WMD the area-weighted spatial mean value of each variable $x$ (T, P, and R) as

$$\bar{x}_{area-weighted} = \frac{\sum_i A_i \bar{x}_i}{\sum A_i},$$

where $\bar{x}_i$ is average value in each catchment $i$ and $A_i$ is catchment area. An area-weighted spatial standard deviation among catchments of interannual variability (temporal standard deviation $\sigma_{x,annual}$) in mean annual $x$ over each period is also calculated as

$$\sigma_{x,annual} = \sqrt{\frac{\sum_i A_i^2 \cdot \sigma_x^2}{\sum A_i^2}},$$

For P and R, corresponding seasonal (to the above annual) area-weighted statistics are also calculated for each WMD.

5 RESULTS AND DISCUSSION

The dampening factor in the 82 study catchments ranges from 0.08 to 0.35 ($\bar{x} = 0.19, \sigma = 0.07, median \ x = 0.17$) in the period 1999–2013 (Figure 2). This is similar to 1984–1998 (Figure S1), which ranges from 0.09 to 0.36 ($\bar{x} = 0.20, \sigma = 0.07, x = 0.18$). This implies a robust regional range of flow dampening, with a 65%–90% lower catchment-characteristic variability in daily R than in daily P. An extension to this section is provided in the Supporting Information.

5.1 Lake and wetland effects on flow dampening

Across all catchments of the North and the South Baltic WMD, there is considerable correlation between the dampening factor and relative lake area, with around 64% of the spatial variation of the flow
dampening factor explainable by the variability of relative lake area in the catchments (Figure 3a). This is also discernible in Figure 2 by observing the colored scale of dampening factor values and comparing catchments that contain lakes, especially the larger ones, with catchments that have few lakes or none. There is some correlation with floodplain wetlands, with up to 36% of the spatial variation of the flow dampening factor explainable by the variability of relative area of floodplain wetlands in the catchments (Figure 3c). For other wetland categories, there is only small or no correlation between the dampening factor and relative wetland area, including for all types of wetlands taken together (Figure 3b), upland wetlands (open and forested; Figure 3d), open upland wetlands (Figure 3e), and forested upland wetlands (Figure 3f). The correlation for these wetland types can only explain up to 12%–18% of the cross-catchment variability in the flow dampening factor despite having greater coverage than floodplain wetlands (Table 1); additionally, the degree of correlation is not much affected by the upland wetlands being open or forested.

The dampening factor correlation to respective area for lakes is only slightly less than that for lakes and floodplain wetlands taken together; the fitted regression equations for these lake or wetland types are also similar (Figure 3a and 3c), indicating that they may be viewed as a continuum of water reservoirs with similar physical function with regard to flow dampening in the landscape. Furthermore, the correlation conditions found are similar when considering the North or the South Baltic WMD separately, as illustrated for lakes and floodplain wetlands in Figure S2.

There is little correlation between the dampening factor and absolute catchment scale (Figure 3g). However, the results for catchment scale are more heteroscedastic (have unequal statistics across the range of investigated catchment scales) than for the other, relative lake or wetland area variables in Figure 3. Specifically, the range of dampening factor values is much greater for small catchments than for large catchments. There is no correlation between the relative area of lakes and floodplain wetlands or between catchment area and the

FIGURE 3 The flow-dampening factor for 1999–2013 plotted against (a) the relative area of lakes to catchment area, (b–f) the relative area of different wetland categories to catchment area, and (g) to the catchment area, for the 82 catchments in the North and South Baltic Water Management Districts.
relative area of lakes or floodplain wetlands (Figure S3); thus, there is no colinearity effect between any combination of these variables on flow variability.

Variables related to, for example, topography and land-cover types other than wetlands and lakes investigated here, may also have large-scale effects on the flow dampening factor (van der Velde et al., 2013) and more generally on flow variability (Botter, Basso, Rodriguez-Iturbe, & Rinaldo, 2013). However, the primary purpose of this study is to specifically compare and contrast the large-scale flow dampening effects of the main water-covered features, lakes and wetlands, in and across multiple catchment landscapes. As described in Section 3, the topographic, land-cover, and soil-type characteristics are, overall, consistent across the investigated catchments. We therefore expect the main differences in the flow dampening factor to reflect quantified differences in wetland and lake occurrence, to the degree that these different water-covered features do matter for large-scale flow-variability dampening in and across catchments. Future work combining the method used here with that used by van der Velde et al. (2013) should be carried out to further test this expectation and the present results for other catchment landscapes in different parts of the world.

5.2 Seasonal differences in lake and wetland effects on flow dampening

Regarding seasonal conditions in the recent period 1999–2013, the dampening factor correlation with relative lake and floodplain-wetland area (taken together) is greater in spring (explaining 64% of the variation among catchments) and winter (62%) than in autumn (42%) and summer (33%; Figure 4). These seasonal results are consistent with lakes and floodplain wetlands contributing most (least) to flow dampening in the seasons with the greatest (smallest) differences in relative P and R variability (CV value), which are spring and winter (autumn and summer; Figure S4, right panels). Spring and winter also have the smallest, whereas summer and autumn have the largest relative differences between average seasonal P and R (Figure S4, left panels); that is, the relative P-water partitioning to ET is smallest (greatest) in spring and winter (summer and autumn). Furthermore, with regard to fitted functional relationships, the dampening-factor decrease with increasing relative lake or wetland area is greatest for spring, followed by winter, autumn, and summer (Figure 4). This magnitude order is opposite to that of average seasonal P-water input, which is smallest for spring, followed by winter, autumn, and summer (Figure S4, left panels).

FIGURE 4 The flow-dampening factor for each season, (a) spring, (b) summer, (c) autumn, (d) winter, and (e) for the whole year, over the time period 1999–2013 plotted against the total relative area of lakes and floodplain wetlands for each of the 82 catchments in the North and South Baltic Water Management Districts shown in Figure 2. (f) Using the regression function for the annual result \( y = -0.017\ln(x) + 0.121 \) as a model, the resulting mean square error in the flow-dampening factor is shown for the annual result (square marker) and for each of the seasonal results (round markers).
In combination, these results indicate that lakes and floodplain wetlands affect the flow dampening in the landscape more by their water-storage capacity than by their influence on P partitioning between ET and R. For a dominant flow dampening effect of remaining unfilled lake or wetland storage capacity, the dampening factor would be expected to decrease (change) less with increasing (changing) relative lake or wetland area for greater seasonal P-water inputs. This expected dampening factor behavior is indeed also observed in the fitted seasonal regression functions (Figure 4), in accordance with seasonal P-water inputs being smallest in spring, intermediate in winter and autumn, and greatest in summer (Figure S4, left panels). A possible dominant effect of greater lake or wetland area within a catchment enhancing ET and thus dampening the average value and absolute fluctuations of R should have been reflected in a relatively high flow dampening correlation with relative lake–wetland area for upland wetlands, which have a much greater relative area than floodplain wetlands, and for the summer and autumn seasons, which have the greatest water partitioning to ET (and thus smallest to R) relative to the total seasonal P input of water. Neither of these effect signals are found in this study; instead, a lower correlation between flow dampening factor and relative lake or wetland area is observed in summer and autumn than in spring and winter or the whole year (Figure 4).

Finally, the fitted whole-year regression function for the dampening-factor relationship with relative lake or wetland area (Figure 4e) is most similar to the corresponding seasonal function for autumn (Figure 4c). It is less similar for winter (with freezing conditions; Figure 4d) and summer (with peaking ET; Figure 4b) and most different for spring (with dominant snowmelt and flood conditions; Figure 4a). These similarity or difference conditions are also reflected in the least mean square error obtained for the seasonal dampening factor using the whole-year relationship as a model, with the error being smallest for autumn, greater for winter and summer, and greatest for spring (Figure 4f). These seasonal results are similar for the preceding period 1984–1998 (not shown).

5.3 Climate-period differences in lake and wetland effects on flow dampening

Over the 33 non-overlapping (first level) catchments in the North and South Baltic WMDs (Figure 2), the area-weighted long-term mean P and R values have increased slightly (by ~5% for P and ~8%–9% for R in each WMD) from 1984–1998 to 1999–2013 (Figure 5). Much of the increase in P has occurred in summer whereas much of the increase in R has occurred in winter (Figure S4). In both the North and South Baltic WMDs, the temporal CV is around 2 for daily P and around 1 for daily R, essentially remaining close to these levels between the periods (Figure 5). Corresponding seasonal results are shown in Figure S4.

FIGURE 5 Temperature, precipitation, and runoff statistics for the North and South Baltic Water Management Districts (WMDs) and the two time periods, 1984–1998 and 1999–2013. The charts on the left show the area-weighted mean annual temperature (°C) in each WMD. Similarly, the area-weighted mean annual precipitation and runoff (mm/year) are shown in the charts in the middle. The temporal coefficient of variation (temporal standard deviation divided by the corresponding temporal mean) for daily precipitation and daily runoff is shown in the charts on the right. For the area-weighted mean values, the error bars show the spatial standard deviation among catchments. These statistics were calculated using non-overlapping catchments (all first-level catchments, Figure 2).
For the lake or wetland effects on the dampening factor, the total relative area of lakes and floodplain wetlands can explain up to 64% of the dampening factor variability among catchments in 1999–2013 and 62% in 1984–1998 (Figure 6). Thus, there is only a slight change in flow dampening factor behavior between the periods. This is consistent with relatively small P and R changes, even though there has been considerable warming (T increase), between the periods.

6 | CONCLUSIONS

This large-scale, multi-catchment study complements previous research, which has mostly focused on single or a few wetlands within one or two comparative catchments. The present results contribute to improved understanding of large-scale ecosystem functions, services, and nature-based solutions that may be provided by multiple wetlands within and across multiple catchments. For the ecosystem service of large-scale flow regulation, this study has shown that lakes and, to a lesser degree, floodplain wetlands dampen flow variability significantly within the investigated catchments. Previous research in the same study area has shown that only lakes (but no type of wetlands) correlate with large-scale retention of waterborne nutrient loads. Thus, the current results support the difference in underlying flow-related regulation mechanisms, outlined in Section 2, between the previously studied large-scale retention of waterborne nutrients and the large-scale flow-variability regulation, investigated here. Overall, lakes are effective in providing both these types of large-scale ecosystem services, whereas wetlands—as generally shallower water-covered features in the landscape—have smaller correlation (for flow regulation in floodplain wetlands) or no correlation (for flow regulation in other wetlands and nutrient retention in all wetland types) with these services in the investigated catchments. While single wetlands may provide local flow regulation (or waterborne nutrient retention) effects, such local effects cannot simply be extrapolated as a general conclusion to the large-scale over whole catchments.

For large-scale flow regulation, this study indicates the water-storage capacity of lakes and of wetlands in relatively downgradient (floodplain) locations as key for considerable large-scale effects on flow-variability regulation. Seasonal correlations and relationships found between the flow dampening factor and relative lake or wetland area converge in supporting this finding. These results do not contradict previous ones on important hydrological connections of, for example, geographically isolated wetlands (Cohen et al., 2016; Evenson et al., 2015; Golden et al., 2016; Lane & D’Amico, 2010). Such wetlands may be hydrologically well-connected (mainly through subsurface flow interactions) to other water features and to runoff generation within catchments, yet still have only small effects on the large-scale dampening of flow variability due to relatively small water storage within them.

For various large-scale wetland functions, further studies are needed that link different types of flow-related functions and services, and their possible future changes. In the present study catchments, the lake and wetland effects on flow-variability dampening are found to be essentially unchanged over the last three decades. However, future hydroclimatic changes may differ from past changes and may affect lake and wetland storages and thereby also their contributions to large-scale dampening of flow variability. The results of large-scale, long-term studies like the present one have implications for decisions on restoration and construction of wetlands as large-scale nature-based solutions, for example, for flood and drought protection. The present results emphasize the need to consider the problem scale and the relative water-storage capacity of wetlands when considering their large-scale potential to provide such ecosystem services.

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Additional supporting information may be found online in the Supporting Information section at the end of the article.

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