The Hydrological Archetypes of Wetlands

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Abstract

Wetlands are valuable and diverse environments that contribute to a vast range of ecosystem services, such as flood control, drought resilience, and carbon sequestration. The provision of these ecosystem services depends on their hydrological functioning, which refers to how water is stored and moved within a wetland environment. Since the hydrological functions of wetlands vary widely based on location, wetland type, hydrological connectivity, vegetation, and seasonality, there is no single approach to defining these functions. Consequently, accurately identifying their hydrological functions to quantify ecosystem services remains challenging. To address this issue, we investigate the hydrological regimes of wetlands, focusing on water extent, to better understand their hydrological functions. We achieve this goal using Sentinel-1 SAR imagery and a self-supervised deep learning model (DeepAqua) to predict surface water extent for 43 Ramsar sites in Sweden between 2020~~ and ~~-2023. The ~~prediction results in~~ wetlands are grouped into ~~five~~the following archetypes based on their hydrological similarity: 'autumn drying', ‘summer dry', 'spring~~-~~ surging', ~~‘spring~~ 'summer flooded', ~~'summer~~ ‘spring flooded'~~,~~ and ‘slow~~-~~drying'~~ and ‘summer dry'~~. The archetypes represent great heterogeneity, with flashy regimes being more prominent at higher latitudes and smoother regimes found preferentially in central and southern Sweden. Additionally, many ~~wetlands~~archetypes show exceptional similarity in the timing and duration of flooding and drying events, which only became apparent when grouped. We attempt to link hydrological functions to the archetypes whereby headwater wetlands~~, for example, we find that~~ like the spring-surging ~~wetlands~~archetype have the potential to accentuate floods and droughts, while slow-drying wetlands, typical of floodplain wetlands, are more likely to provide services such as flood attenuation and ~~water storage during~~ low flow ~~conditions~~supply. Additionally, although wetlands can be classified in myriad ways, we propose that classifying wetlands based on the hydrological regime ~~derived from water surface extent~~ is useful for identifying hydrological functions specific to the site and season~~, and when discharge or water depth data is not available~~. Lastly, we foresee that hydrological regime-based

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classification can be easily applied to other wetland-rich landscapes to understand the hydrological functions better and identify their respective ecosystem services.

1 Introduction

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Wetlands are ecosystems that are seasonally or permanently covered by or saturated with water ~~(Bullock and Acreman, 2003). After centuries of wetland loss (Fluet-Chouinard et al., 2023), wetlands are now viewed as key providers of provisioning and regulating services such as forestry, fishing, food production, flood control, drought resilience, nutrient and sediment retention and carbon sequestration (Ameli and Creed, 2019; Barbier et al., 1997; Colvin et al., 2019; Johnston, 1991; Matthew et al., 2010; Tang et al., 2020; Villa and Mitsch, 2015). Additionally, they offer cultural and supporting services (Margaryan et al., 2022; Mitsch et al., 1991; Wood et al., 2024) and are crucial for achieving the sustainable development goals outlined in Agenda 2030 (Jaramillo et al., 2019)~~(Bullock and Acreman, 2003). After centuries of wetland loss (Fluet-Chouinard et al., 2023), wetlands are now viewed as key providers of provisioning and regulating services such as forestry, fishing, food production, flood control, drought resilience, nutrient and sediment retention and carbon sequestration (Ameli and Creed, 2019; Barbier et al., 1997; Colvin et al., 2019; Johnston, 1991; Matthew et al., 2010; Tang et al., 2020; Villa and Mitsch, 2015). Additionally, they offer cultural and supporting services (Margaryan et al., 2022; Mitsch et al., 1991) and are crucial for achieving the sustainable development goals outlined in Agenda 2030 (Jaramillo et al., 2019).

~~The degree to which wetland environments provide ecosystem services is largely controlled by their hydrological functions (Okruszko et al., 2011) or how wetlands store and transfer water. For instance, hydrological functions such as prolonged water storage contribute to services like flood control and sustaining water supply during low flow periods (Åhlén et al., 2020; Bullock and Acreman, 2003; Gerakēs, 1992). Other functions, such as surface-ground water exchange, relate to provisioning services such as water supply, while surface wetness and soil moisture help regulate the local climate and retain nutrients (Ameli and Creed, 2017; Hansson et al., 2005; Le and Kumar, 2014; Mitsch et al., 2015). Furthermore, large fluctuations of surface water extent is strongly correlated to fluctuations of methane emissions for boreal wetlands (North of 50°N), which is important for services like carbon sequestration~~

The degree to which wetland environments provide ecosystem services is largely controlled by their hydrological functions (Okruszko et al., 2011) or how wetlands store and transfer water. For instance, hydrological functions such as prolonged water storage contribute to services like flood control and sustaining water supply during low flow periods (Åhlén et al., 2020; Bullock and Acreman, 2003; Gerakēs, 1992). Other functions, such as surface-ground water exchange, relate to provisioning services such as water supply, while surface wetness and soil moisture help regulate the local climate and retain nutrients (Ameli and Creed, 2017; Hansson et al., 2005; Le and Kumar, 2014; Mitsch et al., 2015). Furthermore, surface water extent variability is strongly correlated to fluctuations of methane emissions for boreal wetlands (North of 50°N), which is important for carbon cycling (Ringeval et al., 2010).

Quantifying the hydrological functions of ~~wetlands~~any wetland and the ~~provision of~~ ecosystem services it provides is challenging as wetlands are spatiotemporally variable and diverse ~~(McLaughlin and Cohen, 2013)~~(McLaughlin and Cohen, 2013). For example, a wetland type can either reduce or enhance flooding downstream depending on the environmental setting or time of year (Bullock and Acreman 2003). One way to improve our understanding of wetland hydrological functions and related ecosystem services is by quantifying their hydrological regime. This refers to the seasonal availability of water (water, extent, or volume) within a wetland, measured through either in-situ or remote sensing technologies (Acreman and Holden, 2013; Helmschrot, 2016).

The analysis of hydrological regimes to understand hydrological functioning usually focuses on rivers and catchments ~~(Magilligan and Nislow, 2005; Robinson and Sivapalan, 1997). However, over the last two decades, its application for wetlands has steadily increased (e.g., Cuevas et al., 2024; Stevaux et al., 2020; Na and Li, 2022; Vilardy et al., 2011). In fact, methods for studying water extent have been driven by the need to quantify ecosystem services (Park et al., 2022). For instance, by monitoring water level or extent, we can evaluate whether a wetland is in a water storing or transmitting state, which influences its ability to attenuate high flows downstream (Spence et al., 2011; Yanfeng and Guangxin, 2021). Furthermore, analysis of the hydrological regimes based on water extent and level in Siberian wetlands has enhanced the understanding of how water availability in winter influences spring flooding (Zakharova et al., 2014). In Europe, Vera-Herrera et al. (2021) demonstrated that grouping wetlands based on their long-term changes in surface water extent can help to maximize agricultural productivity, while Åhlén et al (2022) distinguished between flood buffering capacity of wetlands in upland and downstream wetlands studying~~(Magilligan and Nislow, 2005; Robinson and Sivapalan, 1997). However, over the last two decades, its application for wetlands has steadily increased (e.g., Cuevas et al., 2024; Stevaux et al., 2020; Na and Li, 2022; Vilardy et al., 2011). In fact, methods for studying water extent have been driven by the need to quantify ecosystem services (Park et al., 2022). For instance, by monitoring certain water level or extent thresholds throughout the year, we can evaluate whether a wetland is in a water-storing or transmitting state, which influences

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its ability to attenuate high flows downstream (Spence et al., 2011; Yanfeng and Guangxin, 2021). For example, analysis of the hydrological regimes of wetlands in Siberia has enhanced the understanding of how their early-year (winter) water availability influences their contribution to spring flooding (Zakharova et al., 2014). In Europe, Vera-Herrera et al. (2021) demonstrated that grouping wetlands based on their long-term changes can help to maximize agricultural productivity, while Åhlén et al (2022) distinguished between flood buffering capacity of wetlands in upland and downstream wetlands using variations in water level.

~~When in-situ water level or dicharge measurements from water gauges are spatiotemporally sparse, water surface extent can be used to understand the hydrological regime. Estimating hydrological regimes from water surface extent is achievable with remote sensing technologies, such as optical or Synthetic Aperture Radar (SAR) (Graversgaard et al., 2021; Ramsar Convention, 2011; Vera-Herrera et al., 2021). For example, multi-spectral optical sensors like Sentinel-2 can help estimate surface water extent at a resolution of 10 m (Brown et al., 2022). Others have exploited the ability of SAR to detect water below flooded vegetation in a range of wetland environments at similar resolutions (Canisius et al., 2019; Kovacs et al., 2013; Melack and Hess, 2011; Widhalm et al., 2015; Peña et al., 2024).~~

~~It is widely recognised that although ecosystem services are not undervalued, they are often poorly characterised and understood in the context of wetlands. Furthermore, generalising hydrological functions and services across different wetlands is not recommended due to their unique characteristics. Here, we quantify changes in water surface extent to understand the hydrological regimes of wetlands and determine their hydrological functions, using the case of Sweden. This study aims to categorise wetlands by their hydrological regime based on recent water surface extent observations using a remote sensing data and a pre-trained self-supervised deep learning model called DeepAqua (Peña et al., 2024). We use the case of 43 Ramsar wetlands as they are well inventoried, and present good spatiotemporal coverage of SAR data and are of national and international importance due to the ecosystem services they provide (Gunnarsson and Löfroth, 2014; Ramsar Convention, 2011). We propose that by grouping hydrologically similar sites into descriptive archetypes (as suggested by Lane et al., 2018), more comprehensive insights can be gained about the hydrological regime (and thus functions) than by studying each wetland's hydrological regime in isolation.~~

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~~2 Methods~~

~~2.1. Wetland dataset description~~

When in-situ water level measurements from water gauges are spatiotemporally sparse, water extent changes can be used to understand the hydrological regime. Estimating hydrological regimes from water extent is achievable with remote sensing technologies, such as optical or Synthetic Aperture Radar (SAR) (Graversgaard et al., 2021; Ramsar Convention, 2011; Vera-Herrera et al., 2021). For example, multi-spectral optical sensors like Sentinel-2 can estimate surface water extent at a resolution of 10 m (Brown et al., 2022). Others have exploited the ability of SAR to detect water below flooded vegetation in a range of wetland environments at similar resolutions (Canisius et al., 2019; Kovacs et al., 2013; Melack and Hess, 2011; Widhalm et al., 2015; Peña et al., 2024).

It is widely recognised that although ecosystem services are not undervalued, they are often poorly characterised and understood in the context of wetlands. Furthermore, generalising hydrological functions and services across different wetlands is not recommended due to their unique characteristics. Here, we quantify changes in water surface extent to understand the hydrological regimes of wetlands and determine their hydrological functions, using the case of the extended set of wetlands under the Ramsar Convention in Sweden. Doing so would help quantify their ecosystem services (unknown to date), particularly emphasising hydrology-based services such as flood attenuation and low flow supply.

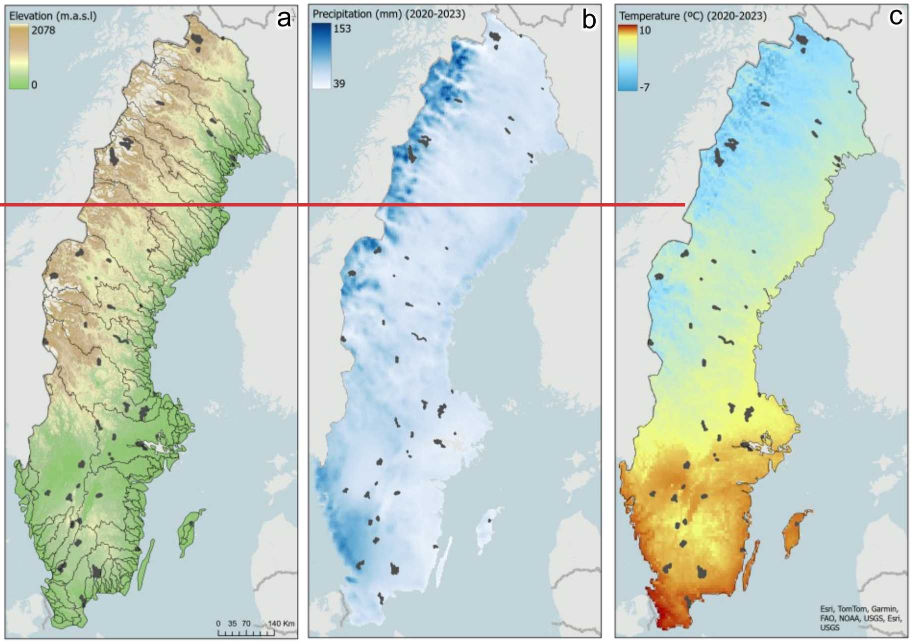
We use a remote sensing approach to categorise wetlands by their hydrological regime based on recent water extent observations (from 2020 to 2023) using a pre-trained self-supervised deep learning model called DeepAqua, which has been used to detect water from Sentinel-1 imagery (Peña et al., 2024). We use the case of 43 Ramsar wetlands as they are well inventoried, present good spatiotemporal coverage of SAR data (~1 pass per week), and are of national and international importance due to the ecosystem services they provide (Gunnarsson and Löfroth, 2014; Ramsar Convention, 2011). We also propose that by grouping hydrologically similar sites into descriptive archetypes (as suggested by Lane et al., 2018), more comprehensive insights can be gained about the hydrological regime (and thus functions) than by studying each wetland's hydrological regime in isolation.

2 Methods

2.1. Wetland dataset description

Sweden has 68 Ramsar wetlands in total ~~(Ramsar Convention, 1971).~~(Ramsar Convention, 1971). Here, we excluded coastal sites because coastal wetlands are hydrologically different from inland wetlands and, thus, should ~~therefore~~ be studied separately. Sites with a total area exceeding 180,000 ha were also excluded due to computational and memory limitations when computing water extent changes with deep learning. Lastly, sites with many low SAR data availability due to processing issues and the loss of Sentinel-1B in December 2021 were omitted from the analysis. This left 43 Ramsar sites suitable for hydrological regime analysis, and each site was delimited based on the boundaries of the Ramsar Convention ~~(Ramsar Convention - Sweden, 2023)~~(Ramsar Convention - Sweden, 2023) (Fig. 1).

~~The sites are distributed throughout all regions in Sweden, albeit with a higher concentration of sites in central and southern Sweden. Site areas range between 200 ha and 28,900 ha and encompass various wetland types, including marshes, fens, bogs, mires, palsa mires, lakes, streams, wetland forests, peatlands, and shrub wetlands. For these wetlands, during the observation period (2020-2023), the average temperature and precipitation were 5.76°C and 706.5 mm, which was 0.68°C warmer and 25.6 mm wetter on average compared to the 1990-2020 climate normal (Johansson, 2002). Additionally, the mean number of snow days in Sweden between 2020-2023 was 108.0, which is 12.3 days less compared to the last climate normal (Climate indicator – Snow, 2024). Daily precipitation from the Copernicus Climate Change Service E-OBS ensemble (0.1° grid) for each Ramsar site is available in Figs A7-11 (Cornes et al., 2018).~~



The sites are distributed throughout all regions in Sweden, albeit with a higher concentration of sites towards the south. Site areas range between 200 ha and 28 900 ha and encompass various wetland types, including marshes, fens, bogs, mires, palsa mires, lakes, streams, wetland forests, lakes, peatlands, and shrub wetlands. For these wetlands, during the observation period (2020-2023), the average temperature and precipitation were 5.76°C and 706.5 mm, which was 0.68°C warmer and 25.6 mm wetter on average compared to the 1990-2020 climate normal (Johansson, 2002). Additionally, the mean number of snow days in Sweden between 2020-2023 was 108.0, which is 12.3 days less compared to the last climate normal (Climate indicator - Snow, 2024).

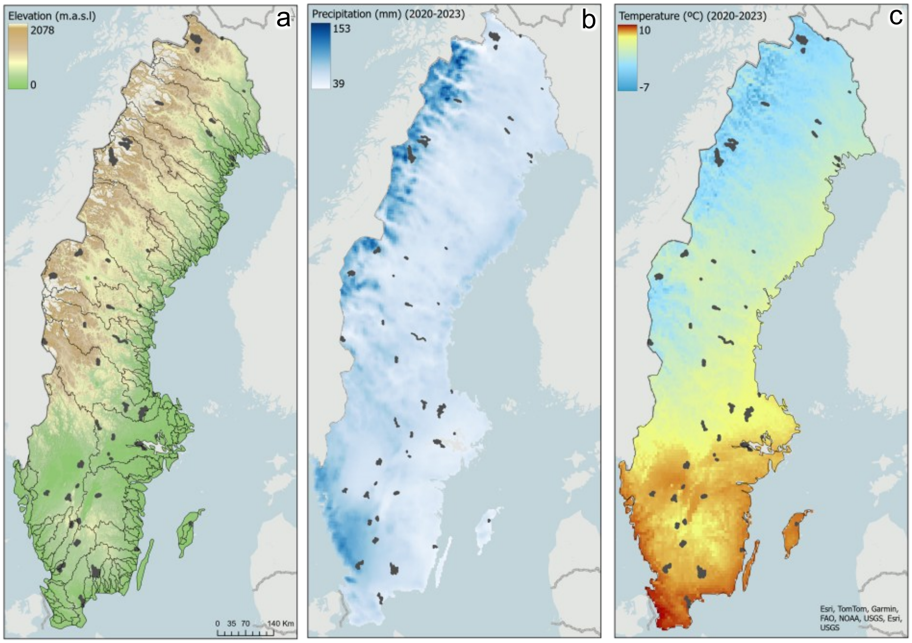


Figure 1. Spatial distribution of Ramsar wetland study sites (grey polygons) in terms of ~~(~~a) ~~Elevation~~elevation from a 50m resolution DEM by ~~*Landmäteriet*~~Landmateriet (grey thin lines denote main catchments), ~~(~~b) ~~Average~~average precipitation ~~in mm/yr~~ and ~~(~~c) ~~Average~~average temperature ~~in °C between~~from 2020 ~~and~~to 2023. Temperature and precipitation data were obtained from the Precipitation Temperature Hydrological Agency's Water Model (PTHBV), available at the Swedish Meteorological and Hydrological Institute (SMHI).

2.2. Wetland characteristics

To place the wetlands into an environmental context, we tabulated each site's latitude, elevation, open water as a percentage of the total area, and general wetland type~~.~~ (Figure 6). The elevation was calculated as the average elevation (m.a.s.l) derived from the Digital Elevation Model 50m (*Markhöjdmodell Nedladdning*, grid 50+) ~~(Lantmateriet, 2022)~~(Lantmateriet, 2022) within the wetland boundary. Open water extent for each wetland was calculated for every month in 2023 using monthly composites of Normalised Difference Water Index (NDWI) binary (water/non-water) masks from Sentinel-2 optical imagery.

The wetland type was estimated using the following databases of wetland classification: (1) The Ramsar Convention database for sites in Sweden, (2) the National Wetland Inventory for Sweden (VMI) ~~(Gunnarsson and Löfroth, 2009)~~(Gunnarsson and Löfroth, 2009), and (3) an updated satellite-based open wetland mapping classification from 2018-2022 ~~(Hahn and Wester, 2023).~~(Hahn and Wester, 2023). Each wetland was assigned a generic wetland class adapted from ~~Gunnarsson and Löfroth (2014)~~Gunnarsson and Löfroth (2014): 'open', 'limnic', 'mixed' or 'mire'. 'Open' refers to meadows, grasslands, and temporarily flooded land, 'limnic' refers to lake shores, beaches by watercourses, overgrown lakes and limnogeneous beach complexes. 'Mixed' wetlands are regarded as a combination of multiple wetland types and may include different mires with open or limnic wetland environments. A 'mire' wetland consists primarily of bogs and fens. A fifth wetland type, '*fjäll*' (mountain), was assigned to wetlands located in Sweden's mountainous regions as they are not classified in the datasets.

2.3. Hydrological regime given by water ~~surface~~ extent analysis

~~We estimated the hydrological regime from water extent using an automated approach based on remote sensing data. Automatic surface water detection was done with a deep learning image segmentation model called DeepAqua (Peña et al., 2024). DeepAqua is a self-supervised model with the principal function of detecting surface water extent in wetlands from Sentinel-1 SAR imagery in the VH polarisation. DeepAqua can detect both open and vegetated water using the C-band SAR sensor onboard Sentinel-1, which can penetrate some types of perennial vegetation due to its emission of longer wavelength radar waves (5.6 cm) (Adeli et al., 2021). Usually, semantic segmentation models require manually labelled images as their training label output. With DeepAqua however, the training labels are binary images (water/non-water) of the NDWI based on cloud-free Sentinel-2 optical imagery of the same location and time as the input training data (SAR imagery), since both missions have a ~1 week repeat cycle over Sweden (~1-2 passes per week between 2020 and 2022, after which spatiotemporal coverage is reduced to ~10-12 days due to the failure of the Sentinel-1B satellite). We use a **pre-trained** version of the DeepAqua model for our analysis, which was trained on a Sentinel-1 and Sentinel-2-based NDWI binary image over central Sweden from the 5th June 2018. When the pre-trained model was tested on three wetlands in Sweden (Peña et al., 2024), DeepAqua outperformed existing land classification models such as Dynamic World (Brown et al., 2022) and thresholding techniques such as Otsu (Otsu, 1979) on multiple evaluation metrics such as pixel accuracy, intersection over union, precision and F1.~~

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DeepAqua (Peña et al., 2024). DeepAqua is a self-supervised model with the principal function of detecting surface water extent in wetlands from Sentinel-1 SAR and Sentinel-2 optical imagery. DeepAqua can detect both open and 'hidden' water using the C-band SAR sensor onboard Sentinel-1, which can penetrate some types of perennial vegetation and detect water due to its emission of longer wavelength (5.6 cm) (Adeli et al., 2021). Usually, semantic segmentation models require manually labelled images as their training label output. With DeepAqua however, the training labels are binary images (water/non-water) of the NDWI based on cloud-free Sentinel-2 optical imagery of the same location and time as the input training data (SAR imagery), since both missions have a ~1 week repeat cycle over Sweden. The model was trained on a Sentinel-1 and Sentinel-2 based NDWI binary image over central Sweden from the 5th June 2018. When tested on wetlands in Sweden (Peña et al., 2024), DeepAqua outperformed existing land classification models such as Dynamic World (Brown et al., 2022) and thresholding techniques such as Otsu (Otsu, 1979) on multiple evaluation metrics. We used a pretrained version of the model, which used Sentinel-1 SAR imagery as the training data and NDWI masks derived from the optical Sentinel-2 as the training labels from the same spatial extent and date.

The output predictions comprised polygonised binary water/non-water images for every Sentinel-1 image available between ~~January~~ 2020~~ and August~~-2023 cropped to within the boundaries of each wetland. The total water area for each image was calculated based on the WGS84 UTM Zone 33N projection (~~Figures~~Figure A2-~~A6~~A7). The monthly average of water extent between ~~January~~ 2020~~ and August~~-2023 was calculated to reduce the risk of annual variability affecting potential clustering while aiming to detect hydrological regimes under 'average' conditions. Due to extensive snow and ice cover complicating the water extent predictions, the winter months (November, December, January, and February) were removed from the hydrological regime analysis. We also validated our water extent predictions from DeepAqua in the wetlands with in-situ discharge data available from nearby upstream discharge monitoring stations.

~~Lastly, due to the lack of ground truth data on temporally dynamic wetland water extent within our Ramsar sites, we validate our water extent predictions using two alternative approaches. Firstly, we compare DeepAqua's predicted water extent with manually delineated water extent derived from Sentinel-1 SAR imagery in the VH polarisation for a systematic sample of wetlands for all available images during 2021. We randomly select one wetland within each of the resulting archetypes to get a representative yet unbiased sample of wetlands. For the second approach, we assess the accuracy of the predicted hydrological regimes by comparing them to daily discharge data from nearby active stations provided by Global Runoff Data Centre (GRDC) and SMHI. In total,~~

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~~there were 23 sites with available discharge data either upstream, downstream or on site of the wetland. For both approaches, we calculate the error between the DeepAqua predictions to (1) manually delineated water extent and (2) daily discharge using the normalised root mean square error (NRMSE). We normalise the root mean square error (RMSE) to the range of water extent as to discount total area from the error result and to make each wetland comparable with the others.~~

2.4. Cluster Analysis

The hydrological regimes ~~based on DeepAqua's water extent predictions~~obtained through DeepAqua (Section 2.~~3~~4) were clustered based on their hydrological similarity using a multivariate K-means cluster analysis technique ~~and means of visual interpretation.~~. K-means clustering is a widely used and simple unsupervised machine learning technique in which groups are identified based on the Euclidean distance between a data point and a centroid (a mean of the data) ~~(Everitt et al., 2011)~~(Everitt et al., 2011). In order to conduct a cluster analysis, data points that characterise the hydrological regime given by water extent are required. We calculated several hydrological parameters based on each hydrological regime and used them as the input data points (Table A1). The hydrological parameters included known hydrological signatures (Olden and Poff, 2003) and custom parameters to describe the hydrological regime in terms of duration, timing, frequency, magnitude, and rate of change. The optimal number of clusters (k) was chosen based on the ~~inflection point on the Elbow Curve~~silhouette score, which ~~calculates the within~~ measures the closeness of data points belonging to one cluster ~~sum of squares (WCSS) for a range~~ to data points of another cluster ~~sizes from 1 to n.~~. The ~~inflection point on the Elbow Curve~~highest value (between -1 and 1) is then interpreted ~~at~~as the ~~optimum~~optimal number of clusters ~~since it indicates the point where adding more clusters results in a diminishing reduction in WCSS~~. The best-performing parameters were picked using visual inspection (inspecting their ability to cluster the regimes) and validated against multicollinearity using the Variance Inflation Factor (VIF). The VIF measures the ~~degree of multicollinearity of one hydrological parameter with all other parameters by calculating how much the variance of the regression coefficient increases due to correlation with other independent variables. We recognise that there is some degree of inherent correlation between the hydrological parameters since they are descriptors of the same hydrological regime. Therefore, we used a VIF value of <10 as an indicator that the hydrological parameters were not highly multicollinear and did not describe the same regime characteristic (Figure 5a).~~multicollinearity between all variables where <10 is deemed a low level of collinearity.

The emerging pattern given by the ~~Elbow Curve~~silhouette scores indicated that individual hydrological regimes among wetlands were best grouped when k = ~~4~~ 6~~ (Figure A1).~~ 7. Upon visual inspection, k = ~~5~~6 was chosen as the best possible distribution of wetlands into roughly equal-sized groups. The number of sites in each cluster ranged between ~~6~~4 and ~~15~~12. Each hydrological parameter was tested individually and in combination with other parameters to see how effectively they helped cluster the wetlands. Certain variables, such as the maximum month, dominated the clustering over other indices and some indices-pairs were extremely collinear, such as maximum month and minimum month, or Spring/Summer slope difference and slope variation. Therefore, these pairs could not be used together for the final clustering analysis.

3 Results and Analysis

3.1. ~~Surface water extent validation~~

~~When comparing water extent predictions from DeepAqua to manually delineated water extent to a systematic sample of wetlands, we find that predicted water extent performs well with their manually delineated counterparts (Fig. 2). *Hjälstaviken* and *Dättern* wetlands had the lowest NRMSE with 0.04 and 0.07, respectively, whereas *Maanavuoma* wetland exhibited the highest error between the manually delineated water extent and the DeepAqua prediction with a NRMSE of 0.12. The majority of error between the DeepAqua's and the manual water extent estimates originates from the spring and autumn months for many of the sampled wetlands. This is particularly apparent in *Maanavuoma* and *Tysöarna* wetlands. In both cases, the water extent is underestimated by DeepAqua compared to the manual estimate. In *Store mosse* wetland, DeepAqua tends to overestimate wetland water extent~~

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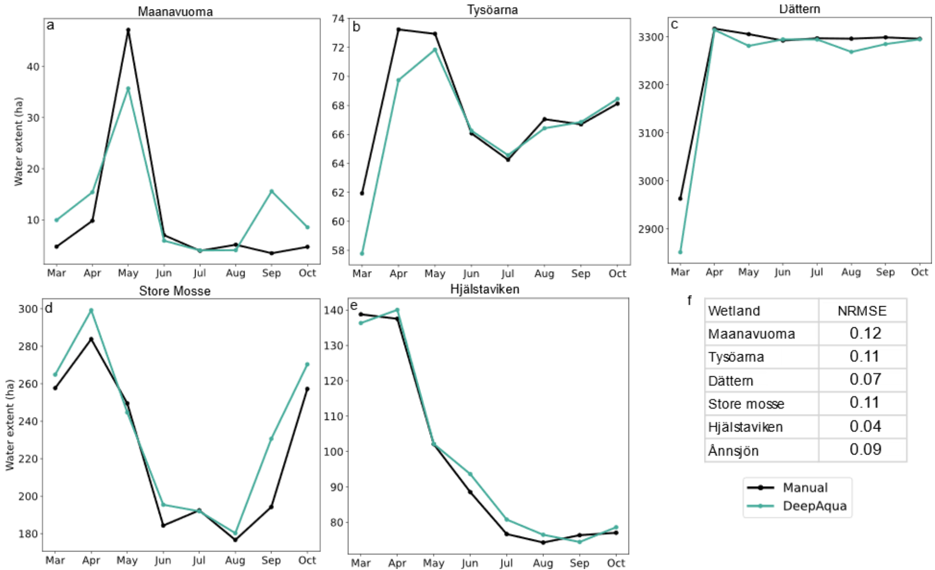

Wetland	NRMSE
Maanavuoma	0.12
Tysöarna	0.11
Dättern	0.07
Store mosse	0.11
Hjälstaviken	0.04
Ånnsjön	0.09

~~**Figure 2. (a-e) Comparison between monthly water surface extent from DeepAqua predictions and manual delineation in 2021. (f) Values of Normalised Root Mean Square Error (NRMSE; RSME divided by the range in wetland extent) between manually delineated and DeepAqua predictions.**~~

~~compared to when the water extent is manually delineated. Overall, all five sampled sites have strong agreement in the shape and magnitude of the hydrological regime, indicating that DeepAqua captures the seasonal hydrological characteristics with good accuracy (Fig. 2f).~~

~~To enhance the strength of our validation approach, we compared the wetland hydrological regimes to in-situ daily discharge measurements. Among the 23 wetlands with available discharge data, three had an active gauging station located upstream, two had onsite stations and sixteen had stations situated downstream (Fig. 3a). Of these, eight sites featured regulatory structures (e.g., dams, weirs, or culverts) along their river courses, which may disrupt the natural flow regime and weaken the correlation between wetland water surface extent and stream discharge. In general, stations with lower mean discharge returned lower NRMSE values between water extent and discharge (Fig. 3b). However, the relationship is weak ($R^2 = 0.17$) and based on a limited number of observations (n = 23). Most sites cluster in the bottom-left portion of the plot, with a few high-discharge, high-NRMSE outliers in the~~

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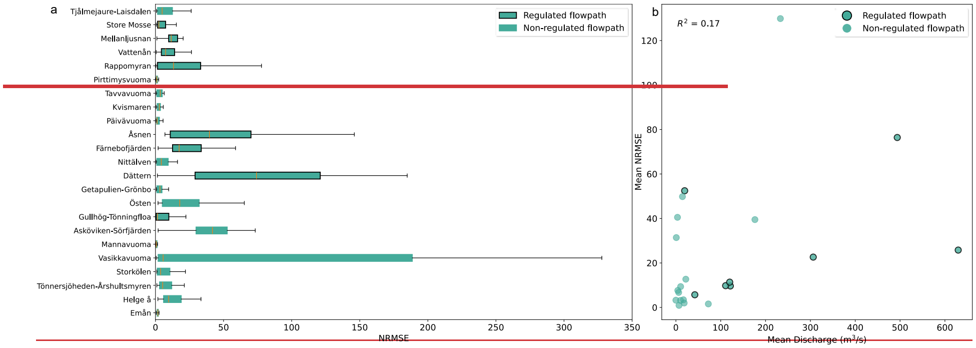
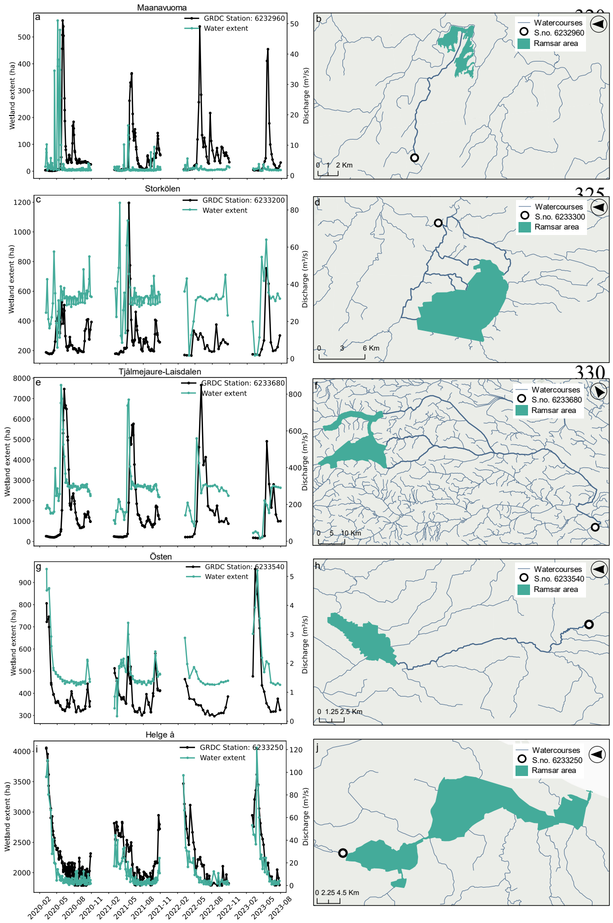
~~top-right. Regulated and non-regulated sites are distributed throughout, with no strong visual separation, although none of the regulated sites exhibit low discharge-low NRMSE values.~~



~~**Figure 3. (a) NRMSE between daily discharge and wetland water extent for the 23 wetlands with available discharge data. Green boxes indicate the interquartile range (IQR), whiskers represent the range, and orange lines show the mean NRMSE. (b) Mean NRMSE versus mean discharge for each wetland, calculated over matching dates from January 2020 to August 2023. Wetlands with regulated flow paths between the wetland pour point(s) and discharge station are indicated by black outlines.**~~

~~Fig. 4 presents a sample of wetlands with discharge data either upstream or downstream and unregulated flow. In general, daily discharge replicates the shape of the wetland's hydrological regime. The correlation between river discharge and wetland hydrological regime is particularly apparent for *Tjålmejaure-Laisdalen* (NRMSE 39.49), *Östen* (NRMSE 31.40) and *Helge å* (NRMSE 12.70) wetlands, whereby increased discharge matches well with increased water extent in the spring months, followed by relatively reduced flow thereafter.~~



~~**Figure 4.** ***Left panel:*** **Comparison of water surface extent and discharge from on-site, upstream or downstream stations for corresponding dates dates in *Maanavuoma*, *Storkölen*, *Tjålmejaure- Laisdalen*, *Östen* and *Helge å* wetlands from January 2020 to August 2023 (excluding winter months). The GRDC station IDs are shown in the upper left of each plot.** ***Right panel:*** **Wetland boundaries (green polygons) as defined by the Ramsar Convention, with discharge stations (black rings), watercourses between station and wetland (thick blue) and other watercourses (thin blue).**~~

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~~Although *Tjålmejaure-Laisdalen* and its' corresponding downstream station are separated by ~116 km of watercourses, the discharge data agrees well with the wetland water extent. For *Maanavuoma* wetland (NRMSE 0.92), data from the discharge station situated ~15 km upstream agrees with water surface extent in 2020 and 2021, however, the spring surge of water in 2022 and 2023 that is present in the river is not experienced by the wetland.~~

~~Lastly, they also agree well in *Storkölen* wetland (NRMSE 9.37) despite greater interannual variability compared to other sites. Notably, both time series show a pronounced peak between April and May 2021, reflecting a concurrent increase in wetland water extent.~~

~~3.2.~~ Cluster Analysis

~~Based on the surface water extent data, we conducted a cluster analysis to explore patterns in the shape and dynamics of wetland hydrological regimes. From~~ We found that from all parameters assessed~~,~~ (Table A1), skewness, kurtosis, normalised maximum slope, number of peaks and baseline month fraction (see graphic depiction in Fig. ~~5a) were found~~2) worked together to ~~collectively~~form to capture ~~key regime~~the characteristics ~~(Fig. 5b).~~of a typical hydrological regime. Upon visual inspection, regimes with similar shapes were grouped together while also maintaining the desired VIF condition (<10) with values of ~~3~~5.96, 1.~~60~~84, 3.27, 4.~~07, 3.01~~40, and ~~6.54~~7.74 for skewness, kurtosis, maximum slope, number of peaks and baseline month fraction, respectively~~. These values indicate~~, indicating a reasonable level of non-multicollinearity ~~between~~with all other variables~~.~~ (Table 1). The chosen parameter combination ~~successfully clusters~~was able to cluster closely related hydrological regimes into ~~five~~six different archetypes, with the number of sites (n) in each archetype as follows: 'autumn drying' (n=12), 'summer dry' (n=10), 'spring surging' (n=~~6~~4), 'summer flooded' (n=5), 'spring flooded' (n=~~8), *'summer flooded'* (n=8),~~ 7) and 'slow drying' (n=~~15) and *'summer dry'* (n=6~~5). Support for the archetype names is given by the hydrological parameter results which have been averaged by ~~the~~ archetype and are described in ~~Section~~section 3.~~3~~2.

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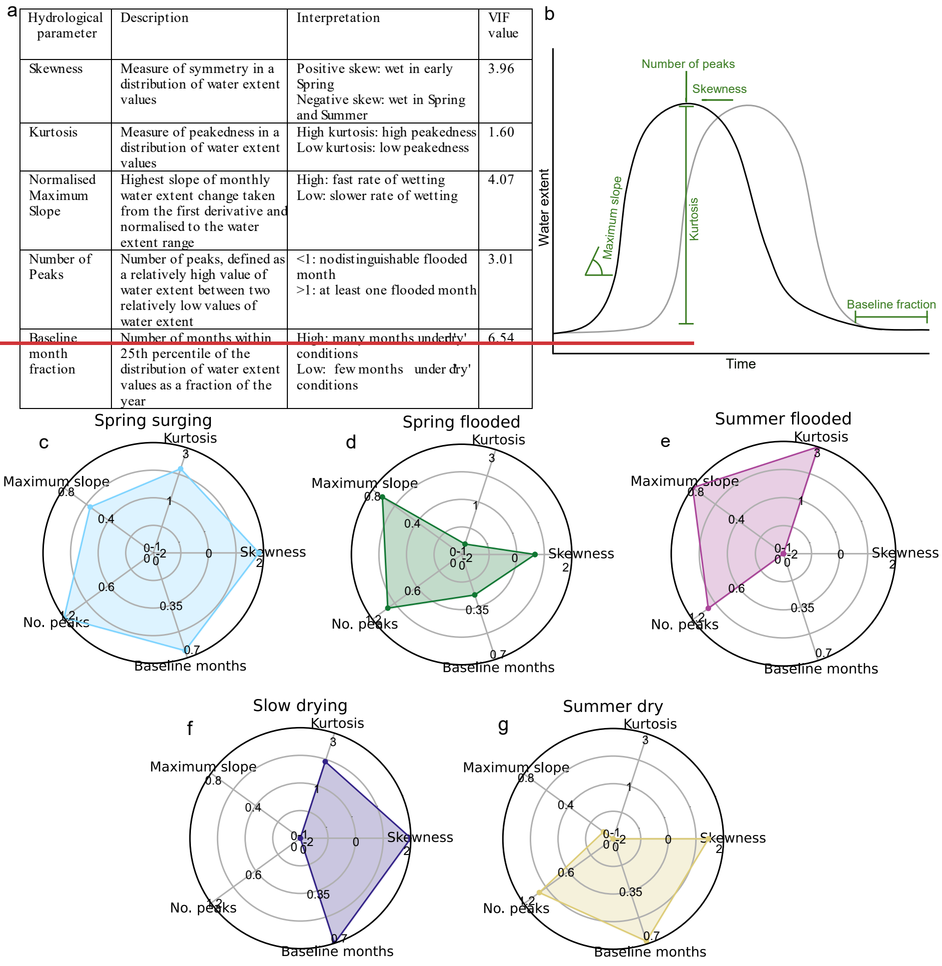

a

Hydrological parameter	Description	Interpretation	VIF value
Skewness	Measure of symmetry in a distribution of water extent values	Positive skew: wet in early Spring Negative skew: wet in Spring and Summer	3.96
Kurtosis	Measure of peakedness in a distribution of water extent values	High kurtosis: high peakedness Low kurtosis: low peakedness	1.60
Normalised Maximum Slope	Highest slope of monthly water extent change taken from the first derivative and normalised to the water extent range	High: fast rate of wetting Low: slower rate of wetting	4.07
Number of Peaks	Number of peaks, defined as a relatively high value of water extent between two relatively low values of water extent	<1: nodistinguishable flooded month >1: at least one flooded month	3.01
Baseline month fraction	Number of months within 25th percentile of the distribution of water extent values as a fraction of the year	High: many months under 'dry' conditions Low: few months under 'dry' conditions	6.54

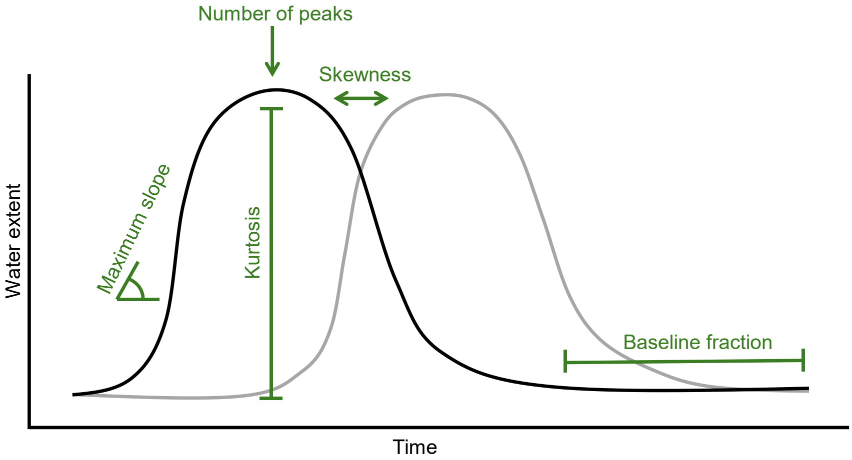

Figure 2.~~Figure 5.~~ ~~(a) Overview of the chosen parameter (unitless) combination (averaged by archetype) used for the final cluster analysis of the hydrological regimes given by water extent and the VIF value for each parameter. (b)~~ Graphical representation of the five selected hydrological parameters used to describe the characteristics of the hydrological regime for the final cluster analysis. ~~(c-g) Radar plots for for final hydrological~~The parameters ~~averaged by archetype.~~ include skewness (timing), kurtosis (magnitude), maximum slope (rate of change), number of peaks (frequency), and baseline fraction (duration).

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~~3.3. Hydrological archetype analysis~~

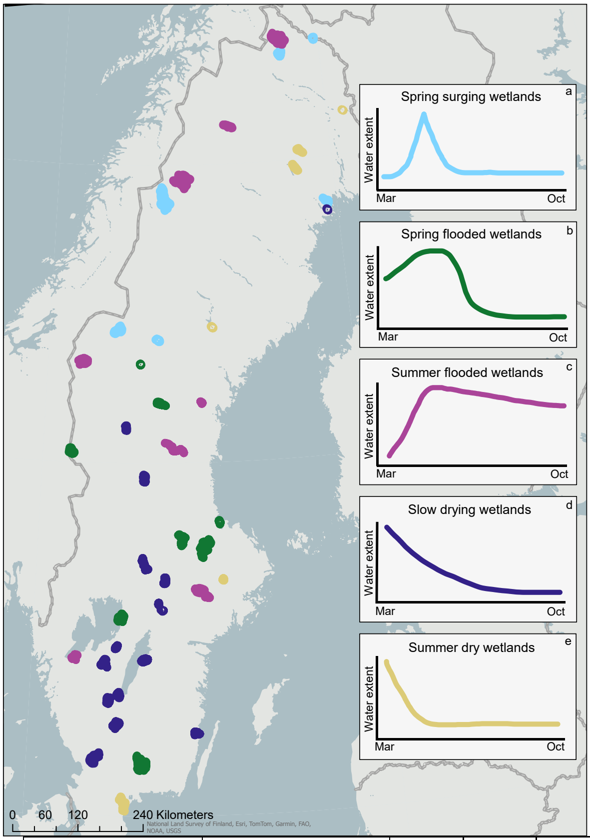

Table 1. Overview of the chosen parameter (unitless) combination used for the final cluster analysis of the hydrological regimes given by water extent. Each hydrological parameter represents a unique characteristic of seasonal wetland water extent, which when combined, results in a quantitative description of the hydrological regime. The parameter results are averaged by archetype and the VIF value for each parameter demonstrates that there is non-significant multicollinearity as all values are <10.

Hydrological parameter	Interpretation	Autumn Drying	Summer Dry	Spring Surging	Summer Flooded	Spring Flooded	Slow drying	VIF value

Skewness	Positive skew: wet in early Spring Negative skew: wet in Spring and Summer	-0.13	1.83	2.00	-0.60	1.18	0.40	5.96
Kurtosis	High kurtosis: high peakedness Low kurtosis: low peakedness	-1.62	2.99	4.44	1.24	-0.10	-0.94	1.84
Normalised Maximum Slope	High: fast rate of wetting Low: slower rate of wetting	0.29	0.10	0.76	0.81	0.23	0.10	3.27
Number of Peaks	<1: no distinguishable flooded month >1: at least one flooded month	1	0	1	1.2	1.14	0	4.40
Baseline month fraction	High: many months under 'dry' conditions Low: few months under 'dry' conditions	0.37	0.71	0.69	0.23	0.64	0.43	7.74

3.2. Hydrological archetype analysis

The overall spatial distribution of the archetypes and thematic graphic descriptions of the general hydrological regime given by water ~~surface~~ extent ~~is~~are presented in Fig. ~~6. The~~3. *Autumn-drying wetlands* (Fig. 3a) encompass sites with a relatively large water extent from March to July/August, from which drying occurs after that. This archetype is predominantly for wetlands in central and southern Sweden. *Summer-dry wetlands* (Fig. 3b) exhibit the maximum wetland extent at the beginning of the spring, preceding generally dry conditions until October. *Spring*~~-~~*surging wetlands* (Fig. ~~6a~~3c) are only found in northern Sweden and have flashy hydrological regimes~~, consisting of~~. Aside from a dry baseline condition~~ and~~, they have a brief, one-month period of increased water extent. ~~Spring-flooded wetlands (Fig. 6b) are limited to southern and central Sweden. The hydrological regime of these wetlands resembles that of spring-surging wetlands, although they have a relatively longer spring peak. Summer-flooded wetlands (Fig. 6c~~*Summer-flooded wetlands* (Fig. 3d) remain inundated from May to October after a rapid wetting period and ~~are spread across Sweden. Southern~~like spring-surging wetlands, they are only present in the north. *Spring-flooded wetlands* (Fig. 3e) have sites throughout Sweden, although preferentially found in the far north. The hydrological regime of these wetlands resembles that of autumn-drying wetlands, although their drying period occurs earlier in the year. Lastly, central Sweden's *slow-drying wetlands* (Fig. ~~6d~~3f) exhibit steadily decreasing water extent throughout the summer, reaching minimum water extent in autumn. ~~Lastly, summer-dry wetlands (Fig. 6e) exhibit the maximum wetland extent in April, preceding generally dry conditions until September October.~~

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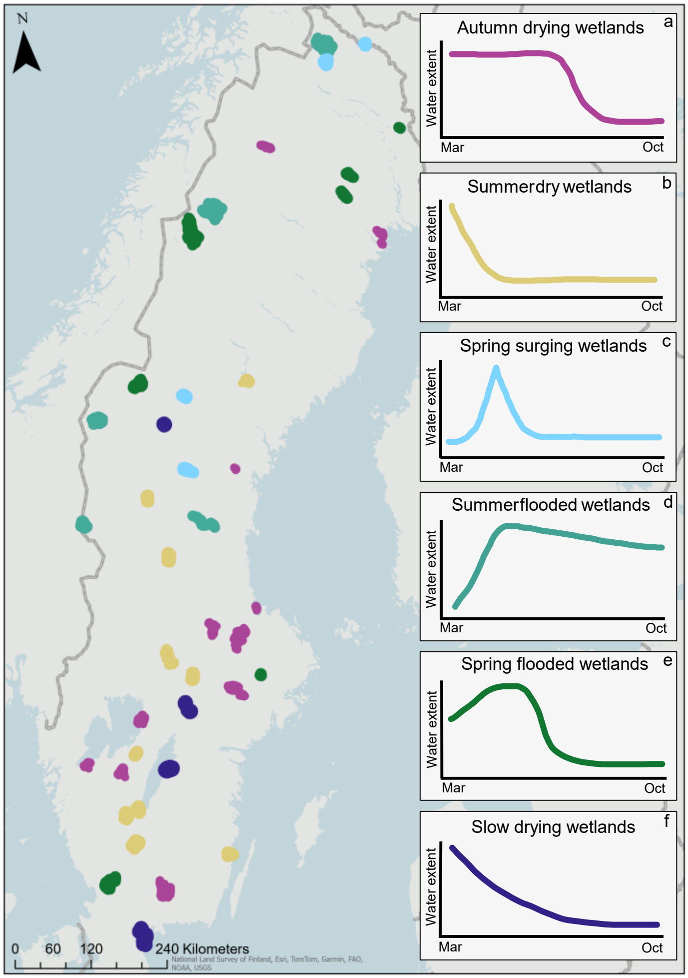

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Figure ~~6.~~3. Spatial distribution of hydrological archetypes for sampled Ramsar wetlands in Sweden (n=43) and representation of their ~~hydrological~~hydrolo9gic regime through the ice-free season (March~~ and ~~-October~~; ()~~; a~~) Spring~~ – autumn-drying wetlands (n=12), b – summer-dry wetlands (n=10), c – spring-surging wetlands (n=~~6), (b) Spring ~~4), d

– summer-flooded wetlands (n=~~8), (c) Summer~~ 5), e – spring-flooded wetlands (n=~~8), (d) Slow~~7) and slow drying wetlands (n=~~15) and (e) Summer dry wetlands (n=6~~5).

One of the most distinctive differences between archetypes is the magnitude of water extent at the beginning of Spring. For instance, autumn-drying, summer-dry, and slow-drying~~ and summer dry~~ archetypes already have large water extents in March and, therefore, do not undergo a rapidly inundating period during Spring or Summer. The lack of any inundation period is reflected in the normalised maximum slope values~~ (Fig. 5f,g).~~, which are the lowest out of all archetypes, suggesting smaller changes in water extent across the year (Table 1; 0.~~21~~29, 0.10, and 0.~~14~~10 for autumn drying, summer-dry, and slow-drying, respectively). Additionally, archetypes with large water extent in Spring tend to be found in central and southern Sweden~~, while~~. On the other hand, archetypes such as spring-surging and summer-flooded wetlands start with a small water extent in March ~~preceding~~which precedes a rapid inundation period. These archetypes, with higher normalised maximum slope values of 0.~~59~~76 and 0.~~77~~8, respectively, are more abundant in the north~~ (Fig. 5c,e).~~.

A second defining feature between different archetypes is the duration of the ~~dry period (baseline fraction),~~'dry period', defined by months with water extent within the 25th percentile of the range. Archetypes with a significant dry period, such as summer-dry~~,~~ and spring-surging ~~and slow-drying ~~wetlands, have both high baseline ~~month~~ fractions (0.~~65, 0.63~~71 and 0.~~66~~69, respectively) and positive skewness (1.~~14, 1.45~~83 and ~~1.58 ~~2.00, respectively), which indicates that wet conditions are limited to the ~~spring~~Spring months~~ (Fig. 5g,c,f).~~. Conversely, with a negative skewness and low baseline month fraction (-~~1~~0.60 and 0.~~17~~23, respectively~~; Fig. 5e~~), summer-flooded wetlands are the only archetype that retains its large water extent throughout the year.

~~The resulting~~It is worth noting that there is an evident distinction between archetypes ~~show how wetland~~with 'peaky' and 'smooth' hydrological regimes~~ can be broadly differentiated into two primary ‘modes’: *peaky* and *smooth*. We~~. Here we define ~~*peaky*~~'peaky' as hydrological regimes ~~as those ~~with large ~~fluctuations~~variations in water extent, while smooth ~~regimes~~archetypes follow a more consistent~~, gradual changes in ~~ pattern of monthly water extent~~.~~ changes, which is illustrated in the hydrological parameter results shown in Fig. 4. Peaky archetypes, ~~such as~~including spring-surging (Fig. ~~7a~~4c) and summer-flooded wetlands (Fig. ~~7c~~4d), exhibit relatively high values of kurtosis (~~2.27~~4.44 and ~~2.93~~1.24, respectively), maximum slope (0.~~59~~76 and 0.~~77~~81, respectively), and the number of peaks (1~~.2~~ and 1.~~0~~2, respectively). This is reflected in polar plots that are shifted towards the left hemisphere and occupy a larger total area. On the other hand, ~~*smooth*~~'smooth' archetypes, ~~like slow-drying and~~such as summer-dry ~~wetlands are characterised by relatively stable water extent from March to October (Fig. 7d,e).~~

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~~Spring flooded~~ and slow-drying wetlands (Fig. 4f), have polar plots either shifted towards the right hemisphere or occupying a smaller total area. Autumn-drying wetlands ~~share some~~(Fig. 4a) do not conform strictly to either 'peaky' or 'smooth' classifications, as they display a mixture of traits ~~with peaky archetypes, particularly a marked increase in water extent during spring (Fig. 7b) and high normalised slope values (0.70). However, they differ from typical spring or summer flooded wetlands in having a low average kurtosis (0.04), which suggests a more even distribution of water extent over time.~~that do not align with neither peaky nor smooth. Although we refer to peaky archetypes here, it is important to note that the number of peaks is not necessarily descriptive of just peakedness (kurtosis). For instance, ~~slow-drying~~summer-dry wetlands have high kurtosis (2.~~03~~99) yet ~~few~~zero peaks ~~on average (0.2),~~, indicating that although they experience large variability in water extent, there is no distinguishable wet month.

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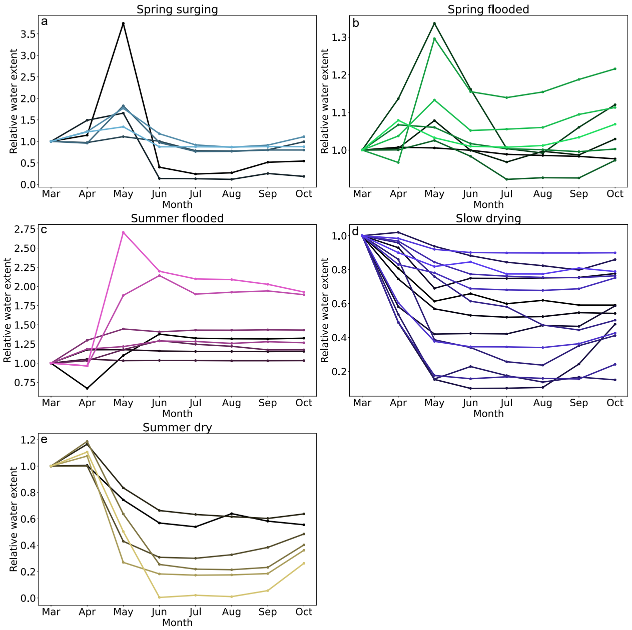

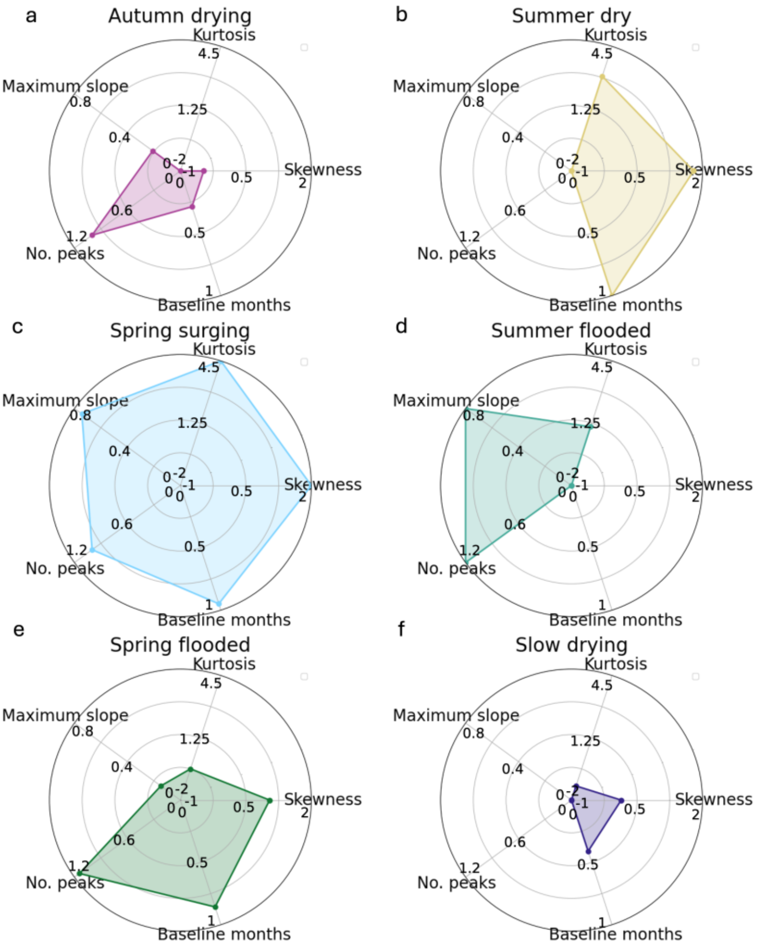

Figure ~~7. Hydrological regimes~~ **4. Polar plots for kurtosis, skewness, baseline fraction, number of peaks, and maximum slope for each archetype. Each parameter was initially calculated for each site, and then the average value was computed across all wetlands within each archetype. All parameters are unitless.**

The distinction between 'peaky' and 'smooth' archetypes is further supported by the monthly water extent relative to March of individual wetlands (Fig. 5). Wetlands within the spring-surging, summer-flooded, and spring-flooded archetypes (Fig. 5c-e) demonstrate a distinct peak in water extent between spring and summer. In contrast, the hydrological regime of summer-dry and slow-drying wetlands (Fig. 5b, 5f) shows a smoother pattern regarding month-to-month water extent variability across all sites. No consistent pattern emerges for autumn-drying wetlands (Fig. 5a), as the archetype exhibits significant variability across different wetlands. 480

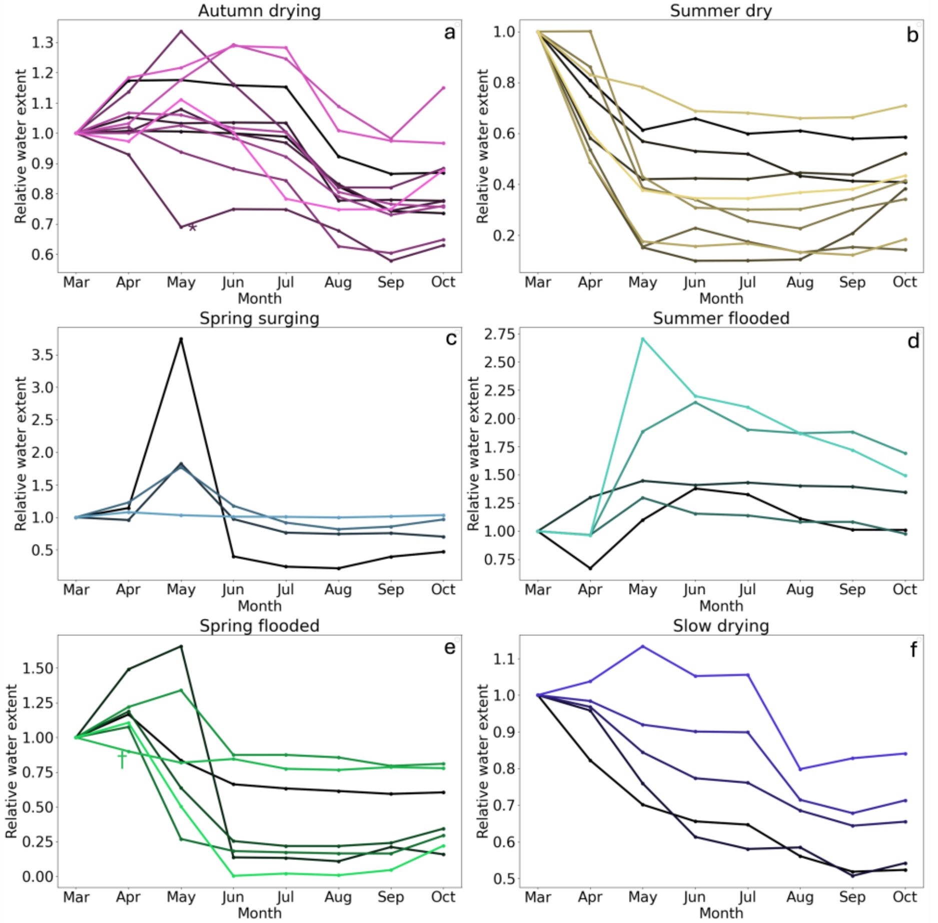

Figure 5. ~~per archetype~~ Hydrological regimes based on ~~a monthly average of surface~~ water extent ~~between January 2020~~for individual and ~~August 2023~~grouped by archetype. The water extent area for each month is shown relative to the water extent area in March. Monthly water extent is an average of all available Sentinel-1 SAR image predictions within each month. Winter months (November to March) are excluded from the hydrological regimes due to snow and ice complicating the water extent predictions. Anomalous wetlands are indicated with an asterisk (*) for Gammelstadsviken and a dagger (†) for Tönnersjöheden-Årshultsmyren.

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Another approach to interpreting archetypes is ~~by examining~~categorising them based on the ~~degree~~breadth of ~~homogeneity within each archetype. This is because some~~ habitats in which they occur and whether they are multihabitat or habitat-specific archetypes~~ share~~. This classification emphasises that wetlands can exhibit similar hydrological regimes despite differences in type or location, facilitating a more ~~similarities in terms~~nuanced understanding of their ~~environmental characteristics and hydrological regimes.~~functions and services. For instance, autumn-drying wetlands can be classified as a multihabitat archetype as they span across the entire latitudinal range of Sweden (Fig. 6). On the other hand, summer-dry wetlands ~~are mostly comprised of~~may be considered a habitat-specific archetype as 80% of its wetlands are classified as mires ~~or open wetlands (Fig. 8d), typically lying~~ (Fig. 6d). Another example of a habitat-specific archetype is slow-drying wetlands, which are predominantly found at low latitudes (Fig. 6a) and elevations ~~and exhibiting similar hydrological regimes (Fig 7e). Spring surging wetlands are~~ with minimal open water (~11%; Fig. 6c). The slow-drying archetype is also ~~considered a homogenous archetype, since they are located~~ primarily ~~in high latitude regions (Fig. 8a), are mainly *fjäll* wetlands, and tend to have little variability in their hydrological regime (Fig. 7a). In contrast, spring-flooded and summer-flooded wetlands are found all over Sweden, across a range of elevations~~composed of wetlands classified as either open or limnic (Fig. ~~8b) and encompass many different wetland types. This highlights that hydrological regimes are not always associated with a specific wetland type, but rather depend on the broader archetype to which the wetland belongs.~~ 6d).

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~~Despite the varing degrees of diversity within archetypes, grouping~~Grouping wetlands into archetypes ~~still~~ reveals a remarkable similarity in the timing of key features of their hydrological regimes. ~~For instance~~Despite the significant variability, 83% of autumn-drying wetlands experience a reduction in water extent between July and August (Fig. 5a). Similarly, most ~~summer~~spring-flooded wetlands reach low water extent by ~~May or~~ June, despite varying ~~rates of drying for the rest of the year.~~increases between March and May. This indicates that the hydrological parameters correctly capture timing characteristics~~, even across archetypes with with more hetereogeneity, such as summer flooded wetlands.~~ . Finally, despite many similarities between wetlands within archetypes, not all wetlands perfectly fit their assigned archetypes. For example, *Gammelstadsviken* deviates from typical 'autumn-drying' behaviour, with its water extent decreasing earlier in the year (Fig. 3a). Similarly,

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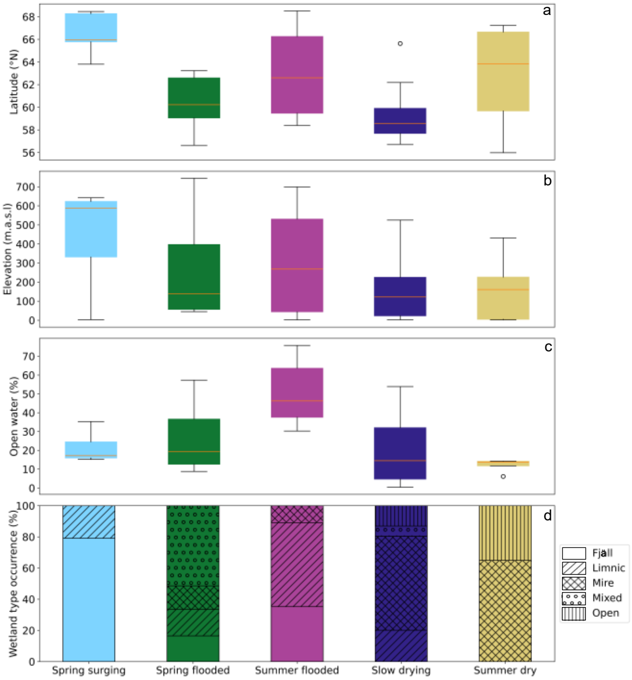
Tönnersjöheden-Årshultsmyren, classified as a spring-flooded wetland, shows a reduction in water extent during spring, unlike others in its archetype (Fig. 3e). A possible reason for this is that these wetlands have unique hydrological regimes that do not conform well with any other wetlands in the dataset, or the hydrological parameter results did not capture the hydrological regime well in these cases.



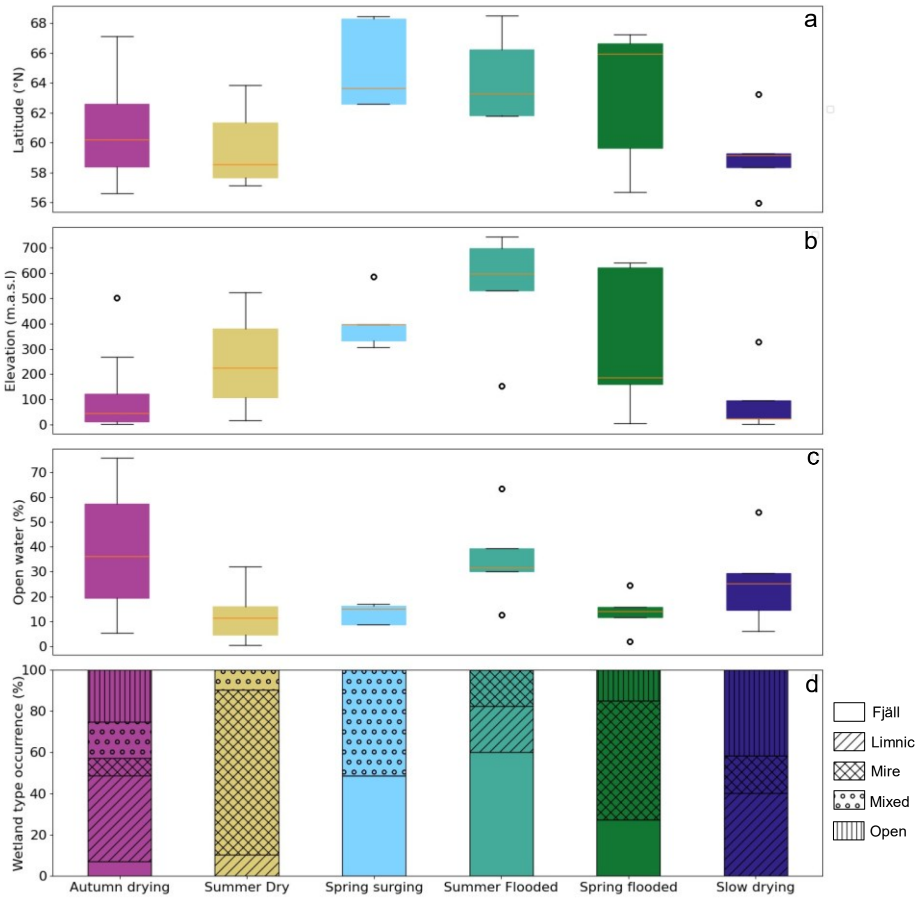


Figure ~~8~~6. (a-c) ~~Wetland topographical and ecological~~Distribution of selected wetland characteristics~~ per~~ according to archetype. The boxes represent the interquartile range (IQR), with orange lines indicating the mean value across all wetlands within each archetype. Whiskers outline the full range, and small black circles denote wetlands with anomalous results compared to the rest of the archetype. (d) Stacked bar plot showing the occurrence of wetland types (*fjäll*, limnic, mire, mixed or open) per cluster as a percentage of the total number of sites in each archetype.

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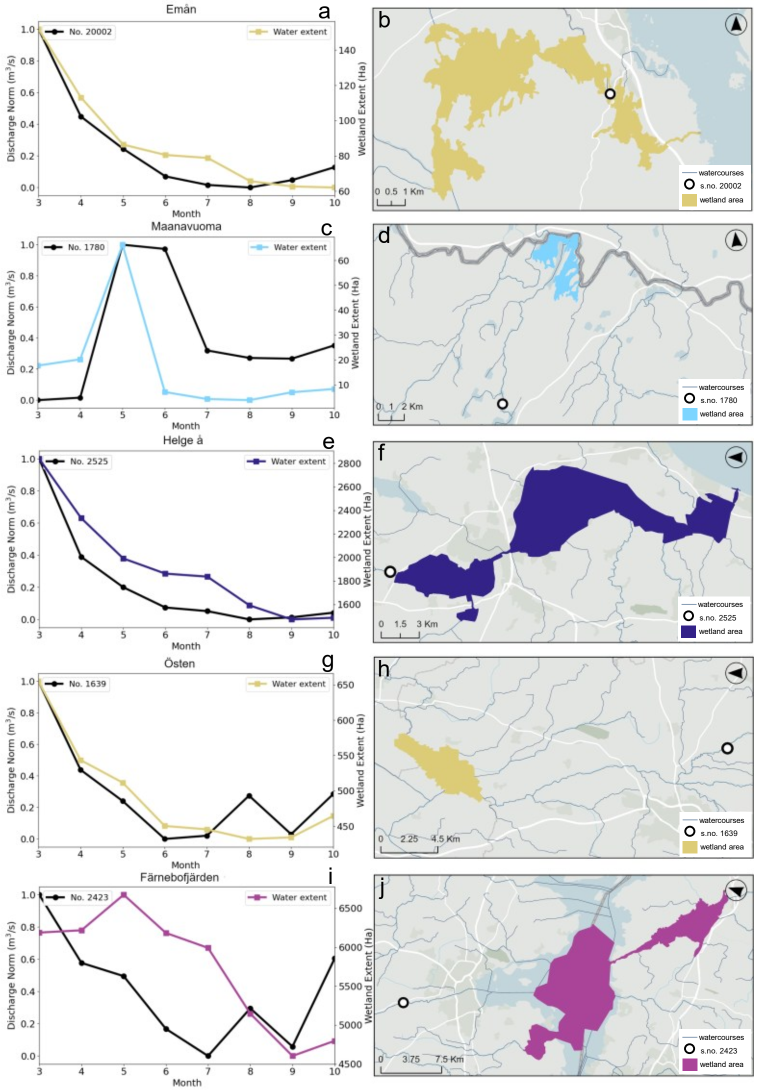
When comparing the hydrological regimes to in-situ discharge data, we found only five wetlands that have an active discharge station located within a reasonable distance upstream (Fig. 7). We validate the hydrological regimes for these wetlands to improve our confidence in the water extent predictions. For wetlands (*Emån*; Fig. 7a-b and Helge å; Fig. 7e-f) with discharge stations very near to (~0.5 km) or within the wetland's boundaries, the average discharge between 2020-2023 agrees well with the water extent data (Mean Squared Error (MSE) 0.01 and 0.02, respectively). As the distance between the discharge station and the wetland increases, the level of agreement between the two inevitably decreases. This is evident in the case of *Maanavuoma* wetland (Fig. 7c-d), where the discharge station is located ~17 km upstream. Although the general shape of the hydrological regime of water extent and monthly discharge are similar, the spring flooding peak of the latter (two months) is more extended than the former (one month) (MSE 0.39). The similarity between the hydrological regime and the monthly discharge was lower (MSE 0.42) for a larger wetland with a high degree of hydrological connectivity such as *Färnebofjärden* (16,866 ha; Fig. 7i-j).



Emån
a
No. 20002
Water extent
Discharge Norm (m^3/s)
Wetland Extent (Ha)
Month
b
watercourses
s.no. 20002
wetland area
0 0.5 1 Km
Maanavuoma
c
No. 1780
Water extent
Discharge Norm (m^3/s)
Wetland Extent (Ha)
Month
d
watercourses
s.no. 1780
wetland area
0 1 2 Km
Helge å
e
No. 2525
Water extent
Discharge Norm (m^3/s)
Wetland Extent (Ha)
Month
f
watercourses
s.no. 2525
wetland area
0 1.5 3 Km
Östen
g
No. 1639
Water extent
Discharge Norm (m^3/s)
Wetland Extent (Ha)
Month
h
watercourses
s.no. 1639
wetland area
0 2.25 4.5 Km
Färnebofjärden
i
No. 2423
Water extent
Discharge Norm (m^3/s)
Wetland Extent (Ha)
Month
j
watercourses
s.no. 2423
wetland area
0 3.75 7.5 Km

Figure 7. Left panel: Comparison of hydrological regimes for *Emån*, *Maanavuoma*, *Helge å*, *Östen* and *Färnebofjärden* wetlands based on water extent data between 2020-2023 (black lines) with monthly discharge data averaged from 2020 to 2023 for active on-site or nearby upstream stations (coloured lines) Station ID from SMHI is given in the top left corner. Right panel: Wetland boundaries as defined by the Ramsar Convention coloured by archetype (yellow – summer-dry, blue – spring surging, purple – slow drying, pink – autumn drying). The location of the discharge stations used for data is marked with black and white circles, and watercourses are shown in dark blue. Light blue background depicts water, and grey indicates land in the basemap.

4 Discussion

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~~4.1. The value of archetypes for understanding wetland hydrology~~

~~One of the defining features for most archetypes was the timing of large changes in surface water extent, which only became apparent when the sites were grouped into archetypes. This highlights the usefulness of employing archetypes in hydrological studies, as hydrological regimes may not be best evaluated across sites when using a single parameter (Cutler and and Breiman, 1994; Huggins et al., 2024; Piemontese et al., 2020). Although our classification was based solely on water dynamics, it also inevitably captured the cumulative effects of other environmental factors, such as vegetation, soil type and climate. The archetype approach to classification is further supported by Bullock and Acreman (2003), who concluded that grouping wetlands based on their local classification term is less intuitive than grouping them by hydrological characteristics This suggests that the hydrological perspective is a valuable lens for understanding ecosystem services of wetlands, especially when complemented with other environmental data (Okruszko et al., 2011; Poff et al., 1997).~~

~~However, despite the overall success of the classification, not all wetlands were easily categorised.~~

4.1. Discussion of results

One of the defining features for most archetypes was the timing of pronounced water extent change, which only became apparent when the sites were grouped. Therefore, we emphasise the usefulness of employing archetypes in hydrological studies, as hydrological regimes may not be best evaluated across sites when using a single parameter.

Overall, we define the following six major archetypes:

1. *Autumn-drying wetlands.* Limnic, open or mixed wetlands found across Sweden with a high proportion of open water undergoing prolonged wet periods that precede rapid drying between July and August.

2. *Summer-dry wetlands.* Predominantly mire wetlands preferentially found in central and southern Sweden with large water extent in early spring followed by a prolonged dry period.
3. *Spring-surging wetlands.* Peaky wetlands in the north of Sweden preferentially dry except for a one-month surge in water extent in May.
4. *Summer-flooded wetlands.* Mire and fjäll wetlands found in northern, mountainous Sweden experiencing rapid inundation period between spring and summer with a prolonged wet period.
5. *Spring-flooded wetlands.* Mire and fjäll wetlands found mainly in northern Sweden with a wet period during the Spring that precede a prolonged dry period beginning in June.
6. *Slow-drying wetlands.* Open or limnic low wetlands in the south with no wetting period between March and October and a slow drying throughout the year.

While classifying wetlands based on hydrological regimes does not account for vegetation, soil type, or climate, we propose that the hydrological regime serves as a proxy for the cumulative effect of these characteristics. In fact, Bullock and Acreman (2003) conclude that grouping wetlands based on their local wetland classification term is less intuitive than grouping them based on their hydrological types. Moreover, multihabitat and specific-habitat archetypes in our study indicate that wetlands can share similar hydrological regimes despite different environmental conditions. Therefore, there is value in using the hydrological regime to understand ecosystem services in wetlands better, providing that it is also complimented with other environmental data (Poff et al., 1997).

We suggest that there are two main reasons why some wetlands ~~were difficult to assign to archetypes.~~like *Gammelstadsviken* and *Tönnersjöheden-Årshultsmyren* were not easily categorised. Firstly, the indistinct nature of some wetlands suggests that some hydrological regimes can sometimes be seen as a continuum rather than easily separated categories, making it challenging to group them into distinct archetypes. Secondly, the limited scope of the wetland database used for clustering might have excluded the existence of additional archetypes that can be obtained when focusing on the hydrological regime from water extent changes. It is also important to note that while we defined archetypes using an average of ~~~~~four years of monthly water extent data, these may only reflect the observed period. Longer observational periods are necessary for determining extended trends and the impact of changing climatological conditions. ~~Since the DeepAqua model we used for water extent predictions was trained to predict water extent on SAR scenes dating between January 2020 and August 2023, we were not able to extend our temporal scope outside of this range. Therefore, we suggest developing any future training of~~

~~the DeepAqua model so that it is more generalisable to longer time periods and less sensitive to changes in Sentinel-1 SAR pre-processing.~~

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Although detailed exploration of the ~~**4.2. Methodological considerations**~~

drivers of the hydrological regime is beyond this study's scope, we theorise that different hydrological regimes in wetlands may partly stem from hydrological factors such as the wetland area to watershed area ratio, watershed location, snow melt upstream and surface connectivity. For example, spring-surging wetlands, with few surface water inlets, rely mainly on snowmelt, remaining dry for much of the year. In contrast, summer-flooded wetlands have a larger supply of water from the inflow of multiple streams and remain inundated longer (Lane et al., 2018). Smaller watershed-to-wetland area ratios such as those found for spring-flooded wetlands lead to quick peaks and rapid declines in water levels, while larger ratios (like slow-drying wetlands) result in lower but more prolonged flood peaks (Davie and Wyndham Quinn, 2019). Additionally, wetlands in headwaters, like spring-surging and summer-flooded wetlands, experience rapid flood peaks characteristics of upper catchment water flows (Morley et al., 2011).

4.2. Discussion of methods

Using water extent as our key measurement, SAR imagery provided data with dense spatiotemporal resolution across 43 wetland sites, which in theory can be applied to any wetland larger than 200 ha. The reliance on remote sensing is driven by a lack of in-situ data, which would have partly or wholly missed the hydrological regime signatures for most of the chosen wetlands in this study.

~~To efficiently process large volumes of remotely sensed data, we chose an automatic deep learning-based approach (DeepAqua) to detect water extent without the need for manual annotation. SAR is particularly useful for wetland studies since most water goes undetected by optical imagery (Sahour et al., 2021). However, it is likely that C-band radar still underestimates surface water extent in wetlands since its relatively shorter wavelength limits penetration into dense vegetation (Adeli et al., 2021). Additionally, we assume that surface water extent is analogous to total water storage, which may not be true for mire types (Acreman and Holden, 2013) or topographically constrained wetlands. Therefore, including water level data from hydrogeodetic technologies such as water levels from the Surface Water and Ocean Topography (SWOT) mission (Hamoudzadeh et al., 2024) or~~

~~soil moisture observations (Mupepi et al., 2024) could improve hydrological regime classification, especially for seasonal wetlands (see more examples in Jaramillo et al., 2024).~~

~~A further challenge arises when observing wetland water extent in winter. Snow and ice interfere with SAR-based water detection methods, which leave winter hydrology poorly observed. The issue is further compounded by the fact that there are few discharge stations are available to fill these observational gaps. Moreover, even where discharge data is available, they can be affected by hydrological barriers or complex flow paths in higher-order streams, limiting their utility for validating wetland hydrological regimes.~~

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~~4.3. Controls and variability in wetland hydrological behaviour~~In order to make use of the abundance of remotely sensed data, we chose the automatic deep learning-based approach (DeepAqua) to detect water extent since the model can predict instances of surface water using SAR imagery for hundreds of images without any manual annotation. SAR is particularly useful for wetland studies since most water goes undetected by optical imagery (Sahour et al., 2021). However, it is possible that C-band radar can underestimate surface water extent in wetlands since its relatively shorter wavelength limits the penetration capacity into denser vegetation (Adeli et al., 2021). Additionally, we assume that surface water extent is analogous to total water storage, which may not be true for mire types where water is predominantly stored within the soil (Acreman and Holden, 2013) or for wetlands constrained by vertical landscape features which may lead to the assumption that the water in the wetland remains constant without considering water level. Therefore, although water extent is a useful descriptor of hydrological regime, it may be beneficial to include water level data, such as from the new Surface Water and Ocean Topography (SWOT) mission that launched in 2023 (Hamoudzadeh et al., 2024). The main caveat of all existing remote sensing-based methods is the influence of snow and ice during the winter months affecting the backscattering signal of the radar sensor. Water extent data for the winter months remain a crucial element for fully understanding hydrological regimes. For instance, many of the presented archetypes have a small water extent in October, which introduces the question of how the wetland is recharged again to reach its relatively high water extent after winter. In-situ discharge data could be used to fill the data between for the winter months, but this is currently challenging since there are so few active stations nearby the observed wetlands.

As well as the lack of discharge stations, discharge data could also not be used to validate the hydrological regime for wetlands with multiple inlets (e.g. *Farnebofjärden* wetland, Fig. 7i-j), since all inlets likely contribute to the overall hydrological regime of the wetland and may deviate from the seasonal discharge pattern observed at the station. A more comprehensive in-situ station network should be installed closer to or on-site of wetlands of interest for future validation efforts.

4.3. Hydrological regimes for hydrological functions

In this paper, we quantified the hydrological regimes for wetlands in Sweden to better understand their hydrological functions. Information on hydrological functions can therefore indicate which ecosystem services are relevant for that wetland. We find that archetypes such as spring-flooded wetlands and spring-surging wetlands, which have high water extent during the spring and low water extent during the summer, are akin to headwater wetlands. Headwater wetlands are known to increase flood flows during the wet season while decreasing dry season flows (Bullock and Acreman, 2003). Therefore, we suppose that wetlands belonging to these archetypes do not provide flood control as a prominent ecosystem service, but rather the opposite; they tend to exacerbate flooding (Åhlén et al., 2022). However, evidence suggests that headwater wetlands can temporarily store immediate floodwaters (Kadykalo and Findlay, 2016), although more data is required to investigate the lag time between wetland storage and downstream discharge for our archetypes.

The converse appears to be true for autumn-drying wetlands and slow-drying wetlands, which have characteristics of floodplain wetlands. There is substantial evidence (Acreman and Holden, 2013; Golden et al., 2021) to suggest that floodplain wetlands reduce or delay floods, which may be shown in the latency of drying throughout the season for autumn-drying wetlands and slow-drying wetlands. These archetypes store the water for longer periods, suggesting that they simultaneously reduce flood peaks and increase water flow during the dry summer. Although we did not do a detailed analysis of ecosystem service delivery or have data from downstream discharge stations to confirm flood attenuation capacity (Andersson, 2012), this work provides a starting point for identifying potential future Ramsar sites or areas to prioritise for protection and management in regions with prominent flooding and summer drought.

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~~Although detailed exploration of the physical drivers of the observed hydrological regimes is beyond this study's scope, we theorise that factors such as position within the watershed and surface connectivity contribute to at least some extent. For example, spring-surging wetlands, with few surface water inlets, rely mainly on snowmelt and tend to dry rapidly, while summer-flooded wetlands benefit from multiple inflows and sustain inundation longer (Lane et al., 2018). Secondly, wetlands located in headwater regions, like spring-surging and summer-flooded~~

~~wetlands, experience rapid flood peaks characteristics of upper catchment water flows. This is in constrast to wetlands such as those within the slow drying archetype, which are located in the lower parts of the catchment, and are therefore linked to less pronounced flood peaks (Morley et al., 2011).~~

~~It should also be acknowledged that hydroclimatic variability plays a critical role in shaping wetland hydrological regimes and represents an important consideration to the interpretation of our archetypes. For instance, on an interannual and seasonal temporal scale, fluctuations in precipitation, snowmelt and evapotranspiration strongly influence wetland hydroperiods (Jaramillo et al., 2018; Winter, 2000). On a climatic temporal scale, warming trends and increasing dryness index has been observed in Swedish wetlandscapes since the 1970s, suggesting that there is a greater evaporative demand and reduced water storage in wetlands, especially during summer (Åhlén et al., 2021). These observations also align with model projections showing substantial summer drying and reduced wetland extent in North America under high-emission scenarios due to evapotranspiration exceeding precipitation input (Xu et al., 2024). Similarly, Xi et al., 2021 projected future declines in inland wetland area across Europe, though with a higher degree of uncertainty in Scandinavia. Furthermore, hydrological stability will likely be reduced in the future, with modelled studies of prarie pothole wetlands showing diminished monthly-scale stability in water storage under uncertain climate conditions (Zhang et al., 2011).~~

~~Despite this, the degree to which wetlands are vulnerable to such changes is dependent on their dominant water sources and topographical setting. For example, wetlands that are reliant on direct precipitation or snowmelt, such as spring suring wetlands, are more sensitive to hydroclimatic variability, while wetlands sustained by regional groundwater inputs on larger floodplains (like slow drying or spring flooded wetlands), have greater buffering capacity to hydroclimatic change (Winter, 2000). These findings highlight the need for long-term observations and the integration of hydroclimatic data when interpreting wetland hydrology in future work.~~

~~4.4. Hydrological regimes as indications of ecosystem services~~

~~In this study, we quantified the hydrological regimes of Swedish wetlands to better understand their hydrological functions, which are closely tied to the ecosystem services they provide. Inland wetlands are estimated to contribute approximately US$27 trillion annually in ecosystem service value, with the majority of the value deriving from water regulating services (Davidson et al., 2019).~~

~~We theorise that hydrological regimes can serve as indicators of the hydrological ecosystem services a wetland may deliver at any given time. For instance, spring-surging wetlands, which are characterised by high water extent during spring and low extent during summer, resemble headwater wetlands. Headwater wetlands are known to increase flood flows during the wet season while retaining baseflow during the dry season (Bullock and Acreman, 2003), suggesting that these wetlands may not provide flood mitigation services but rather exacerbate flooding (Åhlén et al., 2022). This is supported by the Ramsar site descriptions, where no wetlands in the spring surging archetype list flood control as an important service. Nevertheless, headwater wetlands can offer temporary flood storage (Kadykalo and Findlay, 2016), although confirming these dynamics requires temporally dense water extent observations to capture lag times between water storage and downstream flows.~~

~~Conversely, slow-drying wetlands exhibit traits more typical of floodplain wetlands, which are well-documented in their role in flood reduction and water retention (Acreman and Holden, 2013; Golden et al., 2021). The gradual reduction of water extent in these wetlands may suggest sustained water storage, likely contributing to both flood peak attenuation and maintaining summer baseflows. This is supported by the Ramsar site descriptions for the wetlands belonging to the slow drying archetype, since the majority of them have flood control and/or water storage listed as a known ecosystem service. Additionally, Doherty et al., 2014 suggest that wetlands with periodically dry soils (such as slow-drying or summer-dry wetlands) slow down flows and can remove large volumes of water from the system. Although we did not perform a detailed analysis of ecosystem service delivery or have dense downstream discharge data (Andersson, 2012), our results offer a foundation for prioritising wetlands for future conservation or Ramsar designation, particularly in flood-prone or drought-prone regions.~~

Another ~~strength~~important asset of hydrological regime ~~classification~~studies is ~~its~~the ability to ~~infer~~determine hydrological functions at ~~different times of the year, recognising that wetland~~any given time, as these functions ~~are not static in time or space~~can shift depending on the wetland's state (Spence et al., 2011). For ~~example, variability in~~instance, water extent variability can ~~signal~~indicate the ~~transition~~timing of the threshold between ~~water~~ storage and runoff~~-dominated states~~ (Yanfeng and Guangxin, 2021). Flashy water extent variability ~~observed~~ in northern archetypes like spring-surging~~, spring-flooded~~ and ~~to a lesser extent,~~ summer-flooded wetlands~~,~~ suggests a switch to conditions where ~~wetlands act as conduits~~water is not stored but rather ~~than reservoirs. This~~flows straight through the wetland downstream. This shift may result from frozen ground or sporadic permafrost hindering water storage in soils (Yanfeng and Guangxin, 2021) and/or ~~the dominance of rapid~~spring snowmelt ~~inputs~~contributing to over half of the annual flow in a short period (Spence et al., 2011). ~~However,~~

~~further investigation combining water level, connectivity analyses and catchment precipitation data would be needed to verify these hypotheses.~~

~~Aside from hydrological-related ecosystem services, wetlands offer other valuable ecosystem services that are also linked to their hydrological regimes, such as biodiversity and carbon sequestration (Okruszko et al., 2011). Hydrological variability is a major driver of wetland biodiversity due to species' water tolerance thresholds. Additionally, wetlands classified under the 'northern' archetypes are particularly significant carbon sinks, as evidenced in Ramsar site records. Differentiating hydrological regimes in carbon-sequestering wetlands or those with particularly rich biodiversity could improve our understanding of their role in the delivery of other ecosystem services (Kirpotin et al., 2011).~~

~~5 Conclusion~~

~~This research aimed to improve our understanding of wetlands by revealing their hydrological regimes using remotely sensed data on water surface extent.~~Aside from hydrological-related ecosystem services, it is important not to overlook other archetypes that may offer other valuable ecosystem services, such as maintaining biodiversity and carbon sequestration. For instance, biodiversity is driven by the wetland hydrological regime due to variations in water tolerances among vegetation species. Additionally, wetlands classified under the 'northern' archetypes are particularly significant for carbon sequestration. Future research that differentiates between hydrological regimes present in carbon-sequestering wetlands can further improve our understanding of their ecosystem services (Kirpotin et al., 2011).

5 Conclusion

This research aimed to improve our understanding of wetlands by revealing their hydrological regimes using remotely sensed data on water extent. We chose an automatic detection method based on Sentinel-1 SAR imagery because it can operate in cloudy and dark conditions and sometimes detect ~~more~~ water under vegetation~~ compared to optical-based methods~~. The hydrological regimes were grouped based on similar hydrological characteristics identified by custom hydrological parameters. For 43 Ramsar sites in Sweden, the hydrological regimes based on monthly water extent between 2020~~ and ~~-2023 could be grouped into ~~five~~six distinct archetypes. The defining traits were mainly related to the timing of change and the duration of wet and dry periods. Despite heterogeneity in the archetypes' spatial distribution, flashy archetypes with high water extent variability were preferentially found at higher elevations and latitudes, while less variable and drier archetypes were concentrated towards low elevations and latitudes. Additionally, ~~wetlands with~~ mire types were more homogeneous and thus more likely to be part of the same archetype compared to open or limnic wetland types.

While contextual information is vital for our deeper understanding of wetlands, ~~valuable insights into runoff and storage dynamics~~rich data can be ~~gained~~drawn from simply ~~by~~ tracking the water extent ~~over~~through time, such as insight into runoff and storage dynamics. Furthermore, by reducing multiple wetland hydrological characteristics to the hydrological regime, we demonstrated that we could use the ~~concept~~notion of archetypes to infer information about their specific hydrological functionality nationwide. Since many archetypes consist of multiple wetland classifications, we recommend estimating hydrological functions based on the hydrological regimes, not individual wetland types. By being able to draw information from the archetypes, we reveal a new understanding of the hydrological functioning of wetlands with a particular emphasis on hydrological-related ~~regulating~~ ecosystem services such as flood control and water supply during low flow periods.

Appendix A

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Table A1. Hydrological parameters used for cluster analysis. Each parameter was evaluated individually and in combination with others to assess its effectiveness in capturing the characteristics of the hydrological regime. (N) – Normalized to remove the effect of wetland size.

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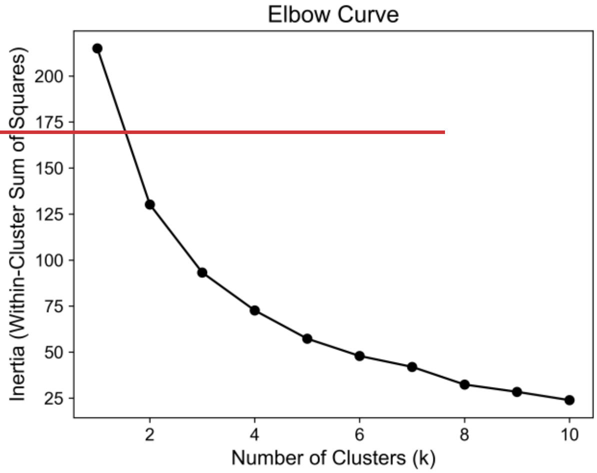
Hydrological parameters	**Description**
Max Month	Timing of the highest water extent
Min Month	Timing of the lowest water extent
Standard Deviation	Measure of dispersion of water extent values in a dataset
Skewness	Measure of symmetry in a distribution of water extent values
Kurtosis	Measure of peakedness in a distribution of water extent values
Coefficient of Variation	Measure of the dispersion water extent values around the mean
Range (N)	Difference between the maximum water extent value and the minimum water extent value, normalised to the mean wetland size
Minimum slope (N)	Smallest slope of monthly water extent change taken from the first derivative, normalised to the water extent range
Maximum slope (N)	Highest slope of monthly water extent change taken from the first derivative and normalised to the water extent range
Spring/Summer Area Difference (N)	Difference between the average spring water extent (in March, April and May) and average summer water extent (June, July, August), normalised to the mean wetland size
Spring/Summer Slope Difference (N)	Difference between the average spring slope of monthly water extent change (in March, April and May) and average summer slope of monthly water extent change (June, July and August), normalised to the mean wetland size
Slope Variation (N)	Standard deviation of all month-to-month slopes of monthly water extent change, normalised to the water extent range
Number of Peaks	Number of peaks, defined as a relatively high value of water extent between two relatively low values of water extent
Baseline Month Fraction	Number of months within 25th percentile of the distribution of water extent values as a fraction of the year



~~**Figure A1. Elbow curve showing the within cluster sum of squares (WCSS) for k values ranging from 1-10. The Elbow Curve helps identify the number of clusters by indicating where adding more clusters result in a diminishing reduction in the WCSS.**~~

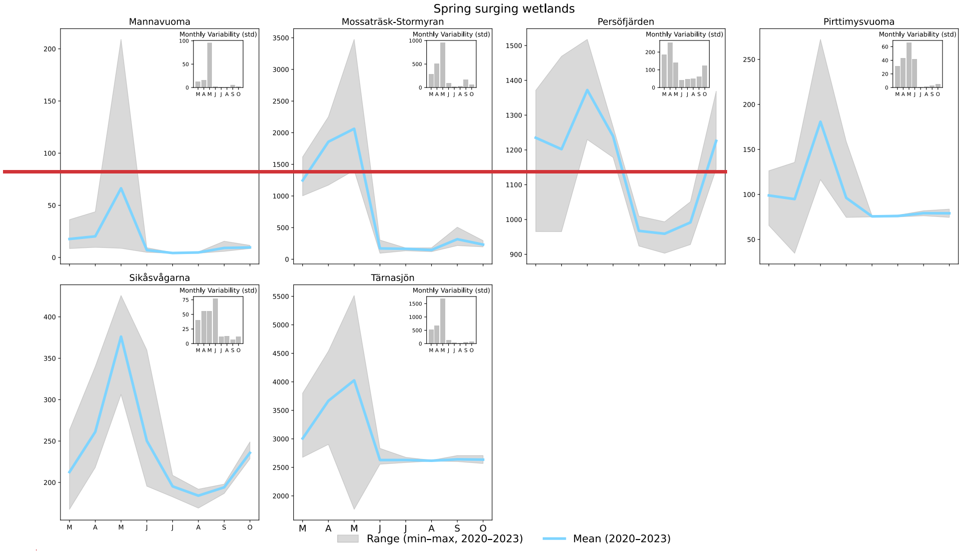

Spring surging wetlands
Mannavuoma
Mossaträsk-Stormyran
Persöfjärden
Pirttimysvuoma
Sikåsvågarna
Tärnasjön
Monthly Variability (std)
M A M J J A S O
Range (min–max, 2020–2023)
Mean (2020–2023)

Figure A1. Silhouette score (range -1 to 1) as a measure of closeness of data points belonging to one cluster to data points of another cluster for k=2-10.

805

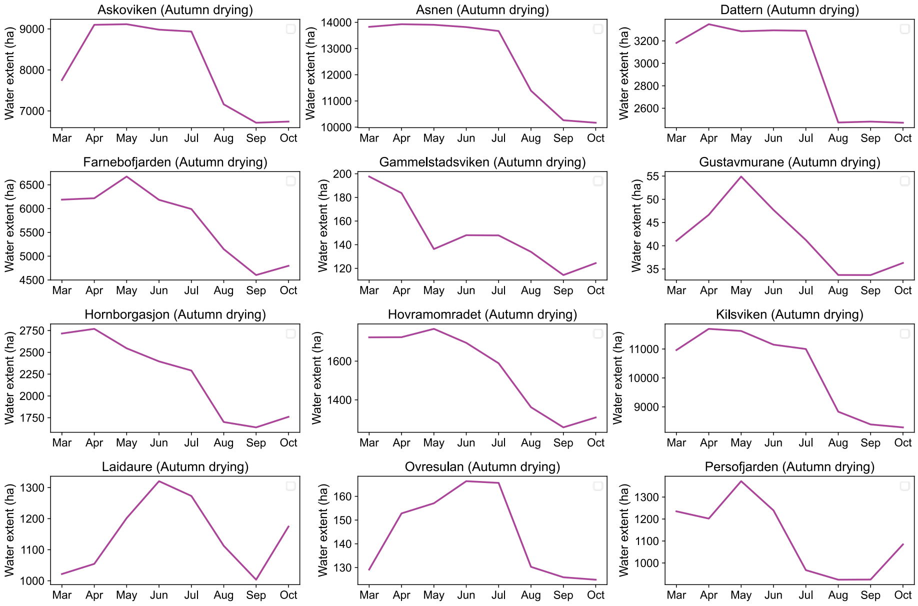
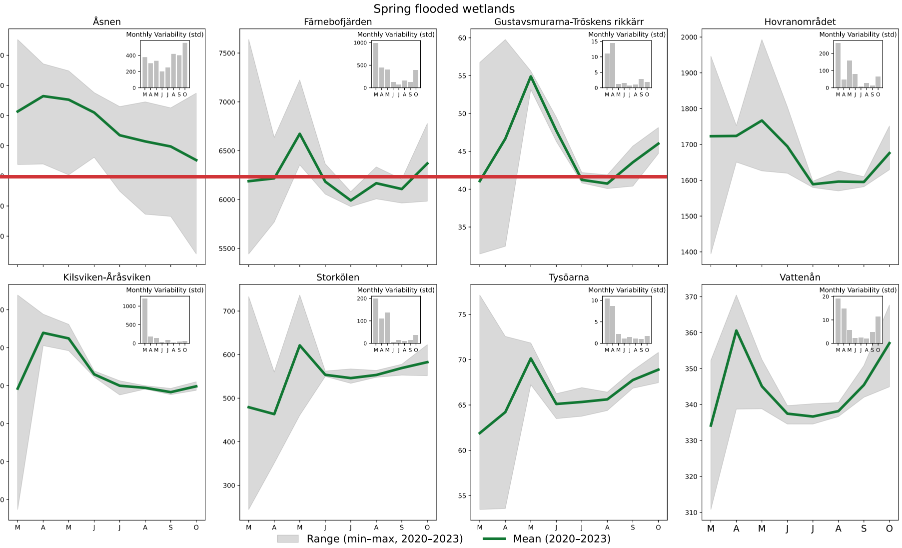


Figure A2. Average monthly water extent (March-October) between 2020-2023 for all wetlands belonging to the ~~**spring-surging archetype. Grey area shows the monthly interannual variability given by the range of water extent from all years. The monthly standard deviation is given in the top right bar plots.**~~ **autumn-drying archetype**


Spring flooded wetlands
Åsnen
Färnebofjärden
Gustavsmurarna-Tröskens rikkärr
Hovranområdet
Kilsviken-Åråsviken
Storkölen
Tysöarna
Vattenån
Monthly Variability (std)
14200
14000
13800
13600
13400
13200
13000
7500
7000
6500
6000
5500
60
55
50
45
40
35
2000
1900
1800
1700
1600
1500
1400
12000
11500
11000
10500
10000
9500
700
600
500
400
300
75
70
65
60
55
370
360
350
340
330
320
310
M
A
M
J
J
A
S
O
Range (min–max, 2020–2023)
Mean (2020–2023)

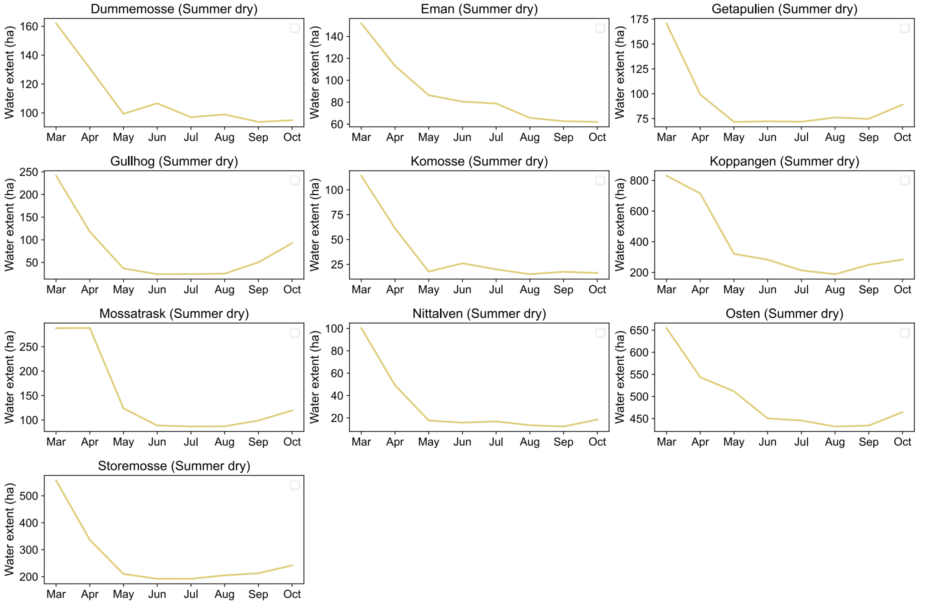
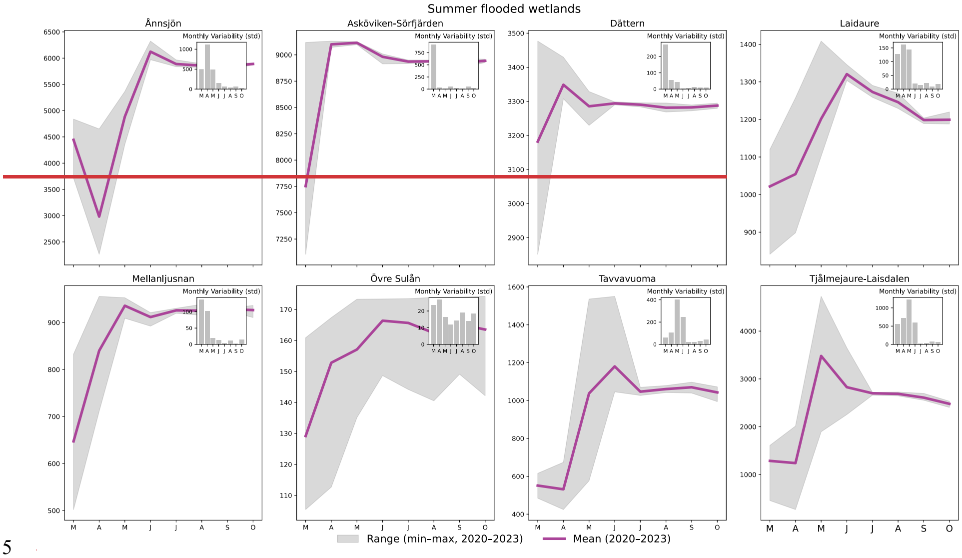


Figure A3. Average monthly water extent (March-October) between 2020-2023 for all wetlands belonging to the ~~spring-flooded archetype. Grey area shows the monthly interannual variability given by the range of water extent from all years. The monthly standard deviation is given in the top right bar plots.~~ summer-dry archetype


Summer flooded wetlands
Ånnsjön
6500
6000
5500
5000
4500
4000
3500
3000
2500
Asköviken-Sörfjärden
9000
8750
8500
8250
8000
7750
7500
7250
Dättern
3500
3400
3300
3200
3100
3000
2900
Laidaure
1400
1300
1200
1100
1000
900
Mellanljusnan
900
800
700
600
500
Övre Sulån
170
160
150
140
130
120
110
Tavvavuoma
1600
1400
1200
1000
800
600
400
Tjålmejaure-Laisdalen
4000
3000
2000
1000
Monthly Variability (std)
M A M J J A S O
M
A
M
J
J
A
S
O
Range (min–max, 2020–2023)
Mean (2020–2023)

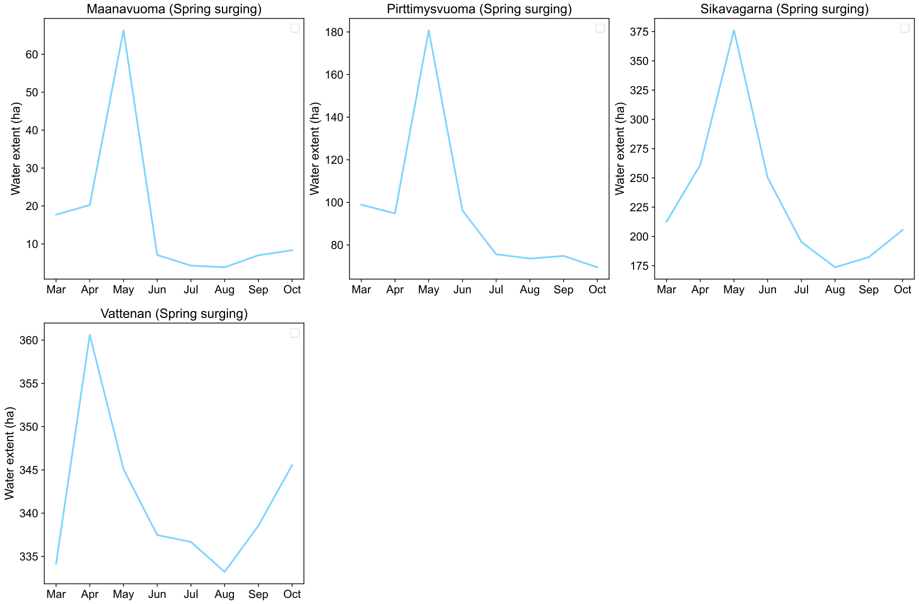
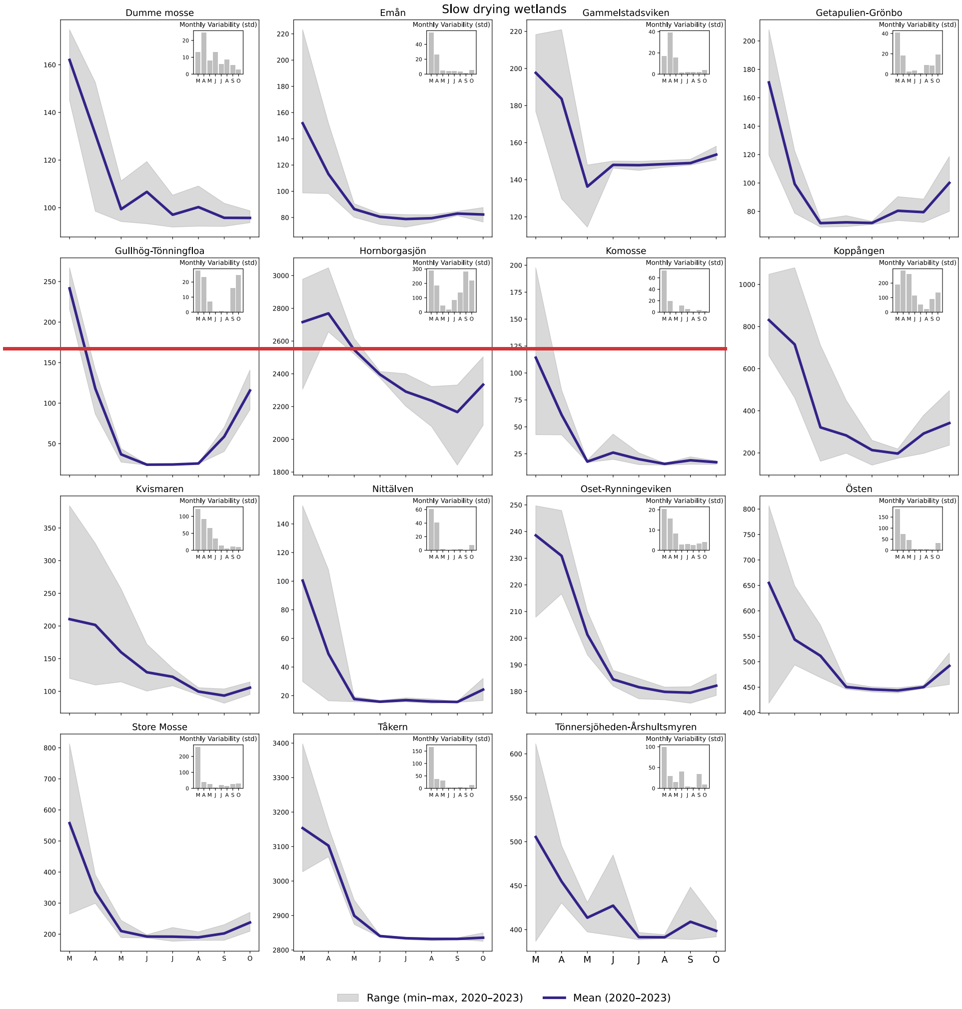


Figure A4. Average monthly water extent (March-October) between 2020-2023 for all wetlands belonging to the ~~summer-flooded archetype. Grey area shows the monthly interannual variability given by the range of water extent from all years. The monthly standard deviation is given in the top right bar plots.~~ spring-surging archetype


Slow drying wetlands
Dumme mosse
Emån
Gammelstadsviken
Getapulien-Grönbo
Gullhög-Tönningfloa
Hornborgasjön
Komosse
Koppången
Kvismaren
Nittälven
Oset-Rynningeviken
Östen
Store Mosse
Tåkern
Tönnersjöheden-Årshultsmyren
Monthly Variability (std)
M A M J J A S O
Range (min–max, 2020–2023)
Mean (2020–2023)

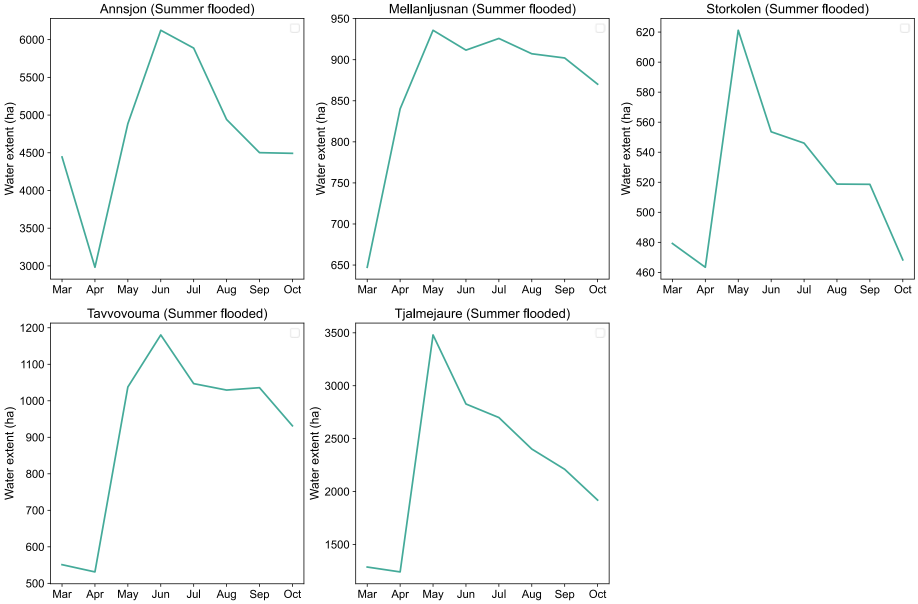


Figure A5. Average monthly water extent (March-October) between 2020-2023 for all wetlands belonging to the summer-flooded archetype

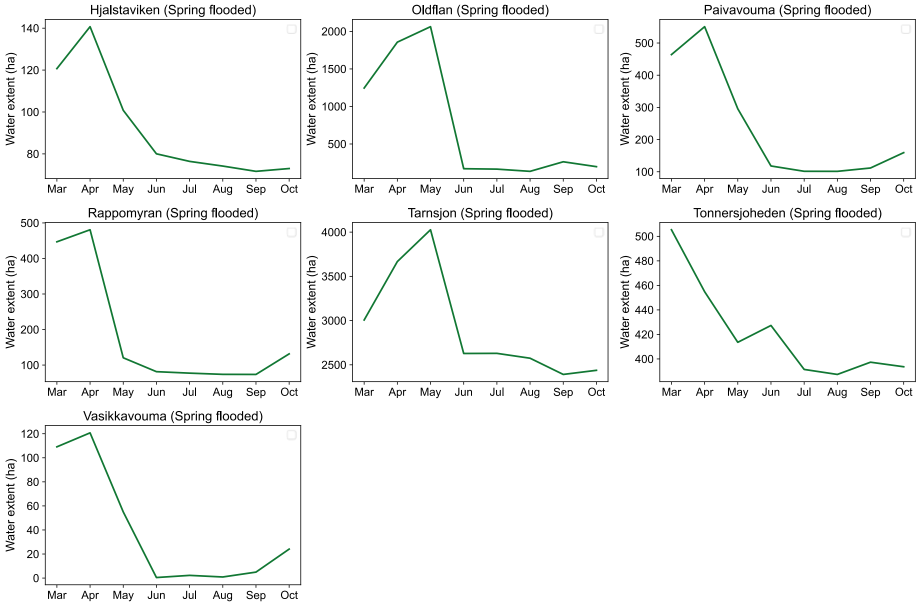


Figure A6. Average monthly water extent (March-October) between 2020-2023 for all wetlands belonging to the spring-flooded archetype

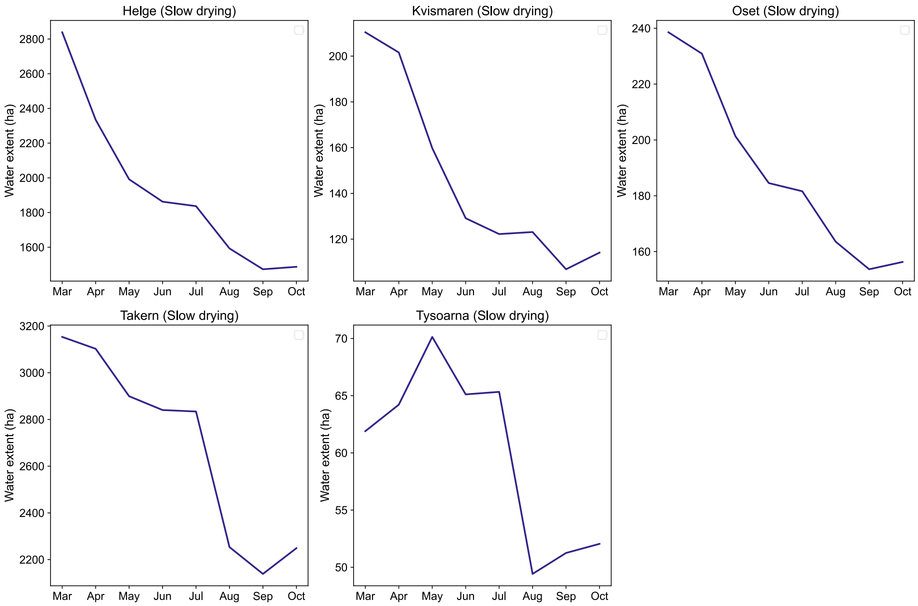
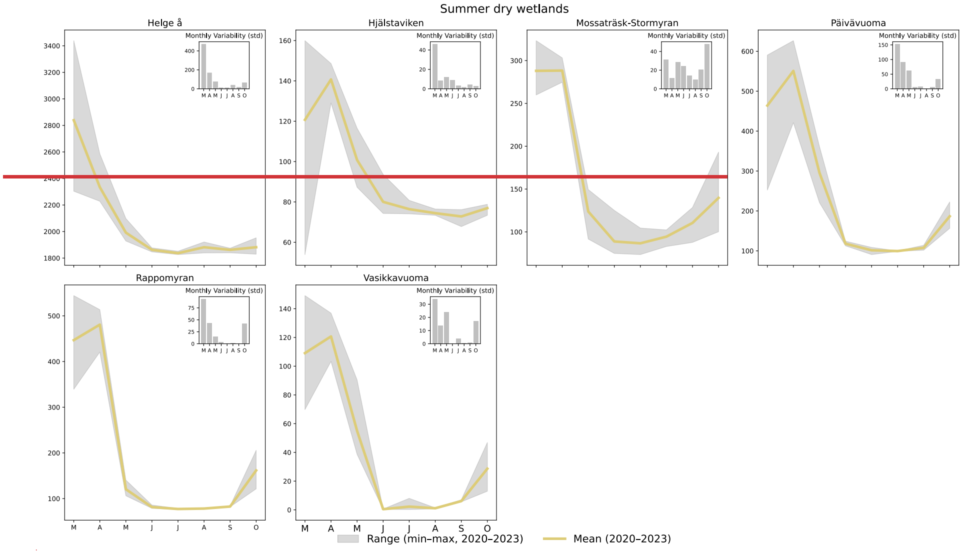
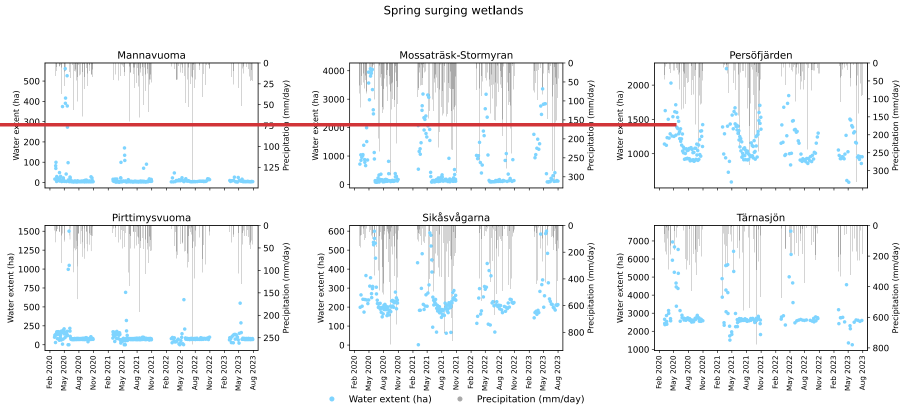


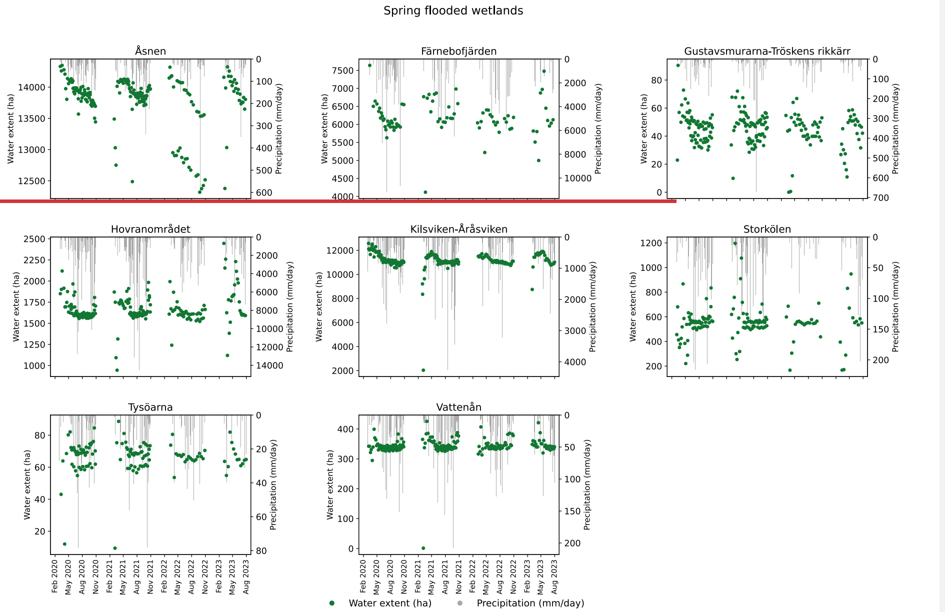
Figure A7. Average monthly water extent (March-October) between 2020-2023 for all wetlands belonging to the **slow-drying archetype**~~. Grey area shows the monthly interannual variability given by the range of water extent from all years. The monthly standard deviation is given in the top right bar plots.~~



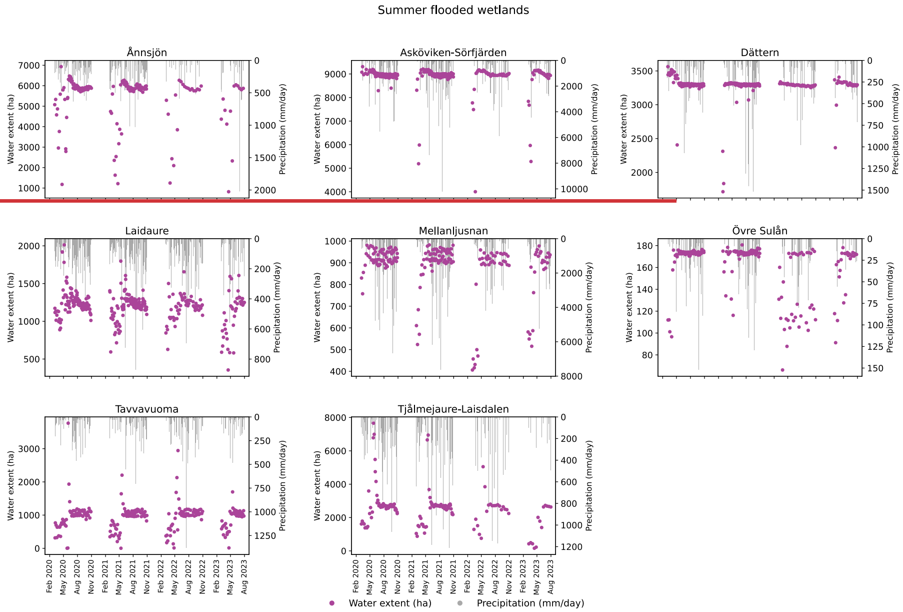
~~**Figure A6. Average monthly water extent (March-October) between 2020-2023 for all wetlands belonging to the summer-dry archetype. Grey area shows the monthly interannual variability given by the range of water extent from all years. The monthly standard deviation is given in the top right bar plots.**~~



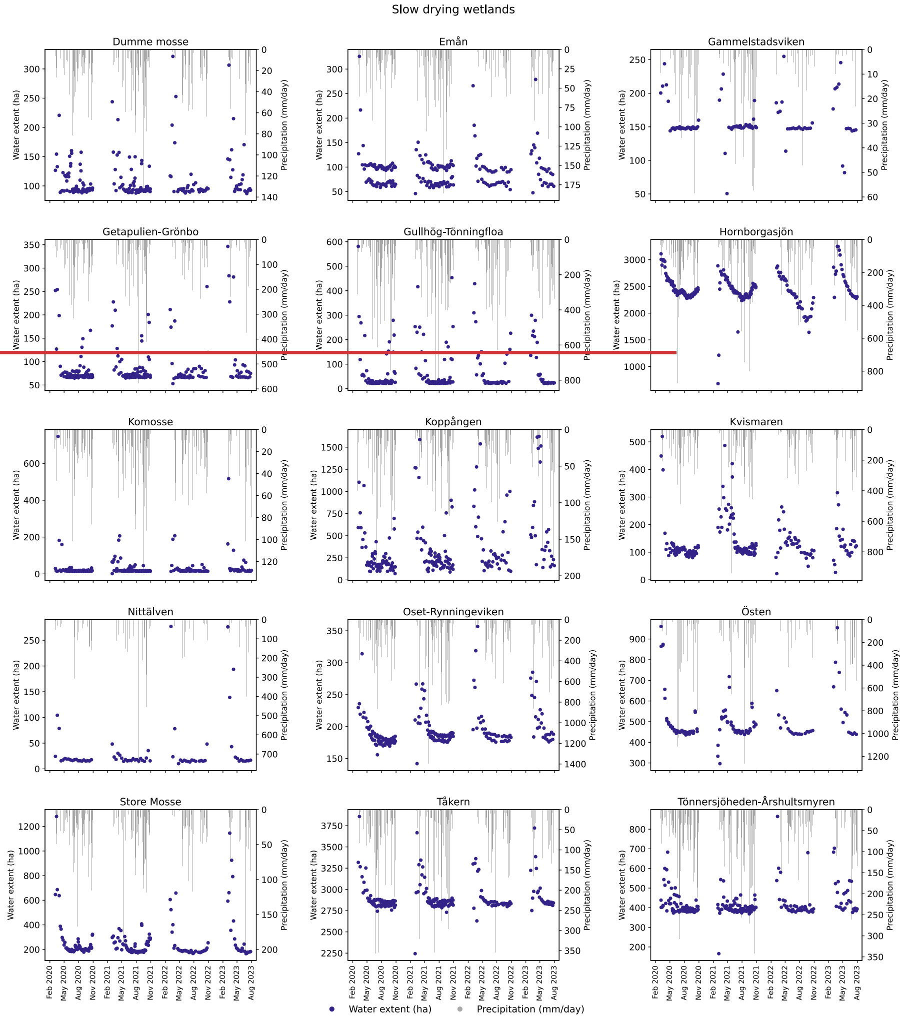
~~**Figure A7.** Wetland water extent from January 2020 to August 2023 (excluding January, February November and December) for spring-surging wetlands, shown alongside daily precipitation totals for matching dates. Precipitation is aggregated separately for each wetland's catchment and Ramsar area.~~



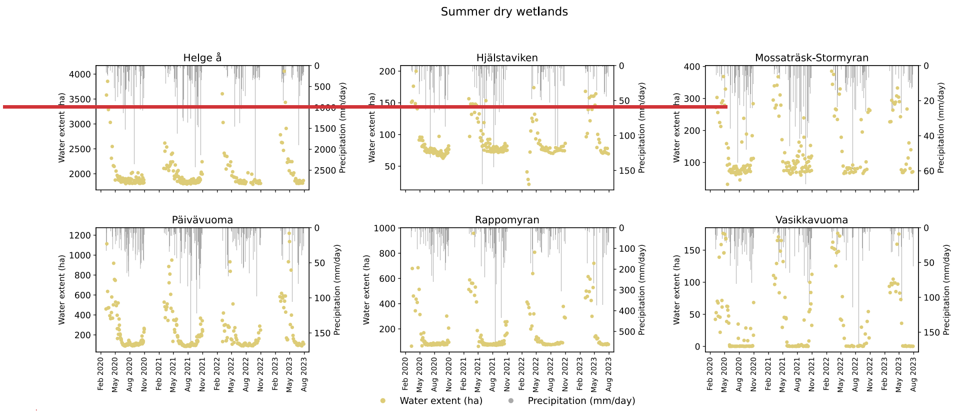
~~Figure A8. Wetland water extent from January 2020 to August 2023 (excluding January, February November and December) for spring flooded wetlands, shown alongside daily precipitation totals for matching dates. Precipitation is aggregated separately for each wetland's catchment and Ramsar area.~~



~~**Figure A9. Wetland water extent from January 2020 to August 2023 (excluding January, February November and December) for summer-flooded wetlands, shown alongside daily precipitation totals for matching dates. Precipitation is aggregated separately for each wetland's catchment and Ramsar area.**~~


Slow drying wetlands
Dumme mosse
Emån
Gammelstadsviken
Getapulien-Grönbo
Gullhög-Tönningfloa
Hornborgasjön
Komosse
Koppången
Kvismaren
Nittälven
Oset-Rynningeviken
Östen
Store Mosse
Tåkern
Tönnersjöheden-Årshultsmyren
Water extent (ha)
Precipitation (mm/day)
Feb 2020
May 2020
Aug 2020
Nov 2020
Feb 2021
May 2021
Aug 2021
Nov 2021
Feb 2022
May 2022
Aug 2022
Nov 2022
Feb 2023
May 2023
Aug 2023
● Water extent (ha)
● Precipitation (mm/day)

~~**Figure A10. Wetland water extent from January 2020 to August 2023 (excluding January, February November and December) for slow-drying wetlands, shown alongside daily precipitation totals for matching dates. Precipitation is aggregated separately for each wetland's catchment and Ramsar area.**~~



~~**Figure A11. Wetland water extent from January 2020 to August 2023 (excluding January, February November and December) for summer-drying wetlands, shown alongside daily precipitation totals for matching dates. Precipitation is aggregated separately for each wetland's catchment and Ramsar area.**~~

Code and data availability. All data including environmental data, hydrological parameter results and raw water extent data for all wetlands is available through ~~(Robinson, 2024)~~(Robinson, 2024) (https://doi.org/10.5281/zenodo.13833605). Code for processing data and cluster analysis is available at https://github.com/ab-e-rob/hydrological_archetypes. Code for predicting water extent in wetlands using DeepAqua can be found at https://github.com/melqkiades/deep-wetlands.

Author contributions. AR conceptualised the project, developed the methodology, conducted data collection and analysis. AS and FP contributed to methodology development and provided research guidance. PH assisted in results interpretation. FJ provided guidance on methodology, data analysis, and interpretation; supervised the

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project. The co-authors all contributed to the preparation of the paper. The use of ChatGPT helped to improve prose.

Competing interests. The authors declare that they have no conflict of interest.

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