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Impact of wetland restoration on river discharge -A case study of Bråån, Skåne, Sweden

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Title page image: A wetland close to Rövarekulan in the Bråån catchment (Luda, 2023).

Impact of wetland restoration on river discharge
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Bachelor thesis, 15 credits, in Physical Geography and Ecosystem Analysis

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Abstract

Land use change is a factor not often considered when modeling river discharge in regard to future flood risk. The restoration of wetlands is an ongoing land use change which affects water storage capacity in the soils of a catchment and could lead to lower flows in rivers. This study analysed the effect of an increased wetland area on river discharge in the Bråån catchment in Skåne, Sweden. Discharge was modeled with the HYPE model, developed by the Swedish Meteorological and Hydrological Institute (SMHI). Input data included land use and soil type data, which are classified into soil-land use classes, as well as climate, discharge and elevation data. Wetlands were modeled as constructed internal wetlands with water regulation capability. A GIS-analysis for future potential wetland areas from The County Administrative Board of Skåne (Länsstyrelsen Skåne) served as the base for a realistic wetland increase scenario. River discharge decreased by 2% with the realistic increase. The main reasons for the reduction of discharge are the increase in peat soils and higher evaporation. However, soil and land use parameter values could be improved, and a more complex incorporation of HYPE's routines could be done to achieve a better model fit. The small reduction in discharge implicates that land use change in form of more wetlands does have an effect on river flow. This should be considered in e.g. future flood mapping and hydrological modeling.

Table of Contents

1. Introduction

In a human-induced warming climate, precipitation and river floods are projected to increase (IPCC, 2021). Sweden's climate is expected to be both warmer, and wetter, which brings a higher risk of longer dry periods, as well as more intense precipitation events (SMHI, 2021a; IPCC, 2021). These events could lead to extreme river flow, increasing flood risk for areas close to water bodies (IPCC, 2021). To identify areas at risk, it is highly relevant to do flood risk analyses (Thieken et al., 2006). In Sweden, the Swedish Civil Contingencies Agency (MSB) provides flood risk analyses of 75 rivers in the country, mapping potential flooded areas around the water course for a 50-, 100-, 200- and 10 000-year flood (MSB, 2022). Future climate change is considered for modeling river discharge, by incorporating the worst-case emission scenario of RCP 8.5 (MSB, 2020). When it comes to modeling river discharge, the way water flows in the landscape plays a vital role. Besides soil types, topography, and climate conditions, land use such as urban areas, agricultural land, forest, or wetlands influence the hydrology of a catchment as well (Yang et al., 2015). Land use characteristics are altered due to human activities, as past studies and observations have shown that land use change influences precipitation and river flow by changing moisture advection and recycling, and the surface energy balance (IPCC, 2021). This underscores the importance of incorporating future land use change into flood risk analyses.

The very dry summer of 2018 in Sweden served as a wake-up call for the County Administrative Board of Skåne (Länsstyrelsen Skåne, 2023b). Extremely low amounts of precipitation and hot temperatures led to a widespread drought and low water levels, which could have been counteracted by more irrigation ponds, wetlands, or deep-drilled wells in the landscape (Länsstyrelsen Skåne, 2023b). However, in the 19th and up until the first half of the 20th century, most of Skåne's wetlands were dried out by lowering the water table (Länsstyrelsen Skåne, 2023a). This was done to make more arable and grazing land available, to increase food production for a growing population (Länsstyrelsen Skåne, 2023a). Today, more action has been taken to construct wetlands again (Länsstyrelsen Skåne, 2023a). This goes in line with one of Sweden's 16 environmental objectives, aiming to maintain the ecological and water-holding function of wetlands in the landscape and to preserve valuable wetlands for the future (Naturvårdsverket, 2023). Wetlands have important environmental benefits, including enhancement of biodiversity and improvement of water quality of rivers and lakes (Naturvårdsverket, 2023). Biodiversity and water quality improvement are often considered the main goals of restoring wetlands along water courses (Länsstyrelsen Skåne, 2023a). On the other hand, the ability of wetlands to act as flood regulators is an important aspect that should also be considered. Flooding can be reduced as e.g., wetlands can act as a sponge, only slowly releasing water to streams and rivers (Huynh & Truong, 2022).

The catchment of one of Skåne's largest rivers, Kävlingeån, has experienced land use change due to wetland restoration already the past decade and more wetland areas are planned to be restored in the future (Kävlingeåns vattenråd, 2011 & Länsstyrelsen Skåne, 2023a). MSB has flood risk mapped Kävlingeån using a hydraulic model, which incorporates topography, but not a land use change (MSB, 2020). As land use change is already ongoing with increasing wetland area, this study will focus on the impacts of wetland restoration on river discharge. One of the contributing rivers to Kåvlingeån is Bråån. River discharge will be modeled for Bråån with the help of the Swedish Meteorological and Hydrological Institutes (SMHI) Hydrological Predictions for the Environment (HYPE) model. Bråån is a suitable river for the study, since it is quite isolated and there are no additional lakes that must be considered, which would be the case for Kävlingeån.

1.1 Objectives

The aim of this thesis is to analyze how an increase in wetland area will affect the discharge of Bråån, Skåne, Sweden. The analysis is based on hydrological modeling with the HYPE model. Total river discharge for Bråån is expected to decrease slightly, as more wetland area should lead to a higher evaporation (Białowiec et al., 2014). Besides this, peak discharge is predicted to be lower for a higher wetland area, as well as delayed due to the higher storage capacity. Model results are evaluated with a comparison of Pearson's correlation coefficient R^2 for the HYPE modeled discharge and the observation data on a monthly, seasonal, yearly, and total scale. Total modeled discharge, as well as Root Mean Squared Error (RMSE) are also compared.

2. Background

2.1 Study area

The Bråån catchment is situated in the South of Sweden and the river Bråån originates close to the town Ormastorp in central-eastern Skåne. It covers an area of 170 km2 (SMHI, 2021b). The river is around 89 km long and flows towards the west, where it flows into Kävlingeån between the towns of Örtofta and Håstad. It passes through Höör, Hörby and Eslöv municipalities. There are no lakes in the catchment area, though it is located close to the lakes Östra and Västra Ringsjön in the north, and Vombsjön and Krankesjön in the south. A wastewater treatment plant is located in the south of Eslöv and its water flows into the small stream Eslövbäcken, which flows into Bråån just before the river's measurement station in Ellinge (VA Syd, 2023). Bråån catchment is divided into 15 subbasins and it makes up 14% of Kävlingeån's catchment area (Fig.1).

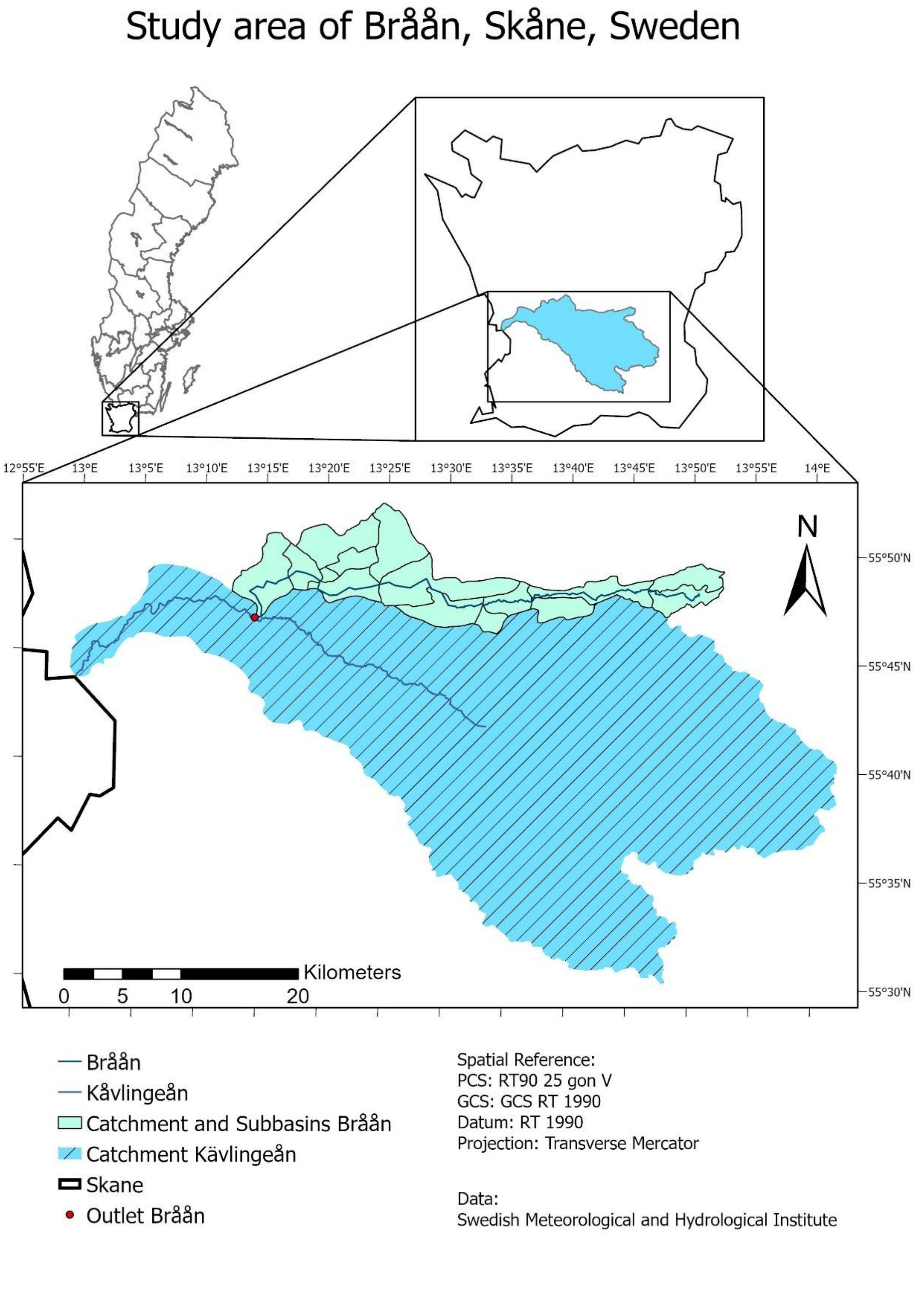

Figure 1. Study area of the Bråån catchment and subbasins, within the Kåvlingeån catchment area. The river Bråån flows into Kävlingeån at Bråån's outlet point. Map producer: Ardis Luda.

2.1.1 Climate

The study area is situated in a temperate climate. The mean annual temperature in the Bråån catchment is 8°C, with a mean temperature in January of 1°C and of 18°C in July (reference period 1991-2020) (SMHI, 2023b). The mean annual precipitation is 695mm, with a minimum of 35mm in April and a maximum of 75mm in August (SMHI, 2023b). Frost days can occur from October to April. Figure 2 illustrates the climatic conditions in the Bråån catchment.

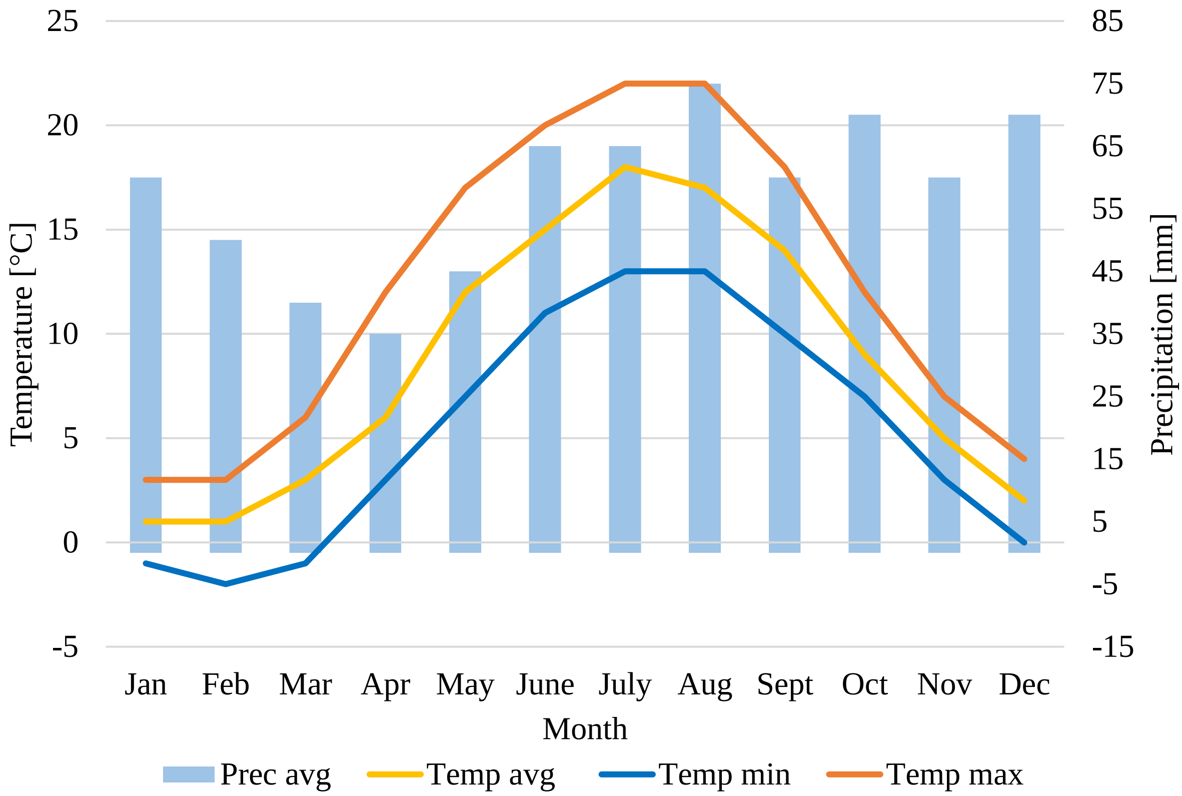

Figure 2. Mean monthly (Temp avg), mean monthly maximum (Temp max) and minimum (Temp min) temperature, and mean monthly precipitation (Prec avg) for the Bråån catchment area (SMHI, 2023b).

2.1.2 Land use

Bråån catchment is made up of 68% agricultural land, 10% open land, 14% forest, 1% forest on wetland, 0.5% wetland and 0.5% water which can be seen in Figure 3 (Naturvårdsverket, 2022). Forests are very diverse, with coniferous, deciduous, and mixed forests present in the catchment. A larger forest area is in the northwestern and eastern part. Furthermore, the town of Eslöv makes up the biggest urban area. Otherwise, urban areas are spread out throughout the catchment. Agricultural areas can be found in all subbasins and the most common crops that are produced are ley, barley, wheat, sugar beet, rape seed and fallow (Fogelfors et al., 2009).

2.1.3 Soils

Most parts of the catchment area are made up of till soil, mainly consisting of larger particles in the form of sand (SGU, 2021). In the western part, till soil can contain more clay and silt and is of finer texture. Sandy glacial and fluvial sediments can be found along the main water course. Additionally, only small parts of the catchment consist of peat. These can be found especially in the upper subbasins and sporadically further downstream. The small amount of area with peat soil indicates that wetlands are not as common in this catchment, as for example in Kävlingeå catchment where more peat soils can be found. Clay soils can be found in the western part of the catchment area. The dominant moraine soils in the Bråån catchment are more nutrient-rich and fertile in the western region. The fraction of clay and silt is higher in this part, compared to the sandy moraine eastern region (SGU, 2021).

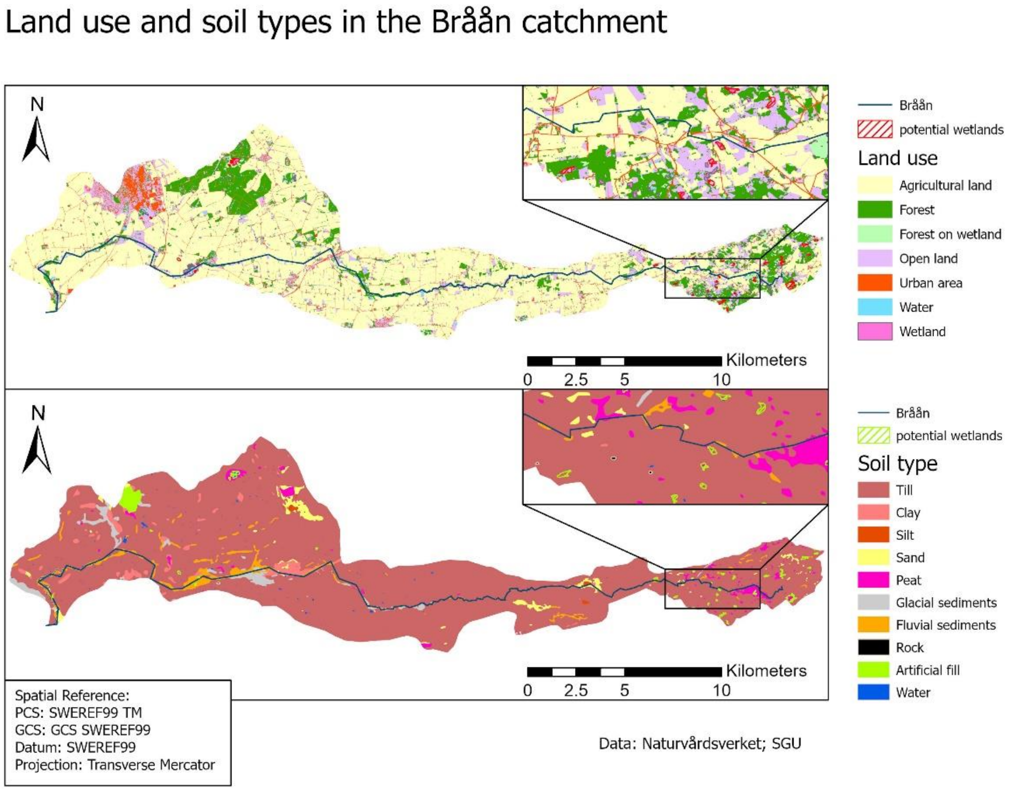

Figure 3. Land use and Soil map of the Bråån catchment, with potential wetland areas. Map producer: Ardis Luda.

2.1.4 Topography and Landforms

Average elevation from source to mouth is 104 meters above sea level (m.a.s.l.). It spans from on average 175 m.a.s.l. in the upper catchment area to 45 m.a.s.l. in the lowest subbasin where Bråån flows into Kävlingeån (Lantmäteriet, 2021). Most of the time the river flows between agricultural fields, however there are also parts where the water has dug itself deep down in the bedrock. A ravine can be found around halfway from the source to the mouth of the river. This place is called “Rövarekulan” and was formed 14,000 years ago during the last ice age (Länsstyrelsen Skåne, 2023c). A glacial lake that had been dammed broke as the ice sheet retreated and as a result, the valley was formed. Since then, the river Bråån has been eroding its way through the clay shale bedrock of Rövarekulan (Länsstyrelsen Skåne, 2023c). The Bråån catchment lies within the Colonus Shale Trough, which marks the area between two fault zones in NW-SE direction in central Skåne (Pool et al., 2012).

2.1.5 Geology and Bedrock

From a geological point of view, Bråån originates in the upper unit of the Sveconorwegian orogen's Eastern Segment, dominated by granitic orthogneiss, granite, syenite and metamorphic equivalents. The Eastern Segment was formed through post—svecokarelian magmatism (Bingen et al., 2020). However, most of the river's catchment is situated on platformal sedimentary cover rocks (SGU, 2023). Here, the present bedrock consists of limestone, shale, sandstone, and clay. The oldest rocks are around 1.7 billion years old, situated at the origin of Bråån (SGU, 2023). Younger, sedimentary rocks in the rest of the catchment are from the Ordovician, Silurian, Rhaetian to Tithonian and Late Triassic 485 to 237 million years ago (SGU, 2023 & Minor, 2013). Furthermore, the area is affected by the Tornquist Fault Zone, which creates a boundary between the Sveconorwegian orogen and the sedimentary cover rocks (Bingen et al., 2020). The catchment has 3 fracture zones in NNW-SSE direction (SGU, 2023).

2.2 Wetland definition

Literature makes clear that a wetland can be defined in a lot of different ways (Gerbeaux et al., 2018). The definition is often based on surface area, depth, vegetation, or soil type, but other factors, such as ecosystem structure or water chemistry, are also used (Richardson et al., 2022). However, a wetland definition is important for conservation and management (Gerbeaux et al., 2018). The Swedish Environmental Protection Agency describes wetlands as open land where the water is close by, in or above the land surface (Naturvårdsverket 2020). The limit of how close the water must be below the surface to be considered a wetland can vary. Most of the time the vegetation can be a good indicator to define a wetland. At least 50% must be hydrophile vegetation. Trees and shrubs on wetlands are less than 5m tall, although single taller trees could occur (Naturvårdsverket 2020). Richardson et al. (2022), classify wetlands to have a depth smaller than 1m and no defined surface area. In contrast, ponds can have a maximum depth of 5m and a maximum surface area of 5ha (Richardson et al., 2022). Länsstyrelsen Skåne considers the terms wetland and irrigation pond in their wetland restoration construction plans (Länsstyrelsen Skåne, 2023b). Figure 4 shows that the shape of ponds is rather geometrical as a circle or square, whereas a wetland has a more irregular shape. Ponds are also deeper as wetlands, although wetlands can also have a deeper part, if their purpose is to serve as irrigation reservoir and only a limited amount of area is available (Länsstyrelsen Skåne, 2023b). This study uses HYPE's simulation of constructed internal wetlands with water regulation capability

(SMHI, 2023c). Here, wetlands are defined as a land class, where depth and surface area can be set individually. A depth of 1m was used in this study and wetlands are not simulated singularly, but as a total area in one subbasin.

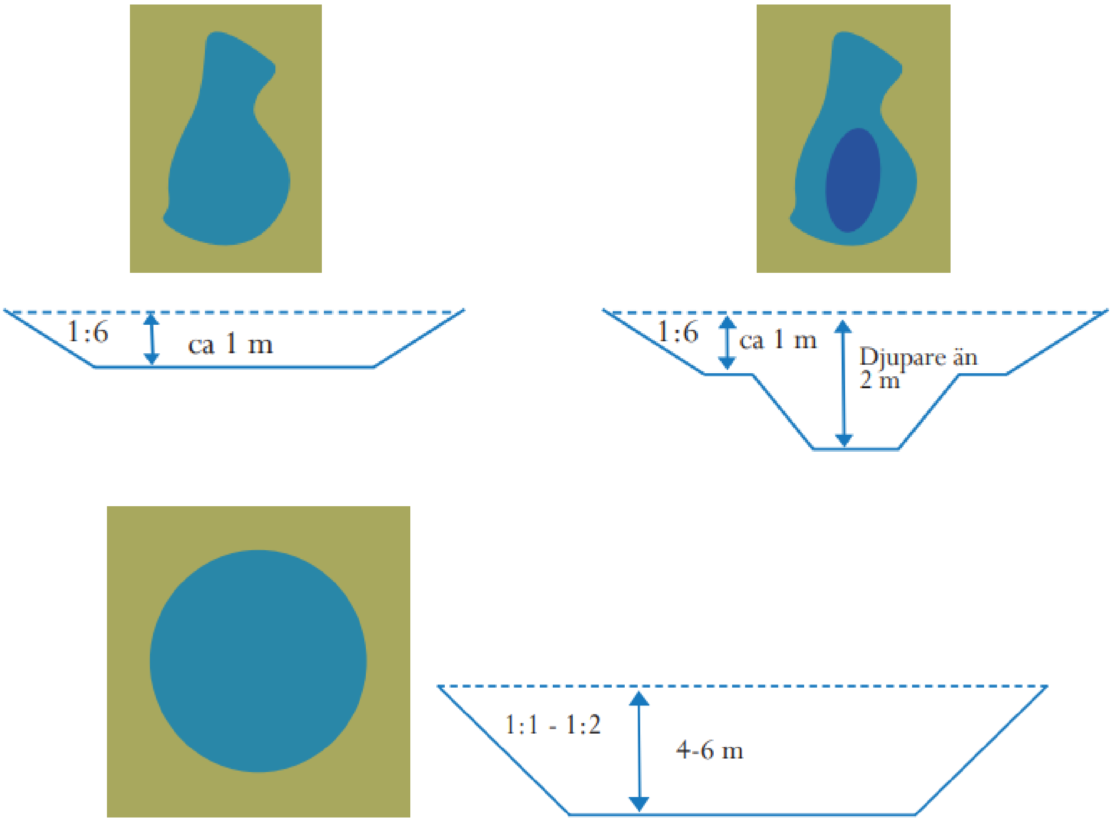

Figure 4. Constructed wetlands (top) and irrigation ponds (bottom), as described by Länsstyrelsen Skåne, 2023b. The upper right figure shows a common constructed wetland, whereas the upper left figure shows a constructed wetland with irrigation purpose and is therefore deeper in the middle part. The lower figure shows a constructed irrigation pond.

3. Methodology

First, model input data and data collection are described, and a detailed climate data description is presented. This is followed by a description of the HYPE model, its set up and input files. The HYPE model uses different calculation routines and the soil, soil water, river and wetland routine are described. To achieve a realistic wetland increase in the catchment area, a GIS-analysis is performed. The model is evaluated against observation data and SMHI's S-HYPE model, which is further described below.

3.1 Data collection

Model input data is shown in Table 1 and was collected from different sources, such as the Swedish Land Survey "Lantmäteriet", the Swedish Environmental Protection Agency "Naturvårdsverket", the Swedish Geological Survey "SGU", the Swedish Meteorological and Hydrological Institute "SMHI". An analysis of potential wetland areas was obtained on request from the County Administrative Board of Skåne "Länsstyrelsen Skåne". This analysis was financed by Metria AB.

Climate data used in this study has been compared to SMHI's average annual temperature and annual precipitation from 1991-2020 (Table 2). 2010 was the only year colder than average, all other years had the same average temperature or were warmer. The warmest year was 2020, followed by 2018 and 2014. 2018 was also the driest year in the study period, with more than 170mm less rainfall. However, some years also showed more rainfall than usual. 2017 for example, had almost 127 mm more precipitation compared to average.

Table 1. Model input data.

Variable	**Data type**	**Description**	**Source**
Elevation	Raster	Swedish National Elevation Model *(GSD-Höjddata, grid 2+ 2019)*	Swedish Land Survey (Lantmäteriet), 2021
Land use	Shapefile	National Land Cover Database *(Nationella marktäckedata 2018 basskikt, Sverige v1.1)*	Swedish Environmental Protection Agency, 2022
Soil	Shapefile	Soil types *(Jordarter 1:50 000)*	Swedish Geological Survey (SGU), 2021
Subbasin areas	Shapefile	Subbasin areas, Swedish Water Archive *(Delavrinningsområden SVAR 2016_3)*	Swedish Meteorological and Hydrological Institute (SMHI), 2021b
Temperature	.csv file	Air temperature (day), Lund, Station number 5343	Swedish Meteorological and Hydrological

		(Lufttemperatur (dygn), Lund, Stationsnummer 5343)	Institute (SMHI), 2023g
Precipitation	.csv file	Total precipitation (day), Vomb, Station number 53 *(Nederbördsmängd (dygn), Vomb, Stationsnummer 53)*	Swedish Meteorological and Hydrological Institute (SMHI), 2023g
Discharge	.csv file	Measurements, Station number 2126, Ellinge, Bråån *(Mätningar, Stationsummer 2126, Ellinge, Bråån)*	Swedish Meteorological and Hydrological Institute (SMHI), 2023h
Potential wetland areas	Shapefile	GIS analysis for wetland restoration *(GIS-analyser för våtmarksrestaurering)*	County Administrative Board of Skåne (Länsstyrelsen Skåne)

Table 2. Difference in temperature and precipitation from annual average for 2010-2021.

Year	**ΔT [°C]**	**ΔP [mm]**	**Year**	**ΔT [°C]**	**ΔP [mm]**
2010	-1.3	-71.9	**2016**	0.9	-105.8
2011	0.5	34.4	**2017**	0.7	126.8
2012	0.0	-46.2	**2018**	1.7	-172.4
2013	0.1	-125.7	**2019**	1.6	-49.2
2014	1.7	105.5	**2020**	2.0	-84.1
2015	1.0	-5.7	**2021**	0.8	40.4

3.2 HYPE model

SMHI's HYPE model is an open source, dynamic and semi-distributed hydrological model (SMHI, 2023a). Water fluxes, as well as fluxes of nutrients and other substances can be modeled and results are used for forecasting, research, including assessment of climate change impacts (SMHI, 2023a). The HYPE model code is available at SourceForge and further model documentation can be found on SMHI's webpage (SMHI, 2023d; SMHI 2023e). SMHI has its own S-HYPE model, which is based on the HYPE model code and applied to all of Sweden (Lindström, 2016). Specific model set up files from S-HYPE are not publicly available. For this study, the HYPE version 3.5.3 was applied. This is because an introductory course with example files to the model was based on this version (SMHI, 2023f). HYPE has no graphical user interface. Instead, the model runs with input text files that can be modified according to how the model is intended to be set up (Appendix 1). Climate forcing data and discharge observation data are also included, as model calculations rely on precipitation and temperature data and discharge data is used for comparison. A description of those files follows in the paragraphs below. To run HYPE, all seven input files need to be placed in the same folder. A model simulation period from 2010-2021 was chosen for this analysis. The model was run four times: one simulation was made for the current land use conditions, and one for a future increase in wetland area planned by Länsstyrelsen Skåne, as well as two more simulations where a scenario of 50% and 100% wetland area in the catchment was applied.

HYPE uses a soil type - land use classification system, where soil type and land use properties are combined into soil type - land use-classes (SLC's). This is equivalent to the setup of hydrological response units in a catchment. ArcGIS Pro 2.8 (Esri, 380 New York Street, Redlands, CA 92373-8100 USA) was used to analyse and classify soil and land use types. Land use and soil layers were clipped to the study area, and later intersected. Soil types in the study area were summarized into 3 classes: clay soils (1), till soils (2) and bare rock/shallow soils (3). Land use was classified into 5 classes: forest (1), agricultural/urban/open land (2), bare rock (3), wetland (4) and water (5). Agricultural, urban, and open land were paired together since the model parameter values in the example HYPE course files were similar (SMHI, 2023f). Open land can be classified with or without vegetation, it includes e.g., grazing land, heathland, moorland and grassland (Naturvårdsverket, 2022). A total of 7 SLC's were identified in the study area. These are defined in the Geoclass.txt input file (Appendix 1, 3.). Besides a land use and soil code for each SLC, the Geoclass.txt file contains a column for special classes, such as internal lakes (2) and internal wetlands (13); a column for tile-depth [m], which is only used for the SLC of agricultural/urban/open land in combination with clay soils, as this parameter describes the depth to drainage pipes for agricultural purposes; a column for stream-depth [m], set to zero for the wetland class and a negative value for the water class as the outflow threshold is above land surface; the last four columns describe the amount of soil layers and the depth of each soil layer.

A summarized table of SLC areas [m2] for each subbasin was extracted to Microsoft Excel (Microsoft Corporation, Version 2304 Build 16.0.16327.20200, 64-bit, Redmond, WA 98052-6399, USA). The areas were converted into fractions for each subbasin, which were then further combined with the other subbasins in one table. This table listed the Sub-IDs of each subbasin in one column, followed by the Sub-ID of the downstream subbasin (the one to which the subbasin flows). The downstream subbasin was identified in ArcGIS Pro by following the main river and streams flow direction. Furthermore, area [m^2], river length of the main river [m], main river wetland area [m^2] and depth [m], as well as elevation [m] and slope [°] were listed for each subbasin. Mean elevation was calculated from the DEM and mean slope with the slope function and zonal statistics in ArcGIS Pro. Fractions of SLC's were listed for each subbasin as well. This table was used as input data for the Geodata.txt input file (Appendix 1, 4.).

An info.txt input file is mandatory to set up for model options and simulation settings (Appendix 1, 1.). It gives information about the model run, output files and performance criteria settings. This study used the simulation period from 01-01-2010 to 31-12-2021, with a warm-up period of 1 year, as suggested by Lindström et al. 2010. Time series input data is with a daily time step and a wetland model, where wetlands are handled as classes with water regulation capabilities, is implemented. The wetland routine will be described in section 3.3. Output variables included computed and recorded outflow [m³], temperature [°C], precipitation [mm] and evaporation [mm], all given on a daily time step for each subbasin.

Model parameters are defined in the par.txt input file (Appendix 1, 2.). The parameters are either general for the whole simulation, indicated by a single value, or have a land use or soil type dependency, where several values are given in a row behind the parameter. Dependent parameters give a value for each land use or soil class defined in Geoclass.txt. Model parameters were chosen with the help of an example simulation provided by SMHI (Pers, 2011). General parameters include factors for potential evapotranspiration, river processes, temperature, groundwater, lakes, and snow. On the other hand, soil type dependent parameters contain recession coefficients for runoff, values for percolation capacity, frost depth, macro-pore flow, surface runoff and soil water. Five land use dependent parameters were used for snow melt, snow density, potential evapotranspiration, surface runoff and frost.

A set of observation input files are used for the HYPE simulation. Temperature and precipitation data are given as forcing data in Tobs.txt and Pobs.txt. The time period ranges from 01-01-2010 to 31-12-2021 and values are given on a daily time step. Temperature input data for this study was used from the close-by city of Lund and adjusted to each subbasins mean elevation (Equation (1), Appendix 2). Precipitation data was available from the weather station at Vombsjön. Temperature is used to calculate the potential evaporation (Equation (2), Appendix 2). Additionally, discharge observation data was downloaded from SMHI Vattenwebb for the measurement station in Ellinge, located in the outlet subbasin of the Bråån catchment. The observation data is presented in the model input file Qobs.txt, where sub-ID's and discharge data are coupled on a daily timescale for the simulation period.

3.3 Soil, Soil water, River, and Wetland routine in HYPE

HYPE uses different routines in its model setup, which incorporates the different parts of how water flows in the landscape well. Within its soil routine, each soil type can have a maximum of three soil layers with different depth (Appendix 1). Water retention parameters include wilting point, field capacity and effective porosity. These are soil type specific, and the model calculates water retention capacity based on these values. Initial soil water content is considered the sum of wilting point and field capacity. Tile drainage can be incorporated, but can also be neglected, if no drainage pipes are present. The maximum depth of drainage to the stream in the subbasin is set by the parameter stream depth. Local runoff does not include soil water below this depth. Surface runoff, runoff from the soil layers and runoff through the drainage pipes are the inputs for calculating local runoff for a SLC. Before the runoff reaches the main river, it passes through the local river of the subbasin.

HYPE includes evapotranspiration, groundwater runoff, runoff through drainage pipes, infiltration, and percolation in its soil water routine. To begin with, the model assumes that the upper two soil layers contribute to evapotranspiration (Equation (3), Appendix 2). A parameter for each soil type can be set to specify the decrease of potential evaporation with depth. The water available below the wilting point in the soil limits the actual evaporation. If soil water is greater than field capacity, evaporation occurs at a potential rate. A linear increase is assumed if soil water is above the wilting point, but lower than field capacity. The model sets soil evaporation to zero if the temperature is smaller than the threshold temperature. Next, groundwater runoff depends on the water available in the soil and the stream depth (Equation (4), Appendix 2). Field capacity, effective porosity, and a recession coefficient, which is assumed to decrease with depth, are key here. If the amount of soil water is above field capacity, runoff occurs. If it is below in a soil layer, it only depends on how much water there is in that specific layer. There is no groundwater runoff from soil layers below stream depth. Drainage pipes generate runoff if the water table is higher than the location of the pipes. Further, rain and snowmelt are added to calculate infiltration. Downward water flow occurs when water is above field capacity. However, a maximum percolation parameter between the soil layers must be set. If the soil is saturated due to the water table being high, surface runoff occurs (Equation (5), Appendix 2). Soil water is calculated in the following steps: first infiltration and percolation, then runoff and lastly evapotranspiration.

The model simulates wetlands either for nutrient retention or water regulation capability. The latter one was chosen in this study. Wetlands are considered a special land class with a class area and depth defined in the GeoClass.txt input file. The water volume of the wetland is the volume that is on top of the soil if it is over saturated. Otherwise, it is dried out. The wetland outflow is determined by a threshold parameter to keep water in the wetland, and this is set by default to minus the stream depth (Equation (6), Appendix 2). Stream depth is the height difference from soil surface to the local stream. It is set to zero for wetlands and cannot exceed the total soil profile depth. There can be both internal and outlet wetlands. Only internal wetlands were used in this analysis. Precipitation and evaporation are also calculated for the internal wetland area. Figure 5 shows that a fraction of local runoff from all land classes flows into the internal wetland and an internal wetland outflow flows into the local river. It is not stated how large the fraction of local runoff from all land classes is.

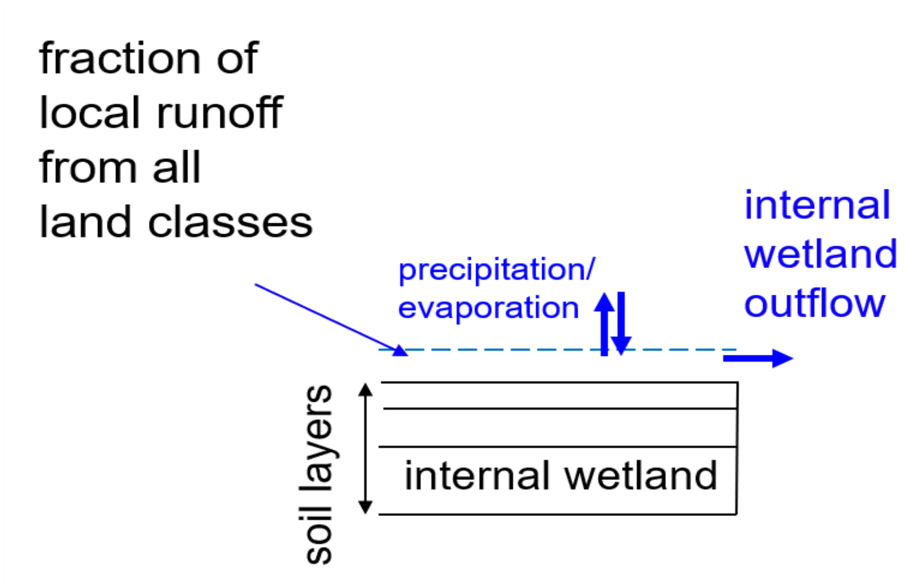

Figure 5. Water flows of internal wetland (SMHI, 2023a).

Rivers in a catchment are simulated as two types: local and main river. Each subbasin has one of each, even if there is no local stream present. The local river then represents a conceptual river that receives all runoff from land, whereas the main river receives the discharge from the upstream subbasins and the local river flow. The river length can be defined in the Geodata.txt input file, otherwise it is modeled as the square root of the subbasin area. To summarize, precipitation and evaporation are calculated first and then a fraction of the local runoff of a subbasin flows into e.g., an internal wetland, if present. It is not stated how large the fraction of local runoff is. After that the internal wetland outflow and the rest of the local runoff flow into the local river (Fig. 6), which, together with the inflow from upper subbasins, flows into the main river (Fig. 7). River velocity, dead water volume and a delay can be set in the model parameters.

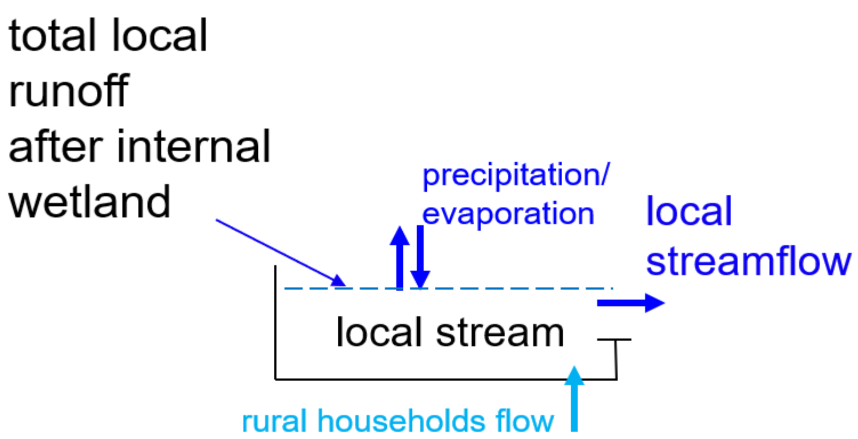

Figure 6. Water flows of the local river (SMHI, 2023a).

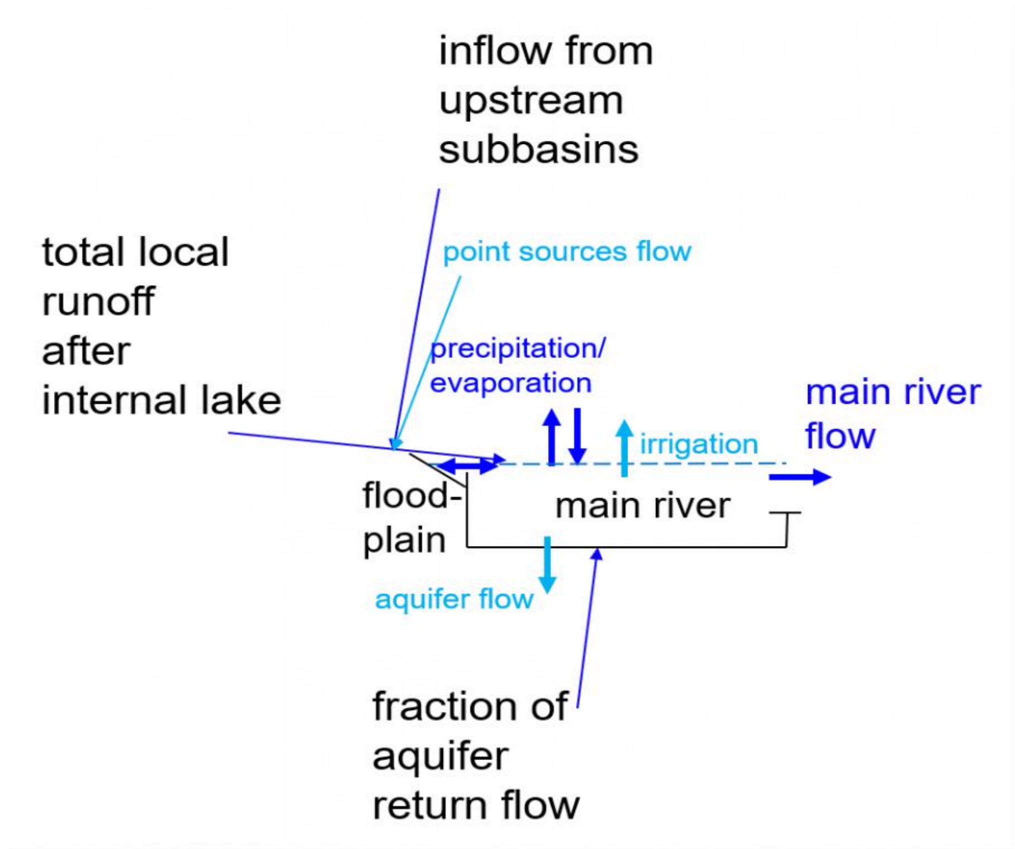

Figure 7. Water flows of the main river (SMHI, 2023a).

3.4 Wetland area analysis

Potential wetland area in the Bråån catchment was obtained from the wetland restoration analysis by Länsstyrelsen Skåne, 2019. Shapefiles for identified potential wetland areas were presented in a geodatabase and opened in ArcGIS Pro. The files were then clipped to the study area and each subbasin. A total of 33 wetlands were identified for the area, most of them situated in the upper part of the catchment, increasing the wetland area in the catchment by only 0.03% (Fig. 8). Total area of potential wetlands, as well as the fraction of agricultural or forest land for a wetland, was extracted to MS Excel. Due to there being two SLC's each for agricultural/urban/open land and forest, the wetland area for a subbasin was divided by two to equally split the wetland area among clay and till soils. SLC fractions were changed accordingly and the Geodata.txt input file was updated for the increased wetland scenario (Appendix 1, 4.).

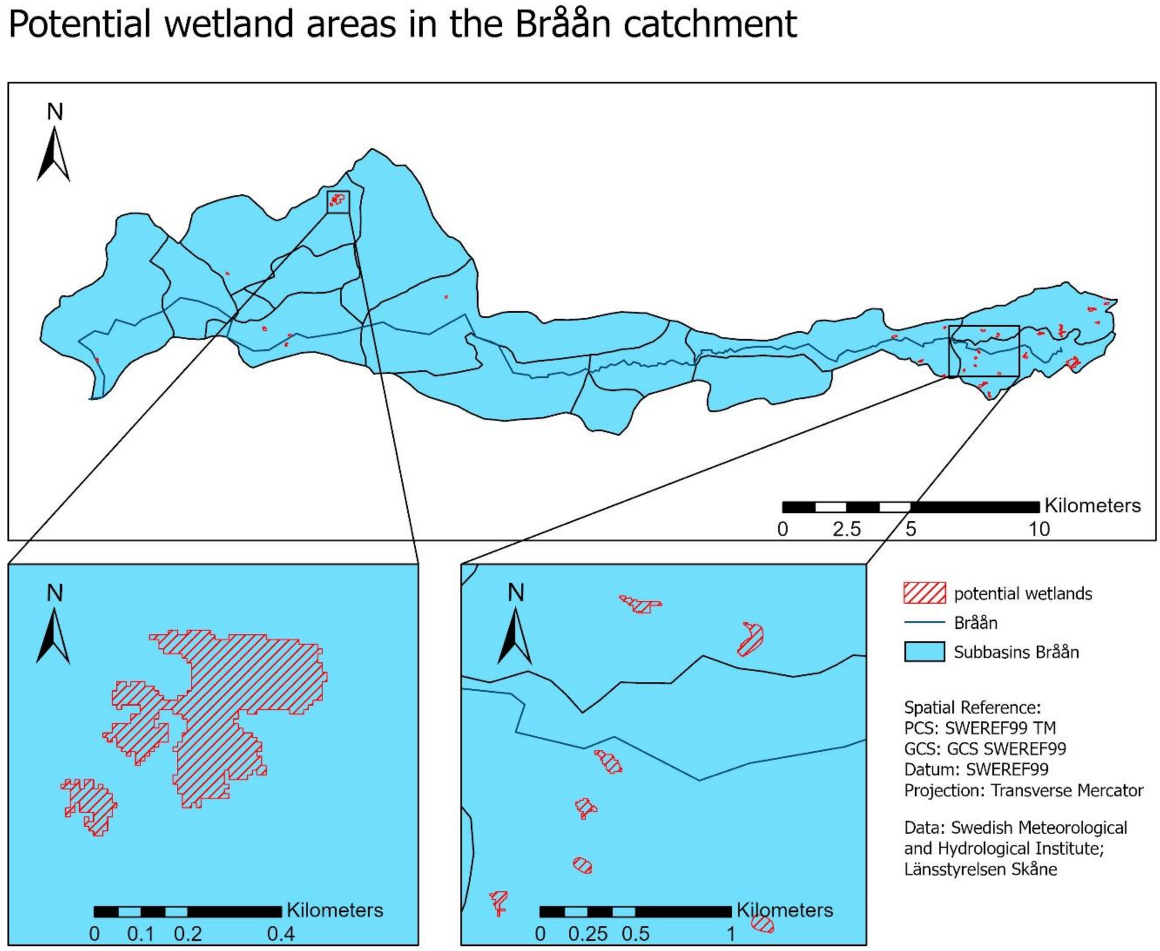

Figure 8. Potential wetland areas in the Bråån catchment.

3.5 Model evaluation

The HYPE model was evaluated by using Pearson's Coefficient of determination (R^2) and determining the goodness of fit between modeled and observed data at Ellinge, as well as between SMHI's S-HYPE model and the observation data. The measurement station at Ellinge is the only one along Bråån's water course. S-HYPE's fit is compared to HYPE's model fit. The data was also compared monthly, seasonally, and yearly. Bråån's water flow was visualized for 2019, due to this year performing best compared to the observation data from Ellinge (Figure 9 & Table 5). R^2 indicates the proportion of variance between the modeled and observed data (Hu, 2022). When R^2 =0, the model cannot match the observations at all. On the other hand, when R^2 =1, the model can simulate the observations 100%. A very good fit is achieved if $0.65<R^2\leq 1$, a good fit if $0.55 <R^2\leq 0.65$, a satisfactory fit if $0.40 <R^2\leq 0.55$ and an unsatisfactory fit if $R^2\leq 0.40$ (Scharffenberg, 2013).

4. Results

4.1 HYPE modeled discharge

Figure 9 shows Bråån's water flow in the outlet subbasin as a hydrograph for 2019. Four different scenarios are displayed: the actual wetland area conditions; a realistic wetland increase with already identified potential wetland areas; a scenario where 50% of the catchment is wetland; and a simulation with only wetlands in the whole catchment to test the sensitivity of the model. Actual wetland conditions show the highest water flow and largest peaks. A little lower flow can be observed for the realistic increase, followed by the 50% and eventually 100% wetland area scenario. The lowest flow and peaks clearly occur if the whole catchment were wetland. For this scenario, a flow of 0 m^3/s has been modeled in most parts of the year, even though there has been precipitation. An increase in wetland area shows lower peak flow and the recession limb has a gentler slope, i.e., discharge remains higher for a longer time until it returns to the base flow level. Lag time is similar for low and high wetland area in the catchment.

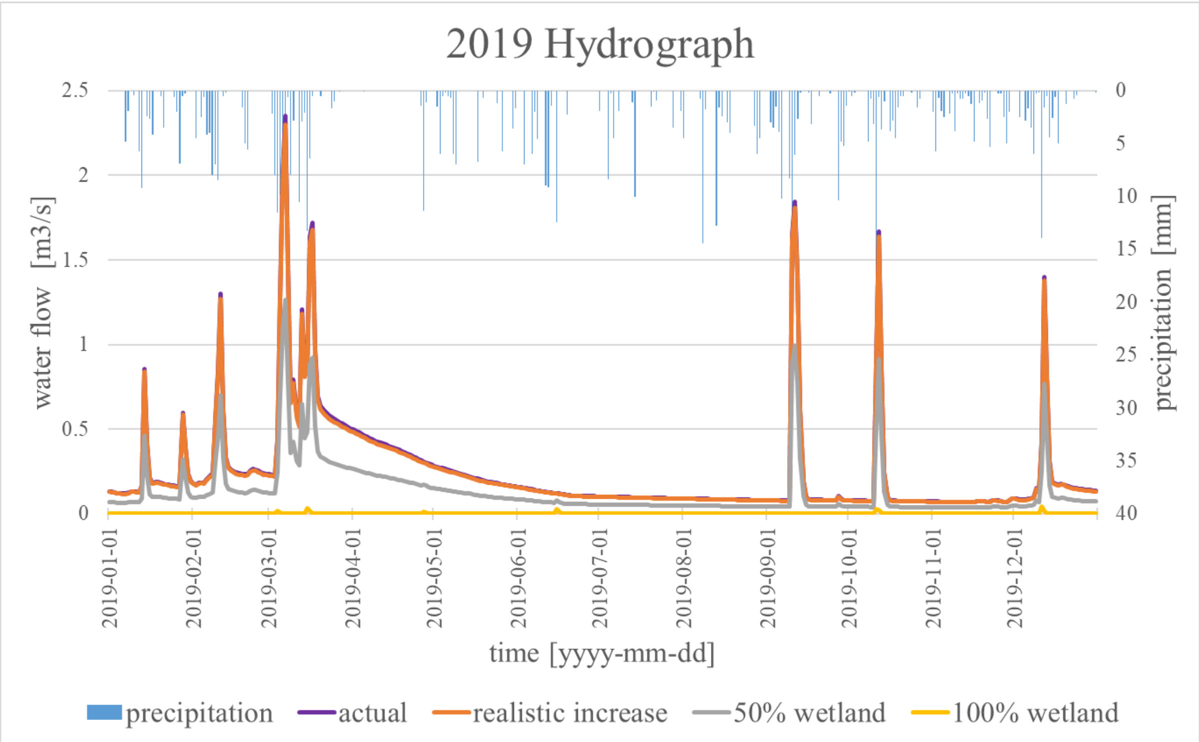

Figure 9. 2019 Hydrograph for the outlet subbasin of Bråån, showing 4 wetland area scenarios and precipitation.

Comparing the wetland scenarios with each other in Figure 10, the realistic restoration of wetland areas in the catchment results in a discharge decrease of 2%. By increasing the wetland area to 50% of the catchment area, discharge is reduced by 42%. The biggest decrease can be seen when simulating the whole catchment area as a wetland. The higher the wetland area, the lower the modeled river discharge. Figure 11 shows the calculated evaporation for the four different scenarios. Evaporation is higher for an increase in wetland area, especially from spring to autumn. During winter months evaporation is rather low for all scenarios.

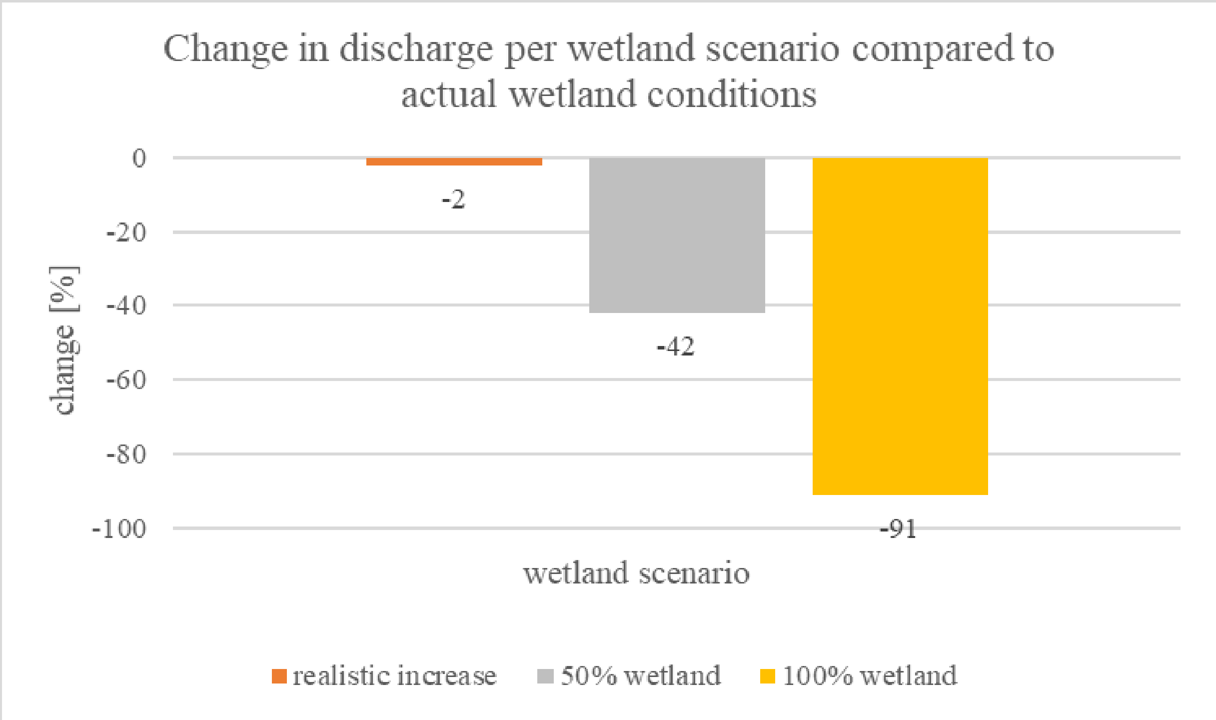

Figure 10. Percentage change in river discharge per wetland area scenario compared to actual wetland area conditions.

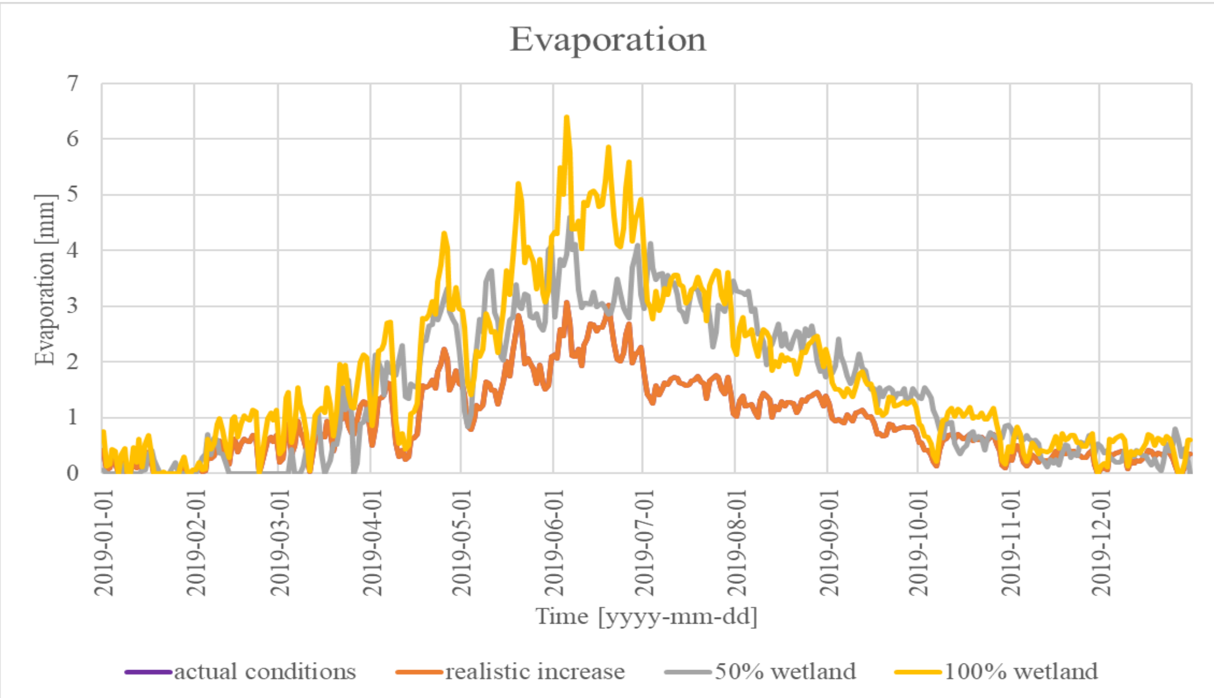

Figure 11. HYPE-modeled evaporation for the four different wetland scenarios.

4.2 Model evaluation

Figure 12 shows a hydrograph for the modeled HYPE flow with actual wetland conditions, SMHI's S-HYPE modeled flow and the observed flow at Ellinge for 2019. When comparing the flow, one can see that the modeled HYPE flow is a lot lower than the observation and S-HYPE data. However, it follows a similar trend.

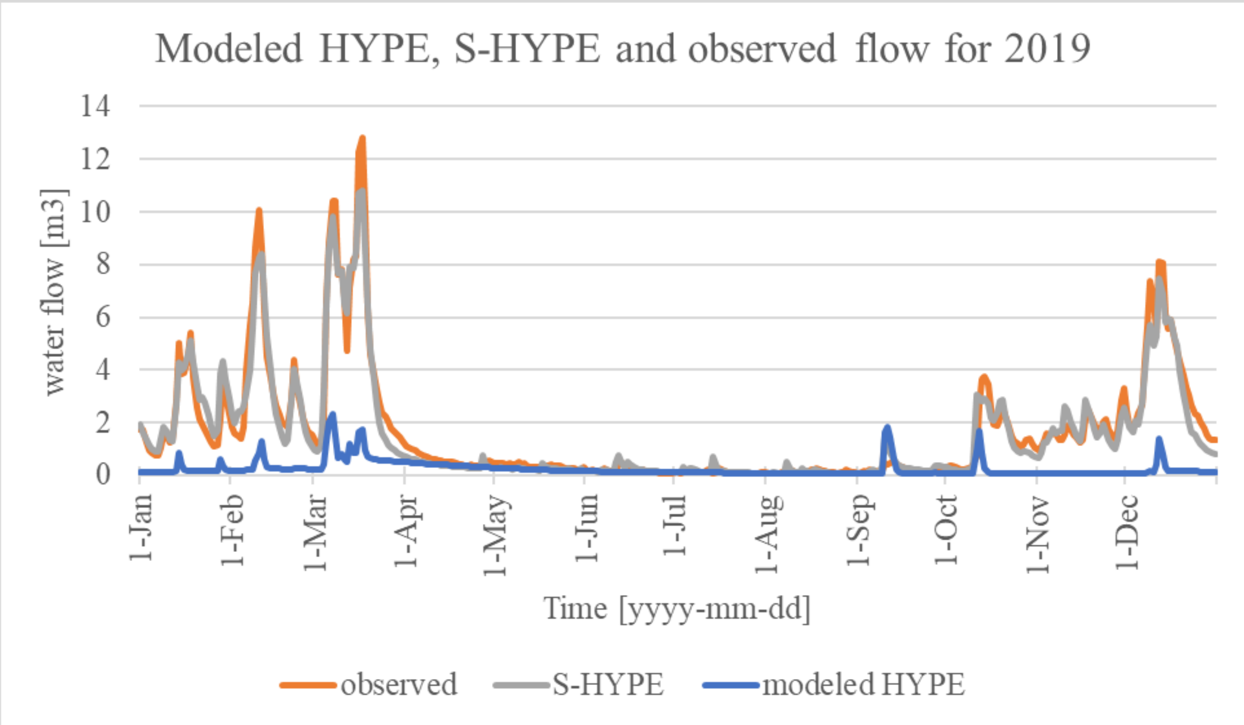

Figure 12. Hydrograph for observed, S-HYPE and modeled HYPE flow for 2019.

The modeled discharge for the simulation period of 2011-2021 results in a positive correlation with a very good fit (R^2=0.83) and reproduces the observations well. This high R^2-value is achieved because of the simulated lower flow in HYPE during large parts of the year, which fits well with the low flow from the observation data. The model especially underestimates higher observed values (Figure 13). A similar underestimation trend can be observed for the positive correlation between S-HYPE and the observation data, although the general fit is a little higher with almost R^2=0.90. There is less variation for the lower values with S-HYPE.

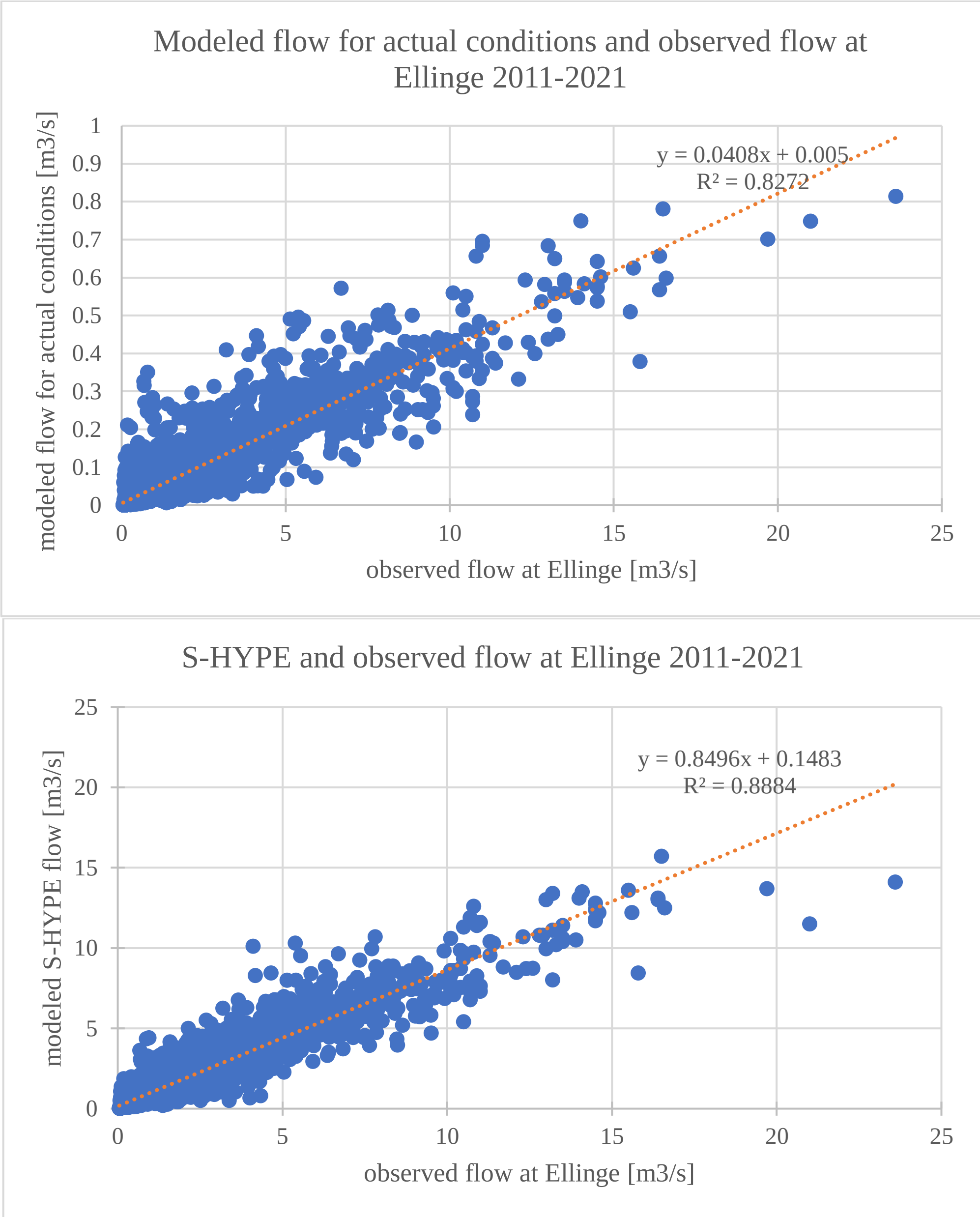

Figure 13. Correlation between modeled HYPE flow and observed flow at Ellinge 2011-2021 (upper figure) and correlation between S-HYPE and observed flow at Ellinge for 2011-2021 (lower figure). Modeled flow on the Y-axis ranges from 0 – 1.3 m^3/s for the upper figure and from 0 – 25 m^3/s for the lower figure.

A monthly comparison makes clear that the HYPE model works best from September to May, where R^2 is higher than 0.65 (Table 3). A satisfactory fit is achieved for July and August, and an unsatisfactory fit for June. S-HYPE follows this trend: except for June all months give a very good fit to the observed data. The best fit is achieved for October both for HYPE and S-HYPE. The seasonal comparison reflects the monthly fits (Table 4). The models work best in Spring, followed by Winter and Autumn. Summer gives an unsatisfactory fit for the HYPE model, with a lot of over- and underestimations of the observed values (Fig. 14). Even though it is the worst fit for S-HYPE, it still gives a very good fit.

Table 3. Monthly comparison of HYPE and S-HYPE model. Green indicates a very good fit, purple a satisfactory fit and red an unsatisfactory fit.

Month	**HYPE model R^2 -value**	**Rank**	**S-HYPE model R^2 -value**	**Rank**
1	0.8315	2	0.8516	4
2	0.7707	6	0.8335	5
3	0.7772	5	0.8645	2
4	0.7212	7	0.8219	7
5	0.6681	9	0.8001	8
6	0.1218	12	0.2611	12
7	0.5213	11	0.7021	10
8	0.543	10	0.7417	9
9	0.6707	8	0.8629	3
10	0.8473	1	0.9235	1
11	0.7893	4	0.8276	6
12	0.7971	3	0.6657	11

Table 4. Seasonal comparison of HYPE and S-HYPE model. Green indicates a very good fit and purple a satisfactory fit.

Season	**HYPE model R^2 -value**	**Rank**	**S-HYPE model R^2 -value**	**Rank**
Winter 12/1/2	0.7963	2	0.847	2
Spring 3/4/5	0.8058	1	0.8859	1
Summer 6/7/8	0.5423	4	0.7543	4
Autumn 9/10/11	0.7945	3	0.7892	3

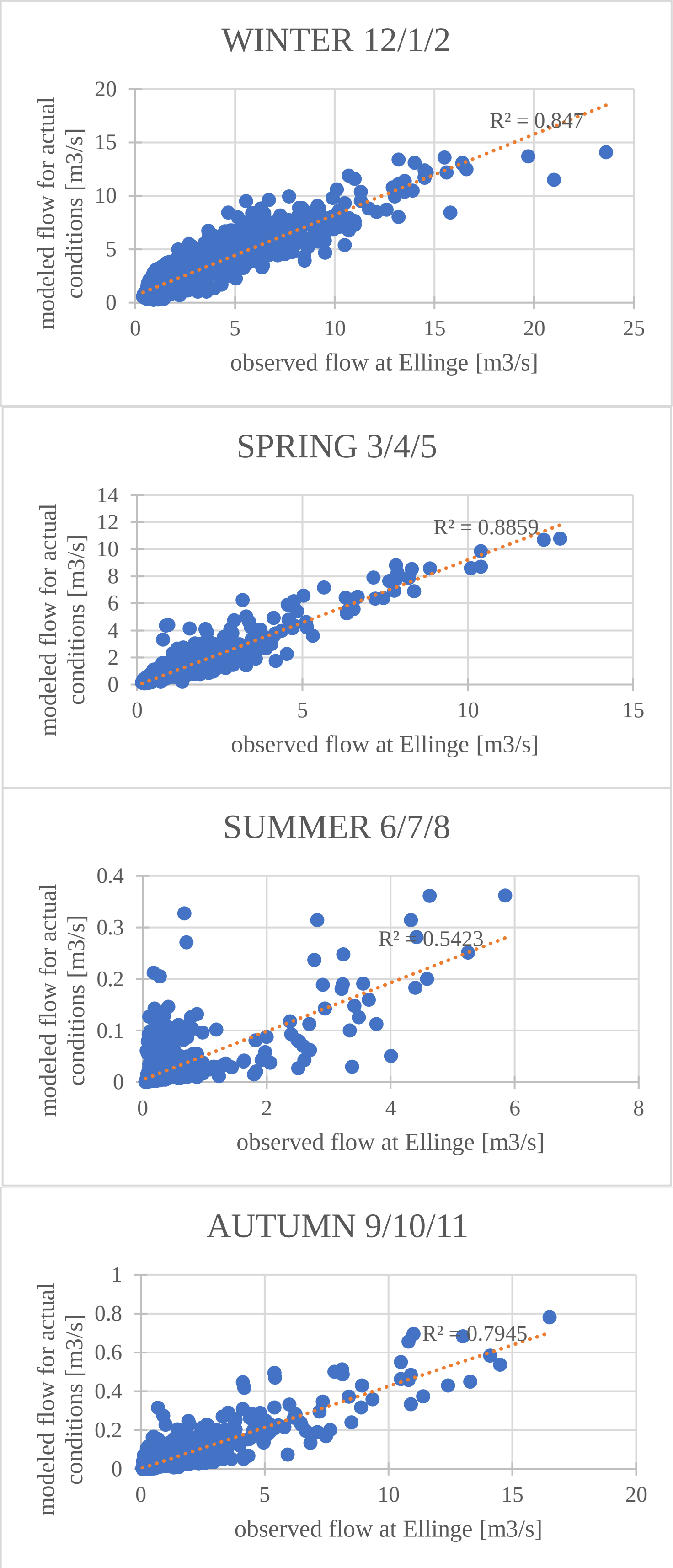

Figure 14. Seasonal comparison for the HYPE model results. Winter includes the months of December, January, and February; Spring includes March, April, May; Summer includes June, July, August; and Autumn includes September, November, December.

When comparing HYPE and S-HYPE model results on a yearly basis, 2018 gave the worst fit for both models, compared to all other years (Table 5). Nonetheless, it is still a very good fit. The best fit was achieved for 2019, where R^2 =0.90 and 0.96 for HYPE and S-HYPE. In general, the observed values are reproduced very well for all years, with a R^2-value greater than 0.65.

Table 5. Yearly comparison of HYPE and S-HYPE model.

Year	**HYPE model R^2 -value**	**Rank**	**S-HYPE model R^2 -value**	**Rank**
2011	0.809	8	0.8405	9
2012	0.8328	5	0.8692	6
2013	0.8231	6	0.9213	3
2014	0.8856	2	0.9209	4
2015	0.8712	3	0.845	8
2016	0.7716	9	0.8512	7
2017	0.8136	7	0.8813	5
2018	0.7369	11	0.8161	11
2019	0.9013	1	0.9572	1
2020	0.8656	4	0.9439	2
2021	0.7481	10	0.8181	10

5. Discussion

5.1 Discussion of results and model evaluation

The modeled discharge for actual wetland conditions was way lower than the observed data from the measurement station at Ellinge, because of the lack of accurate soil and land use parameters. A field study in the catchment area to measure soil and land use characteristics would have been of advantage to make parameters more precise. SMHI incorporates all routines very extensively into the S-HYPE model and therefore it gave a good fit to the observed values. It would have been an advantage to have access to the S-HYPE setup files to achieve a good model fit for this study. The lack of time and knowledge to explore the incorporation of more soil and land use parameters, as well as point sources, was a limitation to this study. Point sources such as the wastewater treatment plant in Ellinge could have been added to the model set up (VA Syd, 2023). Discharge was mainly simulated well for the spring, autumn and winter seasons. During the colder months of the year more water is maintained in the soil, as evapotranspiration is very low and soil gets saturated more easily (Cascone et al., 2019). The storage capacity of wetland areas is exceeded, and discharge can be observed. On the other hand, the simulated discharge for the summer was very low and sometimes reached zero. It was generally lower for the observations during the summer as well, however, it is never zero. The lower simulated values could be due to warmer temperatures and more net radiation leading to higher evaporation rates and more available storage from wetlands (Cascone et al., 2019). Another aspect could be that the groundwater flow was not incorporated properly into the simulation, causing a lower base flow and with that lower modeled discharge.

As expected, river discharge decreased with increasing wetland area. Two factors are most decisive: change in soil type and increase in evaporation rates. Wetlands are usually situated on peat soil which has a high mineral and organic matter content, with high field capacity and porosity. Peat can hold water in the soil for a longer time due to slow percolation and a positive change in storage occurs (O'Geen, 2013). Increasing wetland area would then mean increasing the amount of peat soil and decreasing other soil types, such as clay and silt soils in the catchment. In the HYPE model, this lowered the flow to the local stream and ultimately the main river flow. The second factor to consider is evapotranspiration. When looking at the water balance equation, the river discharge is influenced by precipitation, change in storage, runoff, and evapotranspiration (Villagra et al., 1995). More wetland areas on costs of forested and agricultural land, could lead to a reduction of turbulence in the air and with that to a lower rate of transpiration in those areas (Hollinger et al., 1994). However, evaporation has been found to be higher for a wetland, compared to surrounding agricultural land (Białowiec et al., 2014). Białowiec et al. (2014) describe the "oasis effect", where small-scale wetlands are influenced by a strong advection from the dry surrounding land, enhancing evaporation. Water surface area increases as well, contributing to higher evaporation rates. HYPE calculated higher evaporation values for an increase in wetland area, which is in line with the literature.

The model showed that warm and dry seasons and years, such as the summer season and the year of 2018, have a worse model performance than less warm and wetter years (e.g., 2017). Although 2014 had the same average annual temperature as 2018, this year received 105mm more rainfall than on average in the study area and resulted in a better model fit. It seems like the model did not perform as well if other factors such as evapotranspiration play a bigger role in the simulation, compared to e.g., received precipitation.

The results of this study showed that flood risk might be reduced with the restoration of more wetlands. If an increase in wetland area leads to a lower flow during the year, high rainfall events that could under normal conditions cause flooding, would then be buffered by the higher storage capacity available. There would be a smaller flood risk. During summer months, when evaporation is highest and most of the storage capacity of the wetlands is available, a high rainfall event would be buffered very well and river flow would not rise much. However, the 33 potential future wetlands in the catchment only had a small effect on river discharge, decreasing it by 2%. A higher wetland area would be more effective, as e.g., in the 50% wetland scenario, although it is questionable to what extent this big land use change could be pursued.

Even though the results of this study focus on percentual decrease in discharge overall, it would be interesting to do a more detailed analysis of the impact of wetlands on peak discharge timing and on certain areas of the catchment. In addition to the finding that peaks are slightly reduced in this study with the realistic wetland increase, peak discharge could also be delayed with increased wetland area. The water from the landscape takes a longer time to reach the river if it has to travel through a wetland first. This delay could slow down the flooding, and a flood event would not result in a steep increase and decrease, but rather show a gentler slope for the increasing and recession limb on a hydrograph. With that, the flood event would endure over a longer time frame, however, with a smaller maximum peak. Furthermore, the placement of wetlands plays a role in how they affect river discharge (Martinez-Martinez et al., 2014). Wetlands placed in upstream areas can reduce streamflow more than when placed in lower regions (Martinez-Martinez et al., 2014). In the Bråån catchment most future wetlands are placed in the upstream areas and some in the lower parts of the catchment. A placement of wetlands in downstream regions helps reduce downstream flooding (Ogawa & Male, 1986).

5.2 Land use and soil data, and model parameters

Land use and soil data contained a large number of classes which were grouped together into the most common land use and soil classes to simplify GIS and HYPE model classifications. The incorporation of many classes would result in a complicated soil – land use classification. This simplification could classify some land use and soils in the catchment area with more general class parameters. For example, SGU's soil data contained "silty clay soils", which were then classified as "clay". This neglects the specific silty property of this soil type. Simpler classifications from the original land use and soil data could make model results more accurate.

Another discussion point to mention is the parameter values chosen for the different land use and soil types. As already mentioned, a field trip to measure soil parameter values would have been of advantage to make the model more accurate. Parameters were obtained from literature and example files from SMHI's online available HYPE courses. For land use, agricultural, urban and open land had similar values in the land use dependent parameters. However, in reality they will probably differ in characteristics. Additionally, a sensitivity analysis with some of the field parameters would have provided the model with parameters closer to reality.

5.3 Suitability of study area

Further, the Bråån catchment was maybe not the most suitable to analyze an increase in wetland area, as currently only 0.01% of the catchment area are wetlands. Skåne's wetland analysis showed 33 potential areas in the catchment that could be restored as wetlands in the future (Länsstyrelsen Skåne, 2019). This increases the wetland area in the Bråån catchment only by 0.03%, which did not show a big difference in simulated discharge. Other catchments might be more suitable, such as the Kävlingeån catchment. Its current wetland area is larger and lies at around 2.5%. Additionally, more potential areas have been identified in Skåne's wetland analysis for the Kävlingeå catchment regarding future restoration. Bråån served as suitable for this study, as the incorporation of lakes within the Kävlingeå catchment requires more data on how those lakes are regulated.

5.4 Previous studies and future potential

Lund University's Faculty of Engineering, together with the Royal Institute of Technology in Stockholm, have started the Ecodiver research project (2020-2024) to create an easy-accessible decision support tool for stakeholders regarding future wetland restoration. The focus of Ecodiver is the hydrological function of wetlands, specifically, how they lead to the reduction of flood risk in a catchment area (Ecodiver, 2023). Previously, other studies have tried to incorporate land use change into modeling river discharge. Within the Ecodiver project, Huynh & Truong (2022) used the Soil and water assessment tool for QGIS (QSWAT+) to try to analyse future possibilities of adding wetlands in the Kävlingeå catchment area in Skåne. The QSWAT+ model was found to be a potential tool for analyzing effects of future wetland restoration; however, this model also shows uncertainties. Here, with the incorporation of lakes. Actual land use and simulated land use differed slightly, due to the model not being compatible with the Swedish land use data and the researchers having to use more general land use data, where land use classification was more general (Huynh & Truong, 2022). Another model that could be used is the HBV-N model. Most of the time it is used for modeling nitrogen-removal in catchment areas. Arheimer & Wittgren (2002) modeled nitrogen removal in potential wetlands in the Genevadsån catchment, Halland, Sweden. Their approach of reducing arable land on behalf of wetlands and treating wetlands as small lakes, could be applied to a discharge analysis as well. However, this requires more time and understanding of the HBV-N model. Additionally, Hu (2022) used the HEC-HMS model to simulate discharge in Kåvlingeån, but without considering a special land use class for wetlands. Similarly, Wicher (2016) modeled rainfall-runoff in the catchment area with HEC-HMS, not taking wetlands into account. These studies show that the incorporation of a future land use change into a hydrological model must be researched more to achieve a realistic model fit.

6. Conclusions

The aim of this thesis, to analyse the effect of wetland area increase on river discharge, has been based on an analysis of model results from the HYPE model. The modeled river discharge for the Bråån catchment between 2011-2021 shows a lower flow, compared to the current wetland conditions. It can be concluded that wetlands influence catchment characteristics and with that river discharge. The lower values indicate a reduction of flood risk. Factors such as the ability of peat soils to hold more water and higher evaporation led to a reduced discharge. Next, the modeled flow for actual conditions was lower and did not match the observed data well in quantitative measures. On the other hand, the trend was similar, which is why the correlation between modeled and observed values was still quite high. A comparison between the applied HYPE model and S-HYPE shows big differences in absolute numbers for modeled flow.

To better understand the influence of soil and land use characteristics, field measurements in the study area could be done. Most model parameters are based on soil or land use type, and this would increase the accuracy a lot. Other models, such as the HBV-N and QSWAT+ model, could be applied to test how wetlands are incorporated in their model routines. For now, these tools have not been explored enough for the purpose of this study. To conclude, only little research on the effect of land use change on river discharge and flooding can be found. Further research is needed to better understand what role wetlands play in our landscape, how we can benefit from them and what kind of effects the restoration plans of municipalities have on other parts of the landscape.

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8. Appendix

Appendix 1: Model input files

1. Info.txt file

!! Information about model run			
bdate 2010-01-01			
cdate 2011-01-01			
edate 2021-12-31			
readdaily Y			
riverflowmodel	0		
wetlandmodel	2		
!! Outputs			
basinoutput variable cout rout temp prec evap			
basinoutput allbasin			
basinoutput meanperiod 1			
basinoutput decimals 3			
mapoutput variable cout rout temp prec			
mapoutput meanperiod 5			
mapoutput decimals 3			
!! Criteria			
crit 1 criterium RR2			
crit 1 cvariable	cout		
crit 1 rvariable rout			
crit 1 weight	1		
crit meanperiod 1			
crit datalimit 3			

2. Par.txt file

lp	0.85				
ttmp	0.1	0.5	0.1	0.1	0.1
cmlt	3.75	2.5	3.75	3.75	3.75
cevp	0.175	0.19	0.19	0.19	0.19
cevpam	0.5				
cevpph	45				
rrcs1	0.3	0.05	0.3		
rrcs2	0.004	0.006	0.05		
rrcs3	0.0002				
trrcs	0.5	0.1	0.1		
srrcs	0.1 0.1 0.1 0.1 1				
mperc	5	20	30		
damp	0.01				
rivvel	1				
tcelevadd	0.6				
frost	2	2	2	2	2
sfrost	1	1	1		
macro1	0.15	0.3	0.3		
macro2	10	10	10		
macro3	0.85	0.85	0.85		
srrate	0.15	0.01	0.01		
rcgrw	0				
Qmean	200				
epotdist	3				
wcwp	0.05	0.1	0.2		
wcfc	0.35	0.22	0.8		
wcep	0.4	0.5	0.89		
gldepi	3				
gratp	2.7				
gratk	3.5				
cevpcorr	0	0.1			
snowdens0 0.2					
snowdensdt 0.0016					

3. Geoclass.txt file

!combination(SLC)	Landuse	Soil	cropid-main	cropid-2nd	vegetation-type	special-classes	tile-depth	drain-depth	#soil-layers	depth1	depth2	depth3
1	1	1	0	0	1	0	1	1.4	3	0.25	1	2
2	1	2	0	0	1	0	0	1.4	3	0.25	1	2
3	2	1	0	0	2	0	0	1.2	2	0.5	1.5	
4	2	2	0	0	2	0	0	1.2	2	0.5	1.5	
5	3	3	0	0	1	0	0	1.8	1	0.2		
6	4	3	0	0	3	13	0	0	1	0.5		
7	5	3	0	0	3	2	0	-2	1	1		

4. Geodata.txt files

ACTUAL CONDITIONS

AREA	SUBID	MAINDOWN	RIVLEN	ELEV_MEAN	SLOPE_MEAN	MRWET_AREA	MRWET_DEPTH	SLC_1	SLC2	SLC_3	SLC_4	SLC_5	SLC_6	SLC_7
9150000	34	37	0	174.2	1.21	906642.32	1	0.0203	0.3783	0.0570	0.4438	0.0000	0.0991	0.0015
9260000	35	37	9687	175.43	1.19	108640.41	1	0.0592	0.5137	0.0474	0.3662	0.0000	0.0117	0.0018
8540000	36	37	0	135.37	0.88	198426.42	1	0.0457	0.5282	0.0550	0.2588	0.0876	0.0232	0.0015
13360000	37	38	20885	151.08	0.89	14042.60	1	0.1056	0.8180	0.0014	0.0721	0.0009	0.0011	0.0011
7350000	38	40	8805	126.28	0.96	28940.18	1	0.0800	0.7769	0.0089	0.1283	0.0008	0.0039	0.0016
3790000	39	40	0	124.02	0.75	5751.88	1	0.0537	0.8738	0.0045	0.0653	0.0000	0.0015	0.0013
13420000	40	42	9601	117.91	1.27	19940.86	1	0.0248	0.9013	0.0244	0.0398	0.0000	0.0015	0.0082
17610000	41	42	0	91.63	0.91	11133.10	1	0.0683	0.8323	0.0098	0.0783	0.0047	0.0006	0.0067
5960000	43	45	0	79.9	1.38	11664.99	1	0.5097	0.3431	0.1130	0.0290	0.0000	0.0020	0.0032
16790000	44	45	0	84.58	0.97	2279.67	1	0.7424	0.0473	0.2019	0.0038	0.0000	0.0001	0.0046
25230000	42	46	9440	88.89	1.41	194478.61	1	0.5181	0.1355	0.3204	0.0157	0.0000	0.0077	0.0025
1400000	45	46	0	54.43	1.35	882.42	1	0.1228	0.7839	0.0093	0.0749	0.0000	0.0006	0.0084
11080000	46	47	11365	58.44	1.39	6556.74	1	0.8974	0.0226	0.0734	0.0056	0.0000	0.0006	0.0004
7550000	47	49	5461	54.57	1.81	84205.65	1	0.5765	0.3478	0.0251	0.0315	0.0011	0.0112	0.0070
19540000	49	99	12648	44.7	1.28	67938.08	1	0.5515	0.2703	0.0651	0.0995	0.0020	0.0035	0.0085

REALISTIC WETLAND INCREASE

AREA	SUBID	MAINDOWN	RIVLEN	ELEV_MEAN	SLOPE_MEAN	MRWET_AREA	MRWET_DEPTH	SLC_1	SLC2	SLC_3	SLC_4	SLC_5	SLC_6	SLC_7
9150000	34	37	0	174.2	1.21	1845465.35	1	0.0094	0.3079	0.0464	0.4331	0.0000	0.2017	0.0015
9260000	35	37	9687	175.43	1.19	2231817.97	1	0.0527	0.3448	0.0204	0.3393	0.0000	0.2410	0.0018
8540000	36	37	0	135.37	0.88	198426.42	1	0.0457	0.5282	0.0550	0.2588	0.0876	0.0232	0.0015
13360000	37	38	20885	151.08	0.89	363109.72	1	0.0975	0.8099	0.0007	0.0629	0.0009	0.0272	0.0011
7350000	38	40	8805	126.28	0.96	28940.18	1	0.0800	0.7769	0.0089	0.1283	0.0008	0.0039	0.0016
3790000	39	40	0	124.02	0.75	5751.88	1	0.0537	0.8738	0.0045	0.0653	0.0000	0.0015	0.0013
13420000	40	42	9601	117.91	1.27	19940.86	1	0.0248	0.9013	0.0244	0.0398	0.0000	0.0015	0.0082
17610000	41	42	0	91.63	0.91	11133.10	1	0.0683	0.8323	0.0098	0.0783	0.0047	0.0006	0.0067
5960000	43	45	0	79.9	1.38	11664.99	1	0.5097	0.3431	0.1130	0.0290	0.0000	0.0020	0.0032
16790000	44	45	0	84.58	0.97	1045050.17	1	0.7135	0.0185	0.1997	0.0016	0.0000	0.0622	0.0046
25230000	42	46	9440	88.89	1.41	261349.88	1	0.5172	0.1351	0.3200	0.0153	0.0000	0.0104	0.0025
1400000	45	46	0	54.43	1.35	882.42	1	0.1228	0.7839	0.0093	0.0749	0.0000	0.0006	0.0084
11080000	46	47	11365	58.44	1.39	352556.74	1	0.8866	0.0118	0.0686	0.0008	0.0000	0.0318	0.0004
7550000	47	49	5461	54.57	1.81	84205.65	1	0.5765	0.3478	0.0251	0.0315	0.0011	0.0112	0.0070
19540000	49	99	12648	44.7	1.28	151938.08	1	0.5515	0.2703	0.0629	0.0973	0.0020	0.0078	0.0085

50% WETLAND

AREA	SUBID	MAINDOWN	RIVLEN	ELEV_MEAN	SLOPE_MEAN	MRWET_AREA	MRWET_DEPTH	SLC_1	SLC2	SLC_3	SLC_4	SLC_5	SLC_6	SLC_7
9150000	34	37	0	174.2	1.21	4575000.00	1	0.0051	0.1693	0.0255	0.2382	0.0000	0.5000	0.0008
9260000	35	37	9687	175.43	1.19	4630000.00	1	0.0290	0.1896	0.0112	0.1866	0.0000	0.5000	0.0010
8540000	36	37	0	135.37	0.88	4270000.00	1	0.0251	0.2905	0.0303	0.1423	0.0482	0.5000	0.0008
13360000	37	38	20885	151.08	0.89	6680000.00	1	0.0536	0.4455	0.0004	0.0346	0.0005	0.5000	0.0006
7350000	38	40	8805	126.28	0.96	3675000.00	1	0.0440	0.4273	0.0049	0.0705	0.0004	0.5000	0.0009
3790000	39	40	0	124.02	0.75	1895000.00	1	0.0295	0.4806	0.0025	0.0359	0.0000	0.5000	0.0007
13420000	40	42	9601	117.91	1.27	6710000.00	1	0.0136	0.4957	0.0134	0.0219	0.0000	0.5000	0.0045
17610000	41	42	0	91.63	0.91	8805000.00	1	0.0376	0.4578	0.0054	0.0430	0.0026	0.5000	0.0037
5960000	43	45	0	79.9	1.38	2980000.00	1	0.2804	0.1887	0.0621	0.0160	0.0000	0.5000	0.0018
16790000	44	45	0	84.58	0.97	8395000.00	1	0.3924	0.0102	0.1098	0.0009	0.0000	0.5000	0.0025
25230000	42	46	9440	88.89	1.41	12615000.00	1	0.2845	0.0743	0.1760	0.0084	0.0000	0.5000	0.0014
1400000	45	46	0	54.43	1.35	700000.00	1	0.0675	0.4312	0.0051	0.0412	0.0000	0.5000	0.0046
11080000	46	47	11365	58.44	1.39	5540000.00	1	0.4877	0.0065	0.0377	0.0004	0.0000	0.5000	0.0002
7550000	47	49	5461	54.57	1.81	3775000.00	1	0.3171	0.1913	0.0138	0.0173	0.0006	0.5000	0.0039
19540000	49	99	12648	44.7	1.28	9770000.00	1	0.3033	0.1487	0.0346	0.0535	0.0011	0.5000	0.0047

100% WETLAND

AREA	SUBID	MAINDOWN	RIVLEN	ELEV_MEAN	SLOPE_MEAN	MRWET_AREA	MRWET_DEPTH	SLC_1	SLC2	SLC_3	SLC_4	SLC_5	SLC_6	SLC_7
9150000	34	37	0	174.2	1.21	9150000.00	1	0	0	0	0	0	1	0
9260000	35	37	9687.4	175.43	1.19	9260000.00	1	0	0	0	0	0	1	0
8540000	36	37	0	135.37	0.88	8540000.00	1	0	0	0	0	0	1	0
13360000	37	38	20885	151.08	0.89	13360000.00	1	0	0	0	0	0	1	0
7350000	38	40	8804.9	126.28	0.96	7350000.00	1	0	0	0	0	0	1	0
3790000	39	40	0	124.02	0.75	3790000.00	1	0	0	0	0	0	1	0
13420000	40	42	9600.5	117.91	1.27	13420000.00	1	0	0	0	0	0	1	0
17610000	41	42	0	91.63	0.91	17610000.00	1	0	0	0	0	0	1	0
5960000	43	45	0	79.9	1.38	5960000.00	1	0	0	0	0	0	1	0
16790000	44	45	0	84.58	0.97	16790000.00	1	0	0	0	0	0	1	0
25230000	42	46	9439.6	88.89	1.41	25230000.00	1	0	0	0	0	0	1	0
1400000	45	46	0	54.43	1.35	1400000.00	1	0	0	0	0	0	1	0
11080000	46	47	11365	58.44	1.39	11080000.00	1	0	0	0	0	0	1	0
7550000	47	49	5461.4	54.57	1.81	7550000.00	1	0	0	0	0	0	1	0
19540000	49	99	12648	44.7	1.28	19540000.00	1	0	0	0	0	0	1	0

Appendix 2: HYPE model equations

Equations

(1)

$$T_{gc} = T_i + \frac{tcelevadd * elev}{100}$$

with $\mathrm{T_{gc}}$ = corrected Temperature

$\mathrm{T_i}$ = initial Temperature

tcelevadd = adjustment parameter (°C/100m)

elev = elevation

(2)

$$cseason = 1 + cevpam * sin\frac{2 * \pi * (dayno - cevpph)}{365}$$

$$epot_{base} = (cevp * cseason) * (T - ttmp)$$

$$epot = epot_{base} * (1 + cevpcorr)$$

with cseason=seasonal adjustment factor

cevpam=amplitude of sinus function that corrects potential evapotranspiration

dayno=day number

cevpph=phase of sinus function that corrects potential evapotranspiration

epotbase=basic potential evapotranspiration

cevp=potential evaporation rate

T=temperature

ttmp=threshold temperature

cevpcorr=regional correction factor

(3)

$$epot1 = EXP(-\frac{epotdist * soillayerdepth(1)}{2})$$

$$epot2 = EXP(-epotdist * (soillayerdepth(1) + \left(\frac{soillayerdepth(2) - soillayerdepth(1)}{2}\right))$$

$$area1 = soillayerdepth(1) * epot1$$

$$area2 = \left(soillayerdepth(2) - soillayerdepth(1)\right) * epot2$$

$$epotfrac1 = \frac{area1}{area1 + area2}$$

$$epotfrac2 = \frac{area2}{area1 + area2}$$

with epot1,2=potential evaporation
epotdist=parameter defining decrease with depth
soillayerdepth (1), (2) = depth of soil layer 1 and 2
area1,2= estimated area of each soil layer
epotfrac1,2= fraction of potential evaporation between the two layers

(4)

$$runoff(k) = \begin{cases} rc(k) * \left(soil(k) - wp(k) - fc(k)\right) & wp(k) + fc(k) < soil(k) < wp(k) + fc(k) + ep(k) \\ 0 & soil(k) < wp(k) + fc(k) \end{cases}$$

with runoff=groundwater runoff
k=soil layer
rc=recession coefficient
soil=soil moisture
wp=wilting point
fc=field capacity

(5)

$$srrcs = srrcs * (1 + rrcscorr)$$
$$q = MAX(srrcs * \left(soil(1) - wp(1) - fc(1) - ep(1)\right), 0.)$$

with srrcs=land use parameter
rrcscorr=correction factor
q=surface runoff
soil=soil moisture
wp=wilting point
fc=field capacity
ep=effective porosity

(6)

$$outflow = k * (w - w0)^p$$

with outflow=wetland outflow
k=soil layer
w=depth
w0=threshold for outflow