The Danish Meteorological Institute

DMI Report 21-29 Vejle Pilot Project Hydrological Modelling

Final scientific report of the 2020 National Centre for Climate Research Work Package 2.3.1, Flooding (Oversvømmelse)

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By Michael Butts

The Danish Meteorological Institute

Colophon

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Author(s)	Michael Butts
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Content

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1 Abstract

In our future climate, better flood forecasts and warnings are required. Flooding from extreme rainfall is a significant problem in Denmark both in urban and rural areas. Under our future climate, flood events will be larger and more frequent. Timely flood warning enables both emergency services and public authorities, as well as individual citizens, to better cope and manage the risks from flooding, especially the larger events. It is therefore important to develop a better understanding of where, why and how flooding will occur. This is the main motivation behind the pilot study in Vejle. In this first phase, our goal is to develop a hydrological model of the Vejle (Å) River/ Grejs (Å) River catchments, which will serve as a platform or a testbed, for our future investigations.

Timely and reliable flood warning relies on rainfall data and rainfall forecasts from numerical weather models, which are inherently uncertain. There is an important knowledge gap concerning the appropriate spatial and temporal resolution required to obtain effective flood forecasting and warning. As a starting point, a hydrological model will enable us to investigate the value and utility of DMI's high-resolution radar and numerical weather model data for forecasting floods.

Flooding arises from storm surges, extreme sea levels, heavy rainfall and cloudbursts. Vejle's coastal location on Vejle Fjord at the end of a deep glacial valley makes the township particularly vulnerable to extreme rainfall and rising sea water levels. Flooding occurs from the sea via Vejle Fjord, and from heavy rainfall through Vejle River, and Grejs River, and potentially from a combination of these. Vejle is a microcosm that experiences the different types of flood events found in many parts of Denmark, making it an ideal testbed.

A highly spatially detailed hydrological model has now been established (formulated, calibrated and validated) for the Vejle River and Grejs River catchments. The data used in the model, is available at the national level, so that the same modelling approach can be applied across Denmark. Comparison of the model simulations with measurements of discharge on both Vejle River (Haraldskær) and Grejs River (Planteskolen) demonstrate that this model is able to capture the behavior of historical floods and is therefore a suitable platform for our future research activities. In the next phase, we will evaluate how DMI's new high-resolution radar and weather model data could improve flood forecasts if they were used during major historical flood events.

2 Resumé

Fremtidens klima kræver bedre varsling af oversvømmelser. Oversvømmelser grundet regn er et stort problem i Danmark, både i større byer og på landet. I fremtiden forventes klimaforandringer at medføre flere og større oversvømmelser. Rettidig varsling gør både myndighederne (og den enkelte borger) bedre i stand til at håndtere især store oversvømmelser. Derfor er det vigtigt, at blive klogere på hvor, hvorfor og hvordan oversvømmelser rammer. Det er hovedformålet med pilotstudiet i Vejle. I denne første fase udvikles en hydrologisk model for Vejle Å/Grejs Å som platform, en slags "legeplads" for disse undersøgelser.

Pålidelig og rettidig varsling af oversvømmelser er stærkt afhængig af nedbørsdata og prognoser fra numeriske vejrudsigtsmodeller. Vi ved, at disse i sagens natur er usikre. Vi mangler især viden om de relevante rumlige og tidsmæssige opløsninger for at opnå effektiv oversvømmelsesprognoser og varsling. Udgangspunktet er udvikling af en hydrologisk model af Vejle Å/Grejs Å opland, som platform til vores undersøgelser af værdien og brugbarheden af DMI's højopløselige radar og modeldata til oversvømmelsesprognoser.

Oversvømmelser kommer fra stormflod, ekstrem havvandstand, kraftig regn og skybrud. Vejles placering for enden af ådalen og ud mod havet gør byen særlig sårbar overfor ekstrem nedbør og stigende havvand. Oversvømmelser opstår fra Vejle Fjord, Vejle Å, og Grejs Å, og i nogle tilfælde i kombination. Vejle er et mikrokosmos, der oplever det fulde udvalg af oversvømmelsestyper, som ses i resten af Danmark. Det gør Vejle til et ideelt teststed.

En meget detaljeret hydrologisk model er nu etableret (formuleret, kalibreret og valideret) for Vejle Å og Grejs Å, som vil danne grundlaget for vores planlagte forskning omkring oversvømmelser og varsling. Dataene, der blev brugt til modellen, er offentlig tilgængelig på landsplan, så en lignende modelformulering kan anvendes på tværs af Danmark. En sammenligning med målinger fra både Vejle Å (Haraldskær) og Grejs Å (Planteskolen) viser, at modellen kan gengive de historiske oversvømmelser og dermed er velegnet til vores fremtidige forskningsarbejde. I den næste fase vil vi evaluere hvordan DMI's nye, højopløselige radar og model data vil har kunne forbedre oversvømmelsesprognoserne, hvis de havde være anvendt i de store historiske oversvømmelser.

3 Introduction

The Danish National Centre for Climate Research (Nationalt Center for Klimaforskning, NCKF) has completed its first year in 2020. It has been a source of funding for the Danish Meteorological Institute and collaborators for climate change related research during this year. The 18 work packages fall under 4 general themes:

1. Arctic and Antarctic Research
2. Climate change in the near future
3. Use of climate data
4. Support for the IPCC

This research is carried out under theme 2, Climate change in the near future. The motivation is that there is no single solution to the challenges of climate adaptation. The environmental costs of traditional structural measures and the need for sustainable development have led to a shift from traditional engineering (grey infrastructure) to nature-based solutions (green infrastructure) and non-structural measures, e.g. flood forecasting.

There are physical and economic limits to the level of risk that flood protection structures can provide. Therefore, when a structure is built to protect against, for example, the 1 in 50-year flood, there still remains a risk for larger events but less likely events. This is called the “residual” risk. Forecast and early warning systems provide an environmentally friendly option that supports green infrastructure solutions and one of the few options for managing the “residual” risk.

3.1 Background and Objectives

Flooding from extreme rainfall and the large socio-economic costs associated with these events is an important problem in Denmark. Climate change is expected to lead to more and larger floods. One of the key challenges during flood events in Denmark is to forecast accurately, the location and extent of flooding to deploy emergency staff and resources when and where they are needed.

At the same time, there are a number of unanswered operational and research questions related to the application of hydrological modelling to hydro-meteorological forecasting. These include questions related to the appropriate spatial and temporal scales [1] [2] as well as the impact of model structure [3] [4] . As DMI develops more advanced ensemble NWP forecasts at higher spatial resolution, it is important to understand how the increasing spatial resolution and using ensemble weather forecasts can improve flood forecasting. More generally, we want to develop new knowledge on the value, of high-resolution precipitation information from DMI’s NWP models and of improving the spatial and temporal resolution of weather and hydrological forecasts.

To investigate these questions, in relation to flood forecasting & warning in Denmark, our initial goal is to establish a pilot study area that is representative of other flood vulnerable areas in Denmark. This pilot will be used as a platform for our future research into both the uncertainties in hydro-meteorological modelling at the local scale, user needs and the integration of uncertainties and risk assessment in decision-making at the local scale.

The main types of flooding experienced in Denmark occur under the following hydrological and meteorological conditions: storm surges and extreme tides, long-term heavy rainfall events, snow melt in the river catchment and short-term, intense rainfall or cloudbursts that are particularly damaging in urban areas. The Vejle River/Grejs River/Vejle Fjord system is relevant here because it is subject to flooding from all three flooding mechanisms (cloud bursts, long periods with heavy precipitation and high sea water levels).

The first steps of this investigation are:

• Collection of flood and hydrological data, including recent flood events for the Vejle pilot area and their causes
• Formulation of an initial hydrological model Vejle River/Grejs River based on historical rainfall as a platform

4 Pilot area – Vejle River/Grejs River

The main river, Vejle (Å) River, is approximately 36 km long, emerging in the Engelsholm lake and running south before turning north and east, Figure 1. The main river valley becomes the Vejle Fjord. The main valley is a glacial valley (Danish: tunneldal), also called a glacial trough, stream valley with a distinctive U-shaped or catenary cross section. Glaciated valleys are formed when a glacier travels across and down a slope, carving the valley through scouring. Grejs (Å) River is approximately 22 km long and emerges from the Fårup Lake and flows along another glacial valley. In the township of Vejle, the Grejs River splits into two branches, Omløbs Å and Mølle Å. These two branches flow either side of the centre of Vejle before draining into the Vejle River.

The Vejle River flows therefore through a deep valley, with steep tributaries, see Figure 1. For example, the Grejs River emerges from the surrounding moraine plateau. This means that the tributaries, particularly Grejs River respond rapidly to heavy rainfall. Flooding can occur in Grejs River close to the town of Vejle within a few hours of heavy rainfall, while it may take 12-24 hours before heavy rainfall in the upper part of the Vejle River valley results in flooding in Vejle. Another important consequence of the this deep glacial valley is that the Vejle River drains ground water from neighbouring catchments further west, i.e., the groundwater catchment is larger than the surface water catchment.

Figure 1 The river network and measurement stations. Source: Image from http://www.hydrometri.dk/kommune/vejle/. Used with permission.

4.1 Historical flooding

As part of Danmark's obligations under the EU Floods Directive, Vejle has been identified as one of 14 most important areas in Denmark with significant risks and vulnerability to flooding, Figure 2.

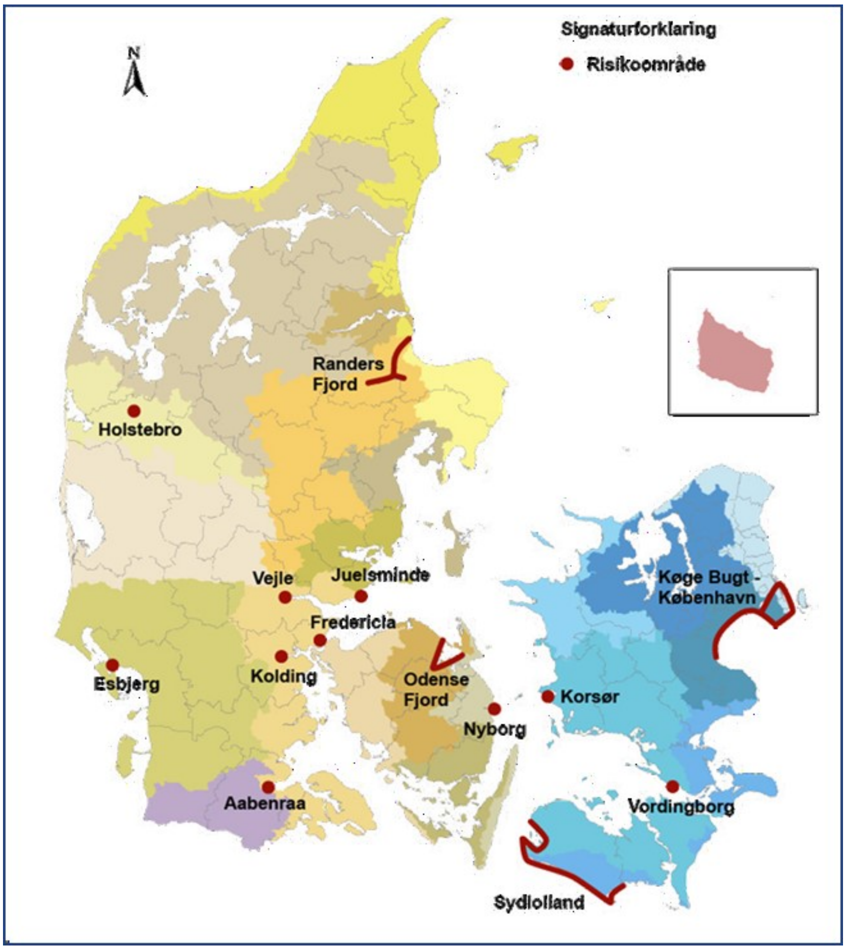

Figure 2 Flood risk areas in Denmark identified for the EU Flood Directive by the Danish Coastal Authority. Source: Kyst.dk, Kystdirektoratet, Miljø- og Fødevareministeriet). https://oversvommelse.kyst.dk/. Used with permission.

Flooding can occur from either short, intense local rainfall or cloudbursts, extreme rainfall over longer periods or extreme sea levels/storm surges. Over the last 10 years, Vejle has experienced more than 10 significant flooding events, encompassing three flood types, Table 1.

More recently, the Vejle River was one of many rivers and streams in Jutland affected by flooding during February 2020, Figure 3.

Table 1 Historical flooding events in Vejle

Date	Flood type
1-2. Nov. 2006[1]	Storm surge, 1,68 m in the fjord
20. Jan. 2007[1]	Extreme rainfall, 9,7 m^3/s
1. Mar. 2008[1]	Extreme rainfall, 5,8 m^3/s
6. Dec. 2013[1]	Storm surge, 1,52 m in the fjord
23. May. 2014[1]	Cloudburst, 8 m^3/s
6- May. 2015[1]	Cloudburst, 8 m^3/s
4 Sep. 2015[1]	Extreme rainfall, 14 m^3/s
26-27 Dec. 2015[1]	Extreme rainfall 11 m^3/s
25. Jul. 2016[1]	Cloudburst 8 m^3/s
26. Dec. 2016[1]	High water levels 1,24 m, in the fjord
4-5. Jan. 2017[1]	High water levels, 1,30 m, in the fjord
9. Jun. 2017[1]	Cloudburst x2
19. Feb. 2019[2]	Extreme rainfall
17. Mar. 2019[2]	Extreme rainfall

[1] Vand i Vejle by Ulla P Geertsen Vejle kommune [http://www.vandibyer.dk/media/1770/ulla-pia-geertsen-vejle-kommune_ny.pdf

[2] pers comm. Paul Landsfeldt, Vejle Kommune

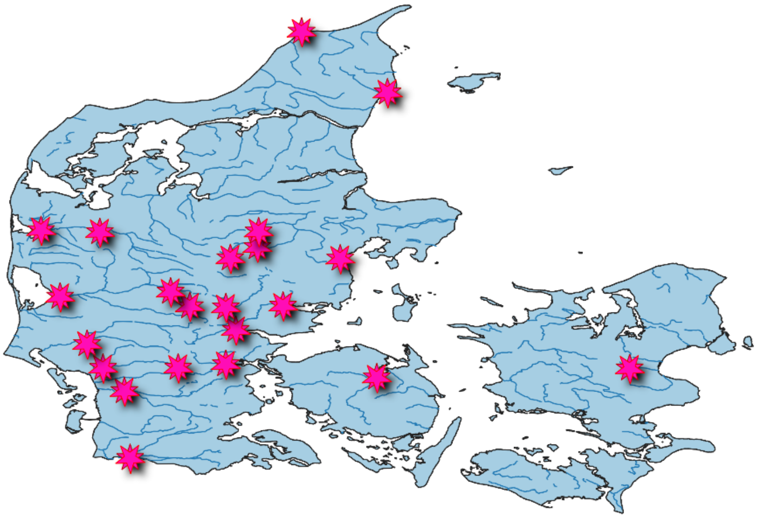

Figure 3 The reported locations of flooding in Denmark during February 2020. Locations are indicative as reported in: Politiken "Forandret klima byder på endnu mere vand", 26 February 2020.

4.2 Hydrological and Meteorological data

Figure 4 shows the location of the gauging stations along the river and in the harbour as well as the SVK (Spildevandskomiteens) automatic rain gauges in the catchment area. Key information regarding the station data collected for the initial hydrological modelling are listed in Table 2.

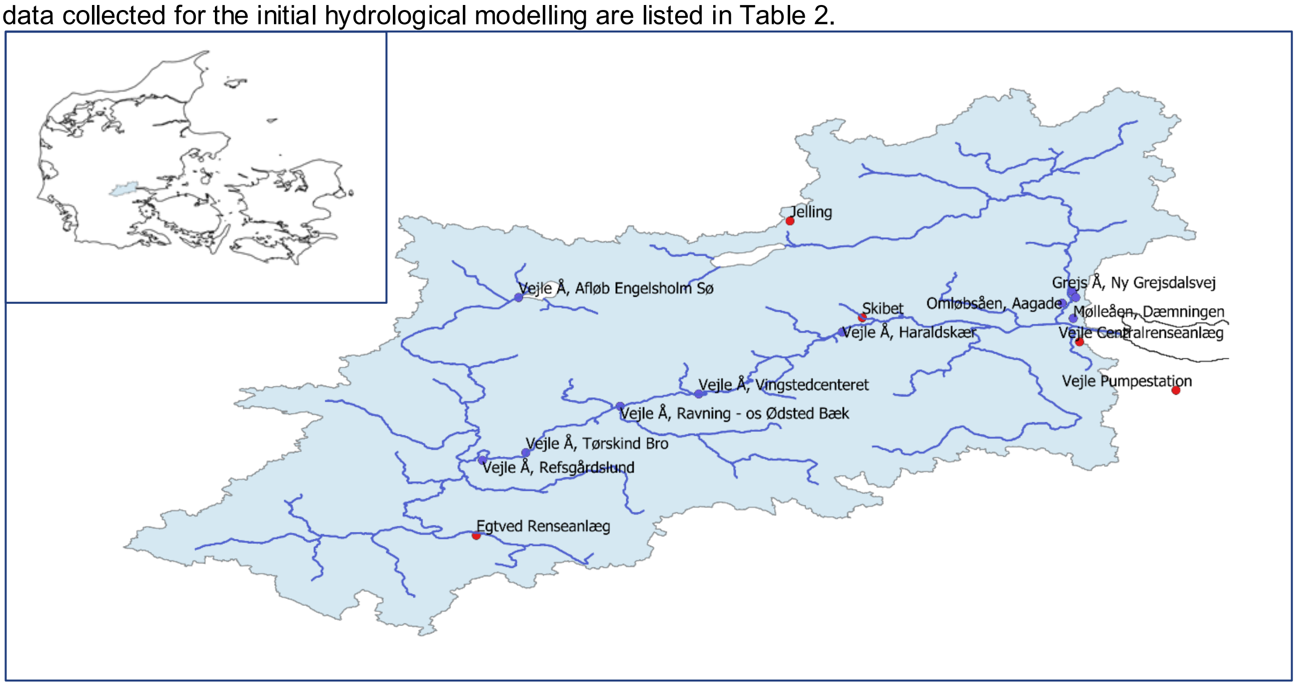

Figure 4 Location map of Vejle catchment & measurement stations on the Vejle and Grejs rivers. River stations are shown in blue and the raingauges from the SVK (Spildevandskomiteens) network in red.

Table 2 Measurement stations in the Vejle River & Grejs River catchments

Stations name	ID	Measurement	Owned /operated by	Established /First measurement date
Vejle Å				
Vejle Å afløb Engelsholm Sø	32.11	Water level & discharge	MST Sydjylland (320000013)	01-01-2011[1]
Engelsholm Bæk NØ for Engelsholm Højskole	32.19	Water level	MST Sydjylland (320000017)	01-01-2010[1]
Refsgaardslund Dambrug	32.03	Water level & discharge	MST Sydjylland (32000002)	08-12-2016[1]
Tørskind Bro	32.30	Water level	Vejle Kommune	14-12-2016[2]
Ravning – opstrøms Ødsted bæk	32.28	Water level	Vejle Kommune	14-12-2016[2]
Vingsted Center	32.29	Water level	Vejle Kommune	14-12-2016[2]
Haraldskær	32.01	Water level & discharge	Vejle Kommune (32000001)	01-01-2010[1]
Rosborg	32.25	Water level	Rosborg Gymnasium	23-11-2014[2]
Mølleåen	32.23	Water level	Vejle Kommune	12-04-2013[2]
Vejle Havn	32.24 DMI 23259	Water level	Vejle Havn (Vejle Kommune og DMI)	Dec. - 2013
Højen Å				
Højen Å – nedstrøms Møgelbæk	32.08	Water level	SVANA	01-05-2013[2]
Grejs Å				
Grejs Å, Basin i Urhøj, opstrøms for Polsterbæk	32.27	Water level	Orbicon	Mar 2017[3]
Grejs Å, Ny Grejsdalsvej	32.22	Water level & discharge	Vejle Kommune	Jul 2016[3]
Grejs Å Abelones Plads	32.20	Water level	Vejle Kommune	Sep. 2013[3]
Omløbsåen, Aagade	32.21	Water level	Vejle Kommune	Aug. 2013[3]

An example of the time series collected is given in Figure 5 for the main station on the Vejle River at Haraldskær.

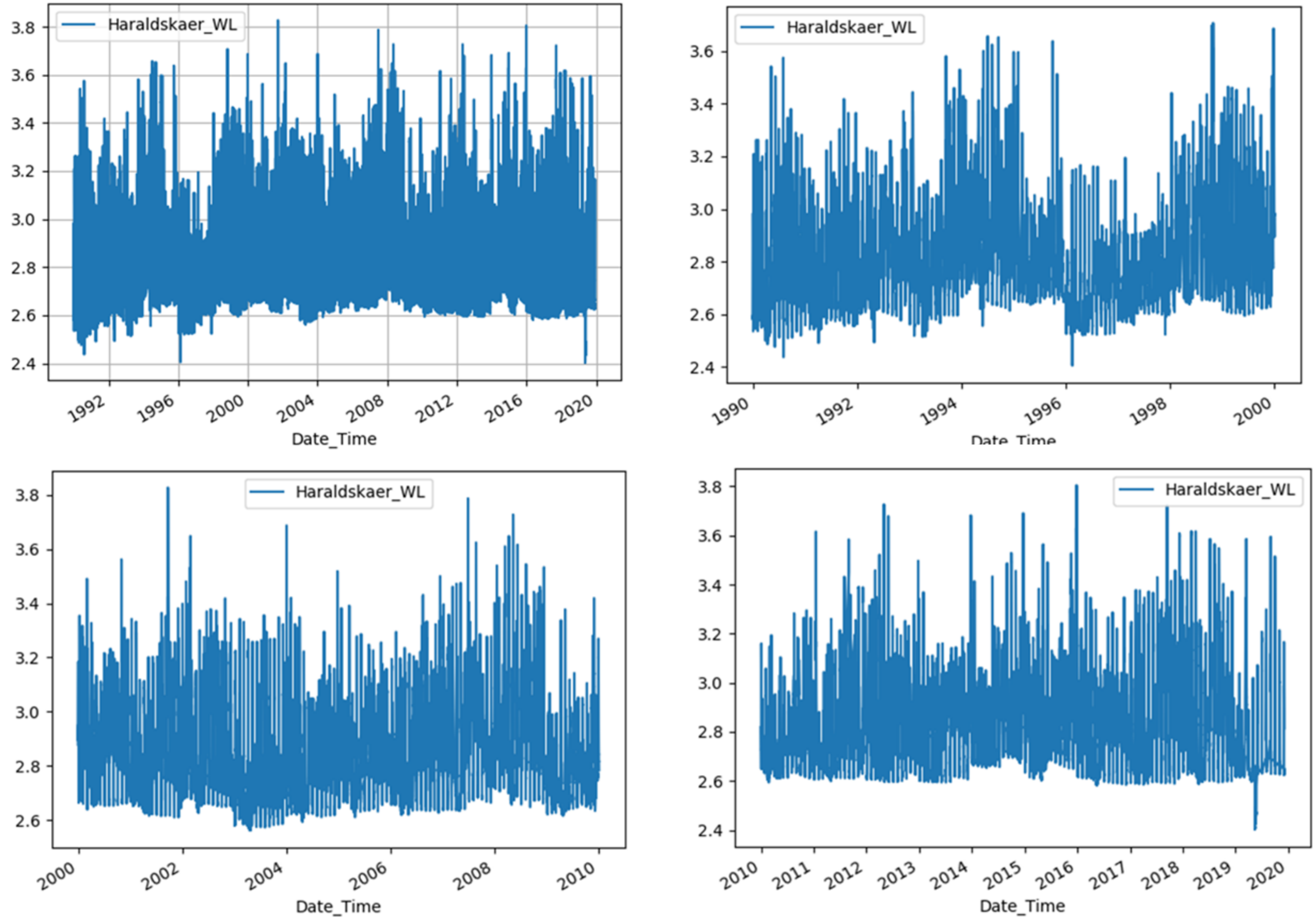

Figure 5 An example of the time series of water level [m] collected for the main observation station on the Vejle River at Haraldskær. The first graph (top left) shows the full 30 years of data. The remainder show the water levels for each decade.

5 Hydrological modelling

While previous studies of the Vejle River were performed using commercial hydrological modelling software, this approach conflicts with DMI's goal of using open source software in its research and operational activities. We have therefore investigated alternative open source modelling software.

5.1 Open source hydrological models

The selection of a first set of candidate hydrological model software was based on the following criteria:

- Open source
- Well-documented
- Well-documented in the scientific literature
- Suitable for both operational use and scientific research
- Fast process-based models, representing both surface water and groundwater

The most promising candidates using these criteria were:

HYPE (& E-HYPE)
The Hydrological Predictions for the Environment, (HYPE), model was developed by the Swedish Meteorological and Hydrological Ínstitute (SMHI), [5] HYPE is a semi-distributed catchment model, which simulates water flow and substances on their way from precipitation through different storage compartments and fluxes to the sea,[6] . The model and code are well-documented, [7] [8]

SWAT (& SWAT+)
The Soil and Water Assessment Tool Plus (SWAT+) is the latest variant of the SWAT catchment model developed in the US by USDA Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research. SWAT+ also simulates both water flow and substances in a similar manner to HYPE. The SWAT model and code are also well documented, [9] [10]

LISFLOOD
The LISFLOOD model is a hydrological rainfall-runoff model that is capable of simulating the hydrological processes that occur in a catchment. LISFLOOD was developed by the floods group of the Natural Hazards Project of the Joint Research Centre (JRC) of the European Commission, [11] While in use for a number of years, LISFLOOD has only recently (September 2019) been released as an open source tool, [12]

5.2 Hydrological Modelling approach

All of these candidates are process-based models in which the individual processes are represented mathematically by conceptual models. Therefore, their performance is expected to be comparable. Since for the SWAT+ modelling system, its predecessor, SWAT, has been used previously in Denmark, there is available experience and an existing modelling community in Denmark. For these reasons, the SWAT+ model was selected for this initial modelling exercise. We expect to evaluate the other candidates in future work. The hydrological modelling work presented here, has been carried out in collaboration with WaterITech who have worked previously with SWAT and SWAT+ for hydrological forecasting.

5.3 Meteorological forcing

The SWAT+ model uses precipitation and reference evapotranspiration as the meteorological forcing variables. The reference or potential evapotranspiration is derived from time series of: minimum and maximum temperature, relative humidity and wind speed. For this first model, these variables are taken from the ERA5 re-analysis data set [13] which provides hourly data over a 31 km grid. The reference evapotranspiration is estimated using the Penman-Monteith method, [14] The precipitation data consists of the 16 DMI (SVK) stations surrounding Vejle. Further details are given in [15]

5.4 Hydrological characteristics

In addition to the meteorological forcing, geographical information for the topography, land use, soil properties as well as the river and lake network are used as model input. These data are obtained from public data sources, so the same approach can be readily applied to other catchments in Denmark.

The topography and river and lake network are used to divide the Vejle River and Grejs River catchments into 13 sub-catchments (or sub-basins) to capture both the meteorological and hydrological variability, Figure 6. The soil, land use and topography is used to further subdivide these into (101) landscape units (LSU's) and (10,942) hydrological response units, (HRU's), [15] This high level of spatial resolution provides a strong starting point for our future investigations of the value of high-resolution meteorological data and forecasts.

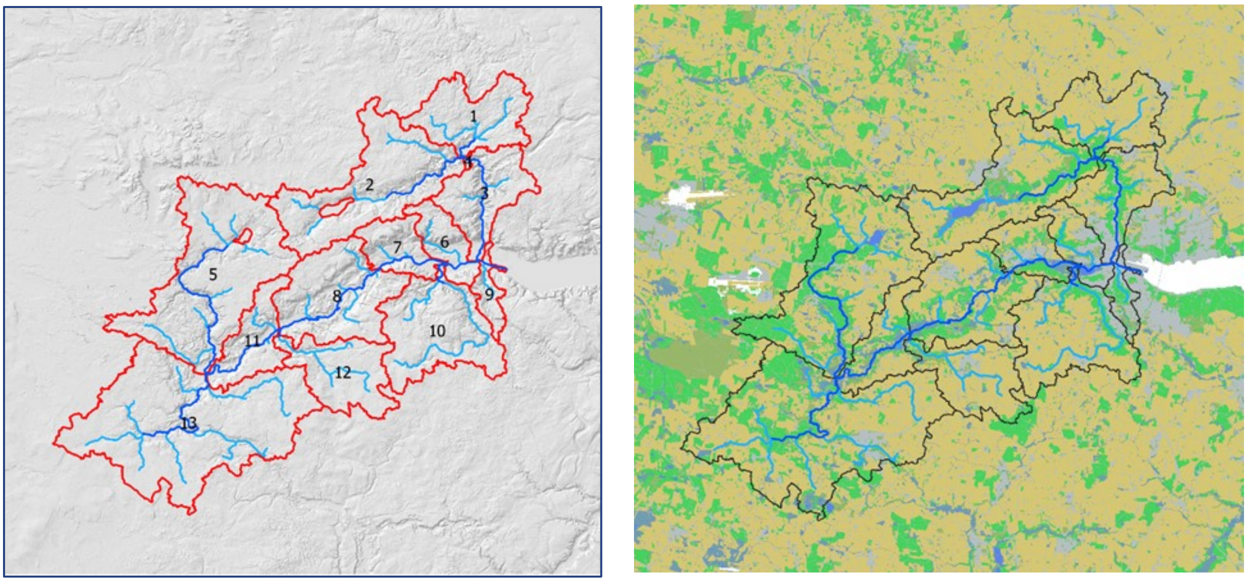

Figure 6 Left: Topography, catchment and sub-catchment boundaries and river network for Vejle River and Grejs River. Right: Land-use map

5.5 Model calibration and validation

The application of such models to individual catchments requires calibration of the model parameters to reproduce the measured response to rainfall in the rivers. For this study, we have used the measured discharge at the two main stations on the Vejle River (station 32000001, Haraldskær) and the Grejs River (station 32000004, Planteskolen), Figure 7. The calibration focused on the overall water balance and flood peaks.

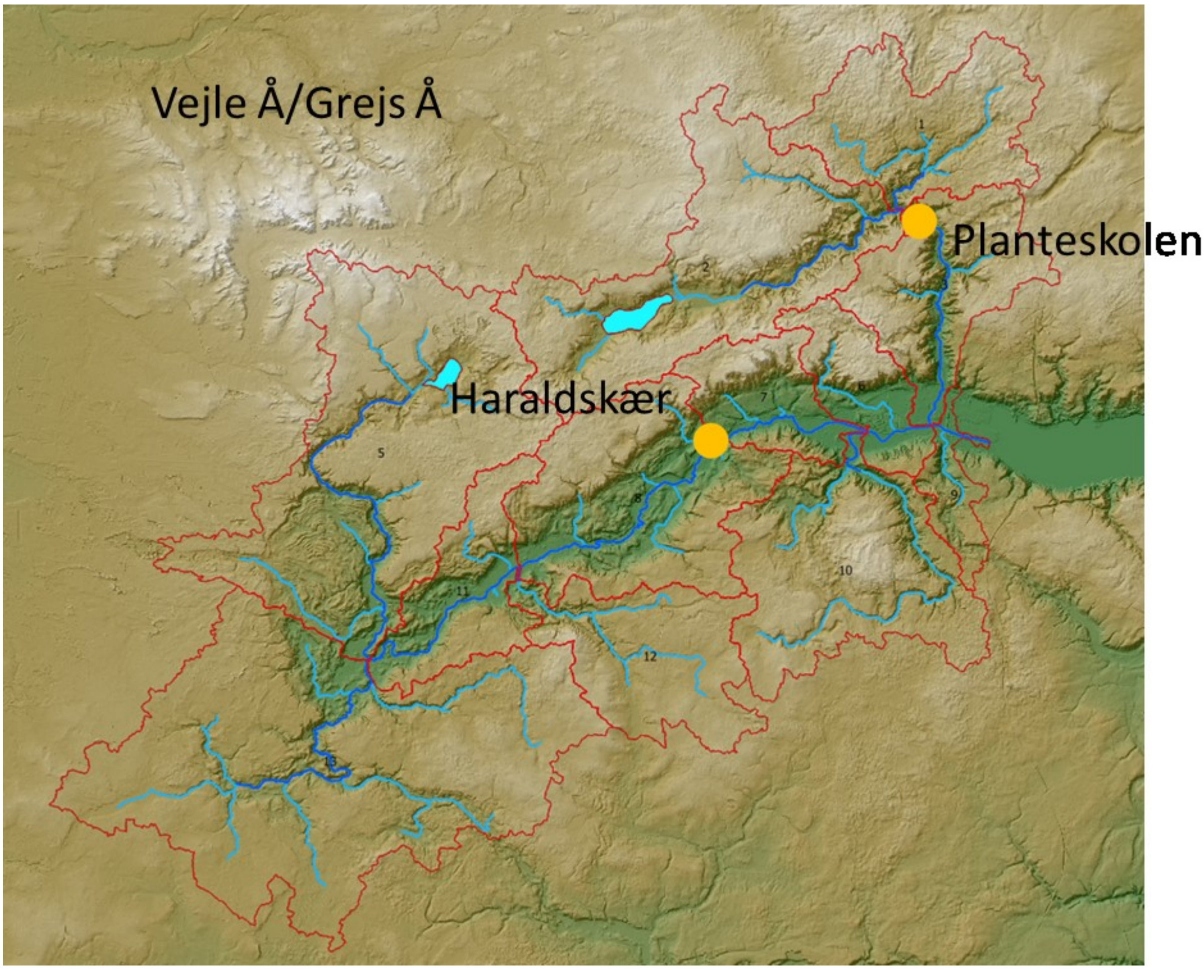

Figure 7 The topography of the Vejle River/ Grejs River catchments, showing the river network in blue and the sub-catchment delineation in red used in hydrological modelling. The two yellow dots indicate the location of the discharge stations used for calibration and validation.

For both the Grejs and Vejle river systems, it is well known that groundwater from outside the topographical watershed contributes to the discharge in both streams. However, little information is available to quantify this contribution. The measured specific discharges (discharge/unit area) for the Planteskolen station (18.6 l/sec/km^2) and Haraldskær station (18.8 l/sec/km$^{2)}$ are considerable higher than the national average of 10.1 l/sec/km^2. It appears that the discharge at Planteskolen and Haraldskær is minimum 30-50% higher than nearby stations, [15] Therefore, this extra contribution was also adjusted in the calibration process.

Model calibration was carried out using a combination of manual and automatic methods. An initial calibration was performed to narrow down the acceptable ranges of model parameters. This was followed by an automatic calibration step using the dynamically dimension search (DDS) approach which is part of the SWAT+ Toolbox. DDS has demonstrated good performance in terms of computational speed and the ability to break through local solutions when calibrating complex hydrological models, [16]

The calibration measure used was optimization against the Nash-Sutcliffe Efficiency (NSE), which, like the coefficient of determination (R^2), is a correlative objective function. Percent bias, which is a residual objective function, was also evaluated. Classification of the performance was carried out by comparing performance against the criteria reviewed by Moriasi et al., [17] . The following periods were used:

- Model warmup: 1. August 2011 - 31. July 2014 (three hydrological years)
- Calibration: 1. August 2014 - 31. July 2016 (two hydrological years)
- Validation: 1. August 2016 - 31. July 2018 (two hydrological years)

5.6 Modelling results

The model performance against the three objective functions: correlation (R^2), the Nash-Sutcliffe efficiency (NSE) and the percent bias (PBIAS) is summarized in Table 3. A graphical comparison of the model results, confirm that model performs satisfactorily in capturing the dynamics of the flow in both rivers and the overall water balance, Figures 8 & 9. These results are based on daily time scales, however further work is needed for subdaily modelling. A review of past sub-daily SWAT studies, [18] has demonstrated that peak flows are generally better reproduced when using hourly rather than daily precipitation input to SWAT. It is expected that sub-daily simulations for SWAT+ will be available and operational within SWAT+ in early 2021 and this will be explored in the next phase of this research.

Table 3 Performance of the SWAT+ model for Grejs River and Vejle River

Objective function	Grejs River calibration[1]	Grejs River validation [1]	Vejle River calibration[1]	Vejle River validation [1]
R^2	0.79 (good)	0.81 (good)	0.8 (good)	0.85 (very good)
NSE	0.68 (satisfactory)	0.75 (good)	0.57 (satisfactory)	0.52 (satisfactory)
PBIAS (%)	-0.18 (very good)	-7.39 (good)	1.18 (very good)	-0.65 (very good)

[1] Classification according to Moriasi et al. (2015) noted in parenthesis.

From these model results, it is possible to derive an overall representation of the water balance, Figure 10. Here it is worth noting, as mentioned earlier, that a large percentage (~70%) of the water entering the rivers as base flow (groundwater discharge) arises from rainfall that has fallen outside of the surface water (topographical) catchment. In this first calibration, this external groundwater source is modelled as point sources with a constant rate of 0.49 m^3/sec upstream in the Grejs Rivers and 1.56 m^3/sec upstream in the Vejle River. These flows correspond to 34% and 35%, respectively, of the observed discharge during the calibration period. This is a reasonable approximation in the cases where high flows with flooding are important. In applications where the overall water balance is important further work will be needed to better quantify this extra groundwater contribution to the river flows.

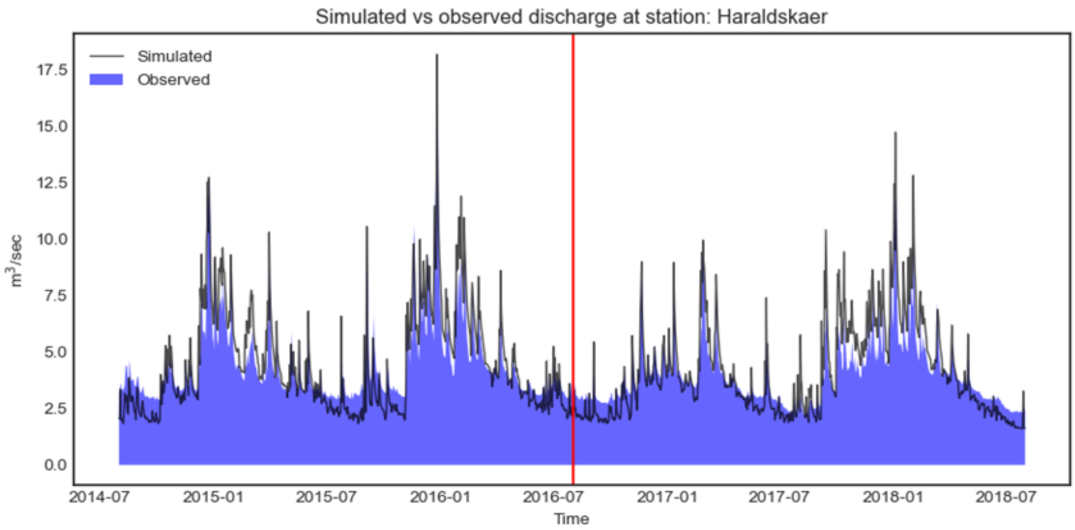

Figure 8 Observed and simulated discharge for Vejle River, at ”Haraldskær” gauge station (2014-2018) for the calibrated model. The calibration and validation periods are separated by the red vertical line.

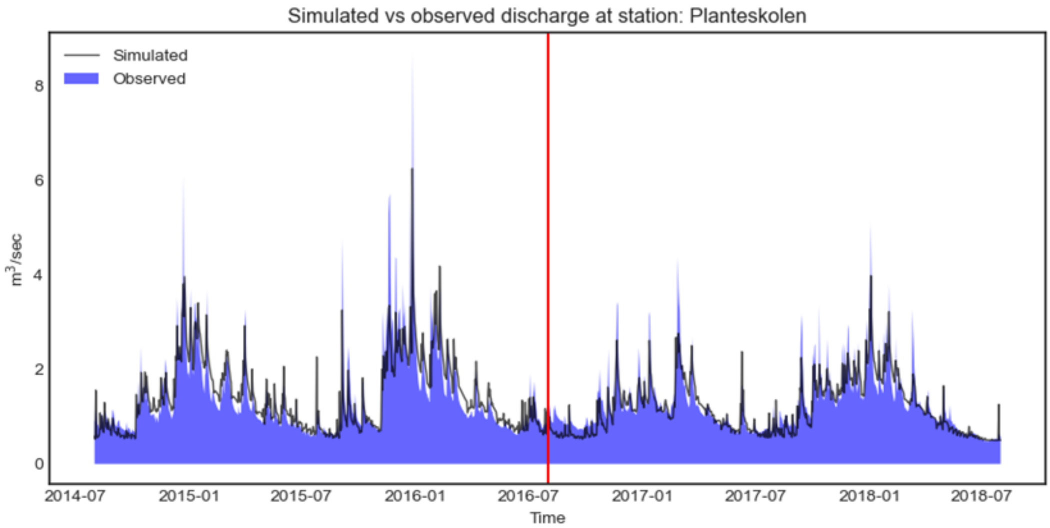

Figure 9 Observed and simulated discharge for Grejs River, at ”Planteskolen” gauge station (2014-2018) for the calibrated model. The calibration and validation periods are separated by the red vertical line.

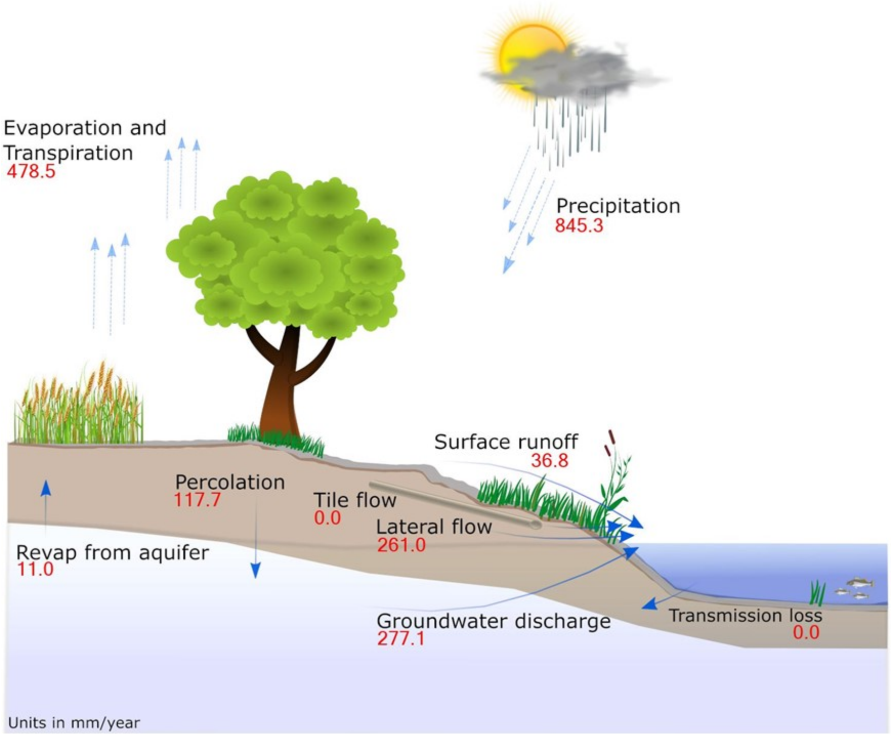

Figure 10 Key catchment-wide hydrology components simulated for the period 2014-2018 (based on the calibrated model). Groundwater discharge includes 192 mm/year from sources outside the topographical watershed.

6 Conclusions and future work

A detailed hydrological model for the Vejle River and Grejs River catchments has been established (fomrmulated, calibrated and validated) using the SWAT+ model. The data used is publically available at national level, and therefore the SWAT+ approach used in this project can be applied all across Denmark. The SWAT+ model was calibrated on a daily time step, and generally produced good results for river discharge at both river gauge stations. A first comparison indicates that the observed peak flows were better reproduced using this SWAT+ model when compared to the existing national water resource (DK) model, [15] but more extensive analysis is needed. Nevertheless, the ability to reproduce the historical flood peaks makes this model suitable for our planned research. While the SWAT+ code for sub-daily simulations still required some minor developments during the time of the Vejle Pilot study, it is expected that this will soon be released by the core developers at USDA in the US, which could potentially improve the simulation of peak flows even further. In the next phase of this effort, we will evaluate the model performance at high temporal resolutions (down to 15 minutes intervals). We will then evaluate how DMI’s new high resolution radar and model data could improve the accuracy and reliability of the flood forecasts were they used in the historical forecasts of large flood events.

7 Acknowledgements

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