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SWAT+ model protocol for Słupia catchment (Poland)

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Introduction

The Słupia catchment is a coastal river basin in northern Poland covering an area of 1623 km^2. It drains into the southern Baltic Sea through the 138 km long Słupia River. The area's climate is classified as warm-summer humid continental (Dfb), with mean annual precipitation is 850 mm/y. The mean water flow at the catchment outlet from period 2000-2016 was 17 m^3/s, with a range of 8.4 to 53 m^3/s. The altitude ranges from 0 to 267 m a.s.l., with the highest parts located in the south-east of the basin. Sands and loamy sand are the most typical soil types.

The main environmental challenges are related to: a) nutrient leaching from agricultural areas; b) the need to increase water retention and slow down water outflow; and c) flash floods in urban areas (Słupsk) caused by extreme rainfall events.

The purpose of this protocol is to set up the latest SWAT+ model, using R-based packages recently developed within the OPTAIN project (Piniewski et al., 2024; Schürz et al., 2022; Plunge et al., 2024a; Plunge et al., 2024b), to apply it for simulation of the main characteristics in the Slupia catchment (river flow, nutrient concentrations and loads, crop yields) under changing climate and application of different, dedicated to the area, Nature Based Solutions. The prepared protocol is based on and is an extension of the SWAT2012 model developed for the catchment within one of the previous projects, namely BONUS-RETURN (Koskiaho et al., 2022), to evaluate effectiveness of River Basin Management Plans (Piniewski, et al., 2021) and recycling ecotechnologies (Koskiaho et al., 2022) on nutrient reduction.

Code versions used

Code	Version number	Availability
R scripted workflow	1v	SWAT+ model setup preparation scripted workflow developed in the OPTAIN project. Plunge, S., Piniewski, M., Schürz, C., & Strauch, M. (2024). SWAT+ model setup preparation scripted workflow (in R language). Zenodo. https://doi.org/10.5281/zenodo.12564534 See Piniewski et al. (2024) for description of individual components of the scripted workflow.
SWAT+ (core model)	61.0	The SWAT+ fortran code is version controlled through bitbucket. Official code releases are available here: https://bitbucket.org/blacklandgrasslandmodels/modular_swatplus/src/master/

Weather input data used

Data	Temporal resolution	Spatial resolution	Availability
Precipitation	Daily	Provided from individual weather stations	Observed daily precipitation data for period 2003-2021 for 29 stations (6 of them with 100% data coverage, and 14 with coverage above 95%; average temporal coverage: 85%) was downloaded from the Institute of Meteorology and Water Management - National Research Institute database available at https://danepubliczne.imgw.pl/en.
Min. and max air temperature	Daily	Provided from individual weather stations	Observed daily min. and max. temperature data for period 2003-2021 for 11 stations (5 of them with 100% data coverage, and 2 with coverage above 85%; average temporal coverage: 85%) was downloaded from the Institute of Meteorology and Water Management - National Research Institute database available at https://danepubliczne.imgw.pl/en.
Relative humidity	Daily	Provided from individual weather stations	Observed daily relative humidity data for period 2003-2021 for 10 stations (5 of them with 100% data coverage, and 2 with coverage above 85%; average temporal coverage: 86%) was downloaded from the Institute of Meteorology and Water Management - National Research Institute database available at https://danepubliczne.imgw.pl/en.
Wind speed	Daily	Provided from individual weather stations	Observed daily wind speed data for period 2003-2021 for 10 stations (5 of them with 100% data coverage, and 2 with coverage above 85%; average temporal coverage: 87%) was downloaded from the Institute of Meteorology and Water Management - National Research Institute database available at https://danepubliczne.imgw.pl/en.
Radiation	Daily	Provided from individual weather stations	Observed daily radiation data for period 2003-2021 for 7 stations (2 of them with 100% data coverage, and 1 with coverage above 95%; average temporal coverage: 68%) was downloaded from the Institute of Meteorology and Water Management - National Research Institute database available at https://danepubliczne.imgw.pl/en.

Note: All weather input data were interpolated for each day to a 5 km grid using the inverse distance weighted method available in the SWATprepR package (Plunge et al., 2024a).

GIS input data used

Data	Map	Resolution	Availability
DEM	NMT PL-KRON86-NH	1 m raster	Official 1 m raster map from LIDAR hosted by the Polish Central Office of Geodesy and Cartography. For SWAT+ purposes, the DEM was resampled to 10 m resolution. The data is available for download from https://geoportal.gov.pl
Landuse	BDOT10k	Vector (shapefile)	Database of Topographic Objects - official land use layer in scale 1:10 000 hosted by the Polish Central Office of Geodesy and Cartography. The data is available for download from https://geoportal.gov.pl
Crops	GSAA	Vector (shapefile)	Polish Geo-spatial Aid Application (GSAA) data collection is managed by the Agency for Restructuring and Modernisation of Agriculture (ARiMR) in scale 1:500 and contains parcel-level data on cultivated crops since 2020. The data is available for download from https://geoportal.arimr.gov.pl (login required).
Soils	IUNG	Vector (shapefile)	Map of soil-agricultural units from the Institute of Soil Science and Plant Cultivation (IUNG) in the scale 1:100 000. Both the map and soil parameters available from the SWAT2012 model setup developed in the BONUS RETURN project (Piniewski et al., 2021).
Lakes (optional)	MPHP10k	Vector (shapefile)	Database of Topographic Objects - official land use layer in scale 1:10 000 hosted by the Polish Central Office of Geodesy and Cartography. The data is available for download from https://geoportal.gov.pl
Rivers (optional)	MPHP10k	Vector (shapefile)	Official layer of rivers reaches (rzeki_r) from the data set Map of the Hydrographic Division of Poland in the scale 1:10 000 hosted by the State Water Holding Polish Waters. Online visual access only via QGIS plugin: Wody Polskie - Baza WMS
Drainage	GeoMelio	Vector (shapefile)	Underground drainage pipes from the official GeoMelio dataset in scale 1:500 hosted by the National Water Management Authority. No online access available.

Discharge data used for calibration and validation

Data	Temporal resolution	Spatial resolution	Availability
Stream discharge	daily	Provided from individual gauge stations	Observed daily discharge data for period 2003-2021 for 2 gauge stations (Charnowo, Soszyca; each with 100% temporal data coverage) was downloaded from the Institute of Meteorology and Water Management - National Research Institute database available at https://danepubliczne.imgw.pl/en.

Model setup

The minimum size of polygons in the land use layer included in the model setup preparation was 3000 m^2. Smaller polygons were joined to the neighboring larger polygons. There were no other restrictions on delineation or input data during model setup generation using the OPTAIN workflow.

The following table presents the main characteristics of the prepared setup. Please note that the model setup generated using the SWATbuildR tool does not have sub-basins due to the very nature of the contiguous object routing approach and lack of conventional watershed delineation step known from QSWAT+. It is worth noting that the model was set up using a single aquifer and channel-aquifer connections are handled using the geomorphic flow method.

A major achievement of this setup is using the field-level crop sequences and respective management schedules. Due to a large catchment size, the process of preparation of land use map and management had to include some generalizations and simplifications. However, the input data used can be considered high resolution and accurate. In addition, management schedules were set based on information provided by the local farmer advisors (Pomeranian Agricultural Advisory Centre in Słupsk) and using the SWATfarmR package that allows weather-dependent scheduling.

Parameter	**Value**
Total area of the watershed in km^2	1,618
Total number of spatial objects in the simulation	47,539
Number of HRUs in the simulation	22,974
Number of routing units in the simulation	22,974
Number of aquifers in the simulation	1
Number of “reservoirs” in the simulation (all impoundments)	501
Number of export “coefficients” in the simulation (point sources)	32
Number of channels in the simulation	1057
Number of crops in rotation	15
Number of wetlands	103

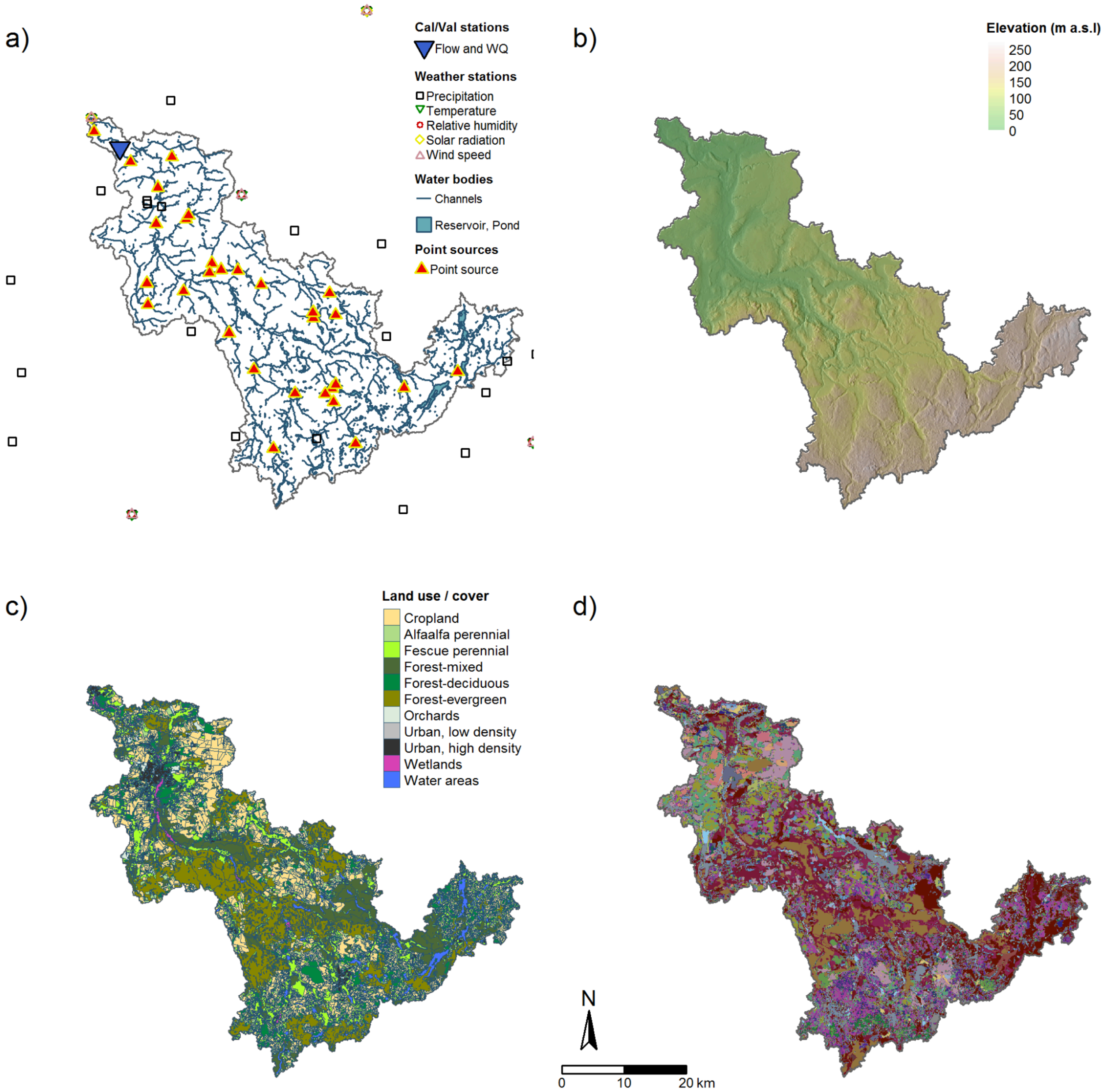

Figure 1. Input maps used for setting up the SWAT+ model for the Słupia catchment: a) weather stations, monitoring points, lakes and point sources; b) Digital Elevation Model; c) Land use; d) Soils (legend not shown).

Potential evapotranspiration method

SWAT+ includes the choice of different potential evapotranspiration methods including Hargreaves, Penman-Monteith, Priestley-Taylor or user-defined time series. In this study, the Penman-Monteith method was selected, due to a good availability of the input data and the strongest physical background among available methods.

Water abstractions

None included in the current version.

Inputs of external groundwater from areas outside topographical watershed

Not deemed relevant.

Calibration and validation

Calibration was done using the approach developed and tested in the OPTAIN project (Piniewski et al., 2024). In the first step, model setup verification was done using the SWATdoctR tool (Plunge et al., 2024b). It helped reveal several issues in the model setup, which led to corrections of input data and redoing the model setup using the scripted workflow. It was checked before moving to calibration that the weather inputs look correct (e.g. plausible PET values), that the crop growth is plausible (PHU values at harvest at reasonable range, expected LAI and biomass development, plant ET much higher than soil ET), that uncalibrated water balance looks plausible, and tile drains are functioning.

The next step was "hard" (i.e. focussing on time series data) calibration of river discharge. The aim of this step is to improve the realism of the model by comparing its output with the real data and searching for parameter combinations that give a satisfactory fit to the observations. To this end, we applied the development version of the new SWATtunR R package (https://github.com/biopsichas/SWATtunR). We used daily discharge data from two gauging stations located at the Słupia river: one in Charnowo, located close to the main outlet (Fig. 1a) and the second one further upstream in Soszyca. Calibration and validation periods were set to 2006-2013 and 2014-2021, respectively (with a warm-up period 1995-2005[1]).

The calibration routine consisted of three main steps: (i) sampling SWAT parameter combinations using Latin Hypercube Sampling (LHS); (ii) parallel running model simulations with SWATrunR package (https://github.com/chrisschuerz/SWATrunR); (iii) evaluating model simulations with pre-selected performance metrics and signatures (Piniewski et al., 2024). The parameter set consisted of 14 parameters (three of them were disaggregated into three groups based on the leaching and runoff potential, see Piniewski et al. (2024)) representing different hydrological processes. Three main objective functions were KGE, NSE and MAE (mean absolute error for average monthly discharge). For each objective function, a weighted average was calculated with weights set to 0.8 and 0.2 for "Charnowo" and "Soczyca", respectively. Selection of well-performing parameter sets was done based on the sum of ranks calculated for particular weighted objective functions. The parameter sets with the highest sum of ranks were designated as the "best" parameter sets. Overall, by performing several iterations, the parameter ranges were successively constrained based on the analysis of the "dotty plots" (parameter values vs. objective function values).

The final selection of well-performing parameter sets is called the calibrated parameter ensemble (Table 1). The most sensitive parameters were marked in bold. Baseflow "alpha" factor (alpha.aqu) was perhaps the most sensitive and the highest objective function values were achieved for very low values of alpha. The range of the soil evaporation compensation factor (esco.hru) was reduced to (0.05, 0.2) in order to increase flow to precipitation ratio. An increase in the percolation coefficient (perco.hru) helped to increase the amount of water recharging the aquifer.

[1] Such a long warm-up period was set due to the problem with initialization of reservoir storage. All reservoirs were empty at the beginning of simulation, so the longer warm-up period helped to reduce the problem.

Table 1 Calibrated parameter ensemble.

Parameter	Change type	Parameter ensemble							
		1	2	3	4	5	6	7	8
esco.hru	Absolute value	**0.10**	0.07	0.07	0.06	0.05	0.11	0.05	0.06
epco.hru	Absolute value	**0.25**	0.74	0.59	0.64	0.10	0.23	0.52	0.88
awc.sol	Relative change	**-0.29**	-0.25	-0.22	-0.25	-0.22	-0.17	-0.29	-0.18
cn2.hru	Relative change	**0.17**	0.08	0.07	0.06	0.13	0.17	0.10	0.06
surlag.bsn	Absolute value	**0.35**	0.22	0.07	0.31	0.12	0.26	0.07	0.16
k.sol.sol	Relative change	**0.08**	-0.21	0.46	-0.08	0.49	0.05	0.62	0.40
flo_min.aqu	Absolute value	**5.05**	5.16	5.79	5.51	6.26	5.50	5.38	5.25
alpha.aqu	Absolute value	**0.0016**	0.0019	0.0021	0.0023	0.0017	0.0016	0.0021	0.0016
sp_yld.aqu	Absolute value	**0.101**	0.120	0.065	0.060	0.081	0.067	0.102	0.060
bf_max.aqu	Absolute value	**1.54**	1.60	1.54	1.68	1.96	1.70	1.95	1.93
k_res.res	Absolute value	**0.008**	0.040	0.003	0.013	0.011	0.023	0.153	0.080
perco.hru (low)*	Absolute value	**0.620**	0.680	0.623	0.626	0.681	0.694	0.695	0.660
cn3_swf.hru (low)*	Absolute value	**0.682**	0.615	0.576	0.523	0.408	0.493	0.641	0.484
latq_co.hru (low)*	Absolute value	**0.060**	0.110	0.190	0.055	0.124	0.084	0.201	0.122
perco.hru (mod)*	Absolute value	**0.896**	0.937	0.899	0.901	0.937	0.946	0.947	0.923
cn3_swf.hru (mod)*	Absolute value	**0.385**	0.329	0.297	0.252	0.157	0.228	0.351	0.220
latq_co.hru (mod)*	Absolute value	**0.214**	0.289	0.410	0.207	0.311	0.251	0.427	0.308
perco.hru (high)*	Absolute value	**0.987**	0.997	0.987	0.988	0.997	0.999	0.999	0.993
cn3_swf.hru (high)*	Absolute value	**0.188**	0.143	0.118	0.082	0.005	0.062	0.161	0.056
latq_co.hru (high)*	Absolute value	**0.514**	0.589	0.710	0.507	0.611	0.551	0.727	0.608

** Parameters perco, latq_co and cn3_swf were modified for three groups of hrus corresponding to low, moderate and high leaching and runoff potential, respectively.*

Table 2 Model performance statistics for the main outlet (Słupia at "Charnowo" gauge station) for the calibration and validation periods. Provided values represent the best parameter set (number 1 from the ensemble in Table 2). See Fig.

Objective function	Calibration	Validation
KGE [-]	0.83	0.84
NSE [-]	0.54	0.76
MAE [m^3/s]	2	1.3
PBIAS [%]	-11.1	-8.0

The model performance metrics are shown in Table 2 (best parameter set) and Fig. 2 (calibrated parameter ensemble), while the comparison of simulated vs observed daily discharge is shown in Fig. 3 (calibration) and Fig. 4 (validation). While in general the model performance can be assessed as good (KGE value a little higher than for the SWAT2012-based study reported in Piniewski et al. (2021)), particularly at the main outlet, the main issue identified was flow underestimation, particularly visible during low flow periods. The Słupia river is characterized by a stable flow regime, with high groundwater contribution and relatively low variability, which can be explained by high precipitation, high soil permeability and thus high groundwater recharge, and high fraction of lakes acting as a buffer. Interestingly, the model performed slightly better for the validation period, which may be partly explained by a longer warm-up period that allowed for more lakes to fill in their storage. The timing of flood peaks was captured well, but their magnitude was often underestimated. The results for the head watershed gauge "Soszyca" were clearly worse than for the main outlet, but still satisfactory. This could be improved in the future with a better matched flow release decision table from lakes.

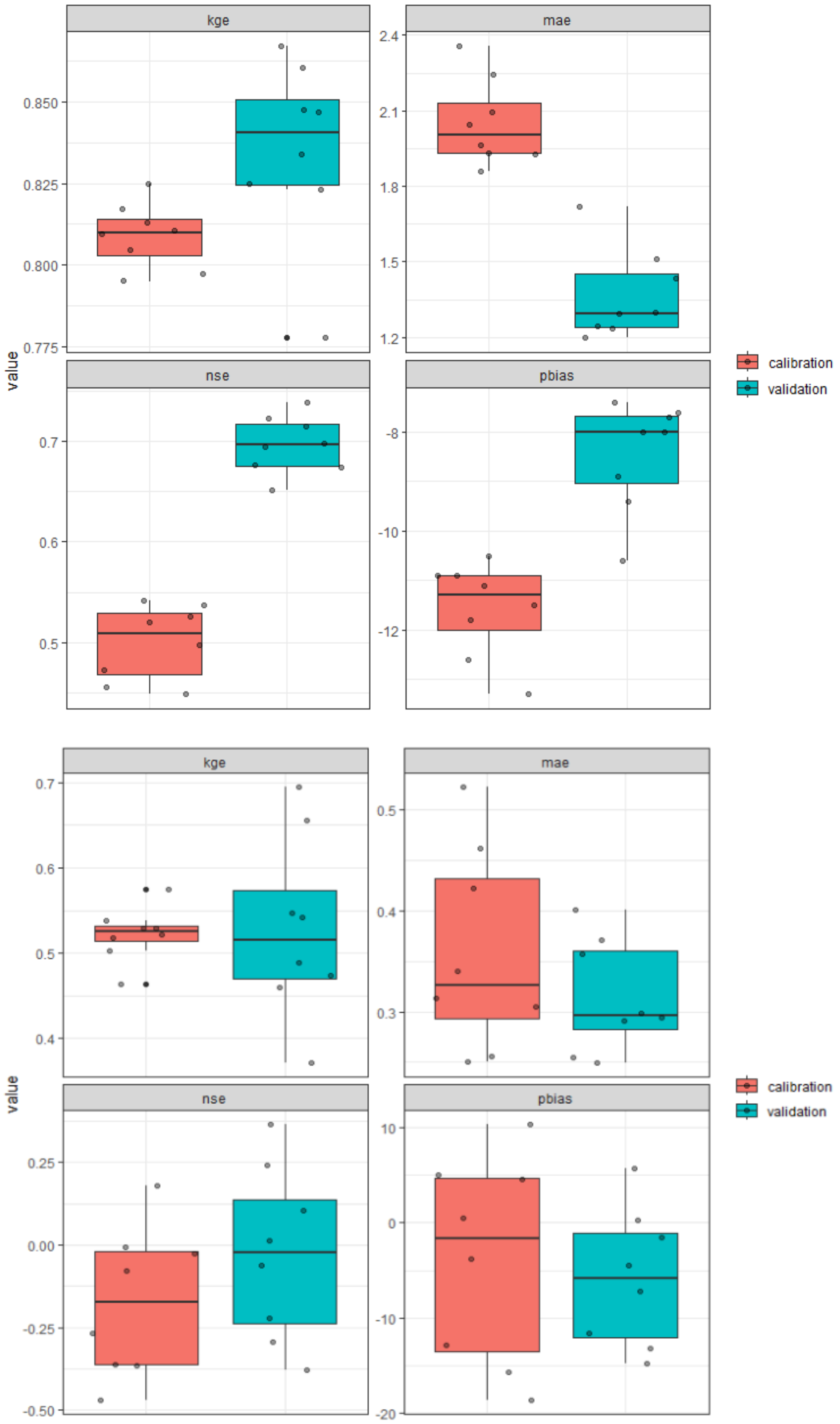

Figure 2. Box plots of model performance metrics for daily discharge for the Słupia river at "Charnowo" (top) and "Soszyca" (bottom) gauge stations.

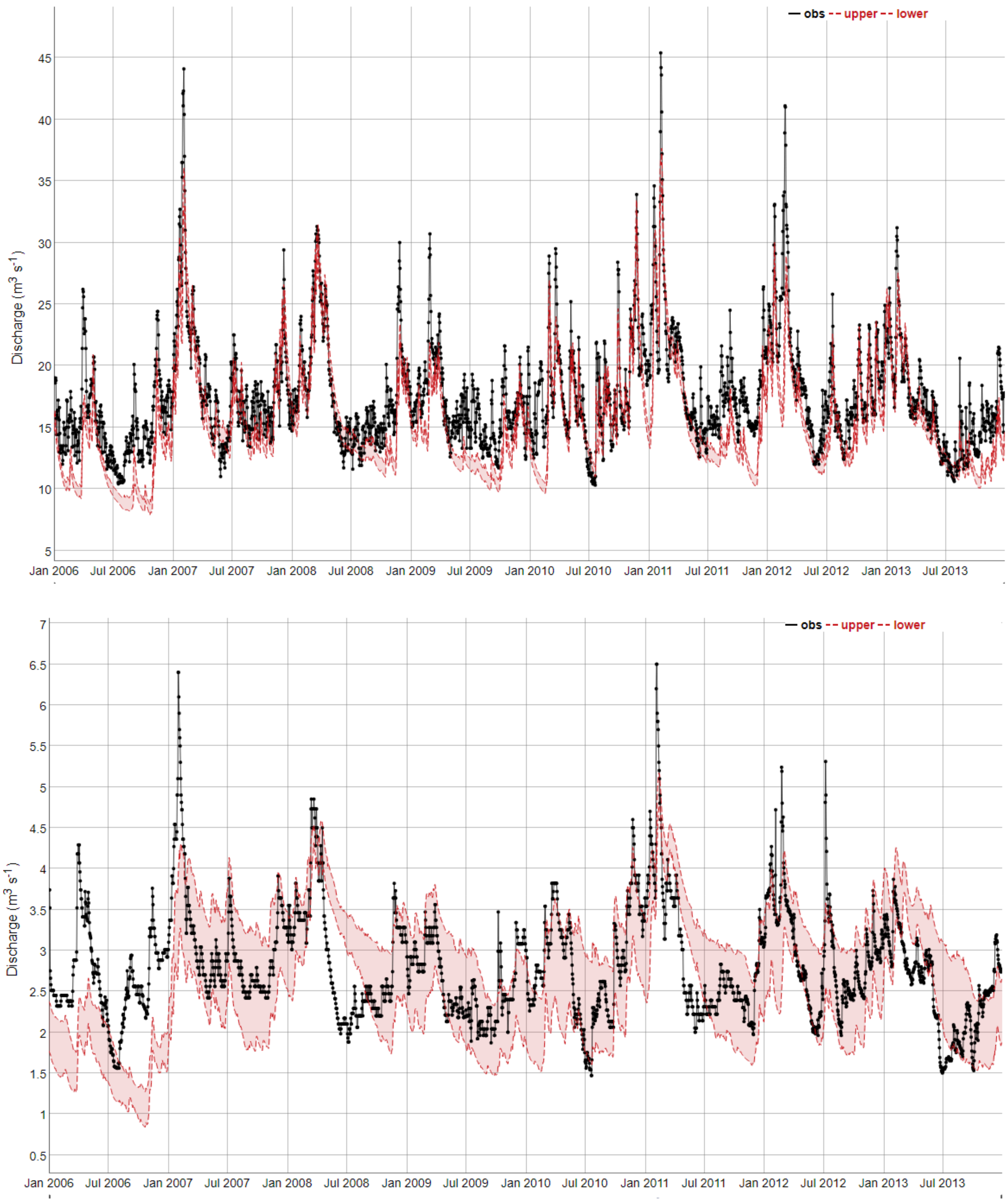

Figure 3. Observed and simulated discharge for the Słupia river, at "Charnowo" (top, main outlet) and "Soszyca" gauge stations (bottom, head watershed) for the calibration period, 2006-2013. The uncertainty band represents the calibrated parameter ensemble.

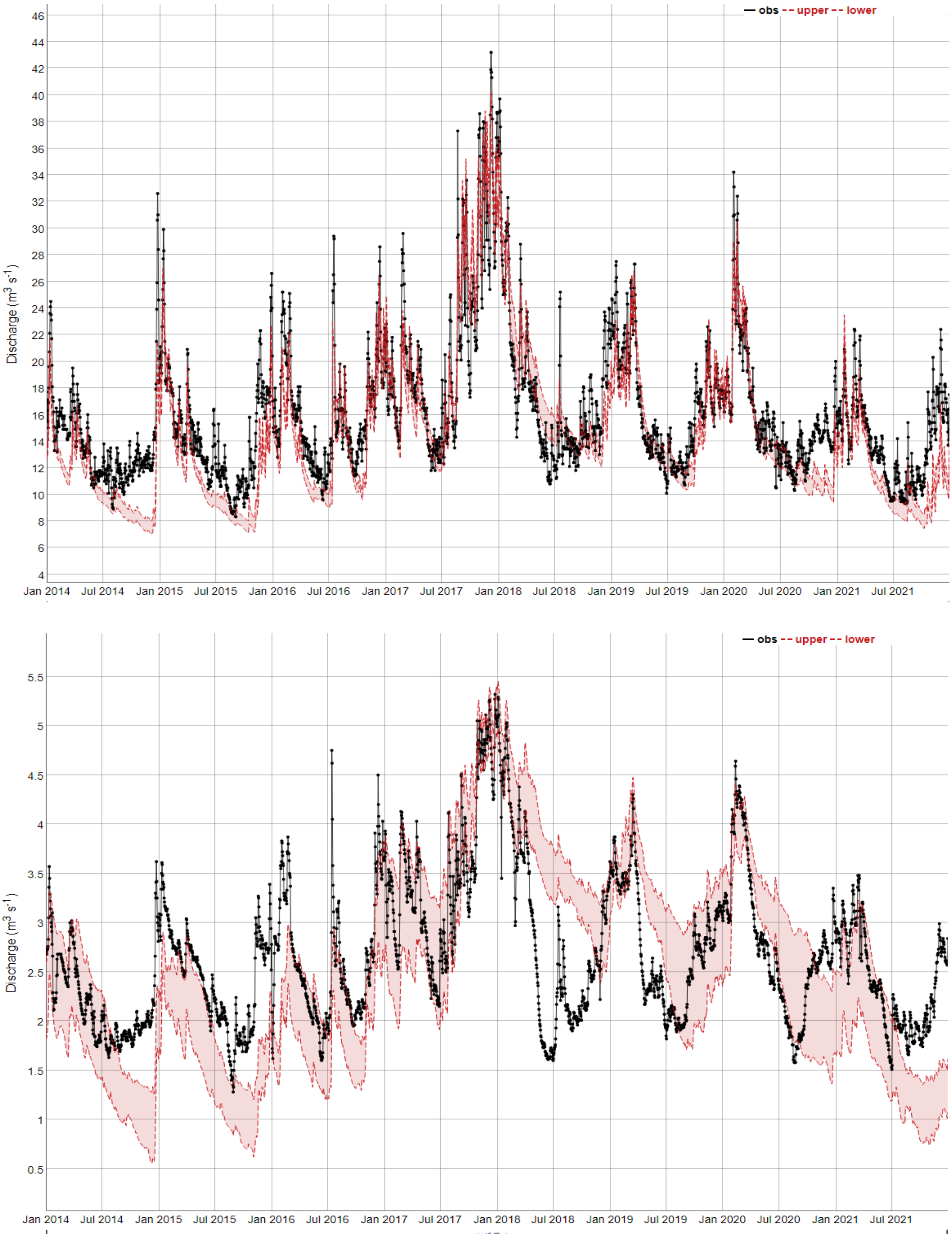

Figure 4. Observed and simulated discharge for the Słupia river, at "Charnowo" (top, main outlet) and "Soszyca" gauge stations (bottom, head watershed) for the validation period, 2014-2021. The uncertainty band represents the calibrated parameter ensemble.

Simulated water budget of the final version of the calibrated model setup (based on the parameter set 1 from Table 2) for the period 2006-2021 is shown in Fig. 5. As expected, the water yield ratio is high and equals 0.39. Groundwater flow is the dominant flow pathway constituting approximately two thirds of the total flow. Contribution of surface runoff is rather low (7%). Plant component of evapotranspiration constitutes 55% of the total ET

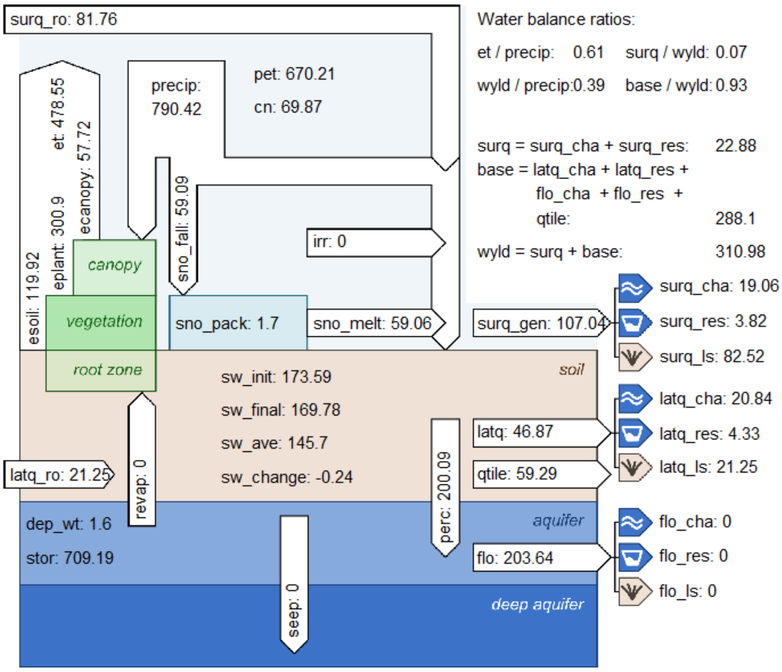

Figure 5. Key basin-wide hydrology components simulated for the period 2006-2021 (based on the calibrated model - parameter set 1 from Table 1). The plot was produced using the SWATdoctR package function plot_waterbalance (Plunge et al., 2024b)..

Summary

A SWAT+ model was set up for the Słupia river system using the scripted workflow previously developed in the OPTAIN project. It is noteworthy that it was the first application of this workflow for a catchment of this size (1618 km^2 compared to 50-200 km^2 in OPTAIN). Input data used in this project are mostly available at national level, but their collection and pre-processing is rather time-consuming. The SWAT+ model was calibrated on a daily time step, and produced generally very good results for river discharge. In the next steps of the WP4 workflow the model will be calibrated and validated for nitrogen and phosphorus concentrations. This will be followed by simulation of effectiveness of selected water quality mitigation measures.

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