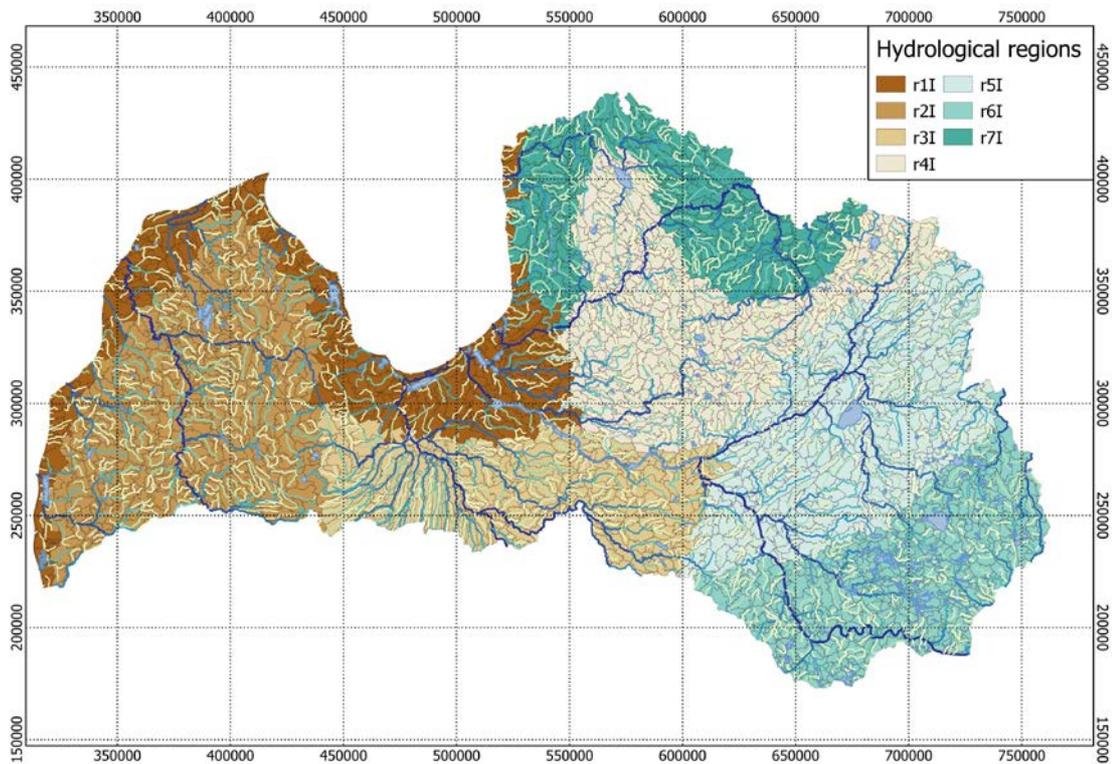# Documentation of Development, Calibration, Validation and Results of SWAT+ Modelling System

Deliverable R4

Prepared within the LIFE GoodWater IP Action C1: "Development of the water quality and quantity system for the territory of Latvia"

Rīga, 2023

Documentation of development, calibration, validation and results of SWAT+ modelling system

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Summary

This document is a description and documentation of development, calibration, validation and results of SWAT+ modelling system.

Document is written in English, it contains 90 pages, 120 figures, 16 tables and 6 references.

Table of contents

Introduction

This document is a description and documentation of development, calibration, validation and results of SWAT+ modelling system. The modelling system comprises of

- data prepared within Deliverable R1 – Data base for model implementation, PAIC (2020);
- water quantity and quality modelling tools described in Deliverable R3 – Modelling results for Reference and Baseline scenarios, PAIC (2022b);
- model setups of the calibrated and validated modelling system for the water quantity and quality in the territory of Latvia delivered as Deliverable R2 – Calibrated and validated modelling system in PAIC (2022a);
- modelling results delivered as Deliverable R2 – Calibrated and validated modelling system in PAIC (2022a).

The overview of the modelling system is given in Chapter 1.

The approach of the calibration and validation is presented in Chapter 2. It includes setting the calibration and validation targets, developing of the calibration strategy, regionalisation and preparing the observational data sets for calibration and validation.

The calibration and validation are performed, and the model results are presented in the Chapter 3 for the water quantity and in Chapter 4 for the water quality.

1.Modelling system

1.1. Elements of modelling system

The water quality modelling system comprises of the several entities:

- **The input data**, which is preprocessed and transformed with the use of the modelling system in Deliverable R1 – Data base for model implementation, PAIC (2020).
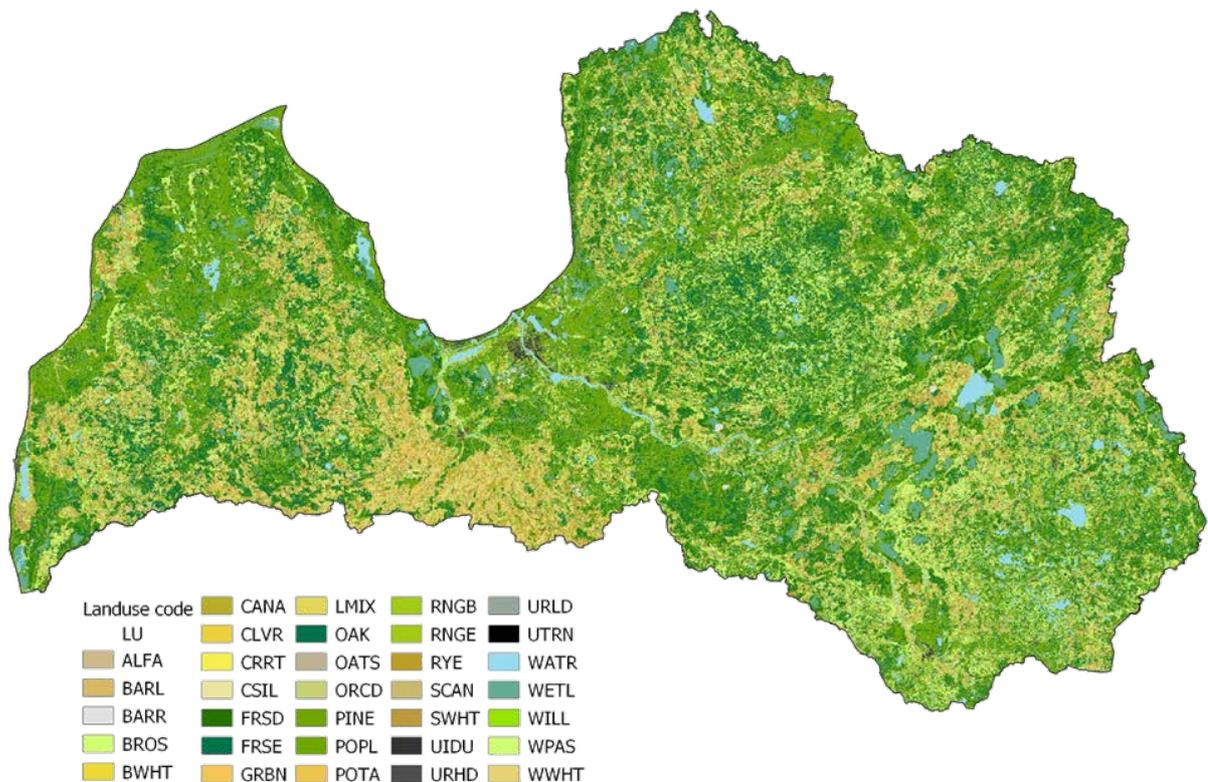

Figure 1.1: Land use distribution in the model.

- **The data storage system** which is based on *Postgre* database and *SVN* versioning system. This system is described in Deliverable R2 – Calibrated and validated modelling system in PAIC (2022a).

- **SWAT+ model software.** This is a command line tool, which read the dedicated input files and produces the model output files. PAIC has debugged the original SWAT+ Fortran source code (>100 errors corrected), and the software source code is versioned in Github. The description of these changes is included in Deliverable R3 – Modelling results for Reference and Baseline scenarios, PAIC (2022b).

- **The Python master script** for the generation of the setups of the modelling system which allows controlled preparation of the system of SWAT+ models (setups), perform the computations and postprocess the results for the visualisation and analysis purposes, see Deliverable R3 – Modelling results for Reference and Baseline scenarios, PAIC (2022b).

- **The data visualisation and analysis tools** – PAICSWAT software for the visualisation of the time graphs and analysing model results, and QGIS layer templates for the 2D mapping of the results, see Deliverable R3 – Modelling results for Reference and Baseline scenarios, PAIC (2022b).

1.2. Input data of modelling system

The input data of the modelling system contain the following elements:
- Terrain, DTM
- River network
- Meteorological observation data
- Atmospheric deposition data
- Land use data, see 33 land use classes in Figure 1.1
- Rural support service data on crops etc.
- Forest data
- Topographic maps
- Soil data with 54 soil classes, see soil groups in Figure 1.2
- Plant growth and agricultural practice data
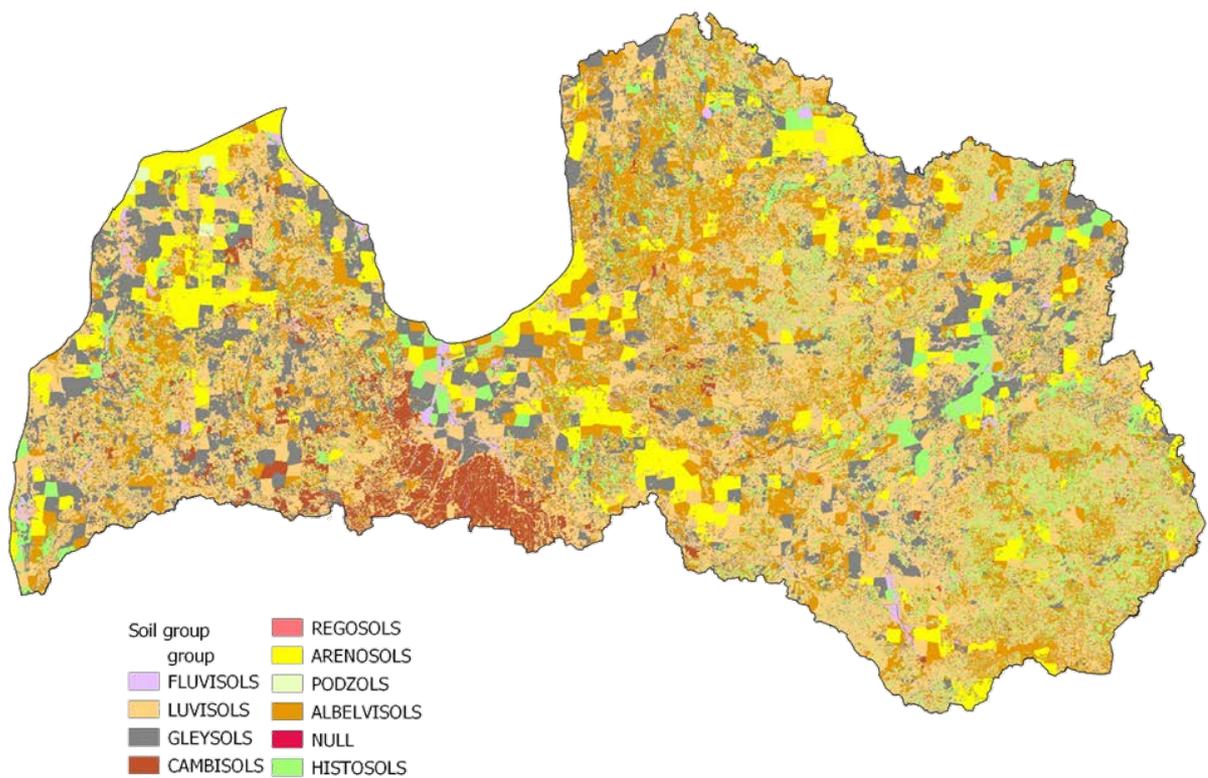- Fertilisation model
- Cattle and organic fertilizer data

Figure 1.2: Soil distribution in the model.

1.3. Structure of modelling system

The structure of the modelling system is as follows:

- The **river network** (Figure 1.3) is divided in the **stream segments**. The delineation of the **catchments** is performed for the each of river segments. Modelling system contains 3780 catchments, see Figure 1.4.

Figure 1.3: River network of the modelling system.
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- The catchments of the modelling system are aggregated in the model **watersheds**. Each watershed corresponds to one SWAT+ model. There are 179 watersheds in the modelling system, see Figure 1.4.

- Each of the watersheds is subdivided into elementary modelling entities – **hydrological response units (HRU).** Each HRU has a unique combination of land use, soil and surface slope. The master script provides all model parameters from the input data to the each of these HRU. There are 194634 HRU in the modelling system.

- The **connection** between the watersheds (SWAT+ models) including their modelling **hierarchy** from the upstream watersheds is ensured by the master script of the modelling system.
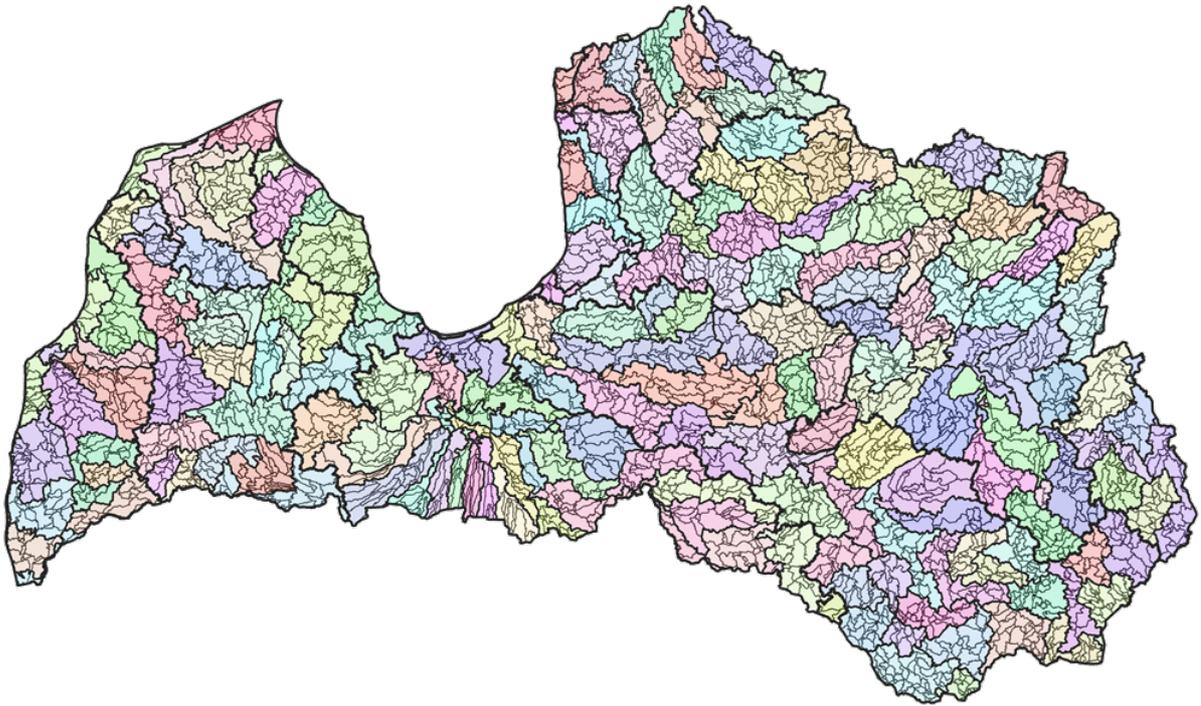
Figure 1.4: Division of the model into 3780 catchments and 179 watersheds.

- Transboundary inflows are realized as:

  o From Lithuania – modelling results of the Lithuanian SWAT+ modelling system PAIC (2022c), see combined river network of two models in Figure 1.5.

  o In the river Daugava – from the observation data.

  o Elsewhere – loads and runoff are assumed to be proportional to the areas of the catchments outside the territory of Latvia.

Figure 1.5: Combined river network of the LV and LT SWAT+ modelling systems.

2. Calibration and validation approach

2.1. Calibration and validation targets

In hydrology and water quality models, the typical criteria used are the 'Nash-Sutcliffe efficiency (NSE) and R-squared. In this project NSE is our primary objective function for various variables (Eq.1). There are other criteria like RSE (Root Mean Squared Error), PBIAS (Percent Bias) and MSE that can be evaluated afterwards to evaluate the results of calibration and validation procedure.

$$ NSE = 1 - \frac{\frac{1}{n}\sum_{i=1}^{n}(y_{i,meas} - y_{i,sim})^2}{\frac{1}{n}\sum_{i=1}^{n}(y_{i,meas} - \overline{y}_{meas})^2} = 1 - \frac{RMS^2}{\text{var}(Y_{meas})} $$

(Equation 1)

Table 2.1: Key residual criteria (Bennett et al., 2013).

ID	Name	Formula	Range	Ideal value	Notes
4.1	Residual plot	~	–	–	Plot residuals against the predictor variable(s), look for curvature or changes in magnitude as the predictor variable changes.
4.2	QQ plot	~	–	–	Plots the inverse distribution (quantile) function of residuals against normal distribution quantile function. Look for curvature and divergence away from the mean diagonal (Fig. 7).
4.3	Bias	$\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)$	$(-\infty, +\infty)$	0	Calculates the mean error. Result of zero does not necessarily indicate low error due to cancellation.
4.4	Mean Square Error (MSE)	$\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2$	$(0, \infty)$	0	Calculates a mean error (in data units squared), which is not effected by cancellation. Squaring the data may cause bias towards large events.
4.5	Root Mean Square Error (RMSE)	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$	$(0, \infty)$	0	MSE error (4.4) except result is returned in the same units as model, which is useful for interpretation.
4.6	Mean Absolute Error (MAE)	$\frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i|$	$(0, \infty)$	0	Similar to RMSE (4.5) except absolute value is used instead. This reduces the bias towards large events; however, it also produces a non-smooth operator when used in optimisation.
4.7	Absolute Maximum Error (AME)	$\max|y_i - \hat{y}_i|$	–	–	Records the maximum absolute error.

Following sample criteria for effective hydrological and water quality optimization are proposed taking into consideration recommendations made by Moriasi et al. (2007) and Bennett et al (2013), Tables 2.1-2.2.

Table 2.2: General performance ratings recommended statistics for a hydrological and water quality model based on research by Moriasi et al. (2007).

Performance Rating	RSR	NSE	PBIAS (%)		
			Streamflow	Sediment	N, P
Very good	$0.00 \leq RSR \leq 0.50$	$0.75 < NSE \leq 1.00$	PBIAS < ±10	PBIAS < ±15	PBIAS < ±25
Good	$0.50 < RSR \leq 0.60$	$0.65 < NSE \leq 0.75$	±10 ≤ PBIAS < ±15	±15 ≤ PBIAS < ±30	±25 ≤ PBIAS < ±40
Satisfactory	$0.60 < RSR \leq 0.70$	$0.50 < NSE \leq 0.65$	±15 ≤ PBIAS < ±25	±30 ≤ PBIAS < ±55	±40 ≤ PBIAS < ±70
Unsatisfactory	RSR > 0.70	NSE ≤ 0.50	PBIAS ≥ ±25	PBIAS ≥ ±55	PBIAS ≥ ±70

The proposed calibration and validation criteria are summarised in Tables 2.3 and 2.4.

o **Water quantity:** targets for daily observed vs modelled discharge are summarized in Table 2.3. The targets are lower as in Table 2.2 because Moriasi et al (2007) consider monthly values.

Table 2.3: Calibration and validation (parameter transfer) targets for hydrological observations vs. model outputs (daily values).

Action	NSE threshold	PBIAS threshold
Calibration	NSE>0.5	PBIAS<20%
Validation	NSE>0.3	PBIAS<30%

o **Water Quality:** monthly averages for all years (2006-2018) are calculated. The resulting 12 values of concentration (mg/l) are compared with related observations, and R^2 (correlation of two arrays of observation and simulation for these 12 values) and PBIAS are calculated. The calibration targets are set in Table 2.4.

Table 2.4: Calibration and validation (parameter transfer) targets for the water quality observations vs. model outputs.

Action	R^2 threshold, N-NO3, N-tot	PBIAS threshold, all parameters
Calibration	R^2>0.5	PBIAS<40%
Validation	R^2>0.3	PBIAS<70%

The following is taken into account defining these targets:

- All targets are applied to concentrations.

- R2 target is not applicable for total phosphorus and phosphates. Concentrations of these substances are dominated by point sources and therefore correlation based on annual cycle is irrelevant.

- PBIAS targets correspond to at least "Good" performance rating[1] for calibration, and to at least "Satisfactory" performance rating for validation (coefficient transfer).

Besides, the hydrographs should be well predicted and the model must represent correct baseflow levels and peaks and recessions of water flow should be comparable to measurement data. Systematic deviations of the modelled hydrographs from the measured hydrographs should be corrected during the calibration.

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[1] According to Moriasi et al (2007).

2.2. Calibration strategy

Latvian territory is divided into regions (see Section 2.3) according to the runoff formation hydrological conditions and pollution generation situation. We consider 7 hydrological regions in our project. One catchment is further selected as a representative case for each hydrological region for the calibration. After the calibration the parameterization will be extrapolated to the catchments within the same region; the other observation stations in the region will be used for the validation of the model.

Selecting the catchments for calibration should ensure that these catchments are located in one specific dominant hydrological region and not influenced with trans-boundaries areas. During the extrapolation (or parameter transfer) several watersheds may belong to different regions. That is perfectly normal, because extrapolation is considering regional differences in more detailed way.

Holistic multi-site calibration strategy should consider several aspects:

1. **Bottom-up or top-down approach** for calibration/validation/regionalization. Calibration could be done by a top-down or bottom-up approach. In a top-down approach, we start from the overall view and try to find rules/strategies that will be applied over the entire area, with the hope that these strategies lead to an overall improvement of the model performance. In a bottom-up approach, small areas are intensively parameterized, and these parameters are then transferred to other areas, also with the hope that these transferred parameter sets lead to better parameterizations. As an example, the top-down looks for strategies that affect the entire basin (e.g. all organic fertilization is reduced by 15%). In this project we use the top-down strategy to calibrate the entire selected basins. Then, after a successful calibration and validation of pilot basins in each hydrological region we can extrapolate the parameters to the other catchments in the same hydrological category (bottom-up). Non-calibrating basins should be validated by using the extrapolated parameters of neighbor basins in the same hydrological category.

2. **Multi variables or single variable strategy.** Multi variable calibration and validation were implemented. The applied variables are river flow and in-stream NO_3 concentration, total nitrogen (N) concentration, PO_4 concentration and total phosphorus (P) concentration to be calibrated simultaneously. Respectively, as it is common in calibration, one starts from upstream to downstream and flow, then nitrate, phosphate and afterwards total N/total P. Because the water quality monitoring is done for concentrations as well as the water management requirements of the WFD are targeting concentration, we decided to use concentrations for the calibrations (instead of loads).

3. **Manual or automatic strategy for calibration.** Automatic calibration methods were available for SWAT2012 using the SWAT CUP 2012 software. This is not the case for

SWAT+ anymore. Therefore, the manual calibration will be performed starting from the model parameters of similar region in Lithuania, PAIC (2022c).

4. **Single-site or Multi-Site calibration and validation (water quantity).** For water quantity modelling we used multi-site calibration. So, there were at least one or more stations which will be used at the same time for calibration. But there were some exceptions for some bigger catchments depending on data availability and the location of the flow station (e.g. if this is so upstream and/or with many transboundary or inlets from neighbor catchments), we may have one station for calibration of flow and another (others) for validation only.

5. **Single-site or multi-site calibration and validation (water quality)** For water quality we have used single site calibration (the station which is more data rich and more downstream and closer to the output of the reach) and we validated the model with other measured points. The reason for this preference is to try to decrease the several sources of parameter and observation uncertainty which might originate from other stations. When there are few measured data points in one station that is used in the calibration procedure, unwanted uncertainty might be added to calibration procedure. Therefore, the decision was made to calibrate only with the high-quality gauging station because otherwise inadequate data will lead to erroneous model parameters and poor model identification. As a consequence, only a limited number of gauging stations had sufficient data points which is not enough to support multi-site calibrations in water quality and the stations that were not used in the calibration were used for validation.

6. **Using additional software** for sensitivity analysis, calibration, validation and uncertainty analysis. SWAT-CHECK. SWAT+ error and mass balance checker which analyses the annual water yield components, phosphorus cycle components, nitrogen cycle components and crop growth cycle was not used. The reason for this is experience in PAIC (2022c), indicating that SWAT Check is not tuned for the work with SWAT+ software yet.

The final practical plan of calibration and validation consists of several steps:

1: Parameterization with change in original coefficients and initial condition: It consists of three different categories:

a) Hydrological Parameterization with Impact on Flow, in stream N and in stream P.

b) Calibration of Water Quality with Nitrogen Parameters with Impact on in stream N concentration. This can be nitrogen initial condition, denitrification rate coefficients and in-stream processes, coefficients etc.

c) Calibration of Water Quality with Phosphorus Parameters and Soil Erosion Parameters with Impact on in stream P concentration. This can be initial condition in the soil profile, soil erodibility and in-stream processes coefficients etc.

2: **Adjustment of fertilization model:** The fertilization model in essence is the output of the simpler plant growth model; as such it cannot be assumed as pure input data. The approach of using two adjustment multiplicators (one for N, another for P) for whole modelling domain was adopted because the overfertilization issue cannot be associated with particular (calibration) catchment.

3: Changing the calculation methods: In all pilot basins, for the calculation of evapotranspiration, IPET.bsn was set to 2 (Hargreaves' method) instead of 1 (default as PET method) and IRTE.bsn was set from IPET=0 the default value as variable travel-time to value 1 which is Muskingum method. The Hargreaves method was chosen to solve systematic underestimation of summer ET and systematic overestimation of baseflow in winter period.

2.3. Observation data and regionalization

The network of monitoring stations of Latvian Environment, Geology and Meteorology Centre is shown in Figure 2.1 for both water quantity and quality stations. The location of the water quality stations is also shown in Figure 2.2.
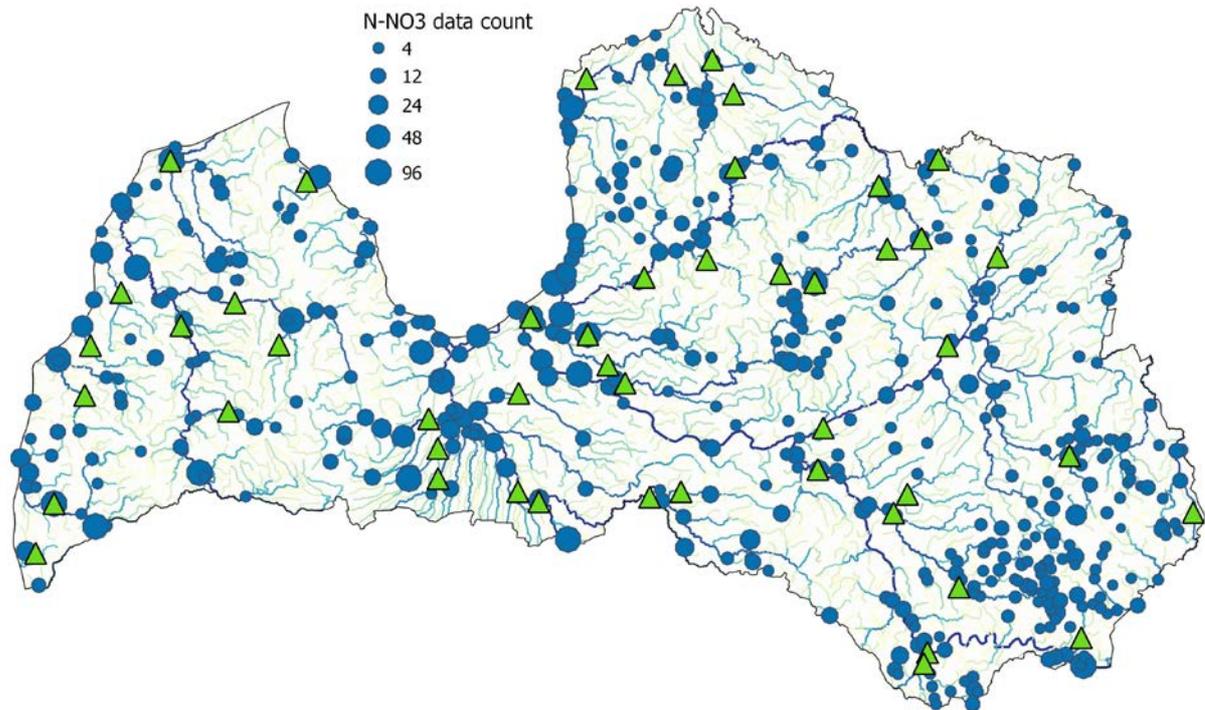
Figure 2.1: Location of the water quantity (green triangles) and quality (blue circles) monitoring stations. Circle size is proportional to the number of observation records.

The hydrometric stations are rather evenly distributed in the river network.

The location of the water quality stations and the number of the observations there follow different strategic patterns:
- There are several stations for monitoring transboundary pollution.
- More than average stations are located:
  - Up- and/or downstream larger towns
  - At the river mouths
- There are multiple stations which are visited for just one year during the six-year period as required by the EU Water Framework Directive, covering the whole seasonal cycle; multiple of such stations can be seen in Latgale, Figure 2.2.

In general, water quality observations reveal higher nitrate-nitrogen values:

1. In transboundary rivers Bārta, Venta, and especially, rivers of Lielupe RBD flowing from the agricultural regions of Lithuania.

2. In the agricultural lowlands – Viduslatvijas, Austrumlatvijas and Kursas lowlands, as well as occasionally in the small streams, directly entering the Baltic Sea.
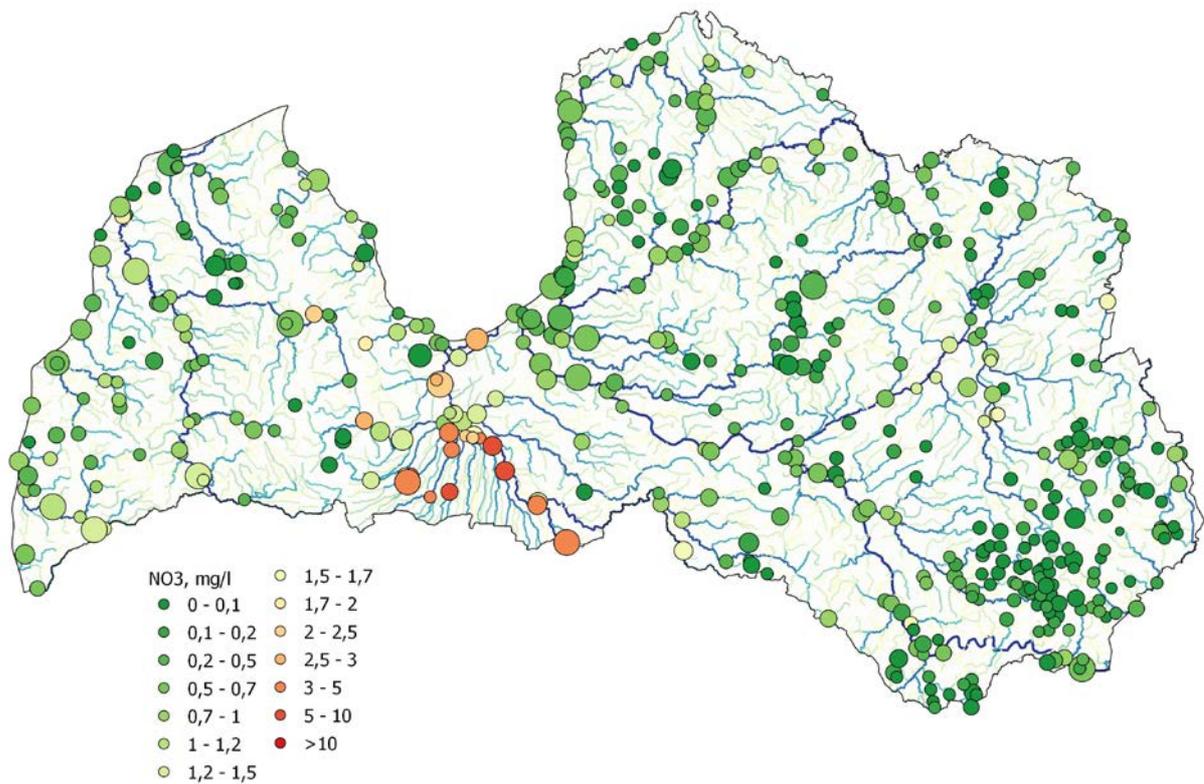
Figure 2.2: Location of the water quality observation stations. Circle size is proportional to the number of observations while color – to the mean N-NO$_3$ concentration.

We used the terrain, soils, river basins borders, and physiogeographic zoning of Latvia[2] for the establishing 7 regions of Latvia for calibration and validation purposes. We expect that SWAT+ model parameters might be similar within each of these regions, see Figure 2.3.

1. Region r1I: Piejūras lowland, extending along the seashore of Latvia.

2. Region r2I: inland part of Kurzeme, including both Kursas high- and lowlands.

3. Region r3I: Viduslatvijas lowland.

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[2] https://lv.wikipedia.org/wiki/Latvijas_%C4%A3eogr%C4%81fija

4. Region r4I: Vidzeme, Alūksne and Idumeja highlands.

5. Region r5I: Austrumlatvija lowlands.

6. Region r6I: Latgales and Augšzemes highlands.

7. Region r7I: Metsepole and Tālava lowlands of northern Vidzeme.
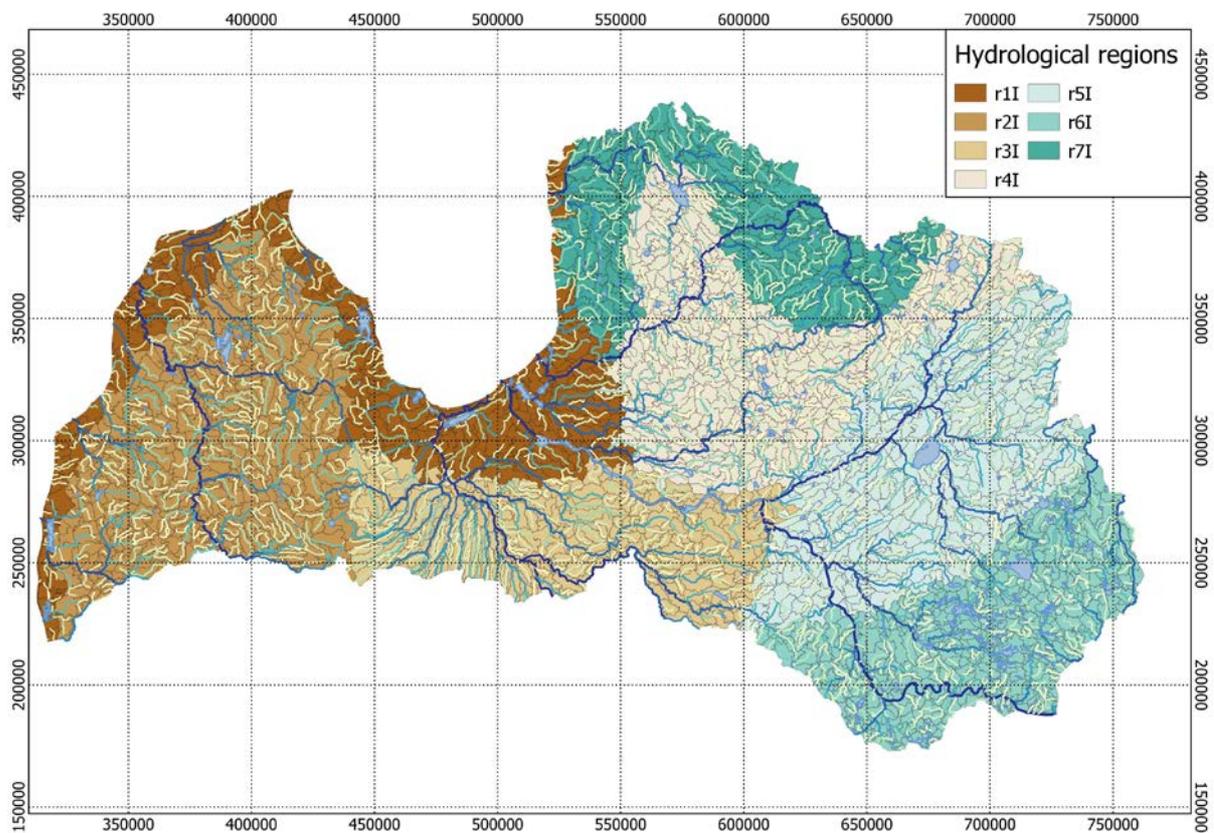
Figure 2.3: Regions for calibration and validation of SWAT+ model

3. Water quantity

3.1. Region r1I

Hydrometric station Misa-Lielveisi was selected for the calibration in the coastal hydrological region r1I.
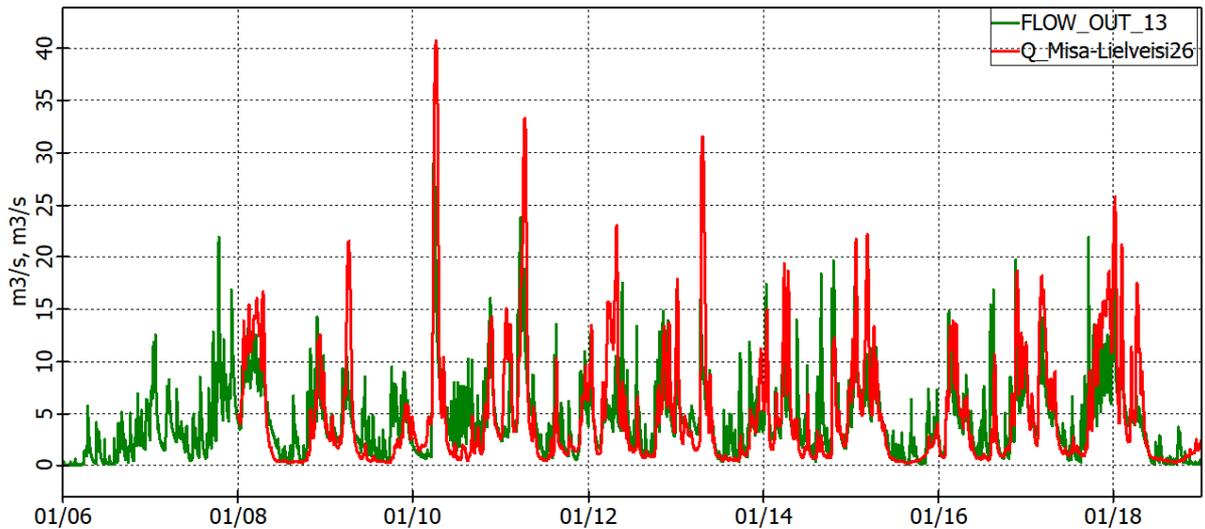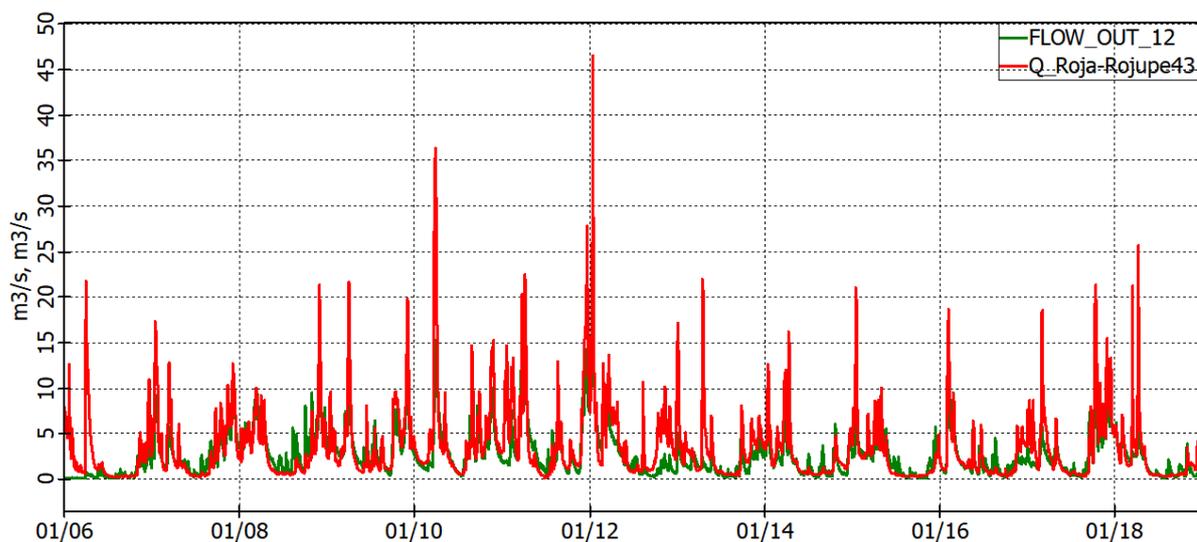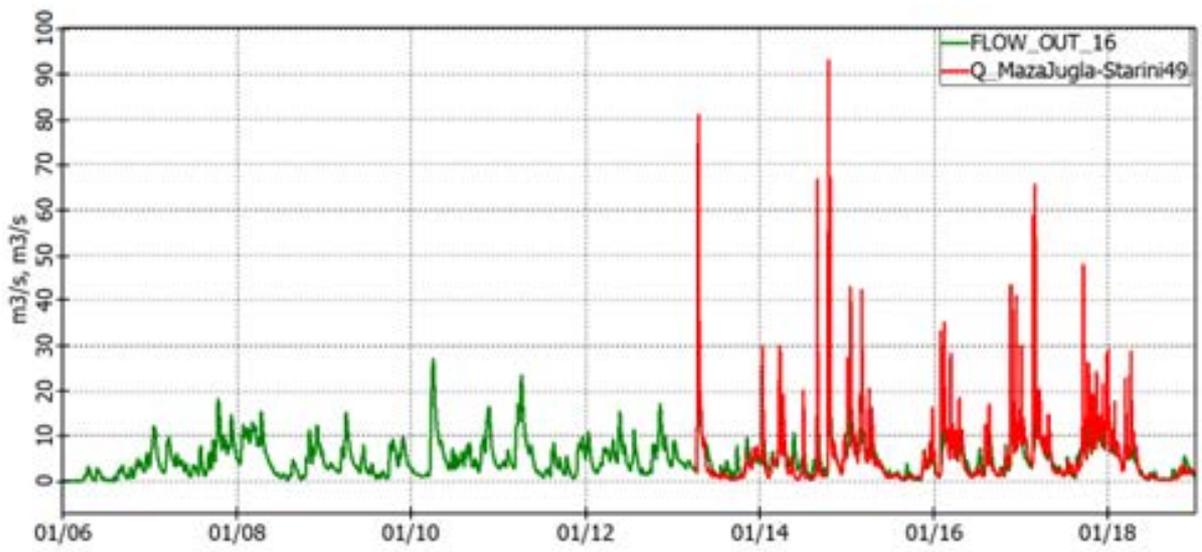

Figure 3.1: Time graph of the observed (red) and modelled (green) discharges at Misa-Lielveisi.
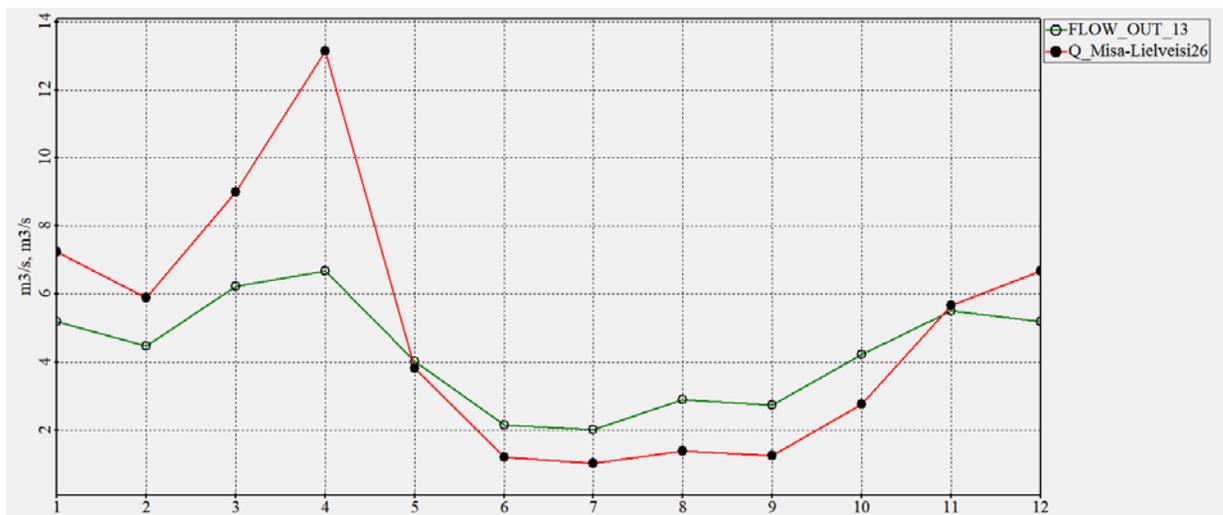
Figure 3.2: Monthly observed (red) and modelled (green) discharges at Misa-Lielveisi.

The calibration targets were reached for Misa-Lielveisi, see Table 3.1.

The time graph of the observed and modelled discharges is shown in Figure 3.1. The average seasonal cycle of discharges is shown in Figure 3.2; it indicates satisfactory representation of Misa seasonal hydrograph. SWAT+ overestimates the summer low-flow and underestimates the spring snowmelt flood in Misa.

Table 3.1: Quantitative results of calibration (bold) and validation in region r1I.

STAID	STANAME	NSE	PBIAS	Region
25	Ogre-Lielpeči	0,09	-62%	r1
26	**Misa-Lielveisi**	**0,50**	**-9%**	**r1**
43	Roja-Rojupe	0,55	-25%	r1
49	Mazā Jugla-Stariņi	0,41	-18%	r1
60	Irbe-Vičaki	0,61	-20%	r1
64	Lielā Jugla-Zaķi	0,54	-13%	r1

The SWAT+ coefficients of the Misa catchment were transferred to the other catchments of the region r1I and the validation was performed.

Validation targets were not reached in station Ogre-Lielpeči, see Table 3.1. The observed mean discharge 33.6 m^3/s seems too high and wrong because it corresponds to unrealistically high annual runoff layer depth 627 mm, and exceeds reported[3] mean discharge of approximately 17 m^3/s.

The validation targets were reached for the other 4 rivers of the region r1I, see Table 3.1.

- The time graph of the observed and modeled discharges is shown in Figure 3.3 and the average seasonal cycle of discharges in Figure 3.4 for Roja-Rojupe. The seasonal cycle is represented rather good in the model underestimating the discharge during the cold half-year.
- The time graph of the observed and modeled discharges is shown in Figure 3.5 and the average seasonal cycle of discharges in Figure 3.6 for Mazā Jugla - Stariņi. The observations start only in 2013 in this station. Model underestimates winter (January-April) discharges in Mazā Jugla.
- The time graph of the observed and modeled discharges is shown in Figure 3.7 and the average seasonal cycle of discharges in Figure 3.8 for Irbe-Vičaki. The correlation of the time graphs of observed and modelled discharges is very good. The model underestimates the discharges during the cold half-year, similar to Roja.
- The time graph of the observed and modeled discharges is shown in Figure 3.9 and the average seasonal cycle of discharges in Figure 3.10 for Lielā Jugla-Zaķi. Similar to Misa, SWAT+ overestimates the summer low-flow and underestimates the spring snowmelt flood and winter discharges in Lielā Jugla.

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[3] https://lv.wikipedia.org/wiki/Ogre_(upe)

The validation results in all rivers of the region R1I are similar, see Table 3.1. Nash-Suttcliff efficiency varies between 0,4 and 0,6. Model shows 15 to 25% lower discharges as the observations.

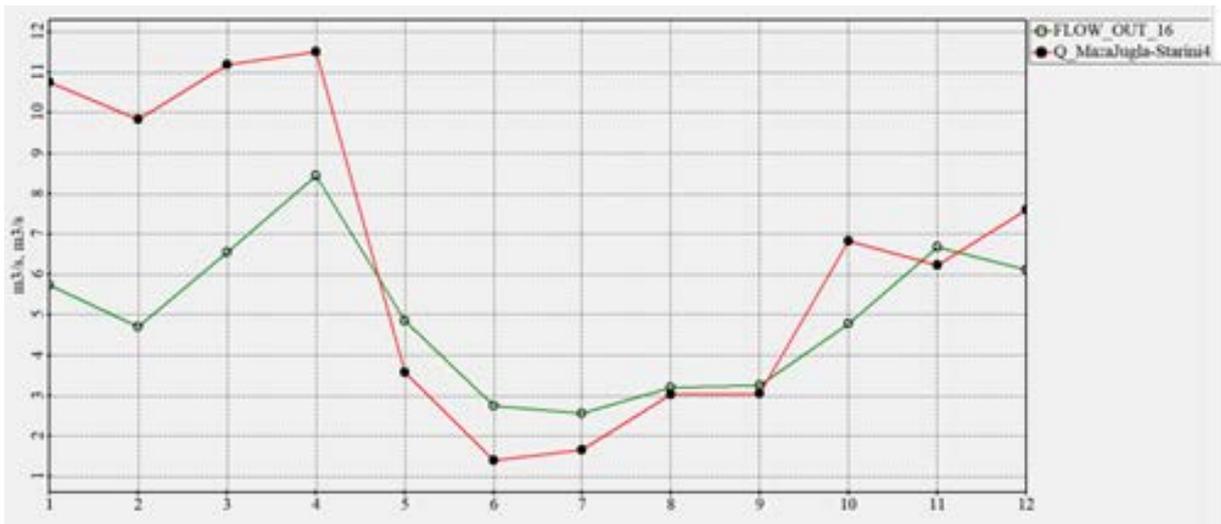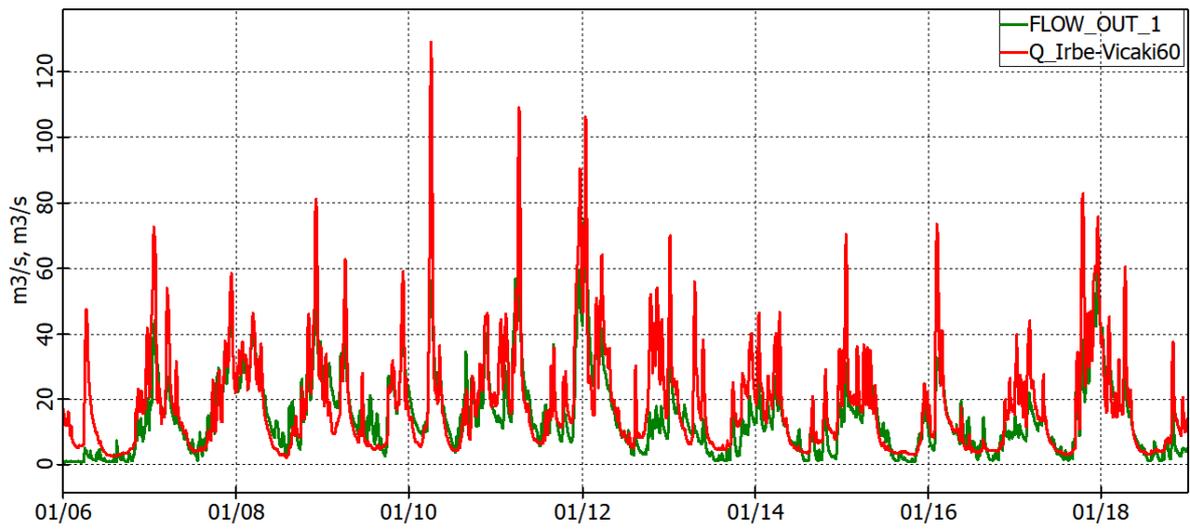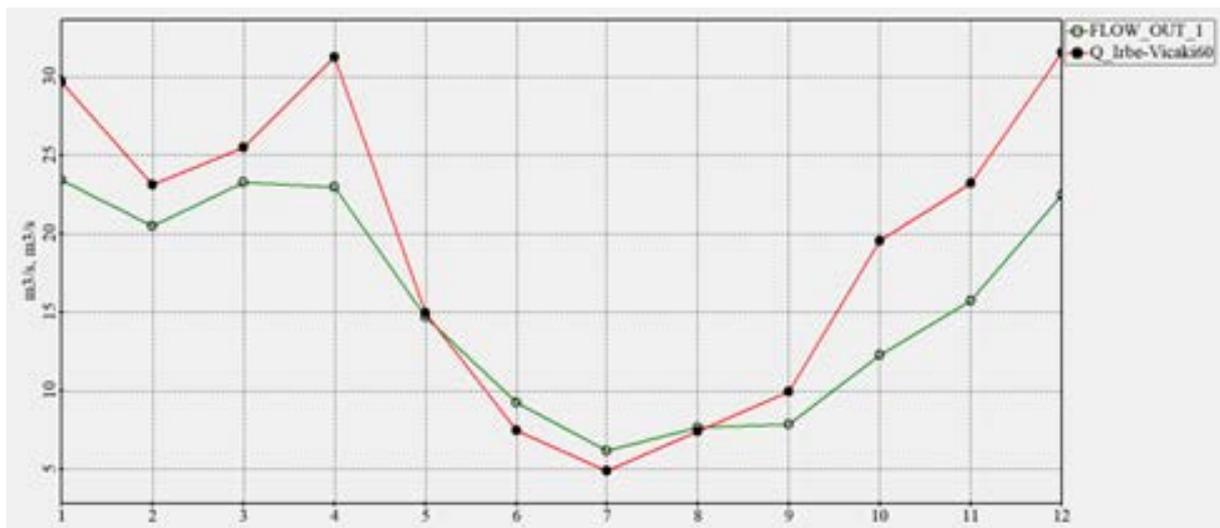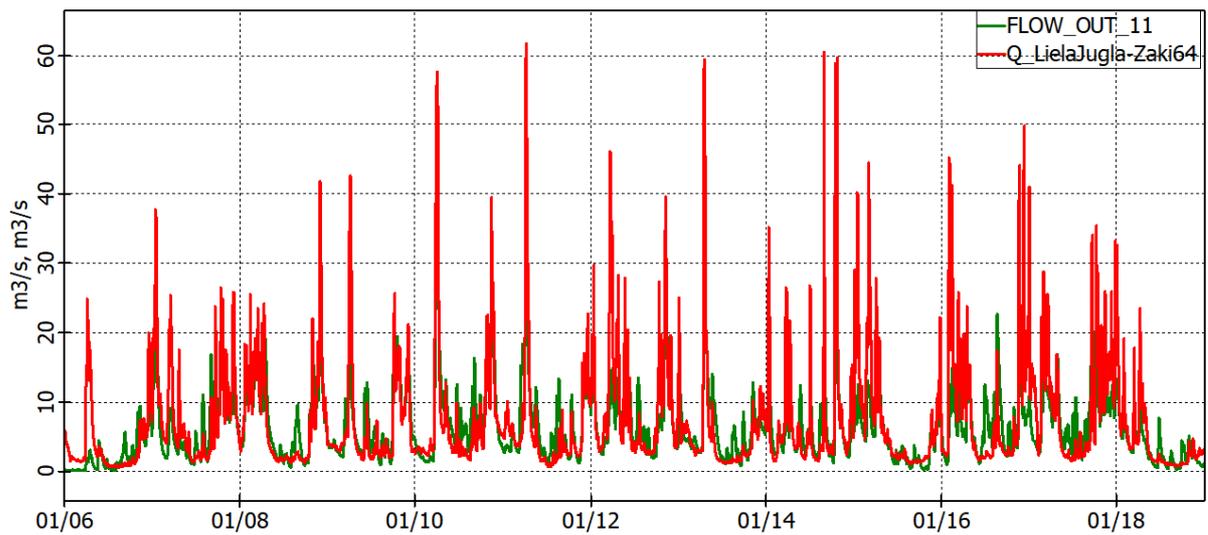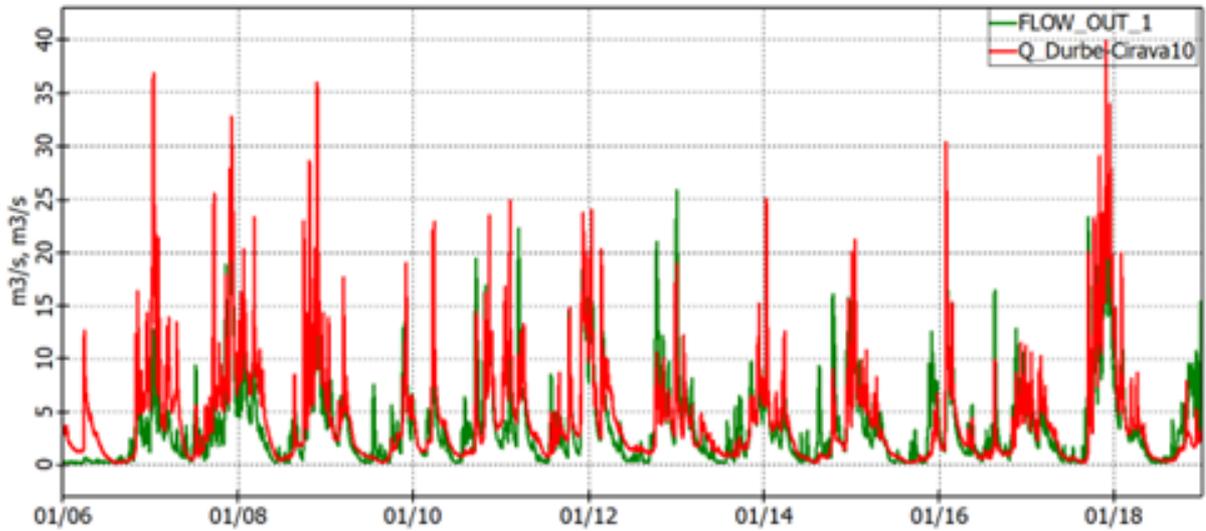Figure 3.3: Time graph of the observed (red) and modelled (green) discharges at Roja-Rojupe.
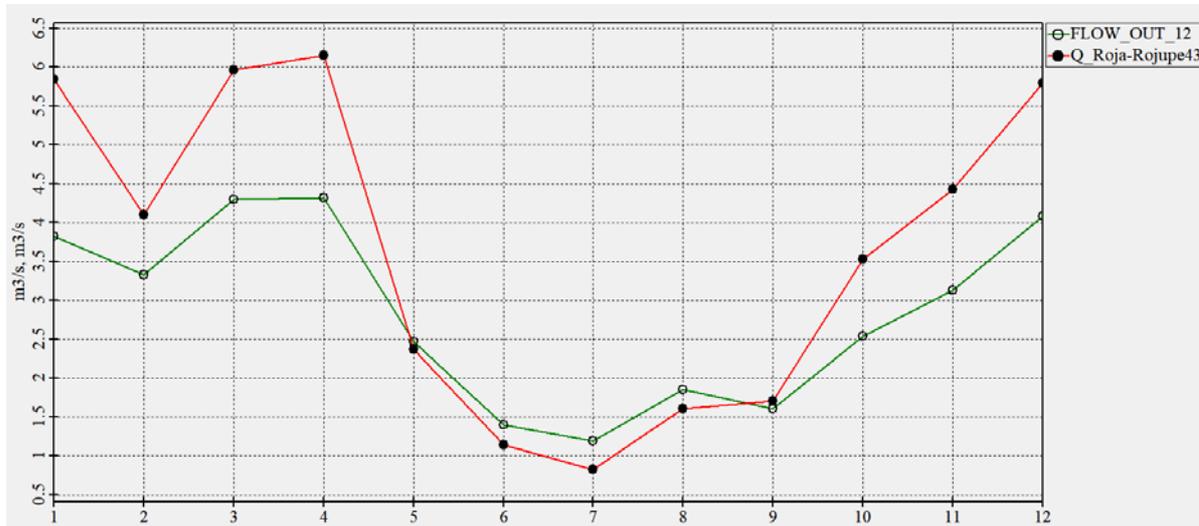
Figure 3.4: Monthly observed (red) and modelled (green) discharges at Roja-Rojupe.

Figure 3.5: Time graph of the observed (red) and modelled (green) discharges at Mazā Jugla - Stariņi.

Figure 3.6: Monthly observed (red) and modelled (green) discharges at Mazā Jugla - Stariņi.

Figure 3.7: Time graph of the observed (red) and modelled (green) discharges at Irbe-Vičaki.

Figure 3.8: Monthly observed (red) and modelled (green) discharges at Irbe-Vičaki.

Figure 3.9: Time graph of the observed (red) and modelled (green) discharges at Lielā Jugla-Zaķi.
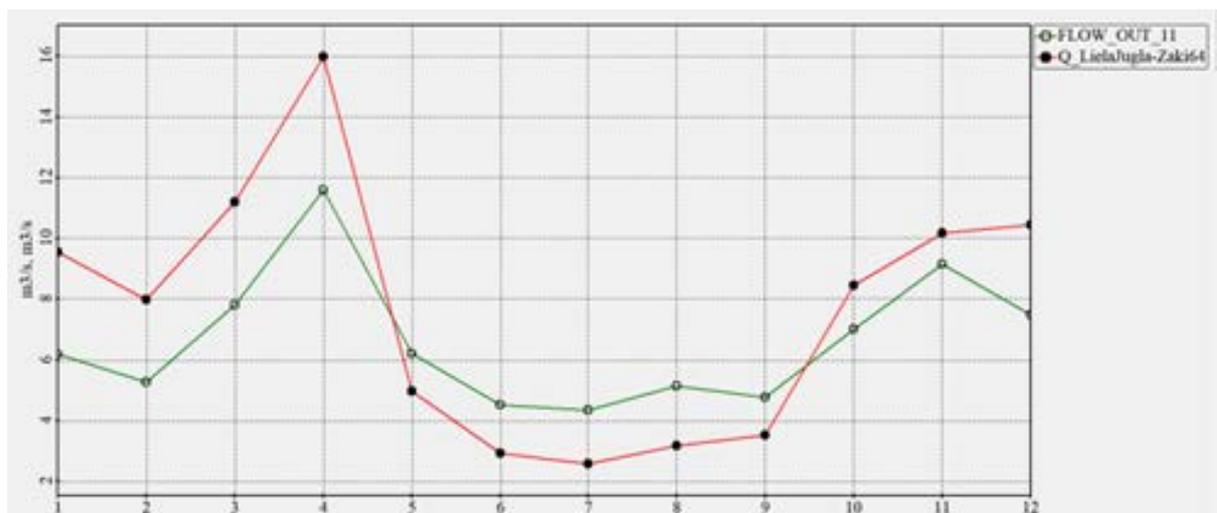
Figure 3.10: Monthly observed (red) and modelled (green) discharges at Lielā Jugla-Zaķi.

3.2. Region r2I

Hydrometric station Durbe-Cīrava was selected for the calibration in the hydrological region r2I of Kurzeme highlands.

Figure 3.11: Time graph of the observed (red) and modelled (green) discharges at Durbe-Cīrava.
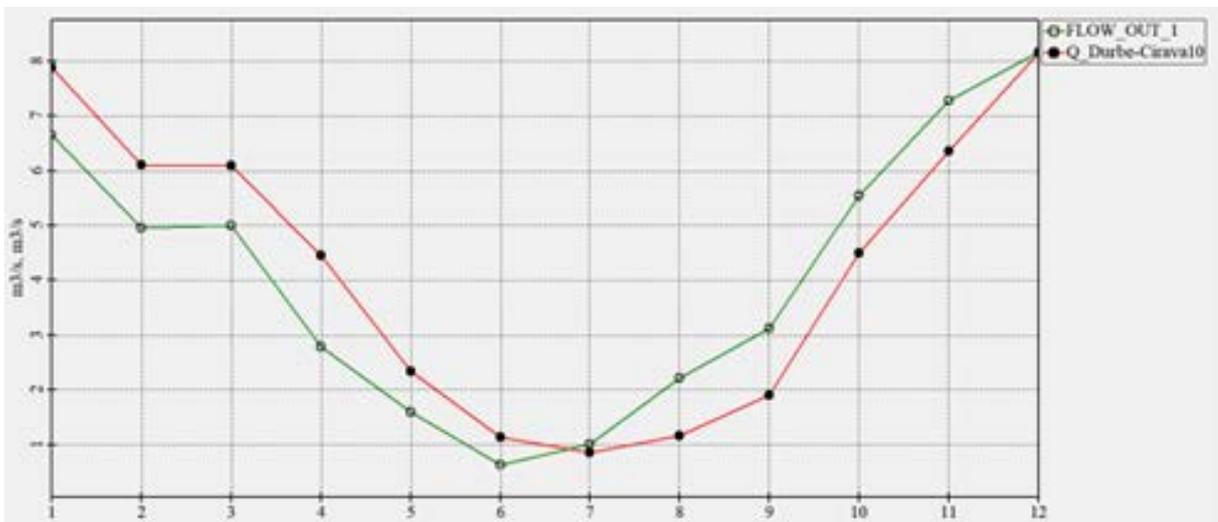
Figure 3.12: Monthly observed (red) and modelled (green) discharges at Durbe-Cīrava.

The calibration targets were reached for Durbe-Cīrava, see Table 3.2.

The time graph of the observed and modeled discharges is shown in Figure 3.11. The average seasonal cycle of discharges is shown in Figure 3.12; it indicates a very good representation of

a seasonal hydrograph of Durbe. SWAT+ slightly overestimates the discharge of the 2nd half-year and underestimates the discharge during the 1st half-year.

Table 3.2: Quantitative results of calibration (bold) and validation in region r2I.

STAID	STANAME	NSE	PBIAS	Region
10	**Durbe-Cīrava**	**0,65**	**0%**	**r2**
12	Bārta-Dūkupji	0,72	13%	r2
20	Venta-Kuldīga	0,43	-44%	r2
37	Ciecere-Pakuļu HES	0,41	-16%	r2
40	Rīva-Pieviķi	0,56	-27%	r2
42	Abava-Renda	0,52	-13%	r2
52	Užava-Tērande	0,65	9%	r2
72	Imula-Pilskalni	0,49	-15%	r2

The SWAT+ coefficients of the Durbe catchment were transferred to the other catchments of the region r2I and the validation was performed.

Validation targets were not reached in station Venta-Kuldīga, see Table 3.2. The observed mean discharge 118 m^3/s is obviously wrong because (a) it corresponds to unrealistically high annual runoff layer depth 514 mm, and (b) it exceeds even reported[4] mean discharge at Ventspils, approximately 93 m^3/s.

The validation targets were reached for other 6 rivers of the region r2I, see Table 3.2.

- The time graph of the observed and modeled discharges is shown in Figure 3.13 and the average seasonal cycle of discharges in Figure 3.14 for Bārta-Dūkupji. The match of the observed and modelled seasonal cycle is excellent, SWAT+ slightly overestimates the discharge throughout year. High NSE value may be a consequence of successful calibration of Bārtuva river basin in the Lithuanian SWAT+ model PAIC (2022c).

- The time graph of the observed and modeled discharges is shown in Figure 3.15 and the average seasonal cycle of discharges in Figure 3.16 for Ciecere-Pakuļu HES. The observations start only in 2013 in this station. Model underestimates winter (January-April) discharges in Ciecere, similarly to Mazā Jugla, see Section 3.1.

- The time graph of the observed and modeled discharges is shown in Figure 3.17 and the average seasonal cycle of discharges in Figure 3.18 for Rīva-Pieviķi. The model underestimates the discharges during the cold half-year.

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[4] https://lv.wikipedia.org/wiki/Venta

- The time graph of the observed and modeled discharges is shown in Figure 3.19 and the average seasonal cycle of discharges in Figure 3.20 for Abava-Renda. SWAT+ slightly overestimates the summer low-flow and underestimates the spring snowmelt flood and winter discharges in Abava.

- The time graph of the observed and modeled discharges is shown in Figure 3.21 and the average seasonal cycle of discharges in Figure 3.22 for Užava-Tērande. SWAT+ model provides an excellent match with the observed seasonal discharge values.
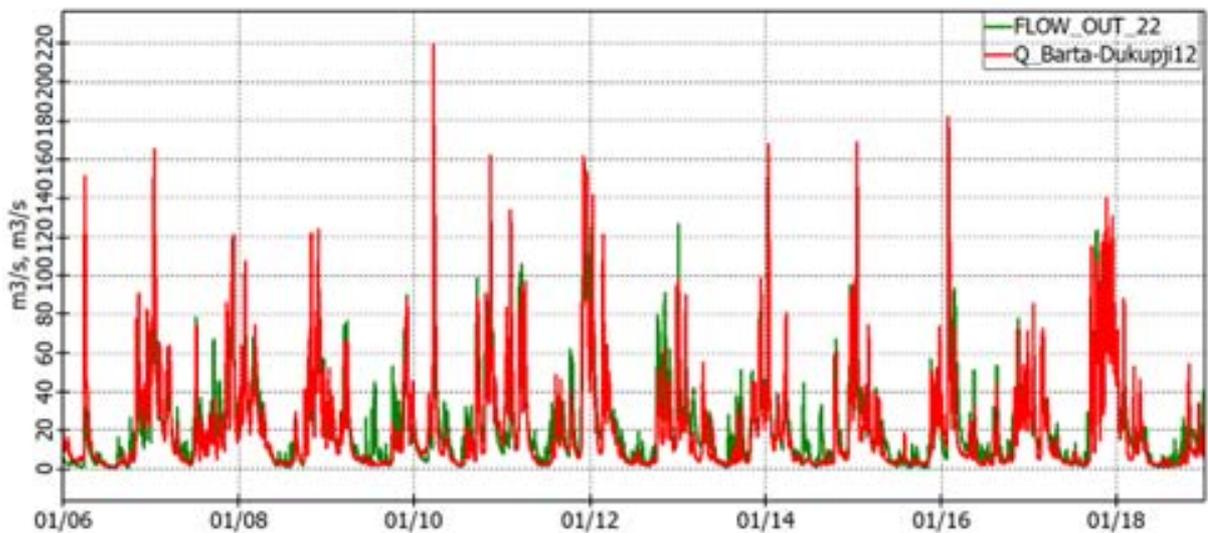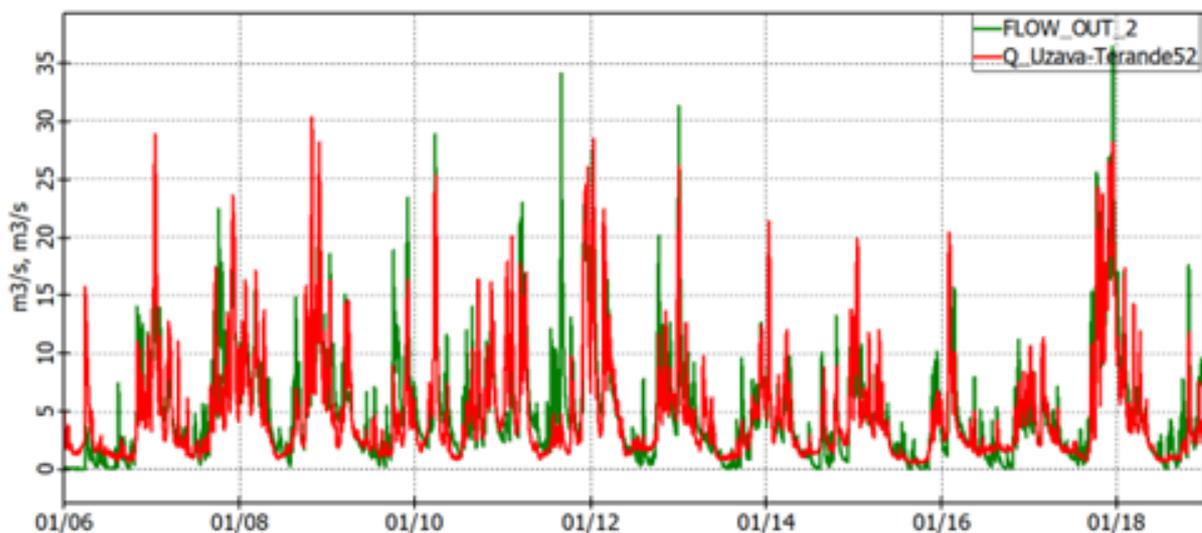

Figure 3.13: Time graph of the observed (red) and modelled (green) discharges at Bārta-Dūkupji.
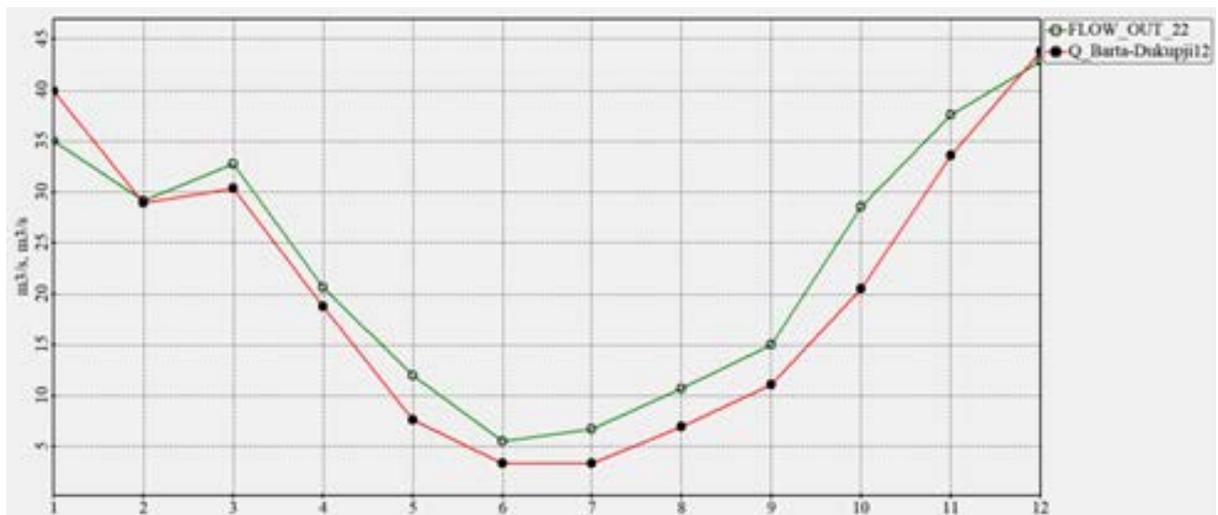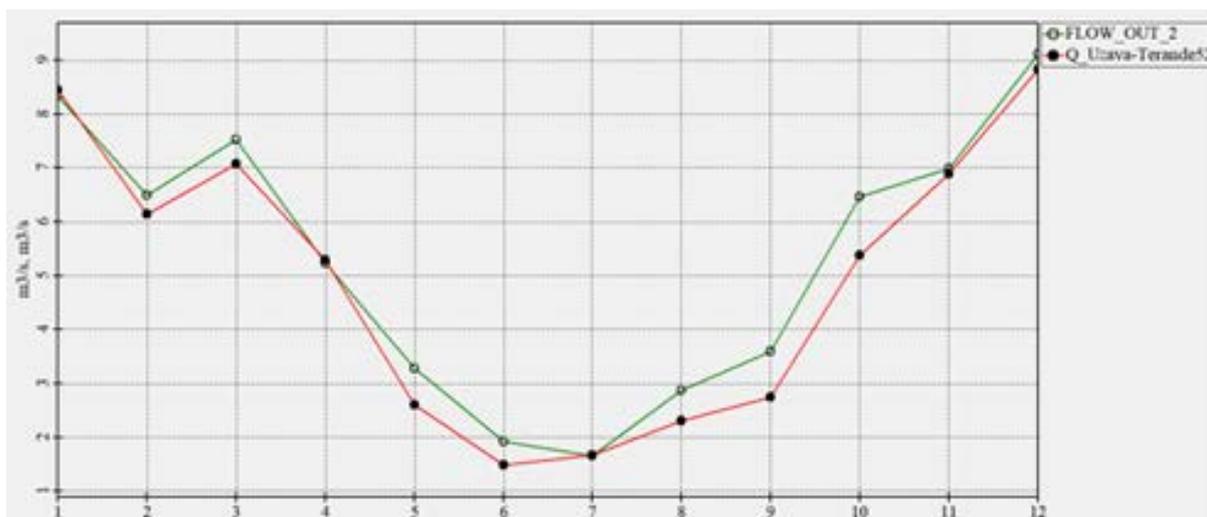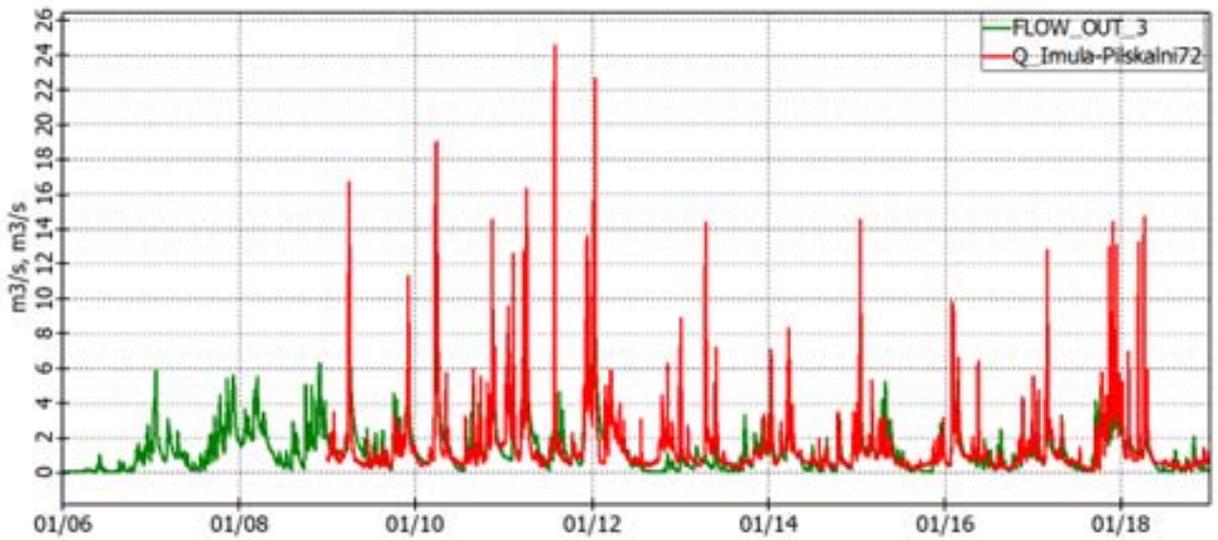

Figure 3.14: Monthly observed (red) and modelled (green) discharges at Bārta-Dūkupji.
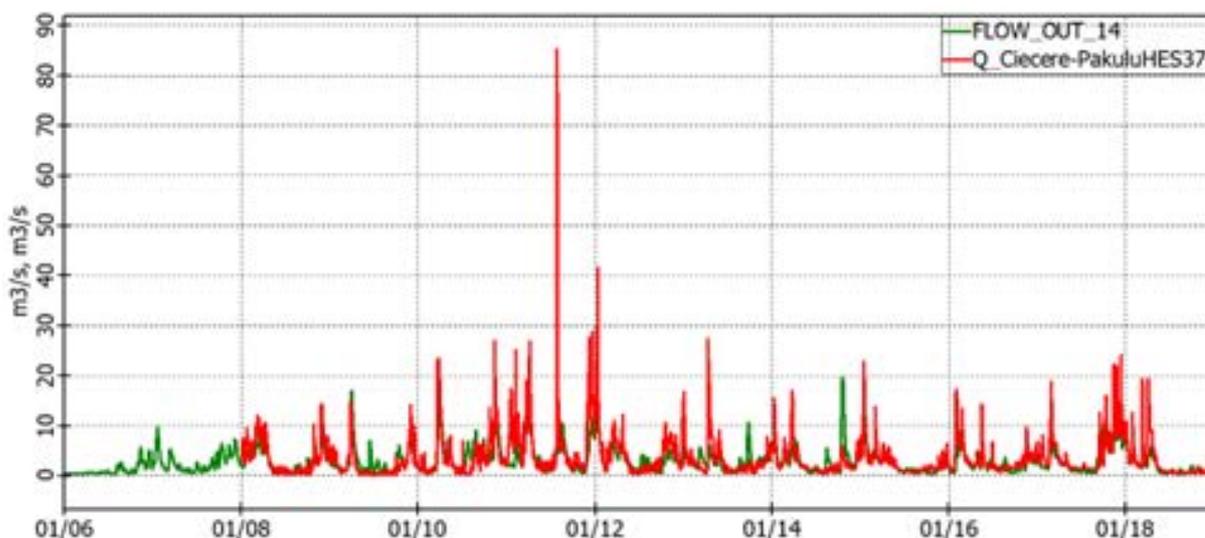
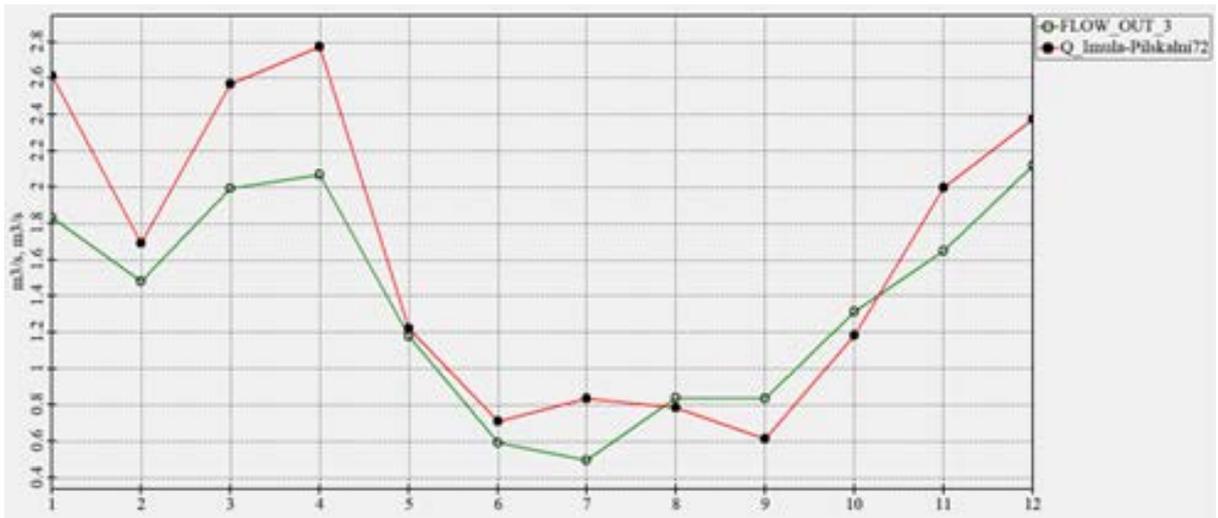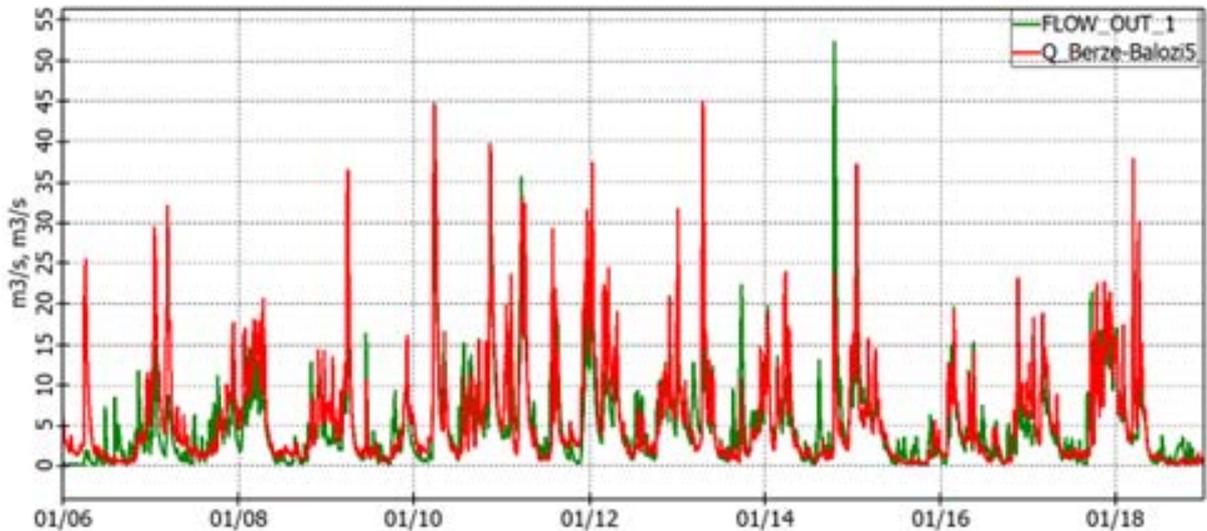Figure 3.15: Time graph of the observed (red) and modelled (green) discharges at Ciecere-Pakuļu HES.
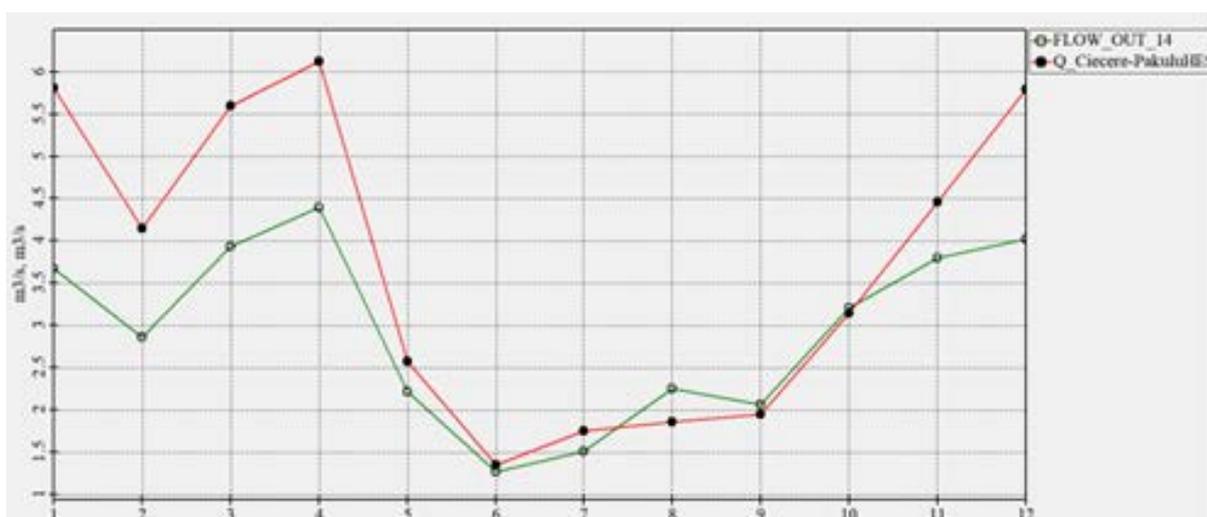
Figure 3.16: Monthly observed (red) and modelled (green) discharges at Ciecere-Pakuļu HES.

- The time graph of the observed and modeled discharges is shown in Figure 3.23 and the average seasonal cycle of discharges in Figure 3.24 for Imula-Pilskalni. Discharge observations in this station are missing for Year 2008. SWAT+ underestimates the spring snowmelt flood and winter discharges in Imula, similar to Abava.

The validation results in region r2I are generally better as in region r1I, see Tables 3.1 – 3.2. Nash-Suttcliff efficiency for some rivers reaches 0,7. The underestimation of the discharges by SWAT+ is not systematic and is slightly lower in this region.
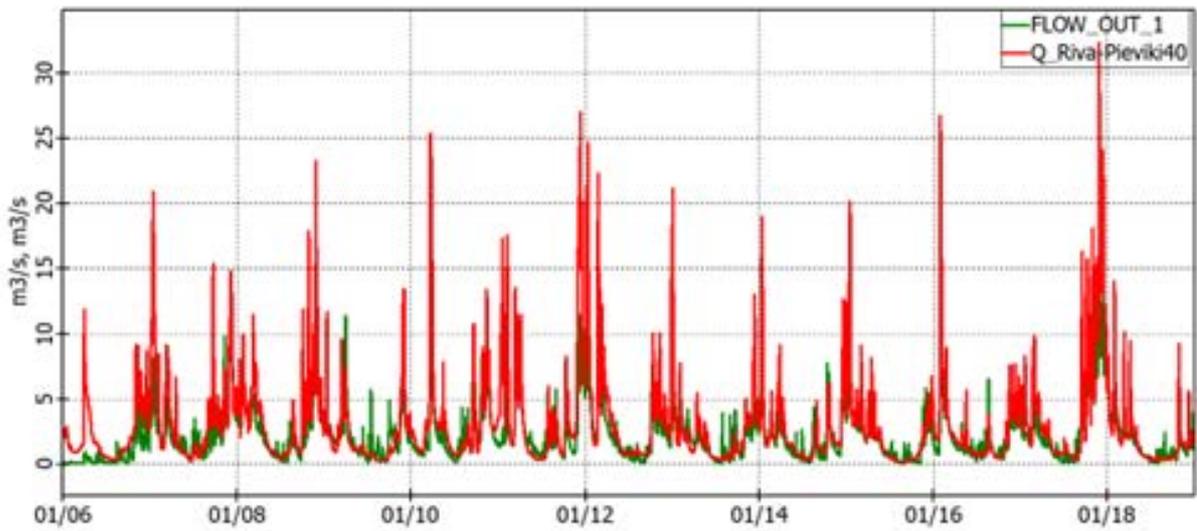
Figure 3.17: Time graph of the observed (red) and modelled (green) discharges at Rīva-Pieviķi.
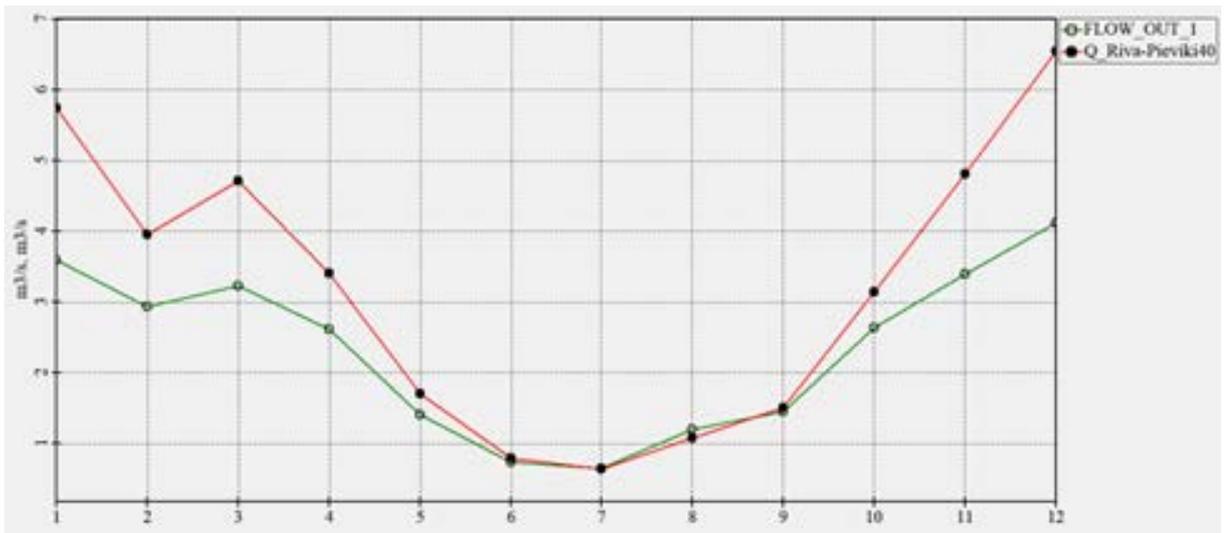
Figure 3.18: Monthly observed (red) and modelled (green) discharges at Rīva-Pieviķi.
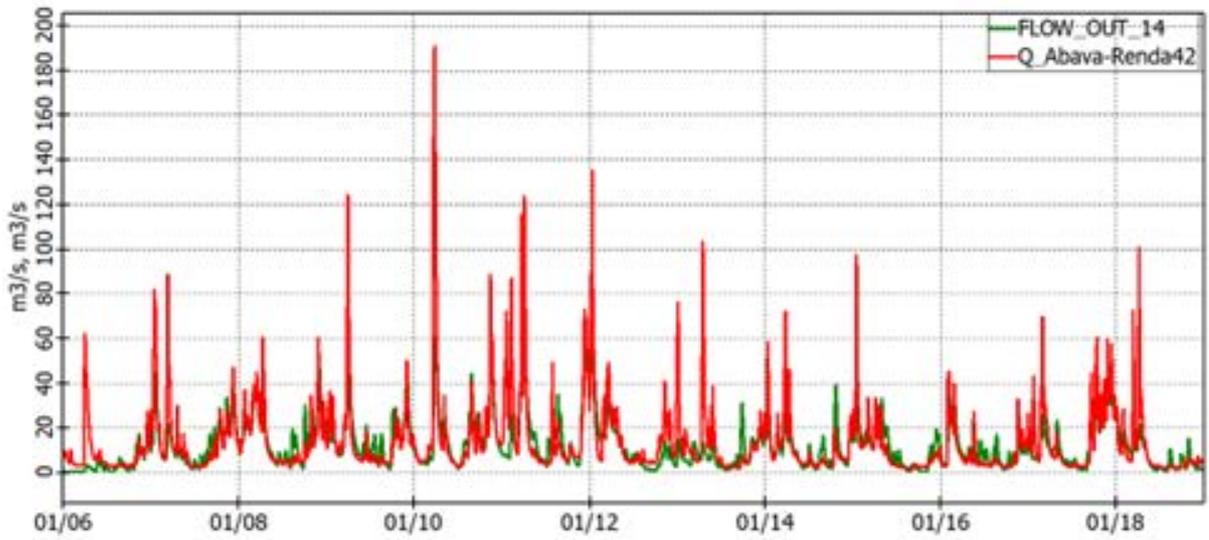
Figure 3.19: Time graph of the observed (red) and modelled (green) discharges at Abava-Renda.
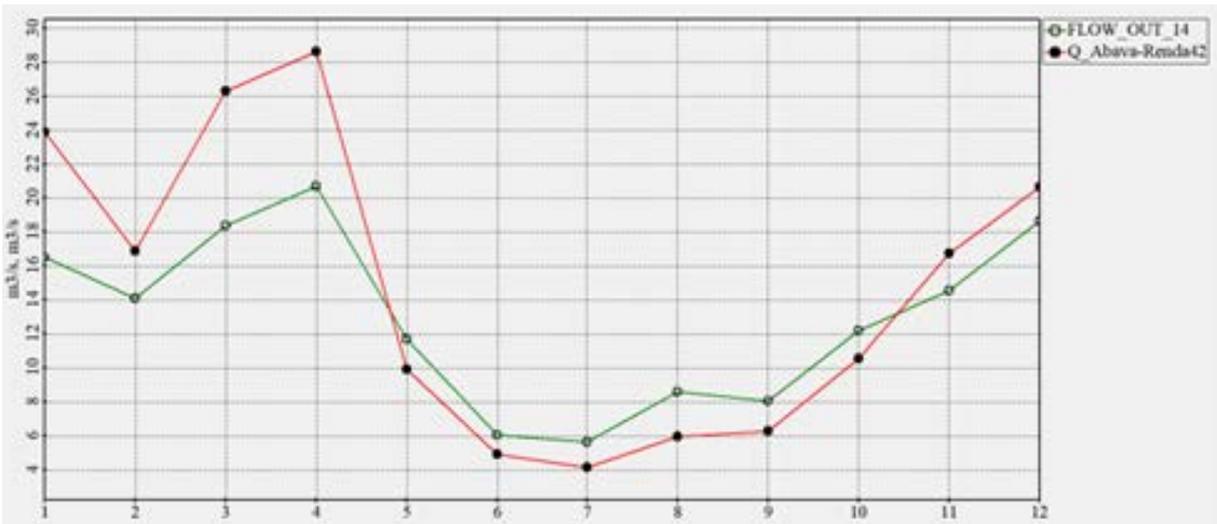
Figure 3.20: Monthly observed (red) and modelled (green) discharges at Abava-Renda.

Figure 3.21: Time graph of the observed (red) and modelled (green) discharges at Užava-Tērande.

Figure 3.22: Monthly observed (red) and modelled (green) discharges at Užava-Tērande.

Figure 3.23: Time graph of the observed (red) and modelled (green) discharges at Imula-Pilskalni.

Figure 3.24: Monthly observed (red) and modelled (green) discharges at Imula-Pilskalni.

3.3. Region r3I

Hydrometric station Bērze-Baloži was selected for the calibration in the hydrological region r3I of Zemgale lowlands.

Figure 3.25: Time graph of the observed (red) and modelled (green) discharges at Bērze-Baloži.
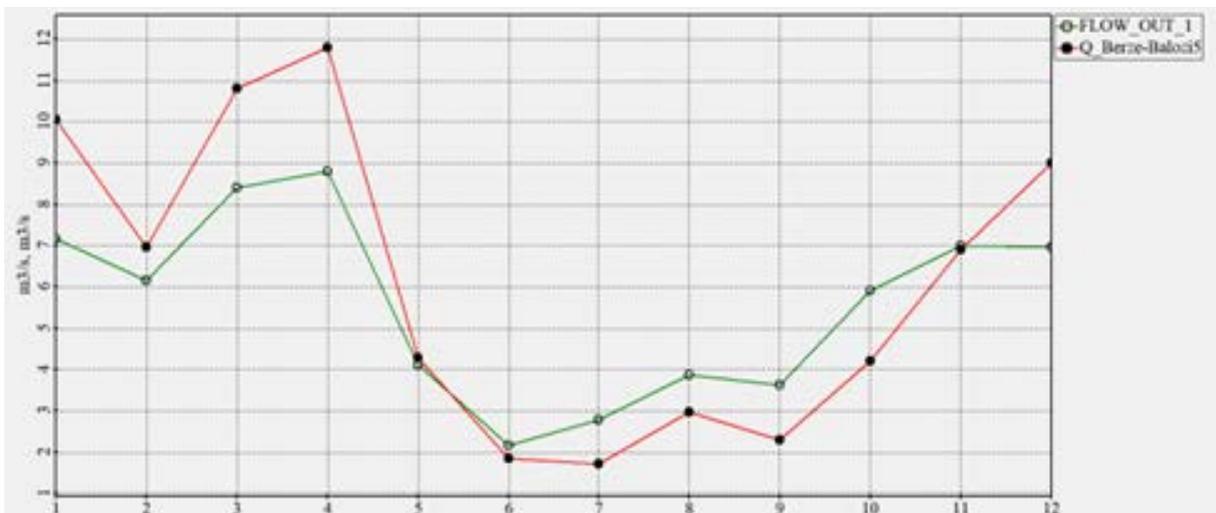
Figure 3.26: Monthly observed (red) and modelled (green) discharges at Bērze-Baloži.

The calibration targets were reached for Bērze-Baloži, see Table 3.3.

The time graph of the observed and modeled discharges is shown in Figure 3.25. The average seasonal cycle of discharges is shown in Figure 3.26; it indicates a good representation of a seasonal hydrograph of Bērze. SWAT+ overestimates the discharge of the warm half-year and underestimates the discharge during the cold half-year.

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Table 3.3: Quantitative results of calibration (bold) and validation in region r3I.

STAID	STANAME	NSE	PBIAS	Region
1	Aiviekste-Aiviekstes HES	0,21	-56%	r3
5	**Bērze-Baloži**	**0,64**	**-6%**	**r3**
6	Mūsa-Bauska	0,71	-2%	r3
7	Tērvete-Bramberģe	0,49	0%	r3
33	Lielupe-Mežotne	0,28	-54%	r3
50	Viesīte-Sudrabkalni	0,42	-22%	r3
51	Mēmele-Tabokine	0,50	-2%	r3
54	Svēte-Ūziņi	0,65	-14%	r3

The SWAT+ coefficients of the Bērze catchment were transferred to the other catchments of the region r3I and the validation was performed.

Validation targets were not reached in 2 stations, see Table 3.3:

- Aiviekste-Aiviekstes HES. The observed mean discharge 105 m³/s is too high because (a) it corresponds to unrealistically high annual runoff layer depth 495 mm, and (b) it exceeds the reported[5] mean discharge, approximately 57 m³/s.

- Lielupe-Mežotne. The observed mean discharge 109 m³/s is supposedly too high; it corresponds to annual runoff layer depth 343 mm. Further, Lielupe is a confluence of Mūsa and Mēmele rivers. The mean discharge at Mūsa-Bauska is in good agreement between the model and observations (26 m³/s). The catchment of Mēmele is comparable with the catchment of Mūsa, and their confluence gives the mean discharge at Lielupe Mežotne 56 m3/s; it corresponds to annual runoff layer depth 177 mm, i.e. almost 2 times lower as in observations. It is possible that the observation errors in hydrographic station Lielupe-Mežotne are caused by the errors of Q/H relations during ice and summer vegetation conditions.

The validation targets were reached for other 5 rivers of the region r3I, see Table 3.3.

- The time graph of the observed and modeled discharges is shown in Figure 3.27 and the average seasonal cycle of discharges in Figure 3.28 for Mūsa-Bauska. The match of the observed and modelled hydrograph and seasonal cycle is excellent. This by part is a consequence of successful calibration of Mūša river basin in the Lithuanian SWAT+ model PAIC (2022c).

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[5] https://en.wikipedia.org/wiki/Aiviekste

- The time graph of the observed and modeled discharges is shown in Figure 3.29 and the average seasonal cycle of discharges in Figure 3.30 for Tērvete-Bramberģe. The match of observed and modelled data is very good in this station. The model slightly underestimates the discharges during the cold half-year and overestimates – during warm half-year.
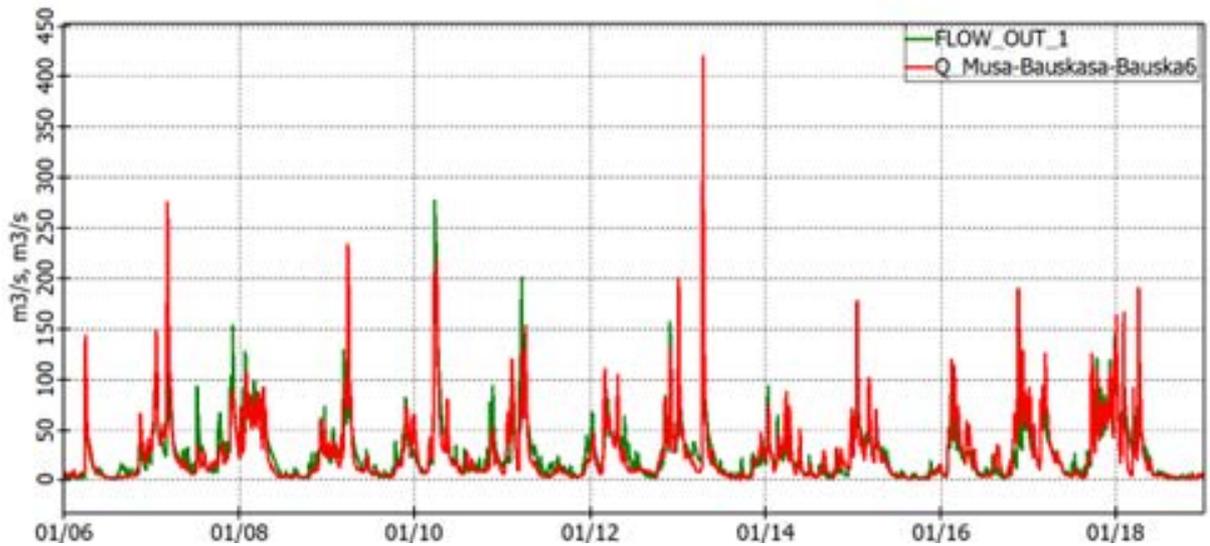

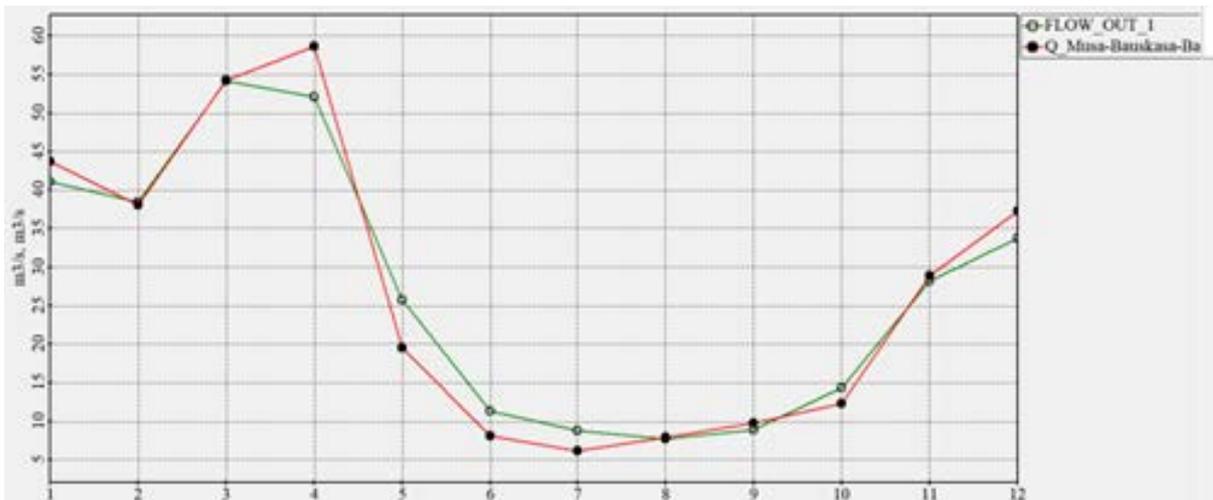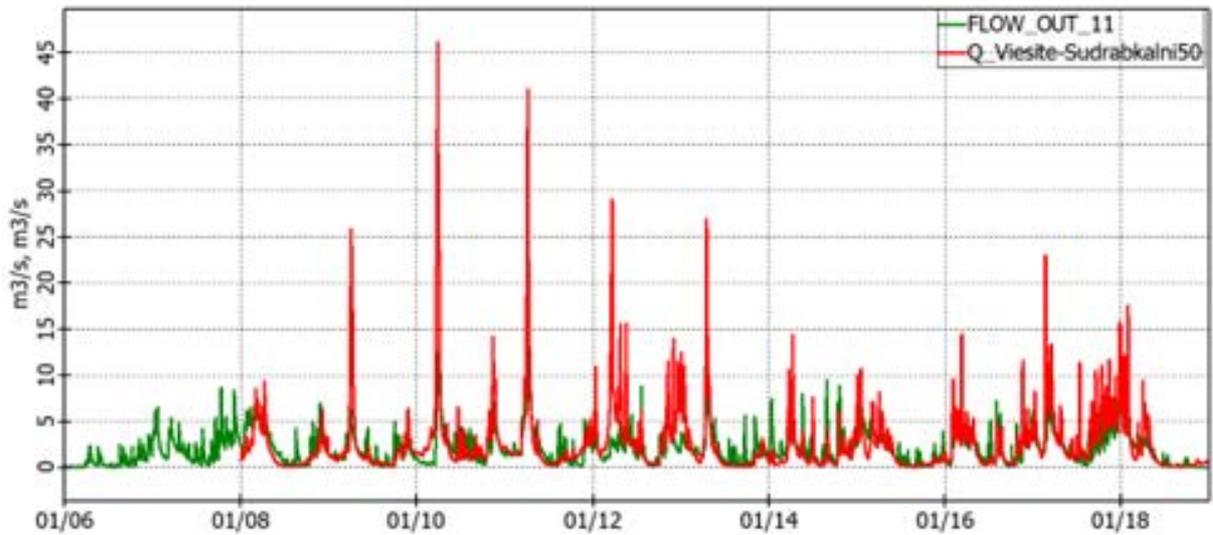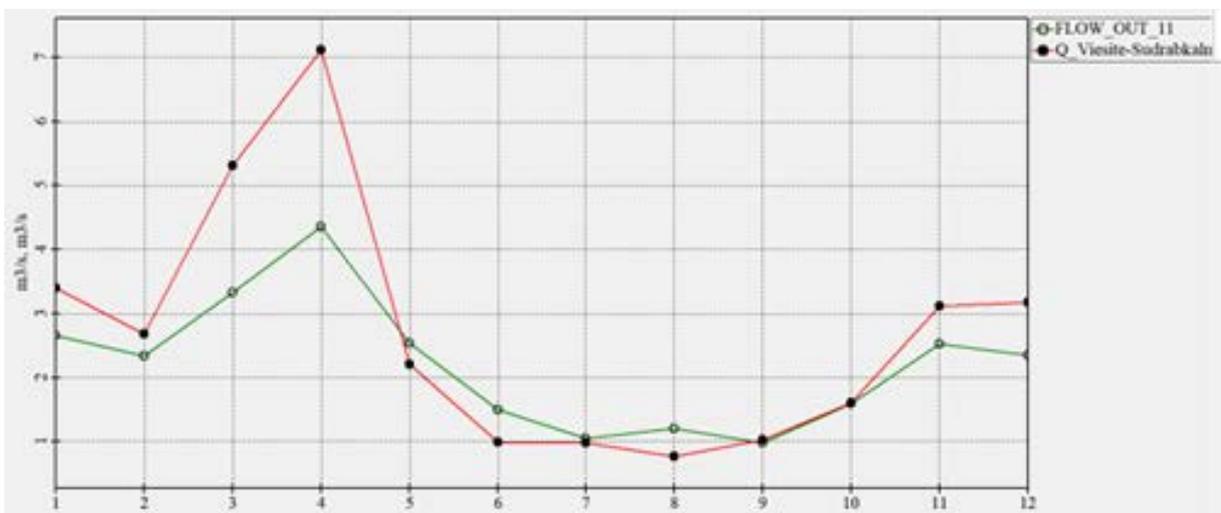Figure 3.27: Time graph of the observed (red) and modelled (green) discharges at Mūsa-Bauska.

Figure 3.28: Monthly observed (red) and modelled (green) discharges at Mūsa-Bauska.
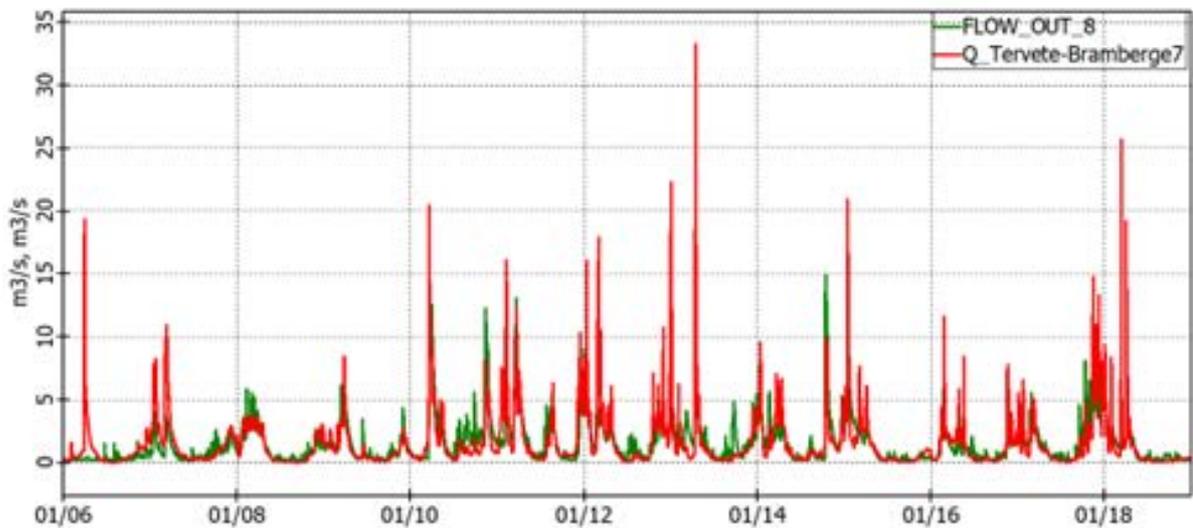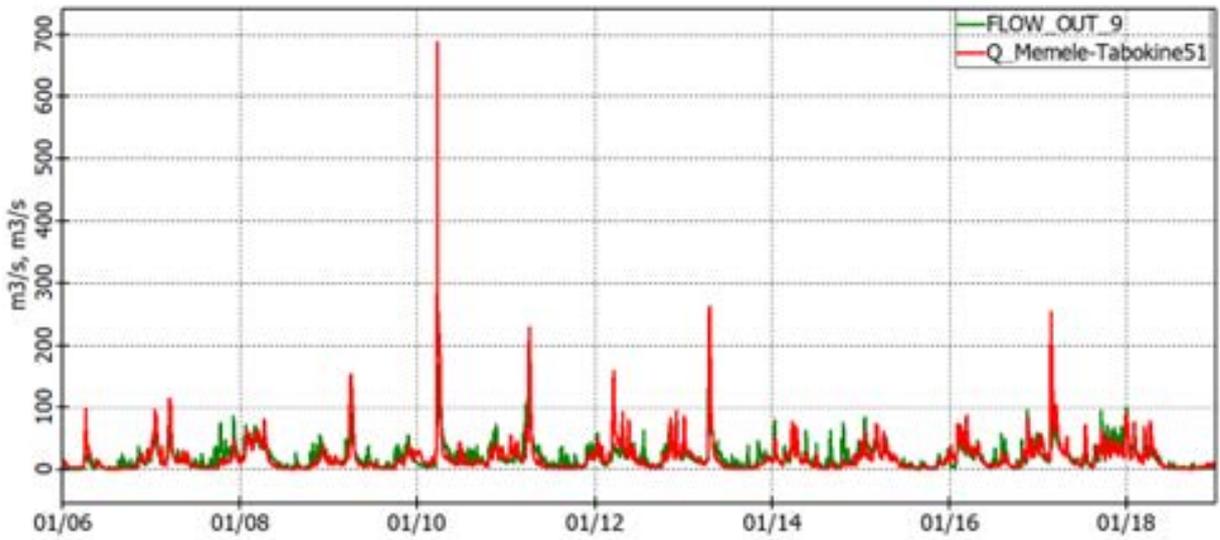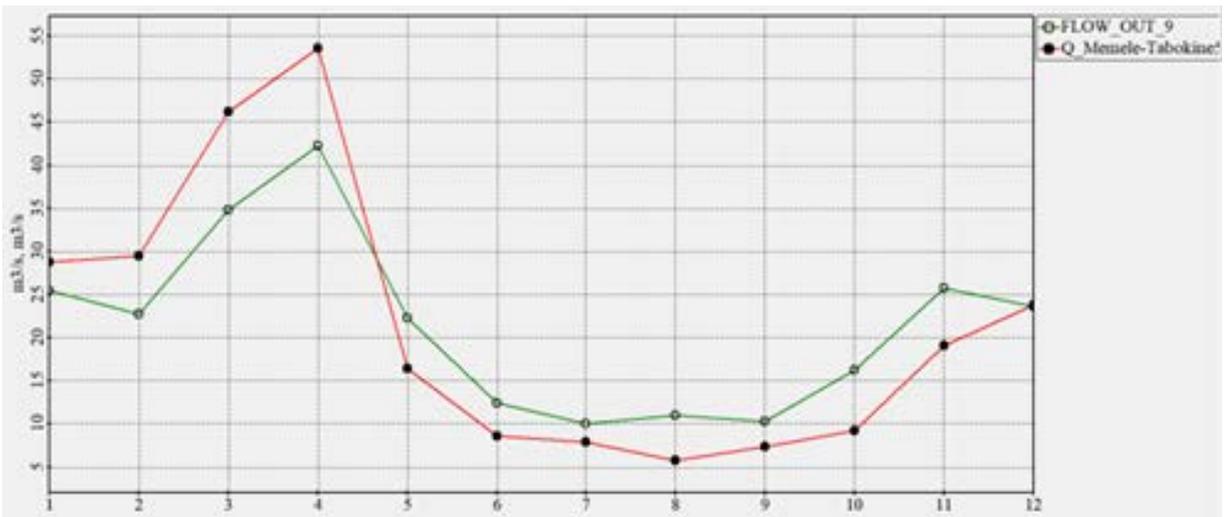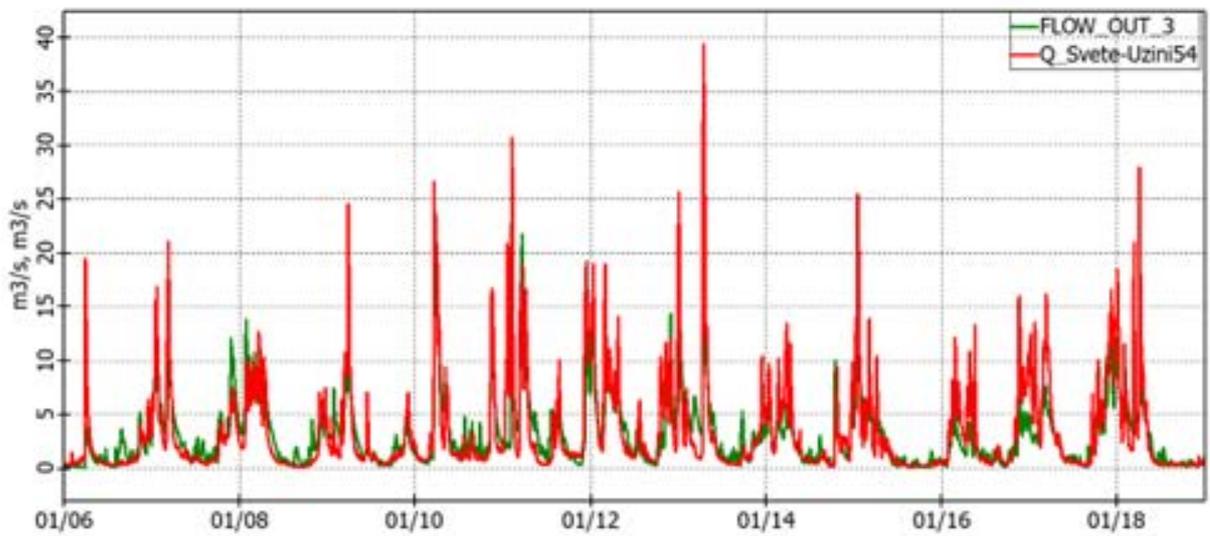
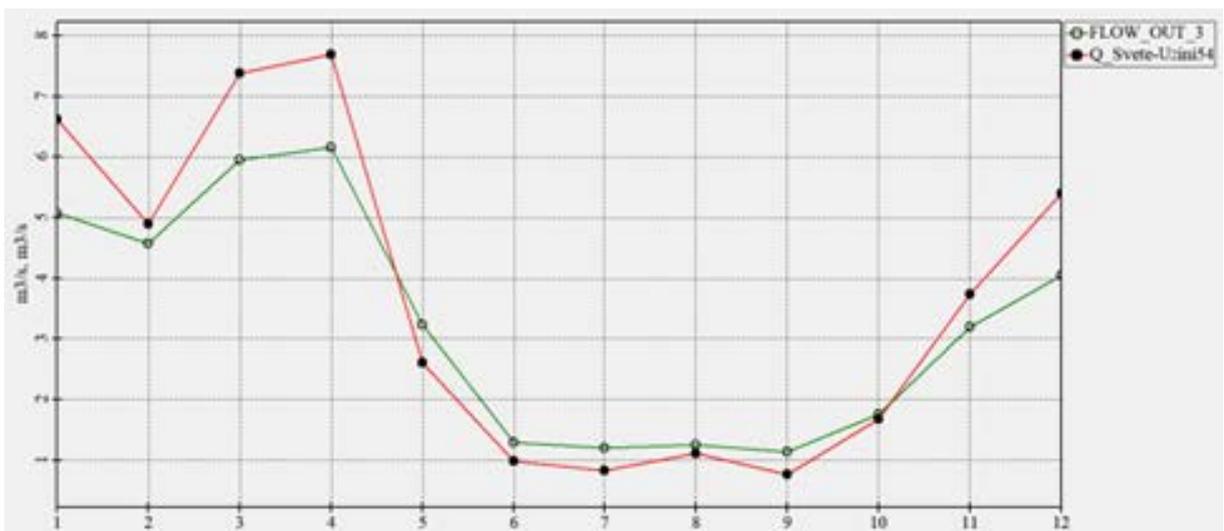Figure 3.29: Time graph of the observed (red) and modelled (green) discharges at Tērvete-Bramberģe.
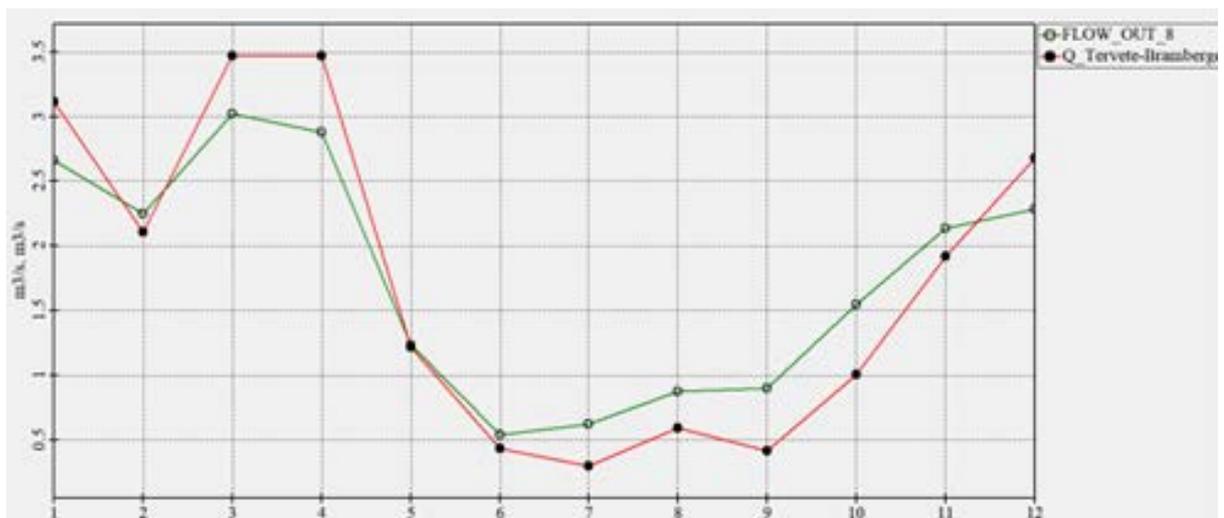
Figure 3.30: Monthly observed (red) and modelled (green) discharges at Tērvete-Bramberģe.

- The time graph of the observed and modeled discharges is shown in Figure 3.31 and the average seasonal cycle of discharges in Figure 3.32 for Viesīte-Sudrabkalni. The model underestimates the peak snow-melt floods in March-April.

- The time graph of the observed and modeled discharges is shown in Figure 3.33 and the average seasonal cycle of discharges in Figure 3.34 for Mēmele-Tabokīne. SWAT+ slightly overestimates the summer low-flow and underestimates the spring snowmelt flood and winter discharges in Mēmele.

- The time graph of the observed and modeled discharges is shown in Figure 3.35 and the average seasonal cycle of discharges in Figure 3.36 for Svēte-Ūziņi. SWAT+ model underestimates the autumn floods (Nov-Dec) and the spring snow melt floods (Mar-Apr).

Figure 3.31: Time graph of the observed (red) and modelled (green) discharges at Viesīte-Sudrabkalni.

Figure 3.32: Monthly observed (red) and modelled (green) discharges at Viesīte-Sudrabkalni.
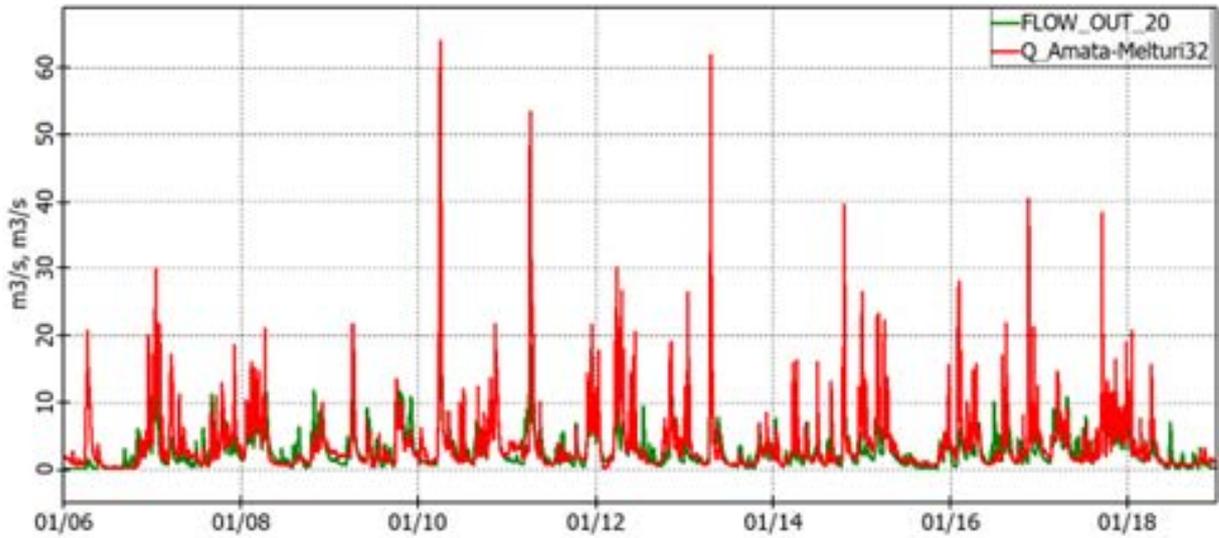
Figure 3.33: Time graph of the observed (red) and modelled (green) discharges at Mēmele-Tabokīne.

Figure 3.34: Monthly observed (red) and modelled (green) discharges at Mēmele-Tabokīne.

Figure 3.35: Time graph of the observed (red) and modelled (green) discharges at Svēte-Ūziņi.

Figure 3.36: Monthly observed (red) and modelled (green) discharges at Svēte-Ūziņi.

The validation results in the region r3I are better as in region r1I and similar to the region r2I, see Tables 3.1 – 3.3. The underestimation of the discharges by SWAT+ is not systematic. One should note that by part the region r3I is influenced by the modelling results of Lithuania, PAIC (2023c) due to the transboundary flow.

3.4. Region r4I

Hydrometric station Amata-Melturi was selected for the calibration in the hydrological region r4I of Vidzeme highland.

Figure 3.37: Time graph of the observed (red) and modelled (green) discharges at Amata-Melturi.
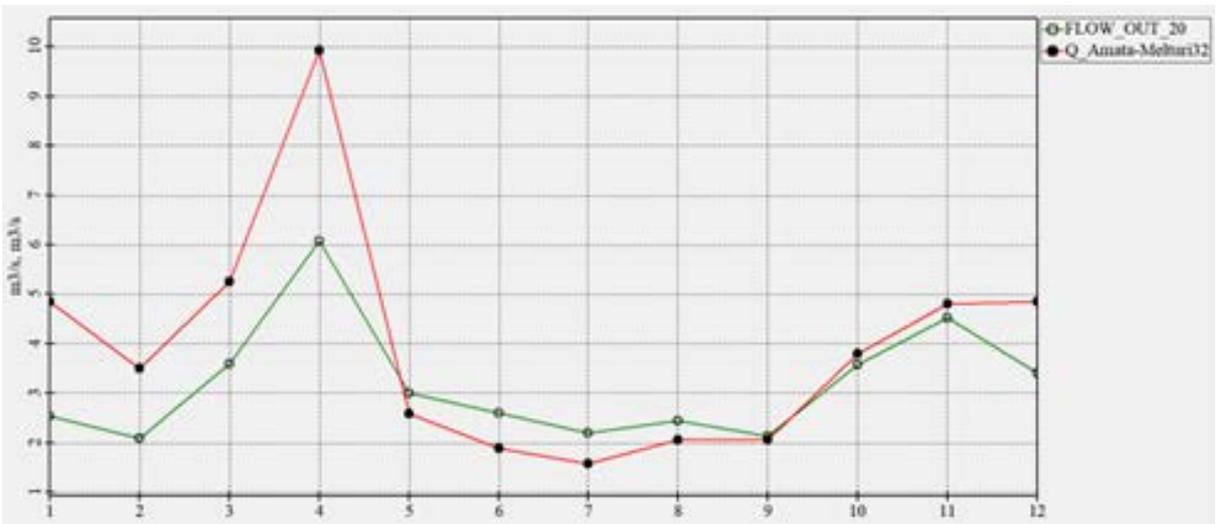

Figure 3.38: Monthly observed (red) and modelled (green) discharges at Amata-Melturi.

The calibration targets were reached for Amata-Melturi, see Table 3.4.

The time graph of the observed and modeled discharges is shown in Figure 3.37. The average seasonal cycle of discharges is shown in Figure 3.38; it indicates a satisfactory representation

of a seasonal hydrograph of Amata. SWAT+ underestimates the discharge during the winter months Dec-Mar and during the spring snow-melt flood in April.

Table 3.4: Quantitative results of calibration (bold) and validation in region r4I.

STAID	STANAME	NSE	PBIAS	Region
32	**Amata-Melturi**	**0,46**	**-20%**	**r4**
45	Gauja-Sigulda	0,14	-54%	r4
56	Gauja-Valmiera	0,58	-1%	r4
58	Gauja-Velēna	0,53	-19%	r4
66	Tūlija-Zosēni	0,40	-16%	r4

The SWAT+ coefficients of the Amata catchment were transferred to the other catchments of the region r4I and the validation was performed.

Validation targets were not reached in the station Gauja-Sigulda, see Table 3.4. The observed mean discharge 132 m^3/s is too high because (a) it corresponds to unrealistically high annual runoff layer depth 612 mm, (b) it exceeds the reported[6] mean discharge, approximately 70 m^3/s, and (c) it contradicts matching of modelled and observed discharges at the station Gauja-Valmiera.

The validation targets were reached for the other 3 stations of the region r4I, see Table 3.4.

- The time graph of the observed and modeled discharges is shown in Figure 3.39 and the average seasonal cycle of discharges in Figure 3.40 for Gauja-Velēna. Similarly, as in Amata, SWAT+ underestimates the discharge during the winter months Nov-Mar and during the spring snow-melt flood in April in this upstream Gauja station.

- The time graph of the observed and modeled discharges is shown in Figure 3.41 and the average seasonal cycle of discharges in Figure 3.42 for Gauja-Valmiera. The match of the observed and modelled data is excellent for this classic hydrograph of large Vidzeme river with distinct snow-melt flood, summer low-flow, and interim autumn flow maximum.

- The time graph of the observed and modeled discharges is shown in Figure 3.43 and the average seasonal cycle of discharges in Figure 3.44 for Tūlija-Zosēni. The model underestimates the peak snow-melt floods in March-April.

The validation results in the region r4I are similar to those in the region r1I, see Tables 3.1 and 3.4. The underestimation of the discharges in the winter months and during the spring snow

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[6] https://lv.wikipedia.org/wiki/Gauja

melt flood by SWAT+ are systematic. However, the need for further calibration effort is not clear because of the uncertainty about winter observation data quality.
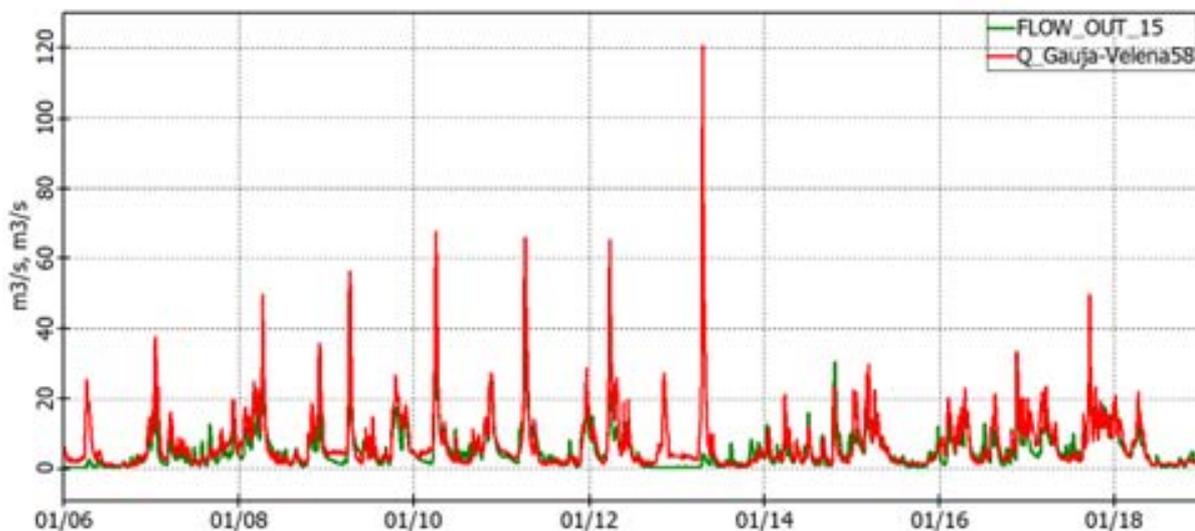

Figure 3.39: Time graph of the observed (red) and modelled (green) discharges at Gauja-Velēna.
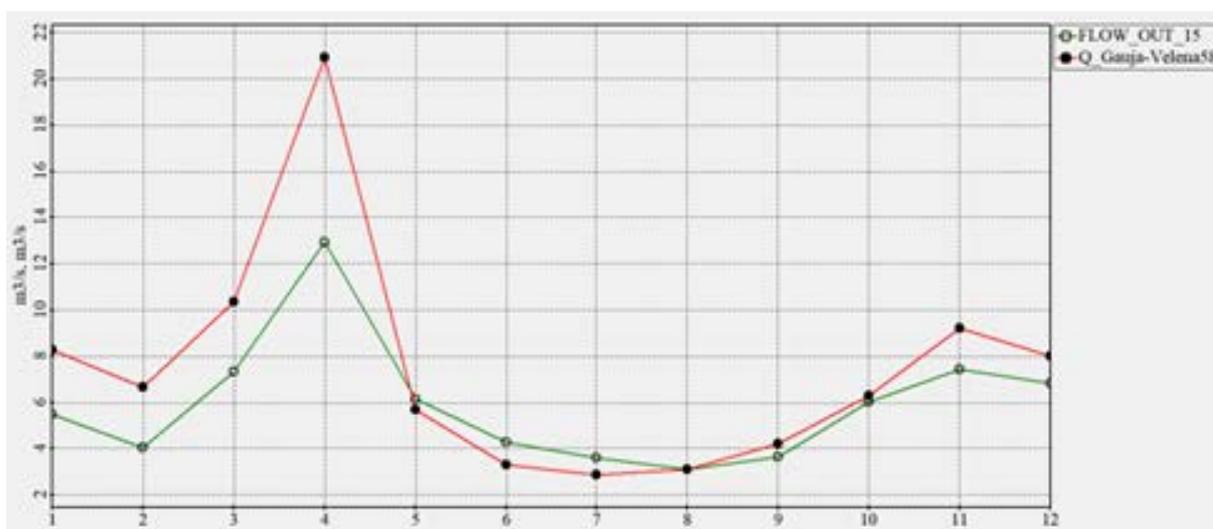

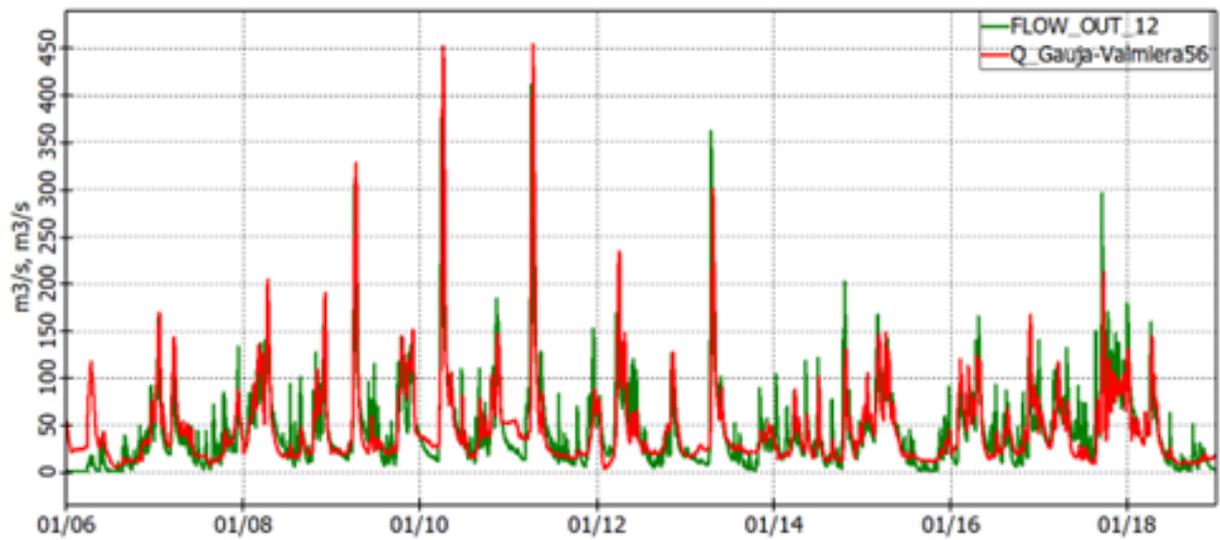Figure 3.40: Monthly observed (red) and modelled (green) discharges at Gauja-Velēna.

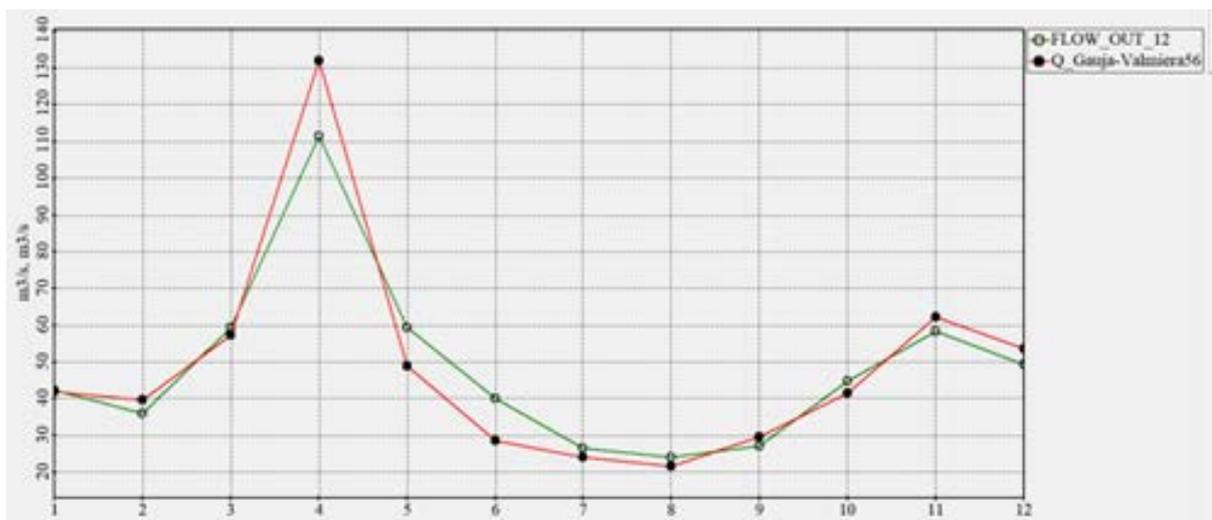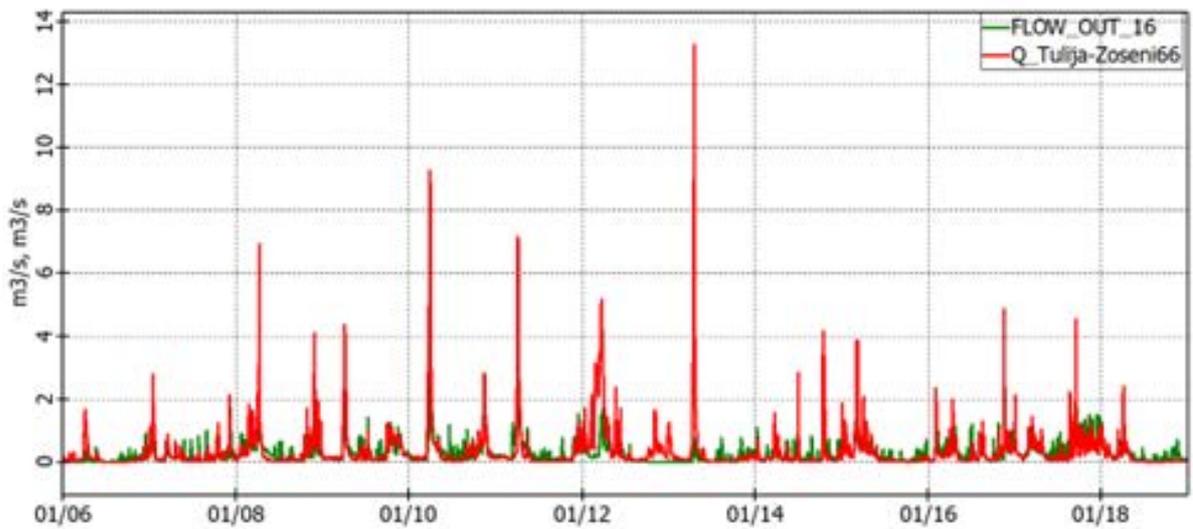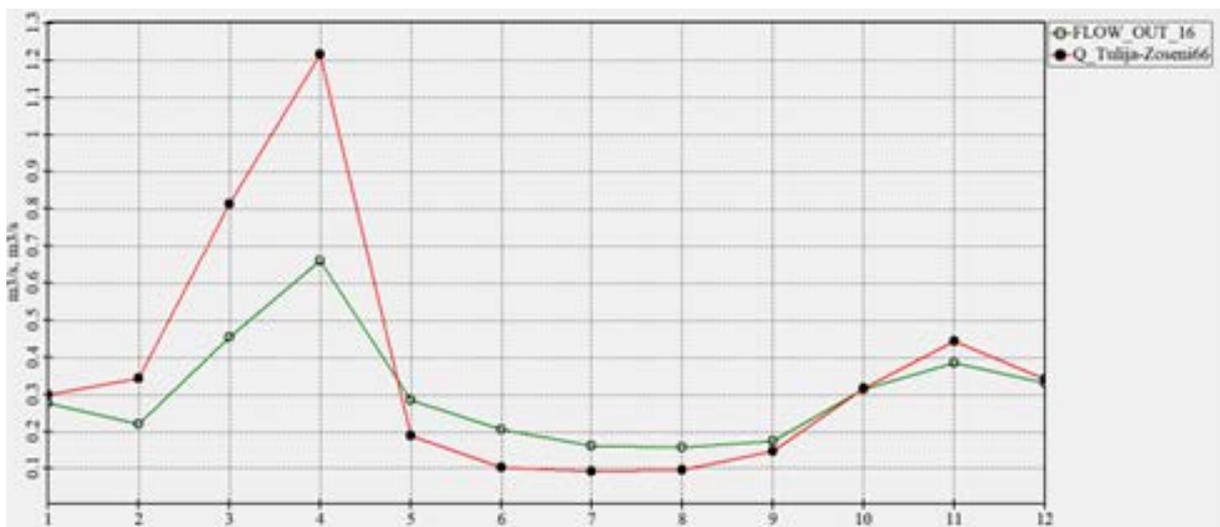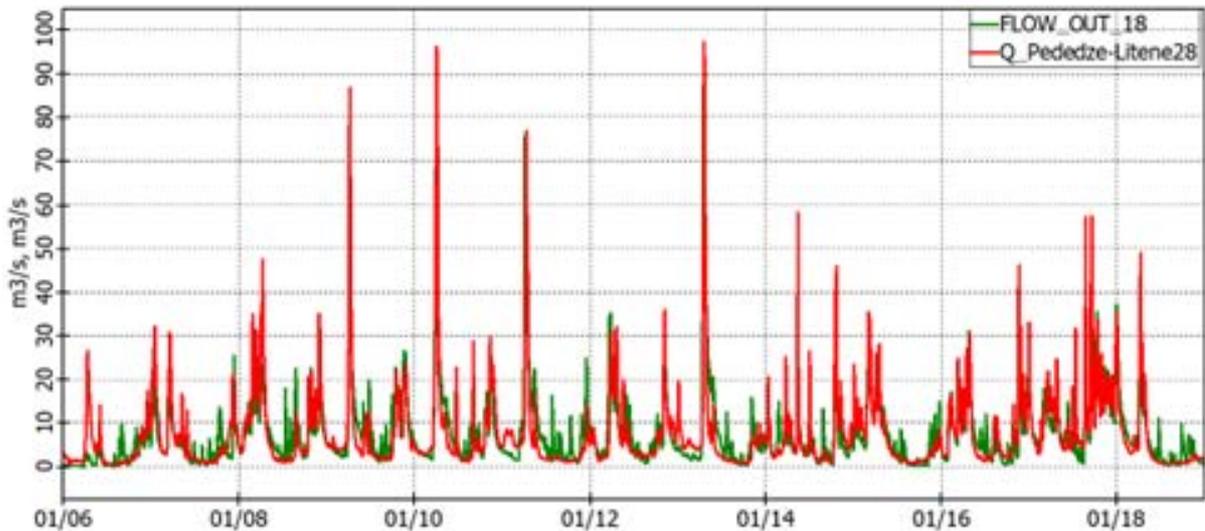Figure 3.41: Time graph of the observed (red) and modelled (green) discharges at Gauja-Valmiera.

Figure 3.42: Monthly observed (red) and modelled (green) discharges at Gauja-Valmiera.

Figure 3.43: Time graph of the observed (red) and modelled (green) discharges at Tūlija-Zosēni.

Figure 3.44: Monthly observed (red) and modelled (green) discharges at Tūlija-Zosēni.

3.5. Region r5I

Hydrometric station Pededze-Litene was selected for the calibration in the hydrological region r5I of Austrumlatvija lowland.

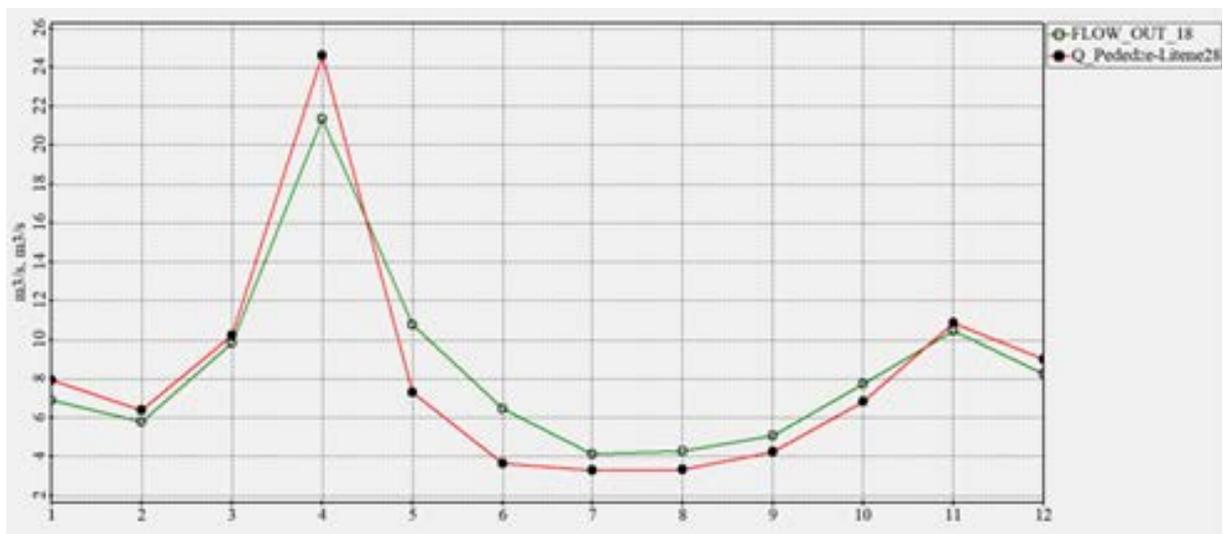Figure 3.45: Time graph of the observed (red) and modelled (green) discharges Pededze-Litene.

Figure 3.46: Monthly observed (red) and modelled (green) discharges at Pededze-Litene.

The calibration targets were reached for Pededze-Litene, see Table 3.5.

The time graph of the observed and modeled discharges is shown in Figure 3.45. The average seasonal cycle of discharges is shown in Figure 3.46. Excellent agreement between modelled and observed discharges is found in both daily and monthly hydrographs of Pededze.

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Table 3.5: Quantitative results of calibration (bold) and validation in region r5I.

STAID	STANAME	NSE	PBIAS	Region
28	**Pededze-Litene**	**0,73**	**5%**	**r5**
29	Aiviekste-Lubāna	0,57	-1%	r5
46	Dubna-Sīļi	0,67	-13%	r5
68	Rēzekne-Griškāni	0,33	10%	r5
69	Oša-Kūlenieki	0,53	-27%	r5

The SWAT+ coefficients of the Pededze catchment were transferred to the other catchments of the region r5I and the validation was performed.

The validation targets set in Table 2.3 were reached for all 4 considered 3 stations of the region r5I, see Table 3.5.

- The time graph of the observed and modeled discharges is shown in Figure 3.47 and the average seasonal cycle of discharges in Figure 3.48 for Aiviekste-Lubāna. Observation data is available since 2011 in this station. SWAT+ produces a very good match with the observation data slightly underestimating the JAN-FEB discharges.

- The time graph of the observed and modeled discharges is shown in Figure 3.49 and the average seasonal cycle of discharges in Figure 3.50 for Dubna-Sīļi. The match of the observed and modelled data is reasonable. The model underestimates the flow in the cold half-year and overestimates it in the warm half-year.

- The time graph of the observed and modeled discharges is shown in Figure 3.51 and the average seasonal cycle of discharges in Figure 3.52 for Rēzekne-Griškāni. The model overestimates the discharge during the summer and autumn.

- The time graph of the observed and modeled discharges is shown in Figure 3.53 and the average seasonal cycle of discharges in Figure 3.54 for Oša-Kūlenieki. The model underestimates the discharge during the cold part of the year, including the snow-melt floods.

The validation results in region r5I are good and similar to those in the region r2I and r3I, see Tables 3.1-3.5. There are no systematic discrepancies between models and observations in this region.
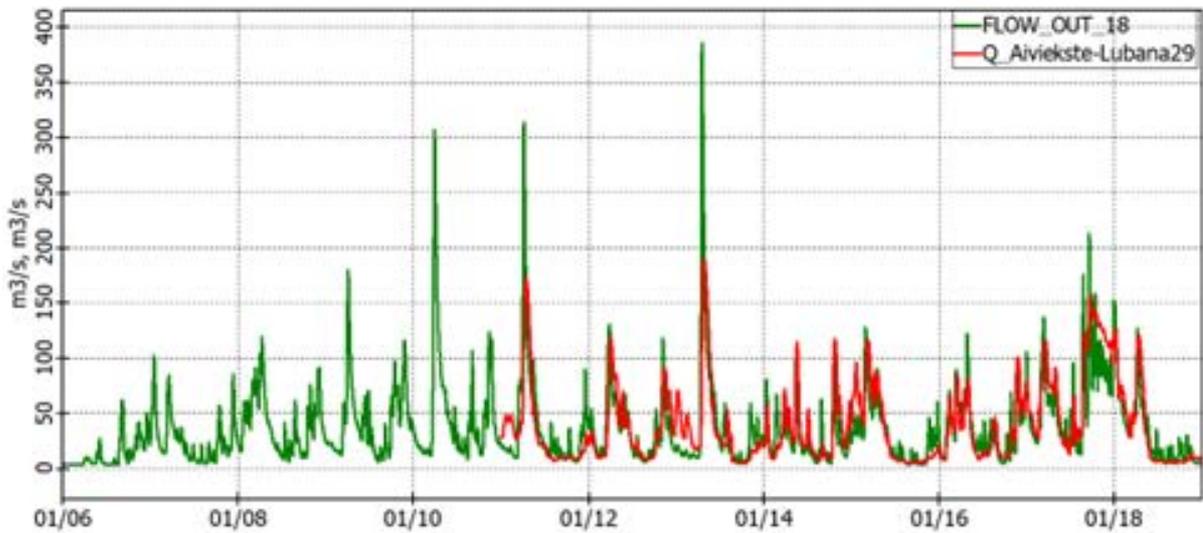
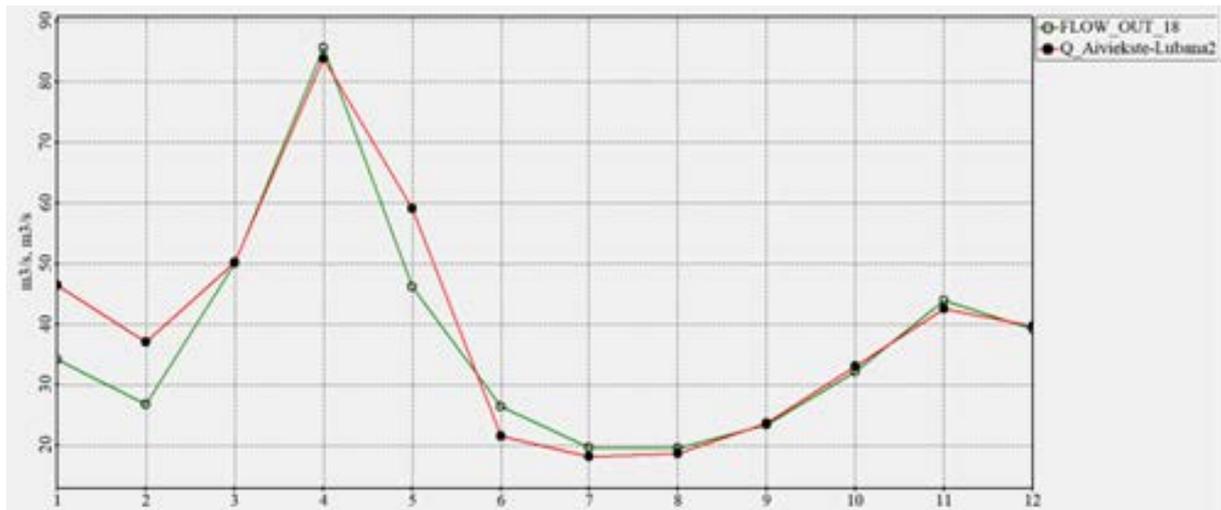Figure 3.47: Time graph of the observed (red) and modelled (green) discharges at Aiviekste-Lubāna.

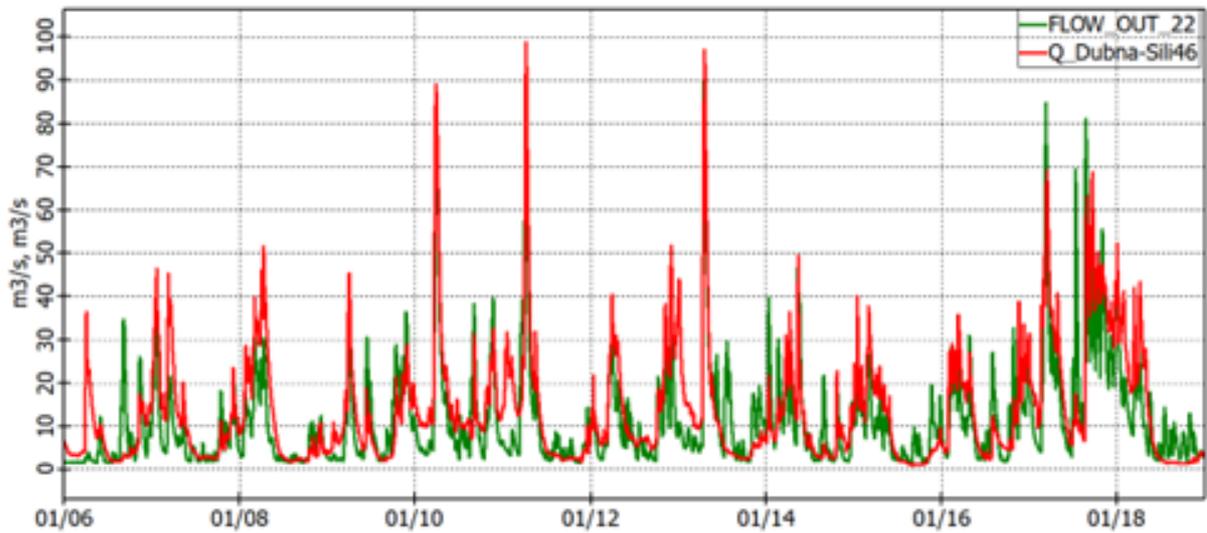Figure 3.48: Monthly observed (red) and modelled (green) discharges at Aiviekste-Lubāna.

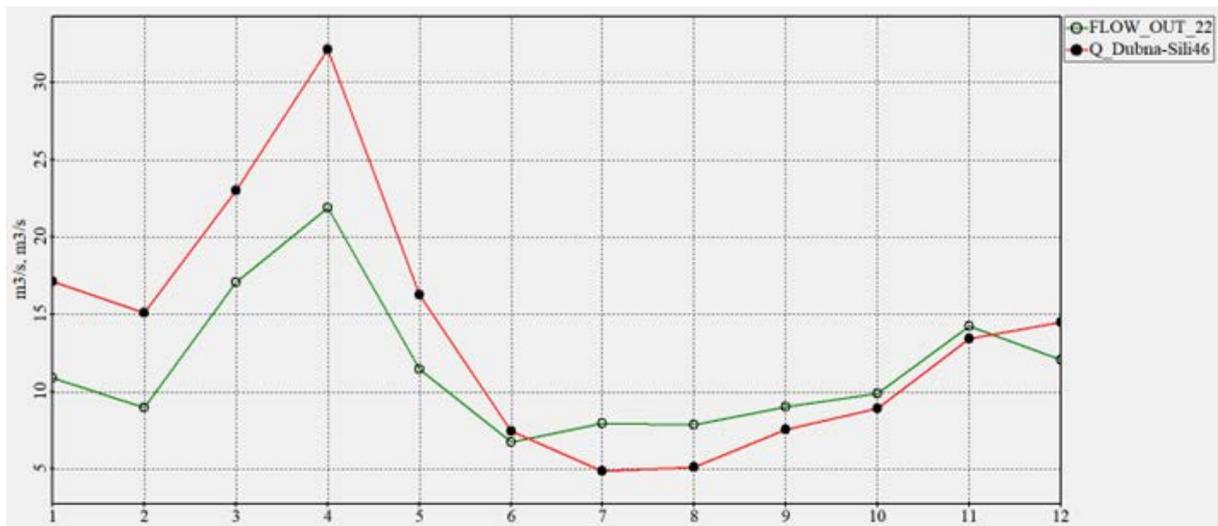Figure 3.49: Time graph of the observed (red) and modelled (green) discharges at Dubna-Sīļi.

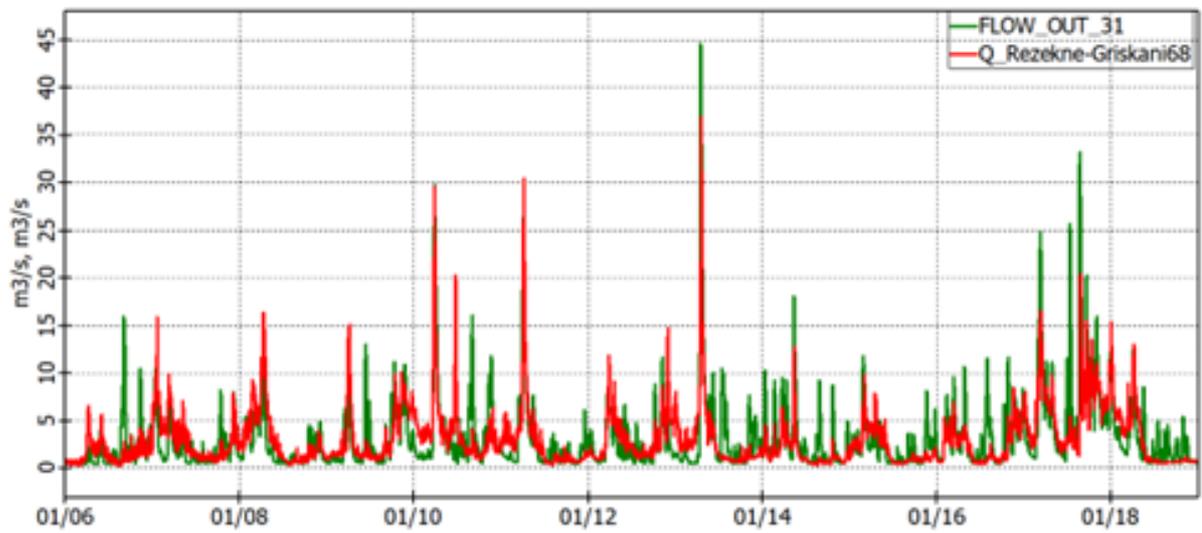Figure 3.50: Monthly observed (red) and modelled (green) discharges at Dubna-Sīļi.

Figure 3.51: Time graph of the observed (red) and modelled (green) discharges at Rēzekne-Griškāni.
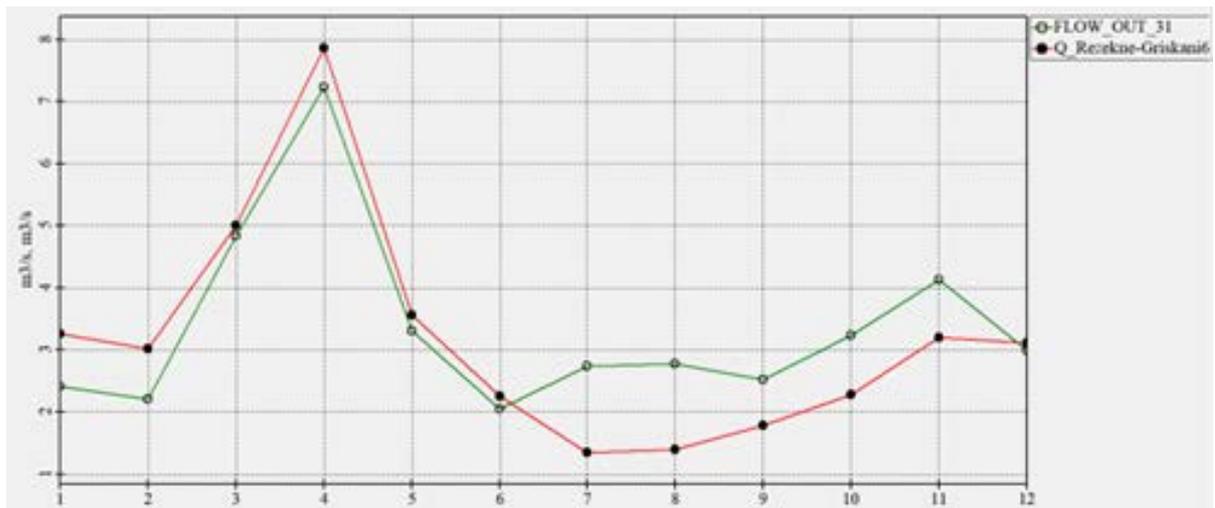

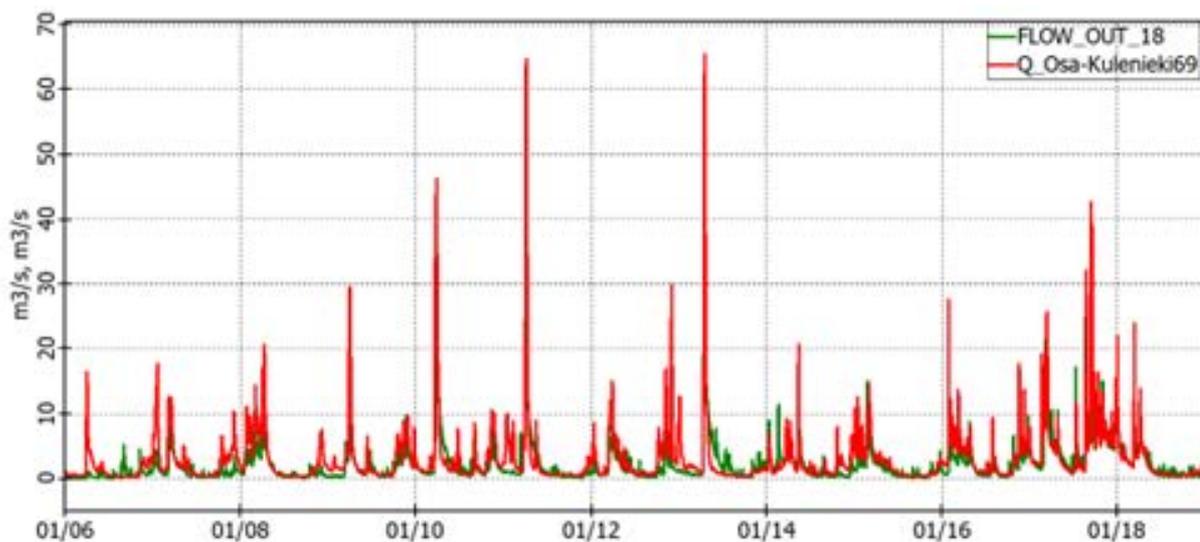Figure 3.52: Monthly observed (red) and modelled (green) discharges at Rēzekne-Griškāni.

Figure 3.53: Time graph of the observed (red) and modelled (green) discharges at Oša-Kūlenieki.
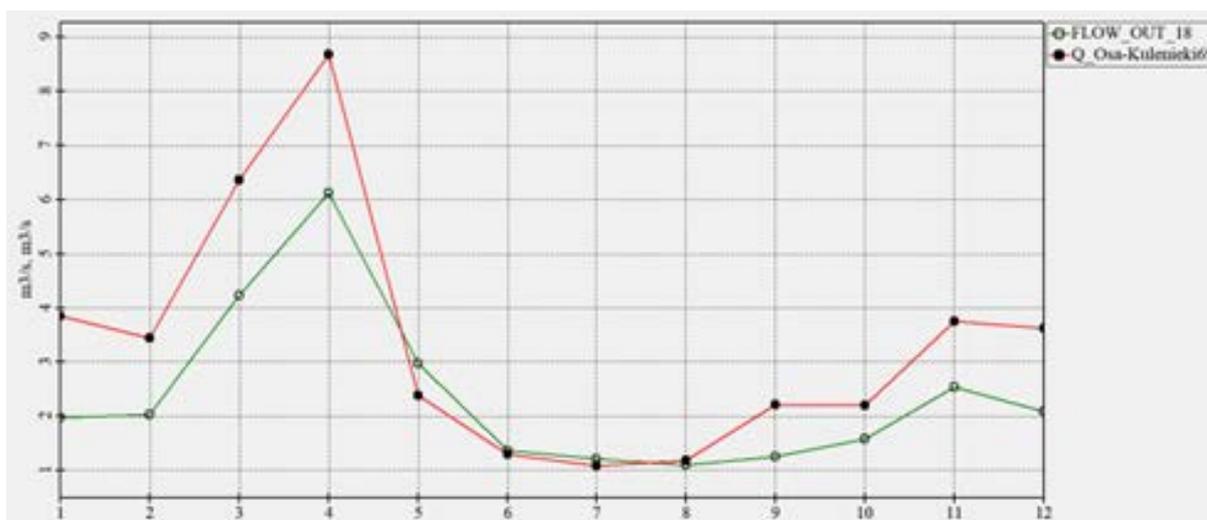

Figure 3.54: Monthly observed (red) and modelled (green) discharges at Oša-Kūlenieki.

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3.6. Region r6I

Hydrometric station Laucesa-Lenderna was selected for the calibration in the hydrological region r6I of Latgale highland.
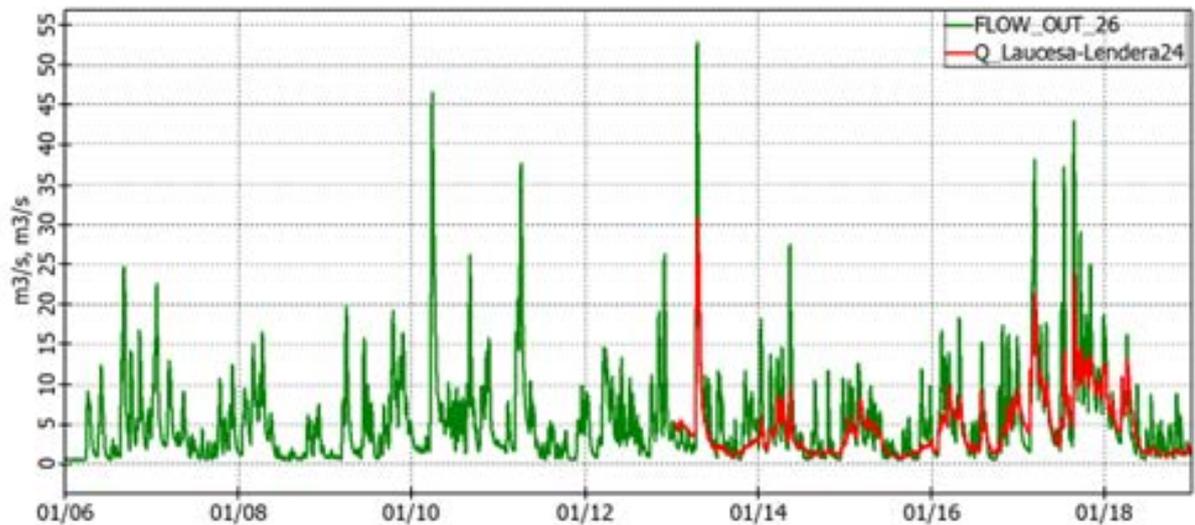

Figure 3.55: Time graph of the observed (red) and modelled (green) discharges Laucesa-Lenderna.
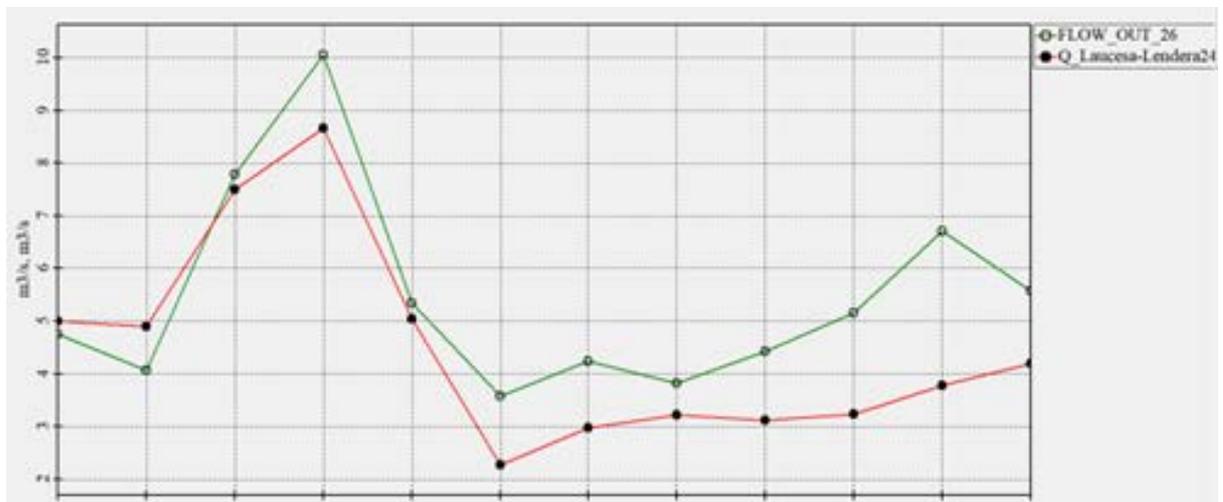

Figure 3.56: Monthly observed (red) and modelled (green) discharges at Laucesa-Lenderna.

The calibration targets were not reached for Laucesa-Lenderna, see Table 3.6 where observation data starts in Year 2013.

The time graph of the observed and modeled discharges is shown in Figure 3.55. The average seasonal cycle of discharges is shown in Figure 3.56. There is some agreement between the modelled and observed seasonal cycle of discharges; however, model overestimates the flow

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throughout the year. This is somewhat confusing because in other regions SWAT+ much more often underestimated the discharges.

Table 3.6: Quantitative results of calibration (bold) and validation in region r6I.

STAID	STANAME	NSE	PBIAS	Region
24	**Laucesa-Lenderņa**	**-0,02**	**33%**	**r6**
63	Dubna-Višķi	0,14	-18%	r6
67	Indrica-Brūnuļi	0,23	34%	r6
71	Zilupe-Pasiene	-0,51	19%	r6

The SWAT+ coefficients of the Laucesa catchment were transferred to the other catchments of the region r6I and the validation was performed.

Only some of the validation targets were reached in the other 3 stations of the region r6I, see Table 3.6.

- The time graph of the observed and modeled discharges is shown in Figure 3.57 and the average seasonal cycle of discharges in Figure 3.58 for Dubna-Višķi. SWAT+ underestimates the discharges in the first half-year and overestimates discharges in the 2nd half year, see Figure 3.58. It is obvious that the model reacts to precipitation events much more than the observations. It is possible that the observation station is affected by releases from the reservoir which do not match the runoff pattern.

- The time graph of the observed and modeled discharges is shown in Figure 3.59 and the average seasonal cycle of discharges in Figure 3.60 for Indrica-Brūnuļi. The observations in this station are available since 2014. The model underestimates the flow in the winter months (JAN-FEB) and overestimates it in the summer-autumn months (JUN-DEC). Most probably the baseflow component is too high in the model.

- The time graph of the observed and modeled discharges is shown in Figure 3.61 and the average seasonal cycle of discharges in Figure 3.62 for Zilupe-Pasiene. The low NSE (Table 3.6 and Figure 3.61) may indicate the effect of reservoir just upstream the observation station. The agreement of the seasonal cycle between the model and observations is better in Zilupe vs Indrica, however, the same overestimation of discharges from July to November may indicate an overestimation of the baseflow.

The validation results in the region r6I are the worst in comparison with other reagons. It may be related to the poor calibration, overestimation of the baseflow and presence of multiple reservoirs with undocumented and unaccounted water release patterns.
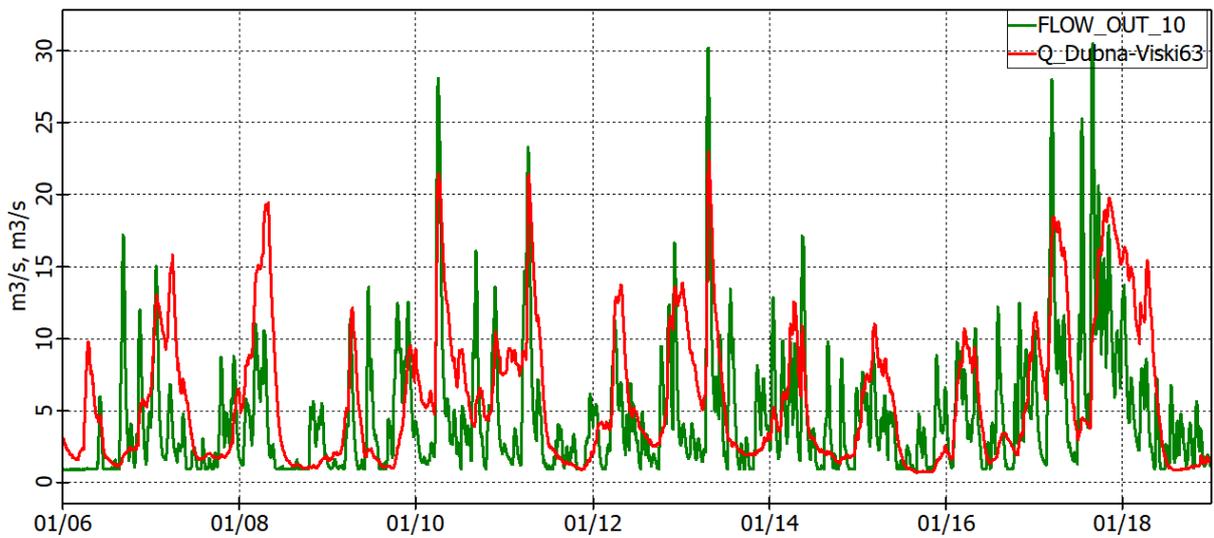
Figure 3.57: Time graph of the observed (red) and modelled (green) discharges at Dubna-Viški.
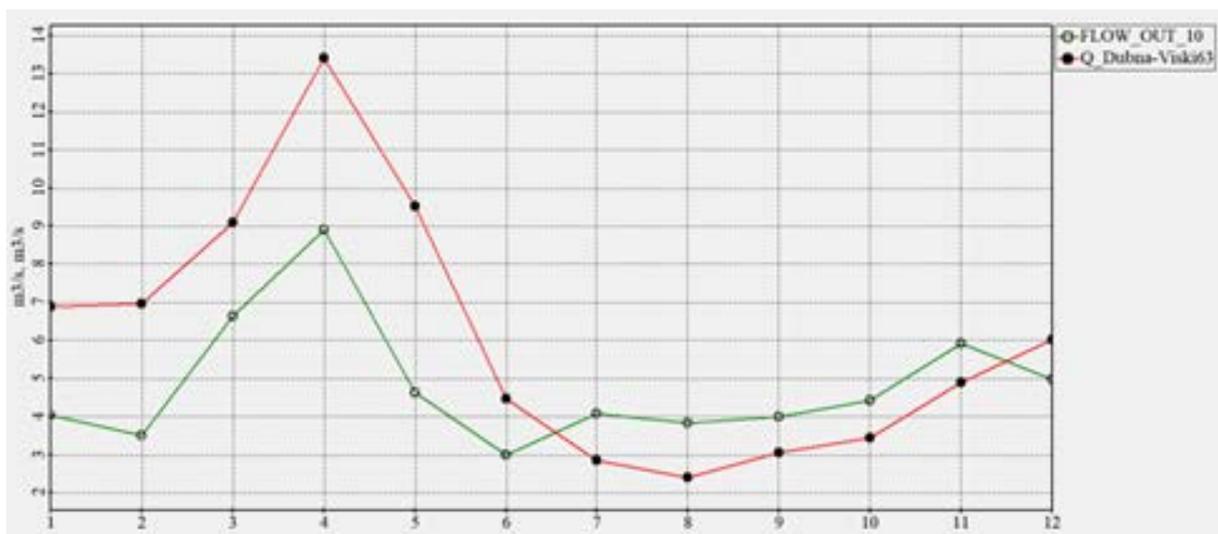

Figure 3.58: Monthly observed (red) and modelled (green) discharges at Dubna-Viški.
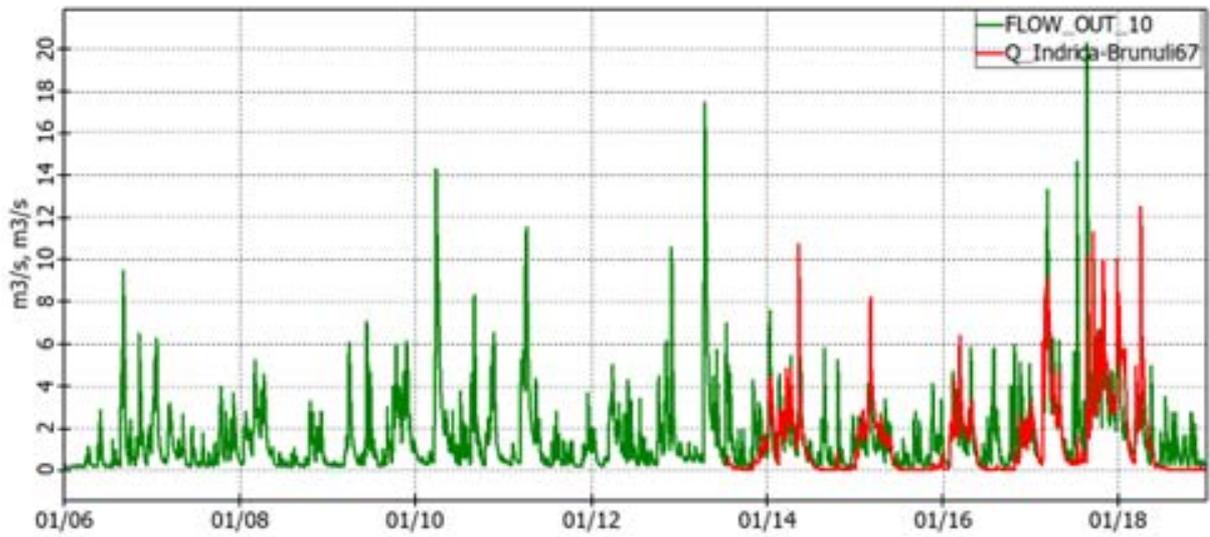
Figure 3.59: Time graph of the observed (red) and modelled (green) discharges at Indrica-Brūnuļi.
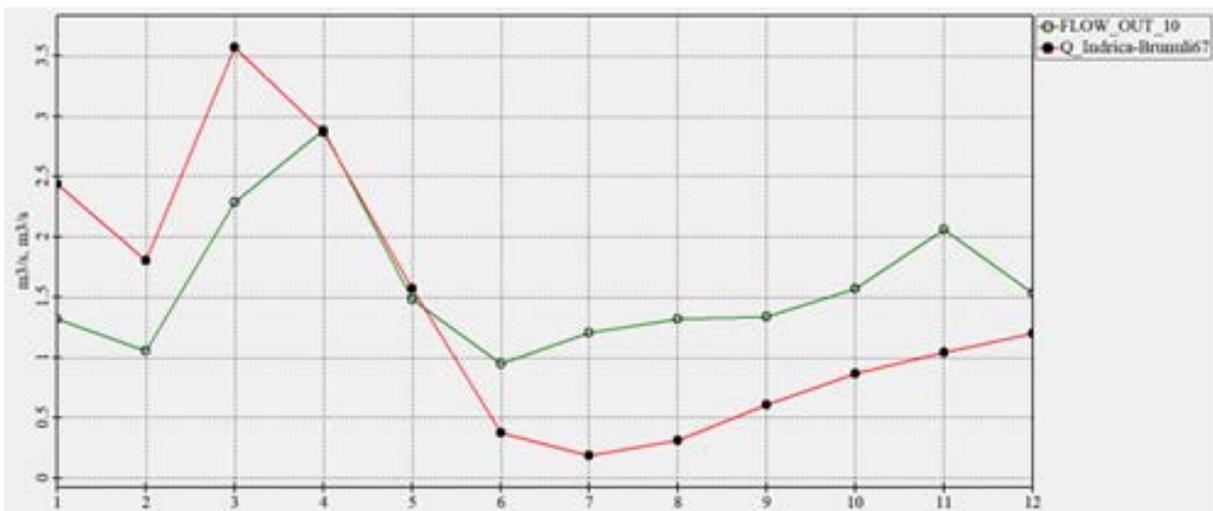

Figure 3.60: Monthly observed (red) and modelled (green) discharges at Indrica-Brūnuļi.
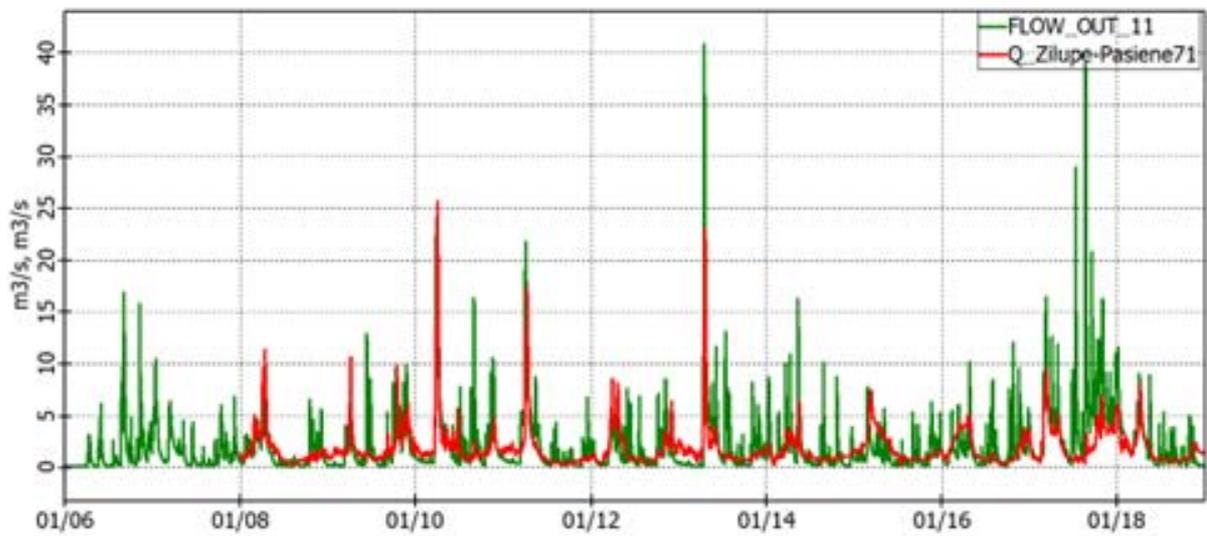
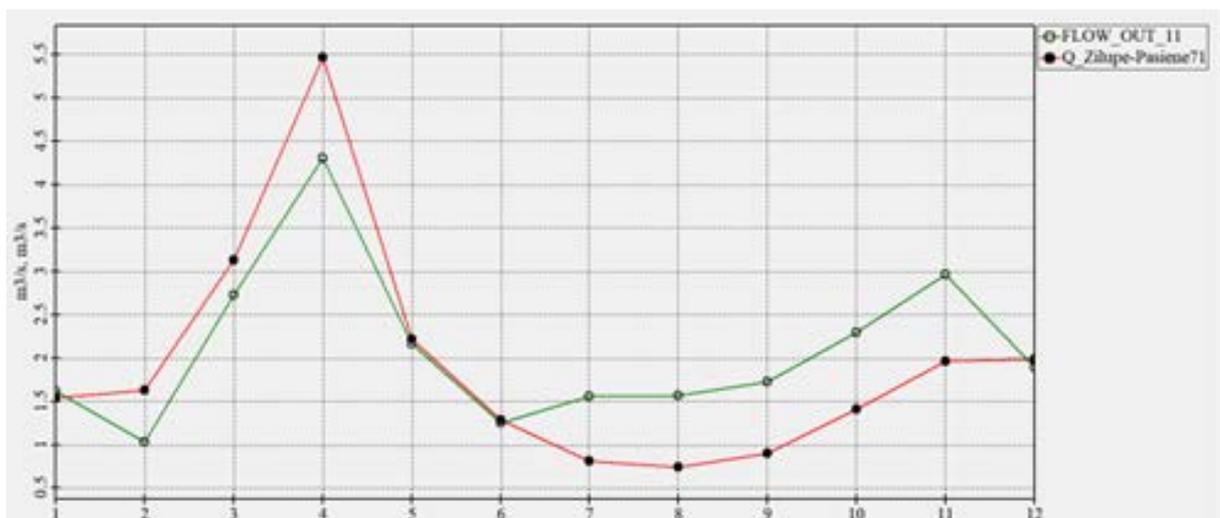Figure 3.61: Time graph of the observed (red) and modelled (green) discharges at Zilupe-Pasiene.

Figure 3.62: Monthly observed (red) and modelled (green) discharges at Zilupe-Pasiene.

3.7. Region r7I

Hydrometric station Vaidava-Ape was selected for the calibration in the hydrological region r7I of Northern Vidzeme.
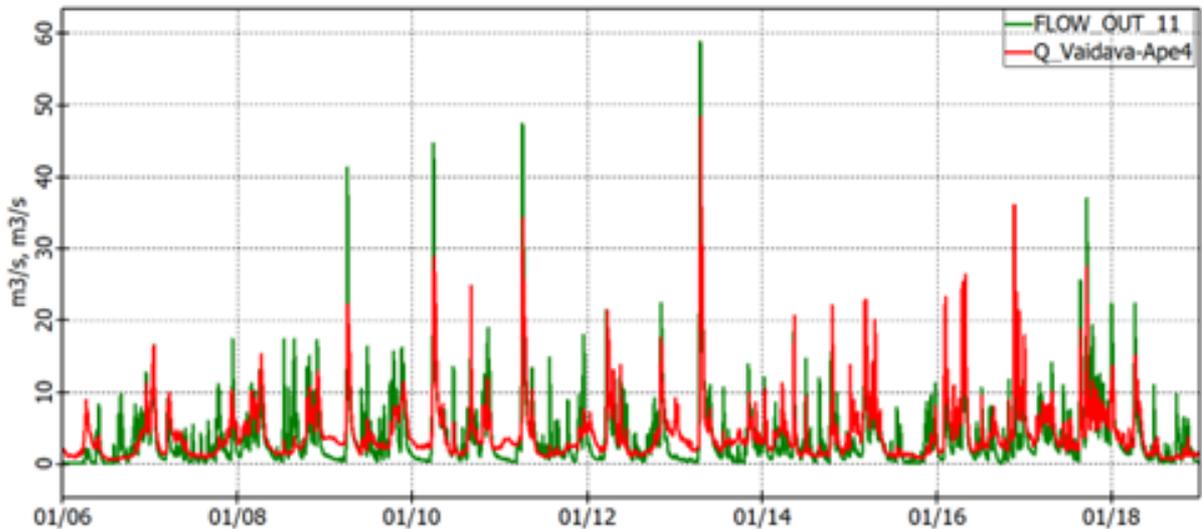

Figure 3.63: Time graph of the observed (red) and modelled (green) discharges at Vaidava-Ape.
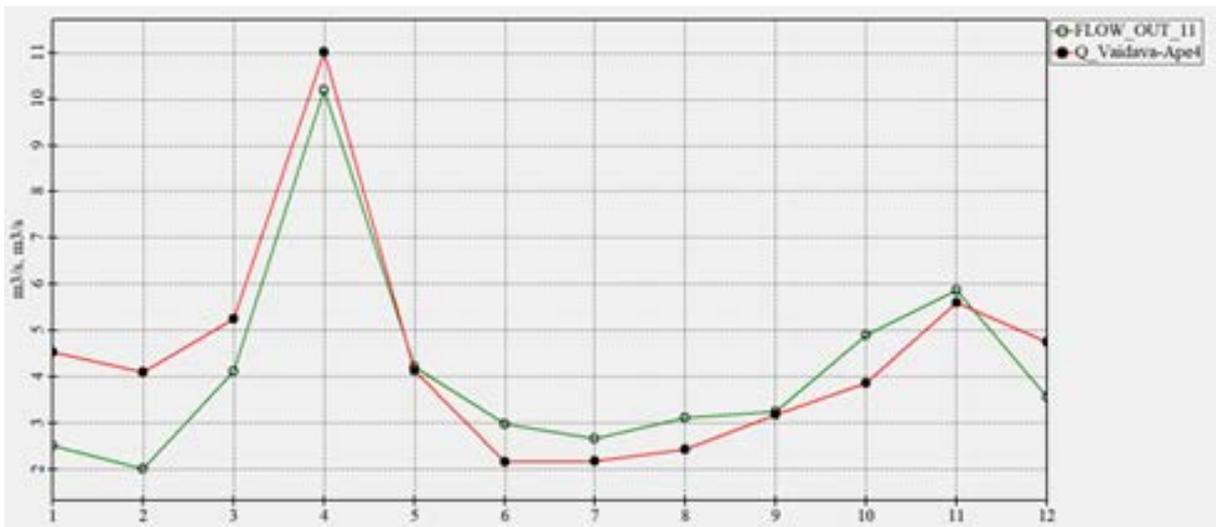

Figure 3.64: Monthly observed (red) and modelled (green) discharges at Vaidava-Ape.

The calibration targets reached for Vaidava-Ape, see Table 3.7.

The time graph of the observed and modelled discharges is shown in Figure 3.63. The average seasonal cycle of discharges is shown in Figure 3.64. There is very good agreement between the modelled and observed seasonal cycle of discharges, with slight model underestimation of

winter and overestimation of the summer discharges. Somewhat lower NSE value may be explained by the regulation of the Ape reservoir on the river.

Table 3.7: Quantitative results of calibration (bold) and validation in region r7I.

STAID	STANAME	NSE	PBIAS	Region
4	**Vaidava-Ape**	**0,43**	**-7%**	**r7**
22	Salaca-Lagaste	-0,30	-66%	r7
23	Tirza-Lejasciems	0,50	-25%	r7
31	Salaca-Mazsalaca	0,43	-25%	r7
36	Seda-Oleri	0,48	-24%	r7
62	Rūja-Vilnīši	0,41	-29%	r7
75	Palsa-Vilkzemnieki	0,59	-20%	r7

The SWAT+ coefficients of the Vaidava catchment were transferred to the other catchments of the region r7I and the validation was performed.

The validation targets were not reached in the station Salaca-Lagaste, see Table 3.7. The observed mean discharge 63 m^3/s is too high because (a) it corresponds to unrealistically high annual runoff layer depth 662 mm, and (b) it twice exceeds even the reported[7] mean discharge at the river estuary, 31,3 m^3/s.

The validation targets were reached in the other 5 stations of the region r7I, see Table 3.7.

- The time graph of the observed and modelled discharges is shown in Figure 3.65 and the average seasonal cycle of discharges in Figure 3.66 for Tirza-Lejasciems. The time graph of the observed and modelled discharges is shown in Figure 3.67 and the average seasonal cycle of discharges in Figure 3.68 for Salaca-Mazsalaca. Although the hydrograph is distinctly different for both rivers, SWAT+ model systematically overestimates the discharges of the cold half-year at these stations.

- The time graph of the observed and modelled discharges is shown in Figure 3.69 and the average seasonal cycle of discharges in Figure 3.70 for Seda-Oleri. The time graph of the observed and modelled discharges is shown in Figure 3.71 and the average seasonal cycle of discharges in Figure 3.72 for Rūja-Vilnīši. Although the hydrograph is distinctly different for both rivers, the SWAT+ model underestimates the discharge for the most of the year (except May-July) in these stations.

- The time graph of the observed and modelled discharges is shown in Figure 3.73 and the average seasonal cycle of discharges in Figure 3.74 for Palsa-Vilkzemnieki. The observations are available since 2013 in this station. Similar to Seda and Rūja, the

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[7] https://lv.wikipedia.org/wiki/Salaca

SWAT+ model underestimates the discharge for most of the year (except May-July) in this station

The validation results in region r7I are similar to those in region r1I. The NSE values are between 0,4 and 0,7, and there exist a systematic underestimation of the runoff in the SWAT+ model.
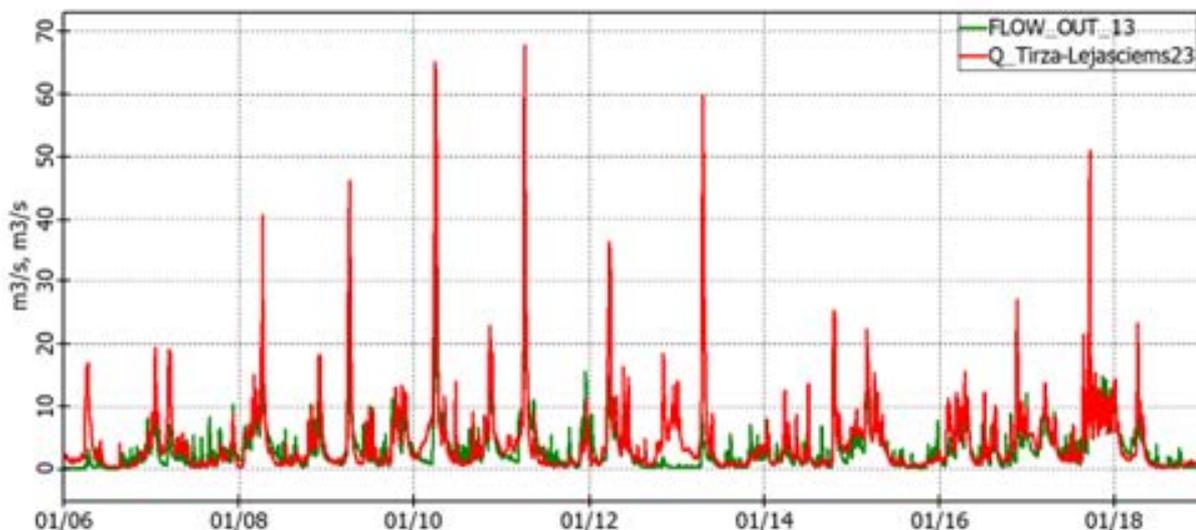

Figure 3.65: Time graph of the observed (red) and modelled (green) discharges at Tirza-Lejasciems.
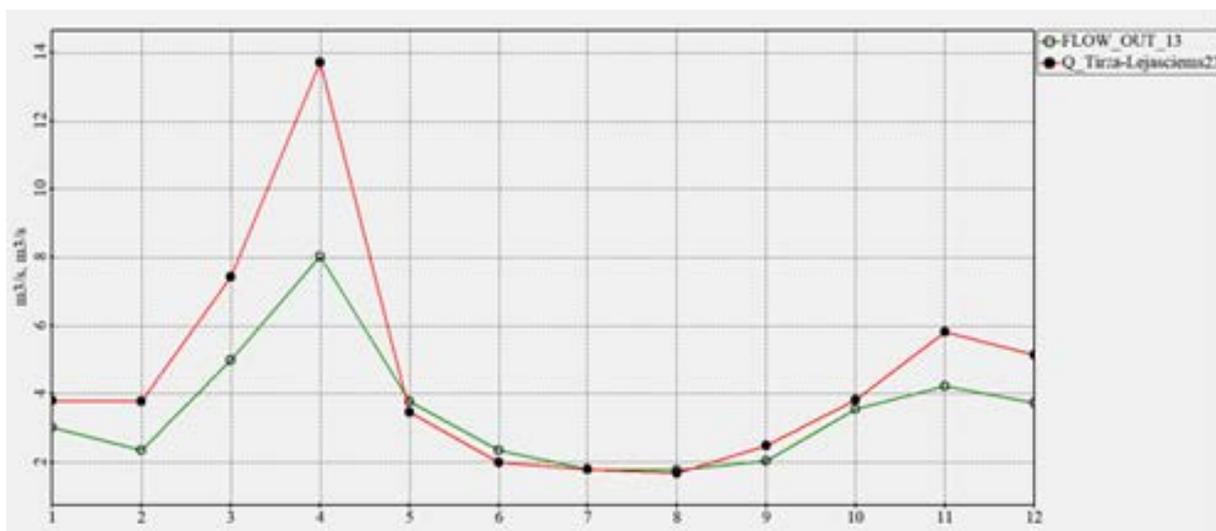

Figure 3.66: Monthly observed (red) and modelled (green) discharges at Tirza-Lejasciems.
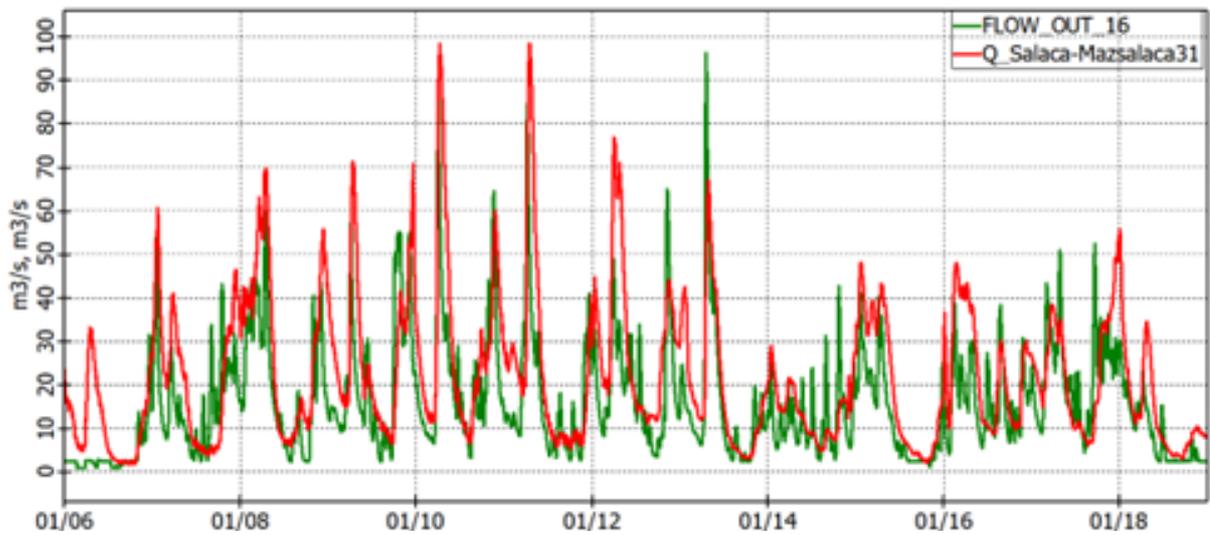
Figure 3.67: Time graph of the observed (red) and modelled (green) discharges at Salaca-Mazsalaca.
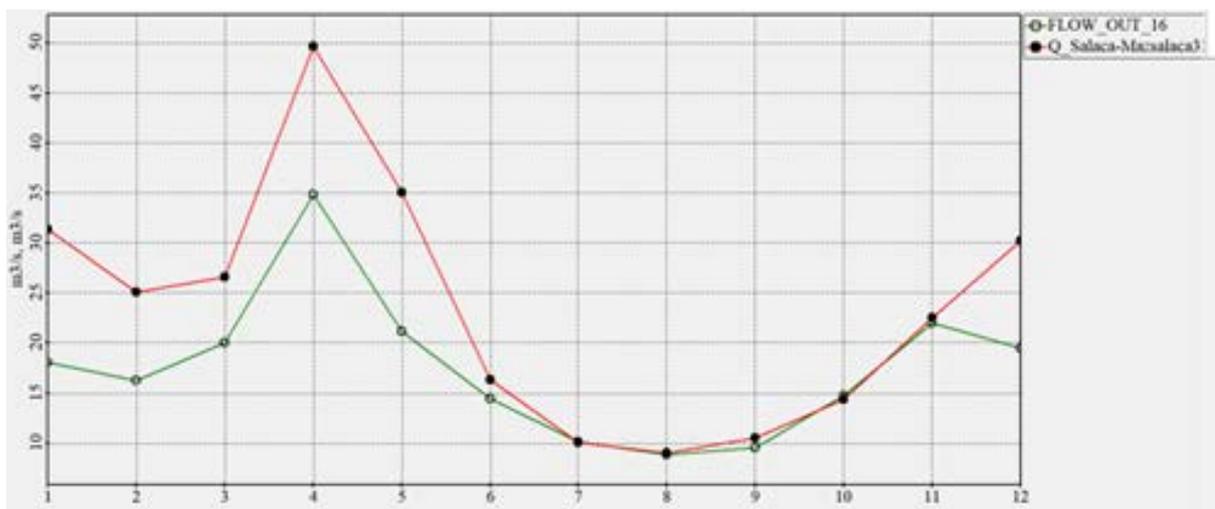

Figure 3.68: Monthly observed (red) and modelled (green) discharges at Salaca-Mazsalaca.
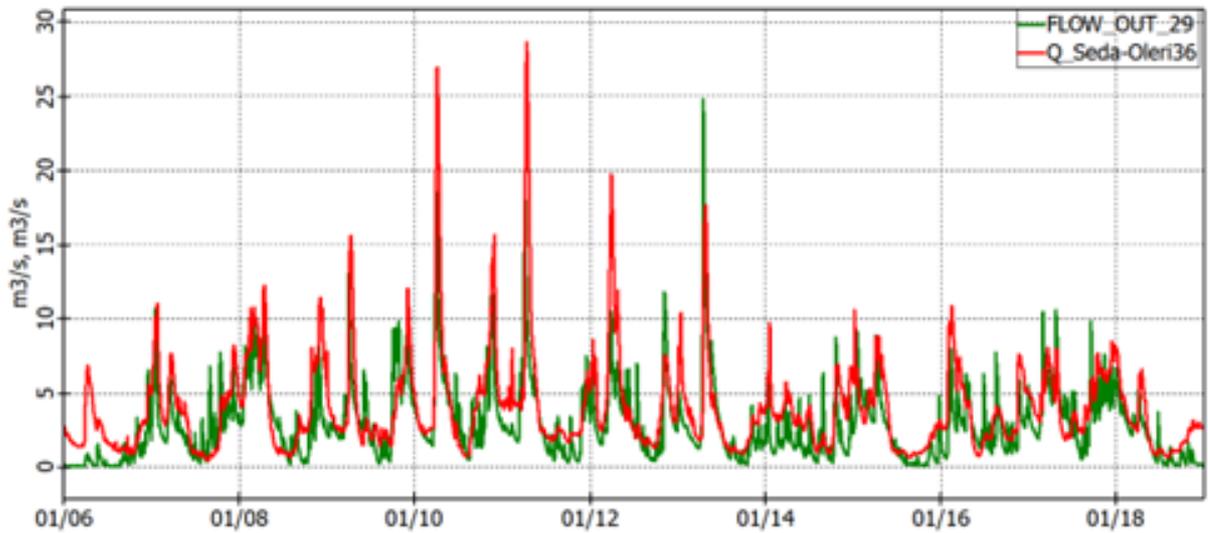
Figure 3.69: Time graph of the observed (red) and modelled (green) discharges at Seda-Oleri.
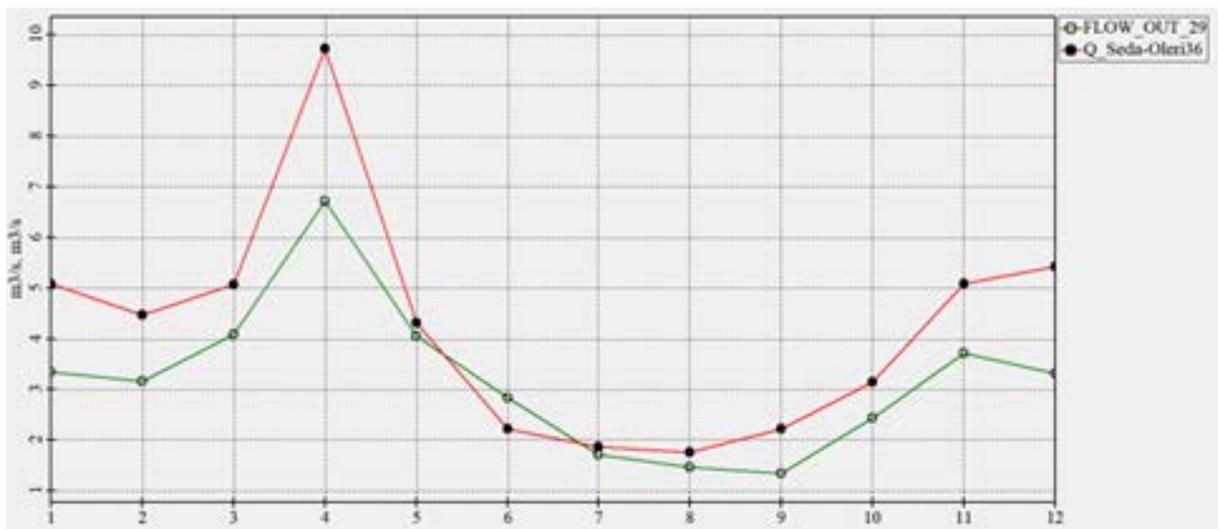

Figure 3.70: Monthly observed (red) and modelled (green) discharges at Seda-Oleri.
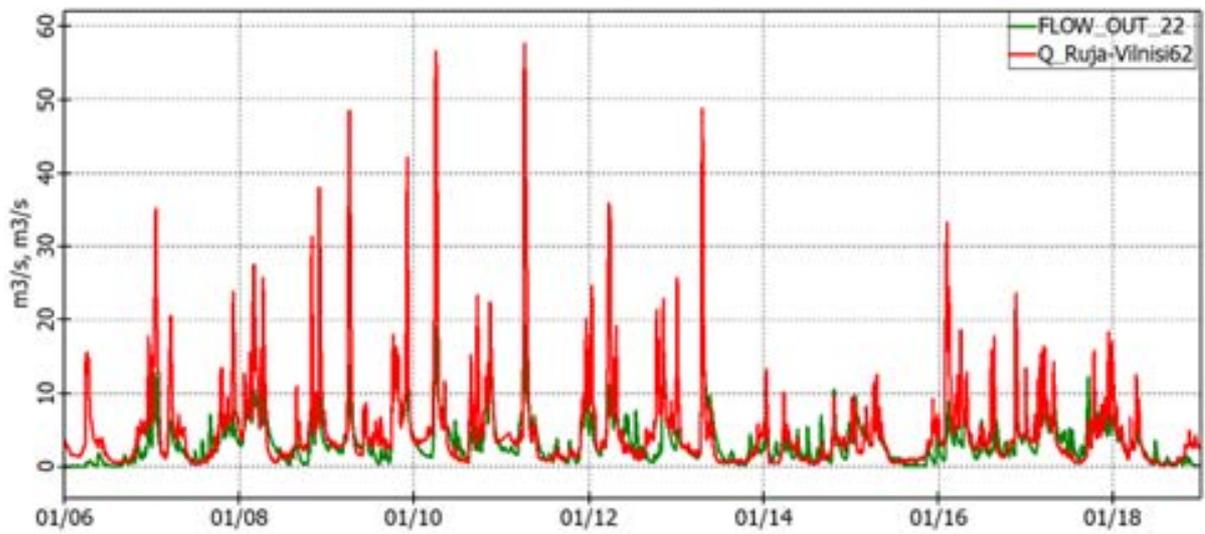
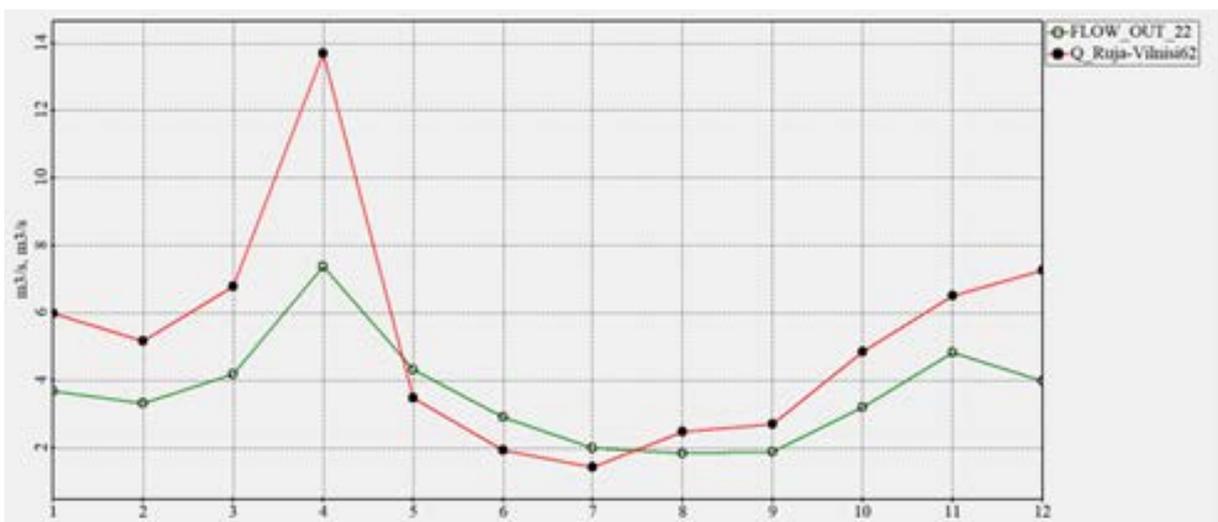Figure 3.71: Time graph of the observed (red) and modelled (green) discharges at Rūja-Vilnīši.

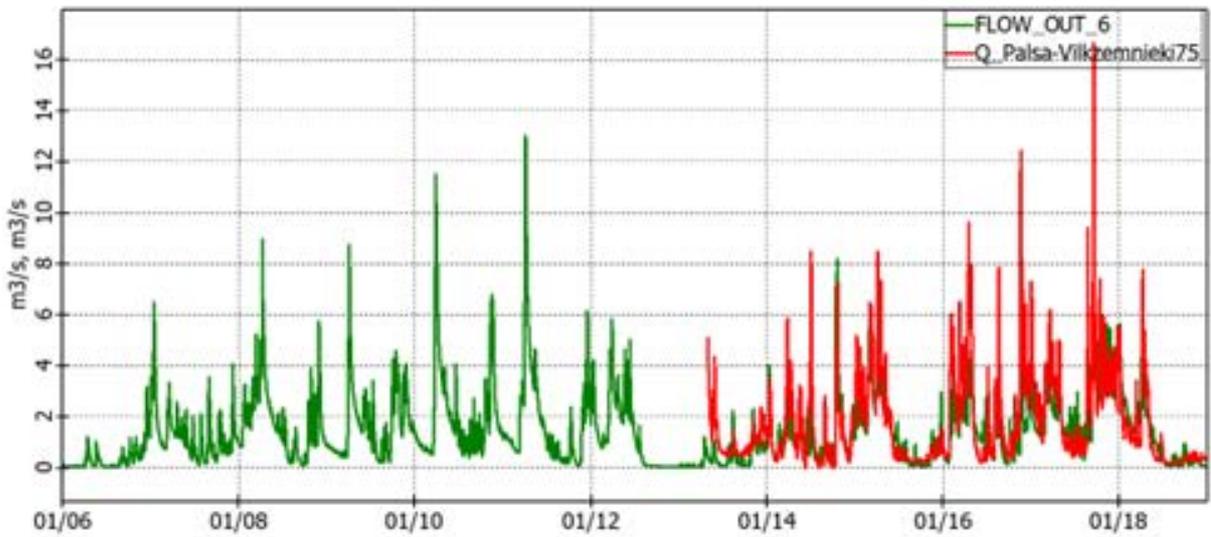Figure 3.72: Monthly observed (red) and modelled (green) discharges at Rūja-Vilnīši.

Figure 3.73: Time graph of the observed (red) and modelled (green) discharges at Palsa-Vilkzemnieki.
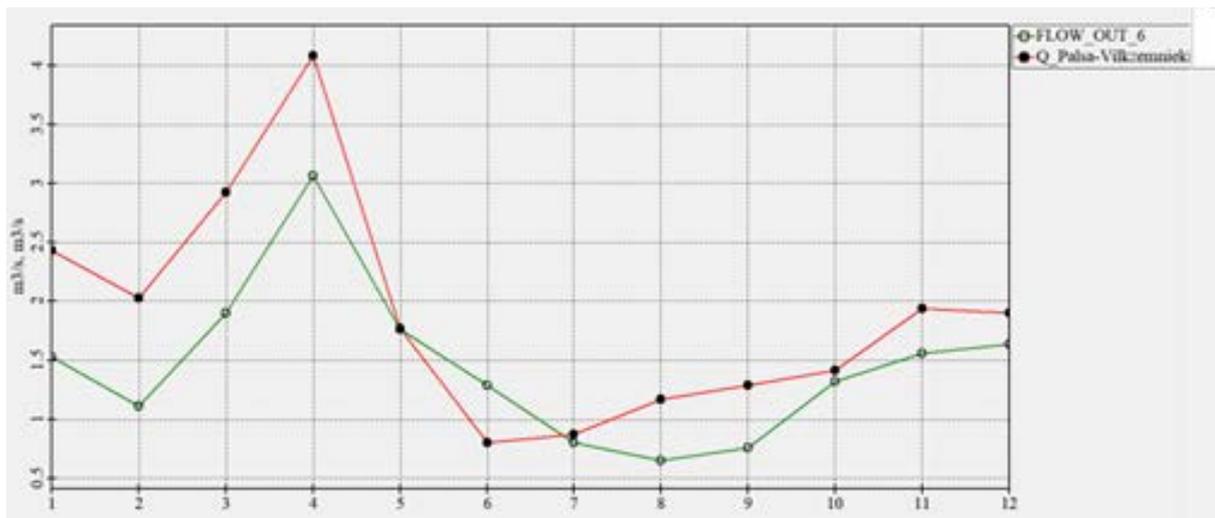

Figure 3.74: Monthly observed (red) and modelled (green) discharges at Palsa-Vilkzemnieki.

3.8. Overview of hydrological model results

The average run-off layer (in mm/day) calculated by SWAT+ for the entire territory of Latvia is shown in Figure 3.75. Higher run-off values are found at the western shores of Piejūras lowland, and in Rietumkursa, Vidzeme, Alūksne and Latgale highlands. The lowest run-off layer is modelled at the Viduslatvijas and Austrumlatvijas lowlands.
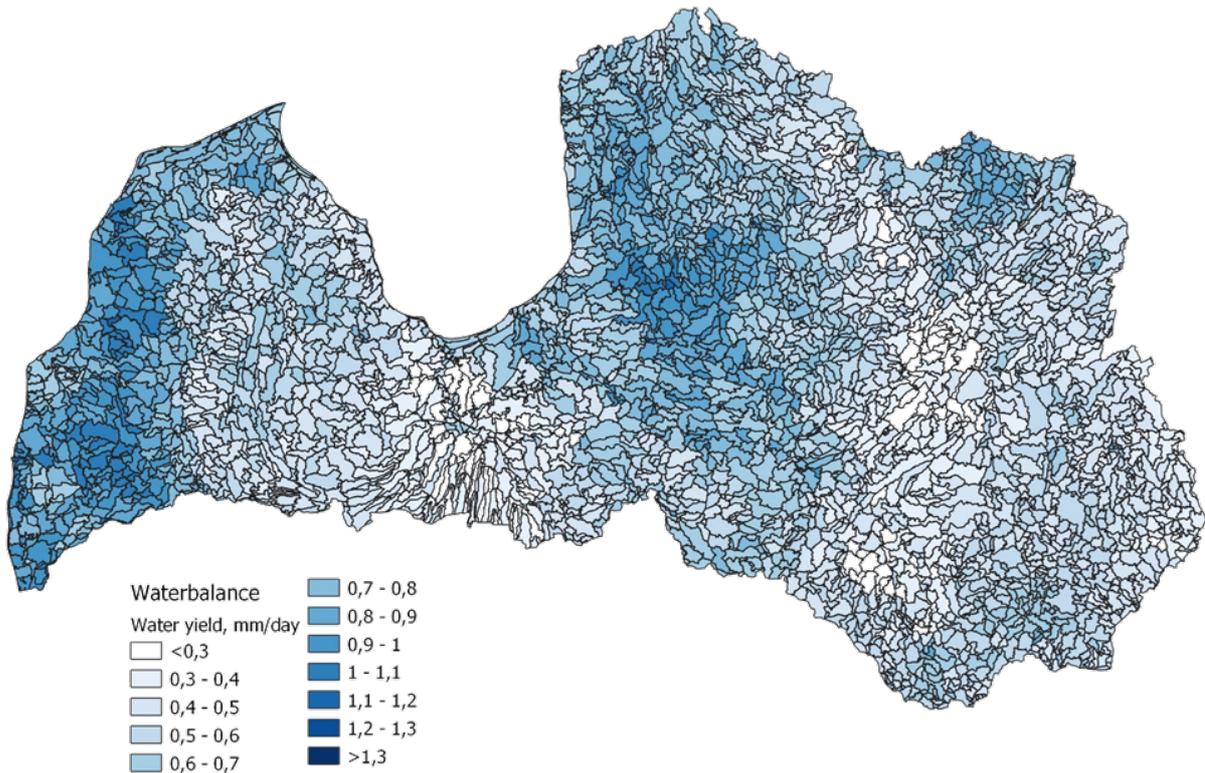
Figure 3.75: Modelled annual mean daily runoff layer.

The overall performance of the water quantity modelling is shown in Figure 3.76. It shows the PBIAS values at the observation stations.

One should note that there exist unsatisfactory discrepancies at all largest rivers – Venta, Lielupe, Ogre, Aiviekste and Gauja. In these stations, the observed discharges are obviously wrong although the reasons of these errors are unclear.

Such a situation raises doubts about the observation quality in smaller rivers, where the errors in observations cannot be easily noticed. Therefore, further improvement of calibration is not rational before the elimination of the systematic errors in observations.

One should also note that the calibration is limited downstream to the regulated reservoirs, where the river hydrograph depends on the regulation of the reservoir outflow.

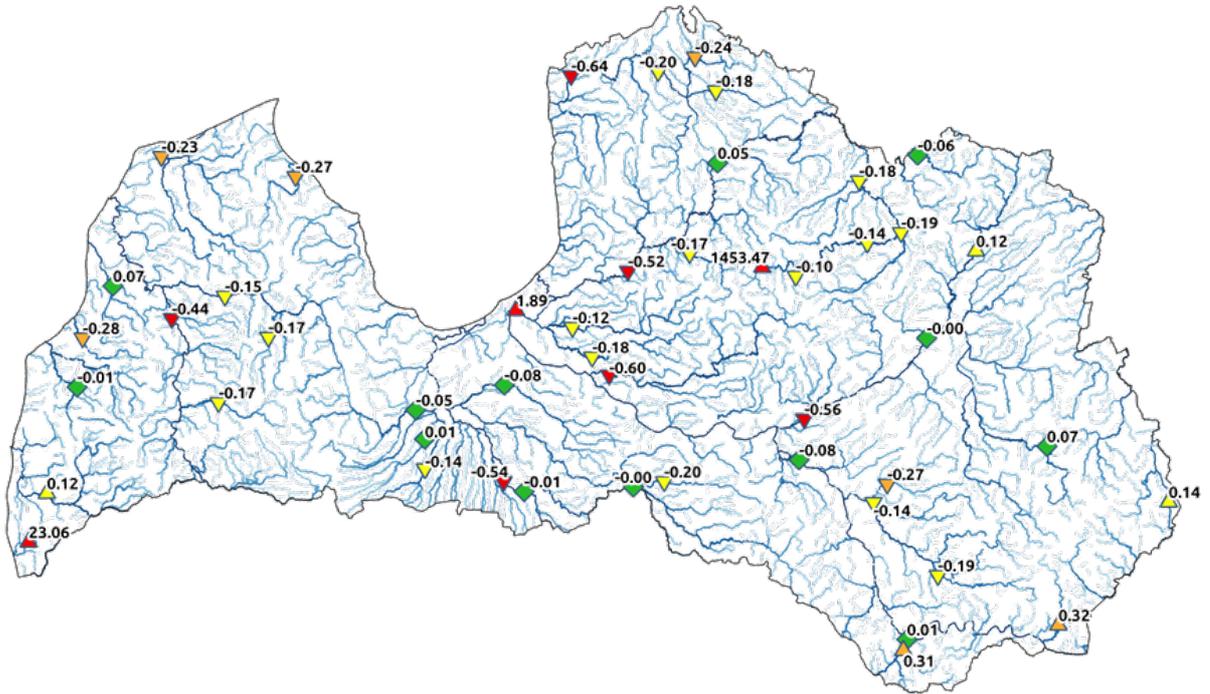Figure 3.76: Comparison of modelled and observed discharges by using PBIAS values: excellent (green), good (yellow), satisfactory (orange), bad (red).

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4.Water quality

4.1. Region r1I

The summary of calibration and validation for the coastal region r1I is provided in Table 4.1. In this table, bold lines correspond to the stations with more than 50 observations, which are analyzed further. PBIAS of monthly concentration values are given for all 4 nutrient fractions, while R2 of monthly values for nitrate and total nitrogen concentrations. Green cells correspond to very good or excellent, yellow – to good or satisfactory, while white – for unsatisfactory agreement between the modelling and observation values.

Table 4.1: Results of calibration and validation for region r1I.

STA ID	STANAME	N-NO3		N-TOT		P-PO4	P-TOT	Region
		PBIAS	R2	PBIAS	R2	PBIAS	PBIAS	
30	Aģe, mouth	-0,09	0,45	-0,51	0,26	-0,66	-0,69	r1
73	Daugava, mouth	0,07	0,30	-0,53	0,55	-0,31	-0,59	r1
74	Daugava, Rumbula	0,05	0,85	-0,55	0,85	-0,32	-0,59	r1
117	**Gauja, mouth**	**0,36**	**0,21**	**-0,21**	**0,09**	**1,48**	**-0,12**	**r1**
139	**Irbe, Vičaki**	**0,71**	**0,91**	**-0,32**	**0,87**	**0,99**	**-0,20**	**r1**
189	Lielais Baltezers lake	0,86	0,79	-0,31	0,93	0,16	-0,28	r1
204	**Lielupe, 0.5km dwnstr Kalnciems**	**0,11**	**0,72**	**-0,10**	**0,93**	**0,81**	**0,18**	**r1**
207	Lielupe, Majori	-0,11	0,71	-0,25	0,86	0,61	0,17	r1
209	**Lielā Jugla, 0.2km upstr Zaķi**	**0,23**	**0,42**	**-0,36**	**0,60**	**1,08**	**-0,02**	**r1**
212	Liepāja, Tirdzniecības channel	0,67	0,75	0,13	0,63	1,77	-0,14	r1
214	Liepāja lake	2,45	0,42	0,43	0,42	0,27	-0,30	r1
217	Lilaste lake	3,28	0,40	-0,23	0,22	0,97	-0,51	r1
238	**Mazais Baltezers lake**	**1,37**	**0,28**	**-0,23**	**0,36**	**0,02**	**-0,35**	**r1**
289	Pape lake	-0,26	0,72	-0,75	0,71	-0,70	-0,76	r1
334	Roja, mouth	0,09	0,91	-0,44	0,95	1,13	-0,31	r1
344	**Rīga reservoir**	**-0,05**	**0,89**	**-0,55**	**0,87**	**-0,28**	**-0,58**	**r1**
346	Rīva, mouth	0,20	0,67	-0,40	0,71	0,30	-0,43	r1
349	**Saka, 4.5 km upstr mouth**	**0,21**	**0,89**	**-0,29**	**0,90**	**0,24**	**-0,36**	**r1**
350	**Salaca, 0.5km upstr Salacgrīva**	**0,06**	**0,50**	**-0,42**	**0,48**	**2,40**	**0,01**	**r1**
419	Užava, mouth	-0,23	0,77	-0,58	0,84	0,48	-0,39	r1
436	Venta, mouth	0,53	0,81	-0,03	0,90	1,52	0,17	r1
484	Ķekava, mouth	1,74	0,25	0,02	0,52	-0,27	-0,56	r1
488	Ķīšezers, Mīlgrāvja channel	0,84	0,65	-0,31	0,89	0,09	-0,33	r1

Let us consider the 8 stations with more than 50 observations of the water quality. Validation criteria were met in 80% of these stations (38 out of 48 criteria).
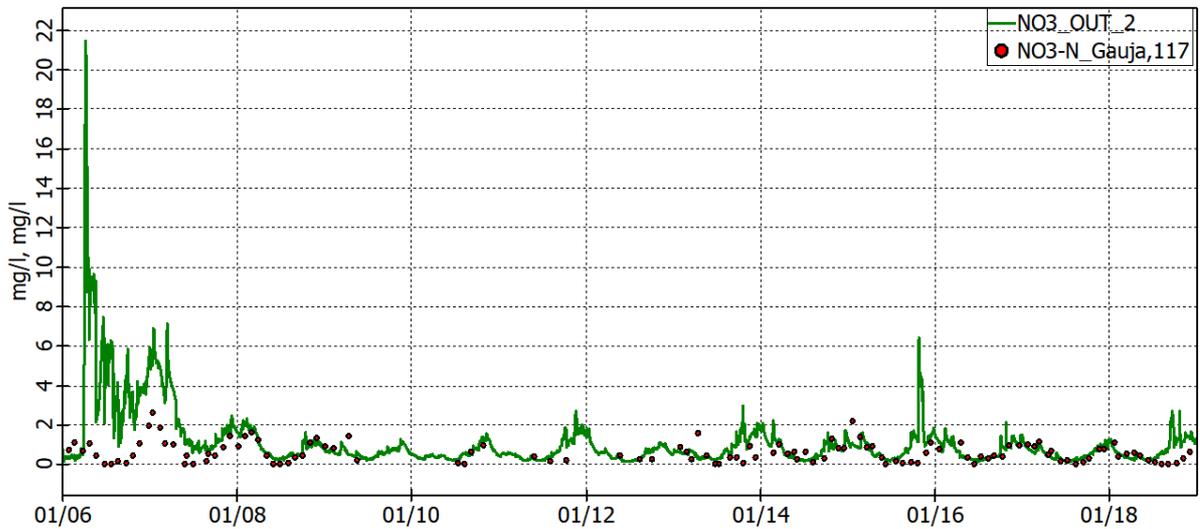
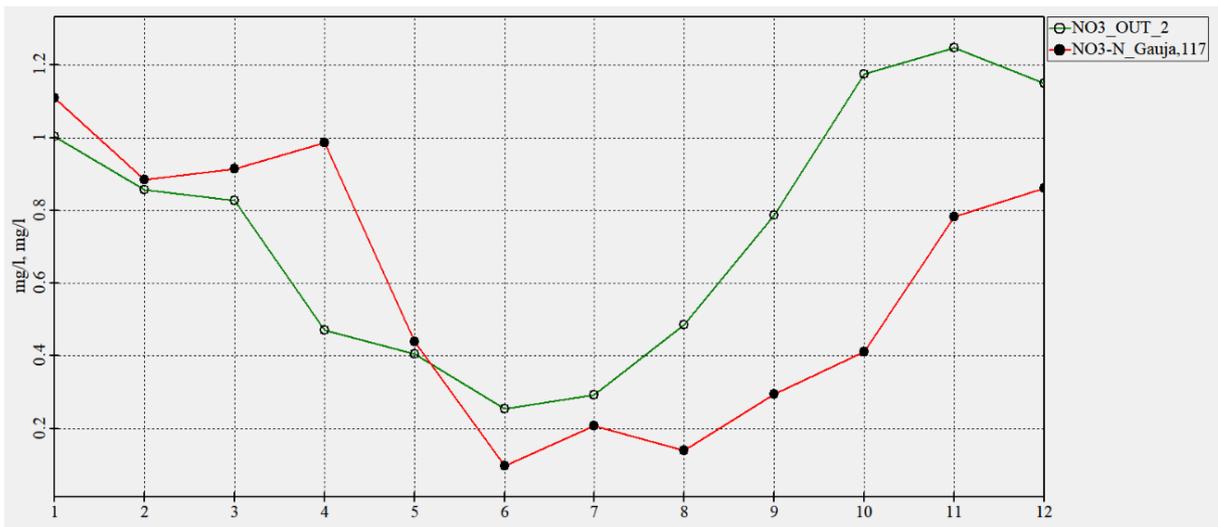Figure 4.1: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at the mouth of Gauja river.

Figure 4.2: Mean monthly values of the modelled (green) and observed (red) N-NO$_3$ concentrations at the mouth of Gauja river.

The comparison of modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.1 and as mean annual cycle of monthly values in Figure 4.2 for Gauja mouth, 2 km downstream Carnikava. The average level of N-NO3 is represented satisfactory, although the model overestimates the nitrate concentrations, especially in the 2nd half of the year. Note that 2-Year spin-off time is required for water quality model, Figure 4.1.
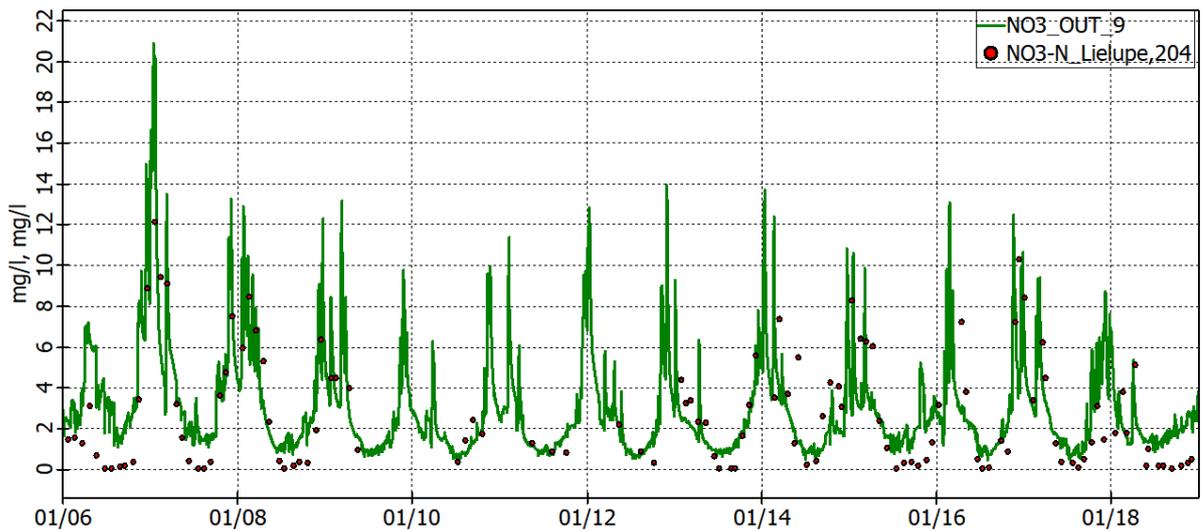
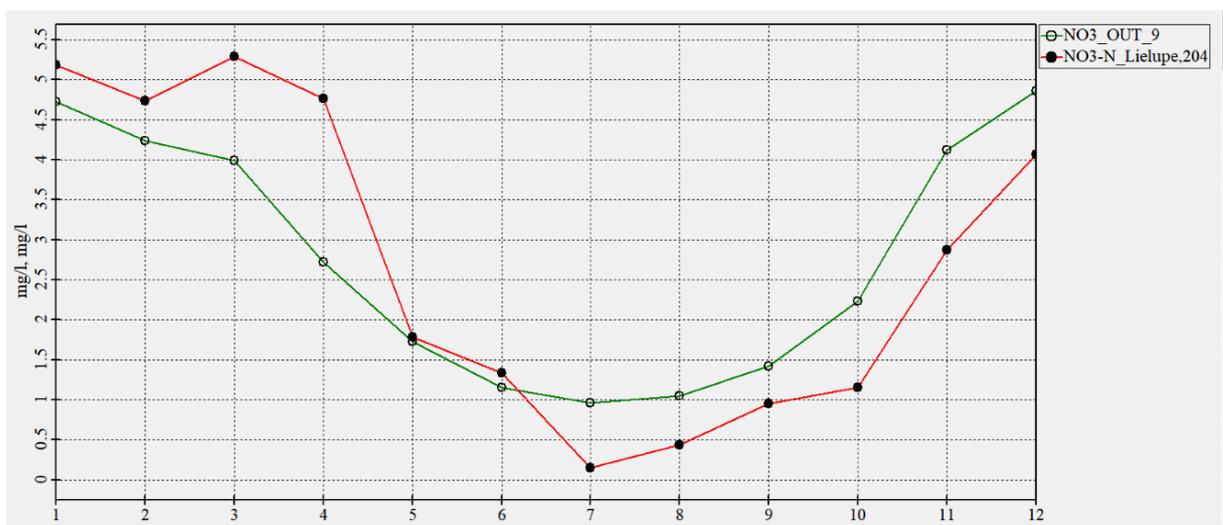Figure 4.3: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Lielupe-Kalnciems.

Figure 4.4: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Lielupe-Kalnciems.

The comparison of modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.3 and as mean annual cycle of monthly values in Figure 4.4 for Lielupe river, 0,5 km downstream Kalnciems. Although the nearly-zero summer concentrations are not fetched by the model, both the average concentrations and the correlation between the model and observations are excellent.
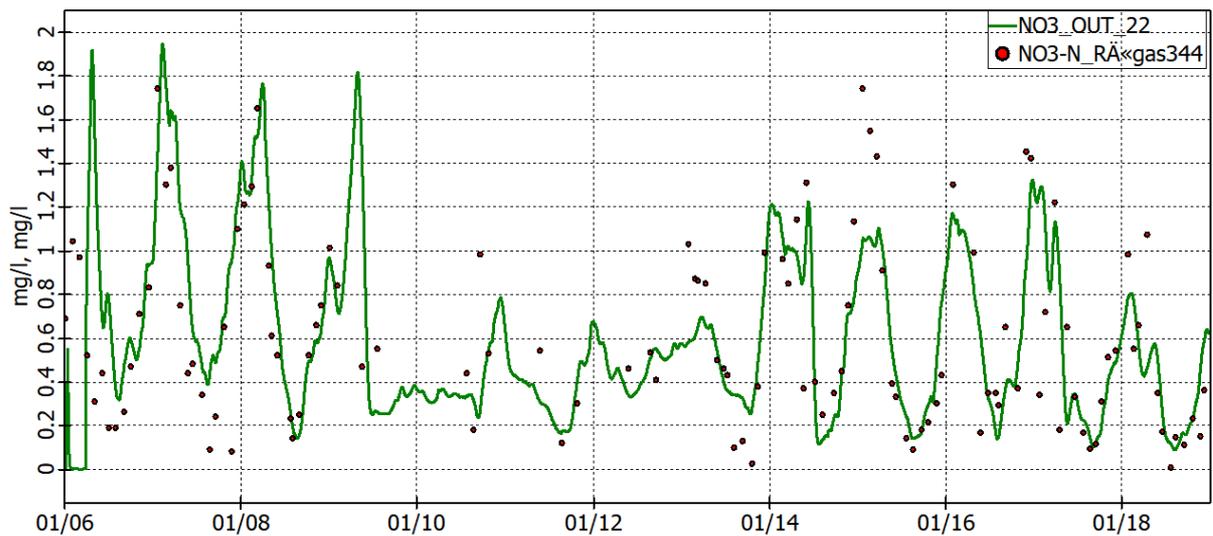
Figure 4.5: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Rīga HPP reservoir on Daugava.
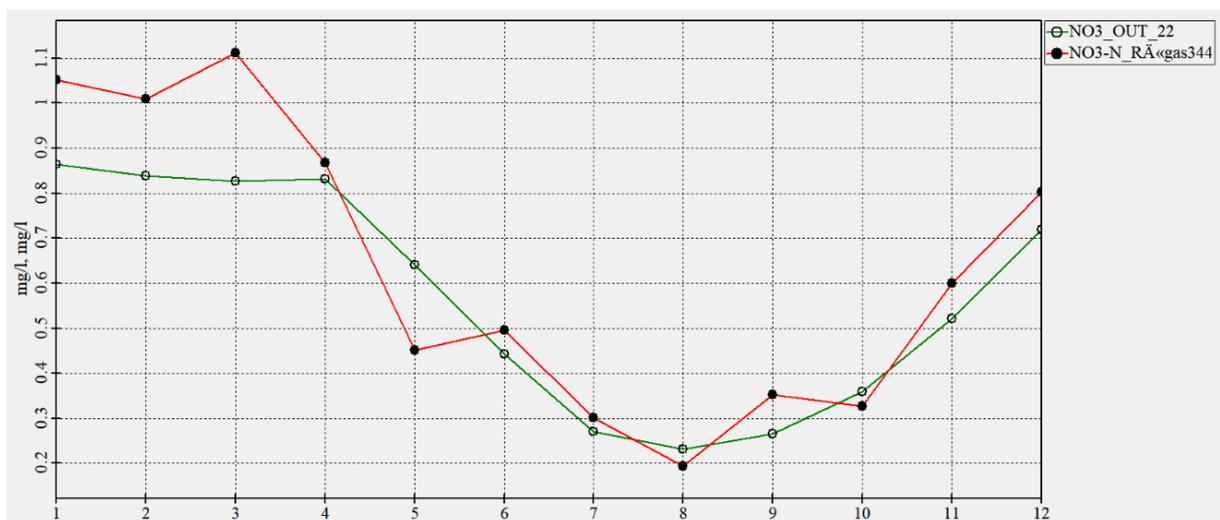

Figure 4.6: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Rīga HPP reservoir on Daugava.

The comparison of modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.5 and as mean annual cycle of monthly values in Figure 4.6 for Rīga HPP reservoir on Daugava River, 1 km downstream Lipši. The average concentrations, their seasonal cycle and the correlation between the model and observations are excellent.
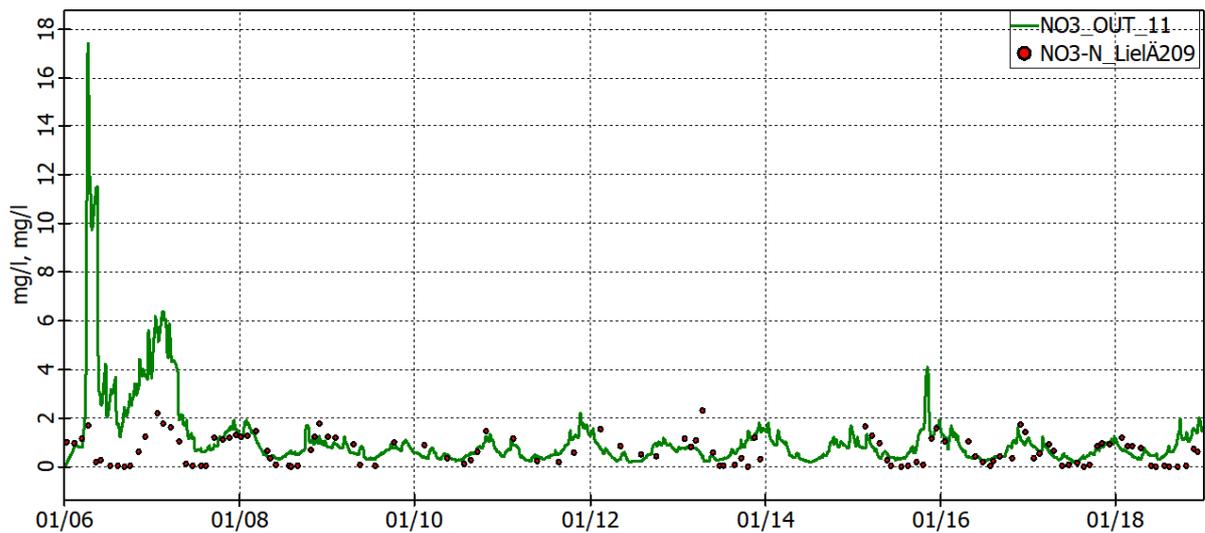
Figure 4.7: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Lielā Jugla upstream Zaķi.

Figure 4.8: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Lielā Jugla upstream Zaķi.

The comparison of modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.7 and as mean annual cycle of monthly values in Figure 4.8 for Lielā Jugla, 200 m upstream Zaķi. The model underestimates winter concentrations and overestimates the low summer concentrations. However, both the average concentrations and the correlation with the observations are rather good.

Figure 4.9: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Salaca, upstream Salacgrīva.
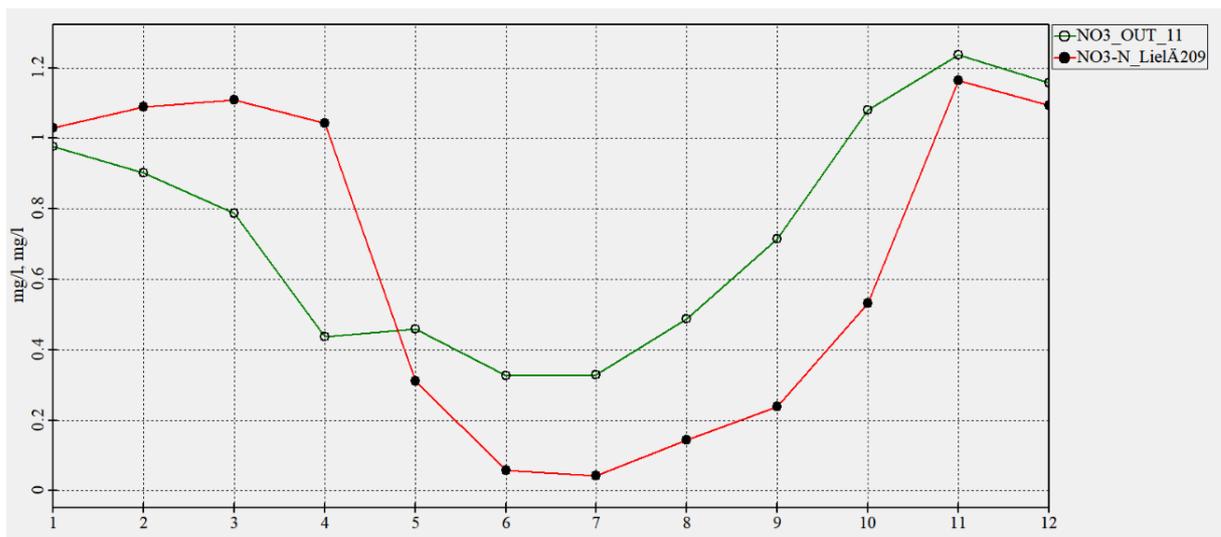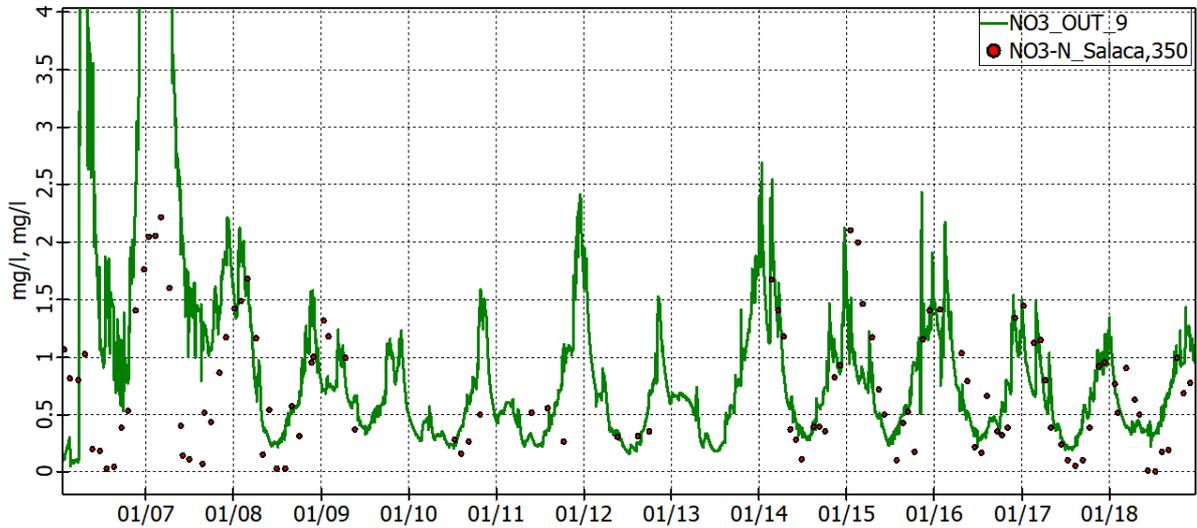

Figure 4.10: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Salaca, upstream Salacgrīva.

The comparison of modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.9 and as mean annual cycle of monthly values in Figure 4.10 for Salaca, 0,5 km upstream Salacgrīva. The model underestimates winter concentrations and overestimates the concentrations during the 2nd half of the year. However, both the average concentrations and the correlation with the observations are good.

Figure 4.11: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Mazais Baltezers lake.
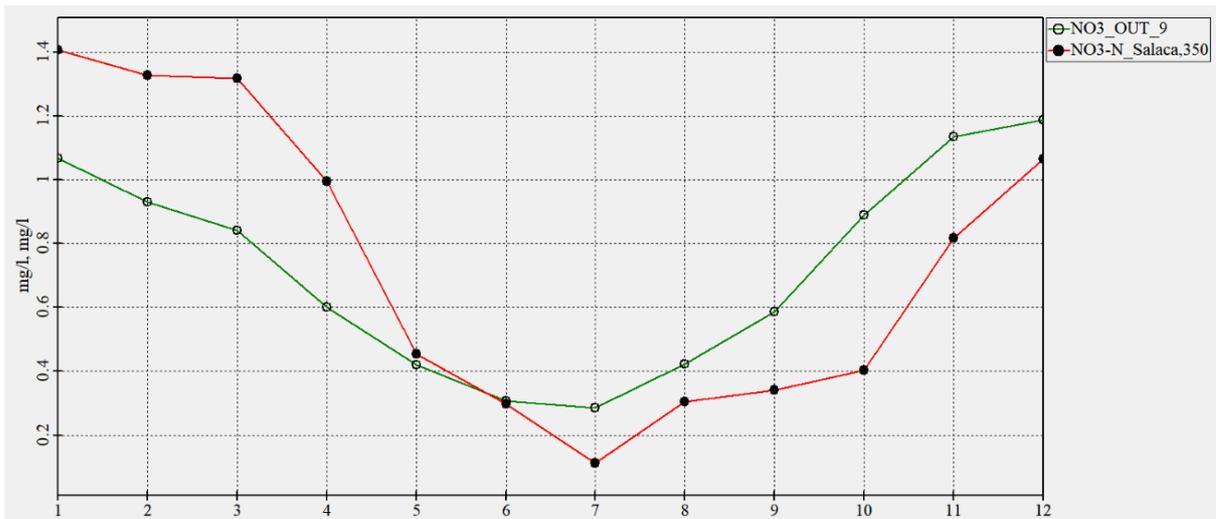

Figure 4.12: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Mazais Baltezers lake.

The comparison of modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.11 and as mean annual cycle of monthly values in Figure 4.12 for Mazais Baltezers lake, upstream the pumping station SWAT+ overestimates the N-NO3 concentrations from May to December failing to reproduce the low summer and especially, autumn values. One may consider that lake parameters or processes are not properly represented in the model.
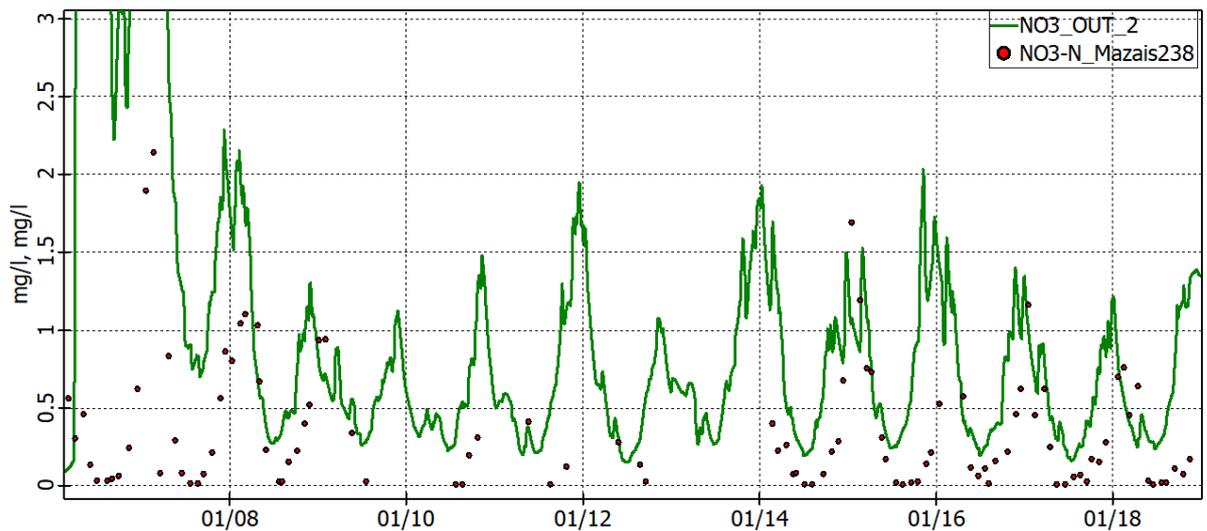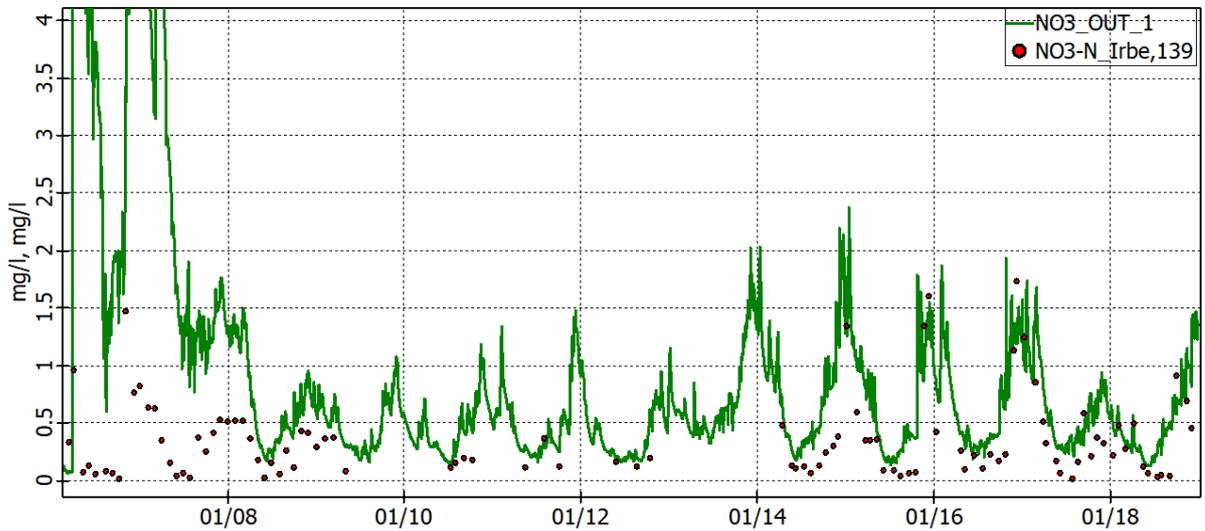
Figure 4.13: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Irbe-Vičaki.
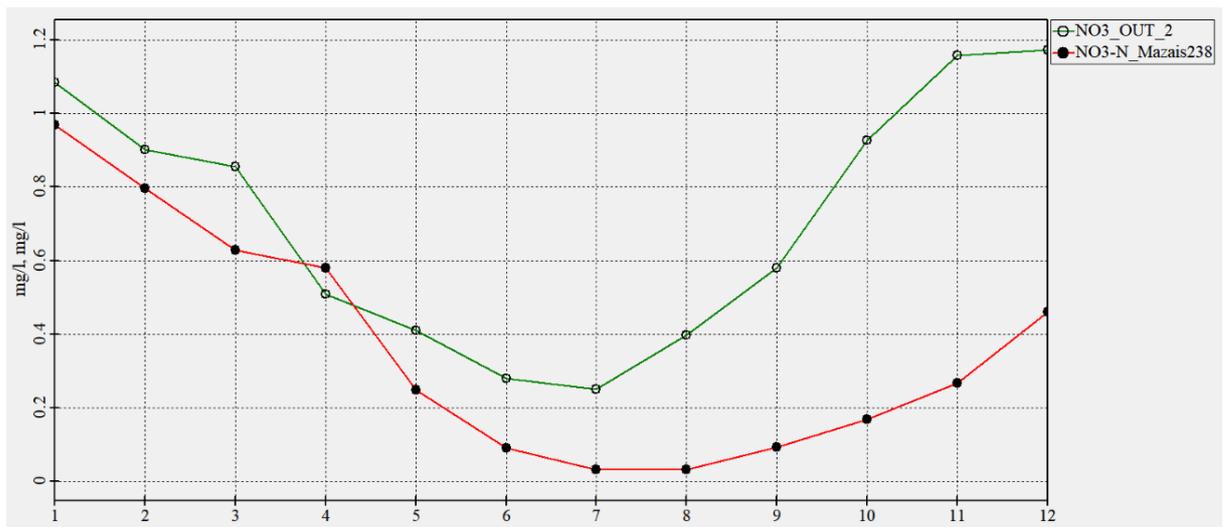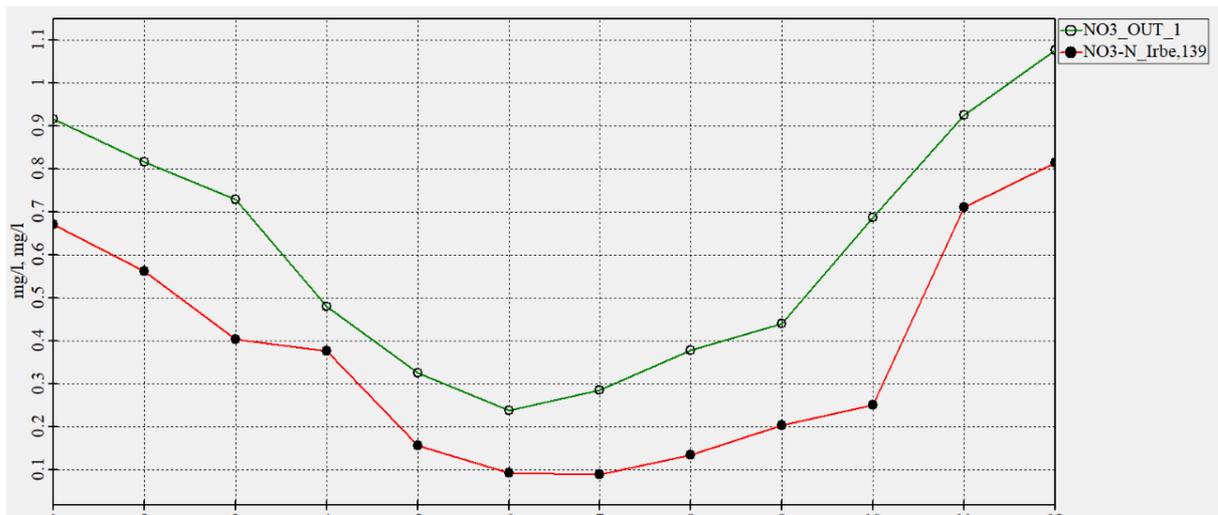

Figure 4.14: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Irbe-Vičaki.

The comparison of modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.13 and as mean annual cycle of monthly values in Figure 4.14 for Irbe-Vičaki. SWAT+ systematically overestimates the N-NO3 concentrations throughout the year, although the correlation between the observed and modelled concentrations is excellent. One may consider that background loads of N-NO3 are overestimated in the model.

Figure 4.15: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Saka, 4,5 km upstream mouth.
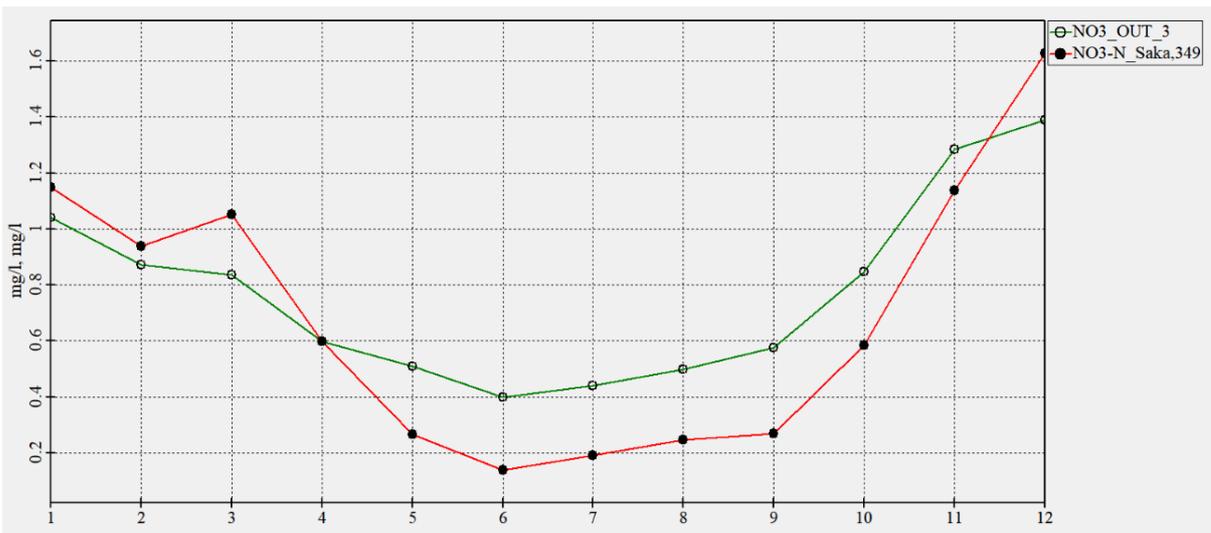
Figure 4.16: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Saka, 4,5 km upstream mouth.

The comparison of modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.15 and as mean annual cycle of monthly values in Figure 4.16 for Saka, 4,5 km upstream mouth. The modelled time series has an excellent correlation with the observations, although SWAT+ overestimates the N-NO3 concentrations during the warm half-year.

4.2. Region r2I

The summary of calibration and validation for the Kurzeme region r2I is provided in Table 4.2. In this table, bold lines correspond to the stations with more than 50 observations, which are analyzed further. PBIAS of monthly concentration values are given for all 4 nutrients, while R2 of monthly values for nitrate and total nitrogen concentrations. Green cells correspond to very good or excellent, yellow – to good or satisfactory, while white – for unsatisfactory agreement between the modelling and observation values.

Table 4.2: Results of calibration and validation for region r2I.

STA ID	STANAME	N-NO3		N-TOT		P-PO4	P-TOT	Region
		PBIAS	R2	PBIAS	R2	PBIAS	PBIAS	
19	**Amula, mouth**	**0,55**	**0,72**	**-0,10**	**0,75**	**3,03**	**-0,02**	**r2**
52	**Bārta, Dūkupji**	**0,24**	**0,90**	**-0,04**	**0,92**	**0,84**	**-0,11**	**r2**
53	**Bārta, LV-LT border**	**0,41**	**0,88**	**0,09**	**0,91**	**0,52**	**-0,21**	**r2**
417	Usma lake	4,83	0,87	-0,10	0,27	2,13	-0,37	r2
432	**Venta, Nīgrande**	**0,22**	**0,79**	**-0,02**	**0,87**	**0,68**	**0,12**	**r2**
435	**Venta, Vendzava**	**0,30**	**0,75**	**-0,02**	**0,92**	**1,89**	**0,29**	**r2**

Let us consider the 5 stations with more than 50 observations of the water quality. Validation criteria were met in 80% of these stations (27 out of 30 criteria). One should note that SWAT+ systematically overestimates the phosphate concentration in the rivers of region r2I.
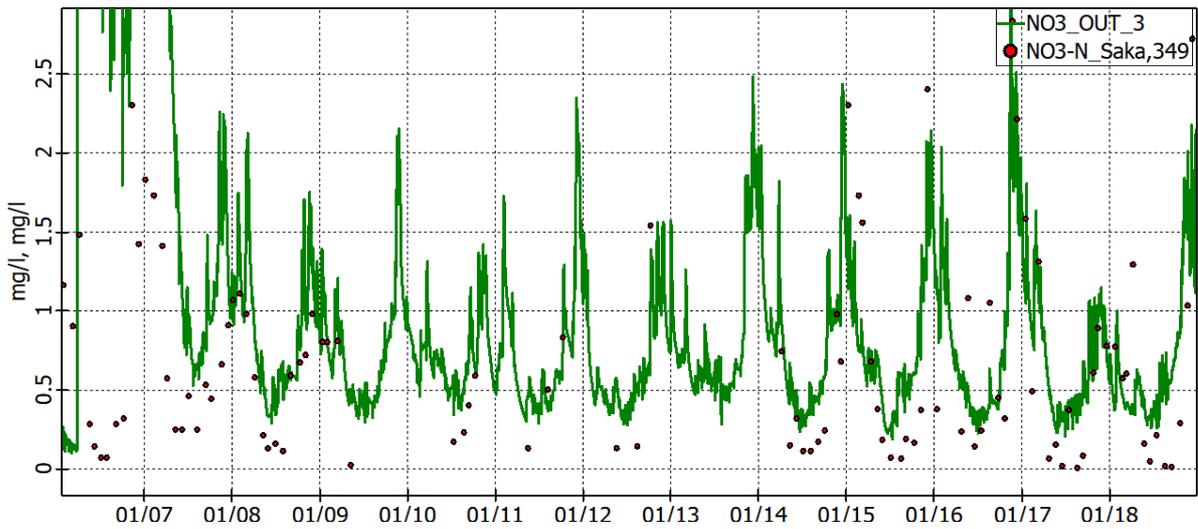
Figure 4.17: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at the mouth of the Amula River.

Figure 4.18: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at the mouth of the Amula River.

The comparison of the modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.17 and as mean annual cycle of monthly values in Figure 4.18 for the Amula mouth. The model nicely represents the annual cycle failing to reach the observed near-zero nitrate values in the vegetation season May-October.
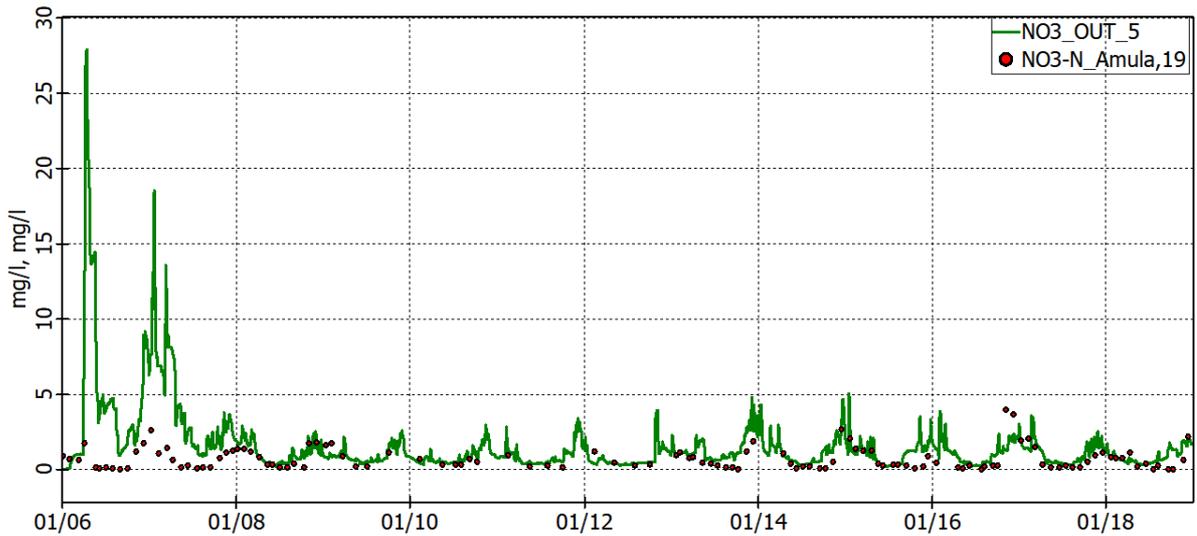
Figure 4.19: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Venta-Nīgrande.

Figure 4.20: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Venta-Nīgrande.

The comparison of the modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.19 and as mean annual cycle of monthly values in Figure 4.20 for the river Venta, 0,5 km upstream Nīgrande. The model shows excellent correlation between the observed and modelled N-NO3 concentrations and accurately represents the annual cycle slightly failing to reach the observed low nitrate values in the vegetation season May-October. This agreement is in part due the well calibrated transboundary inflow form the model of LT water quality, PAIC (2022c).

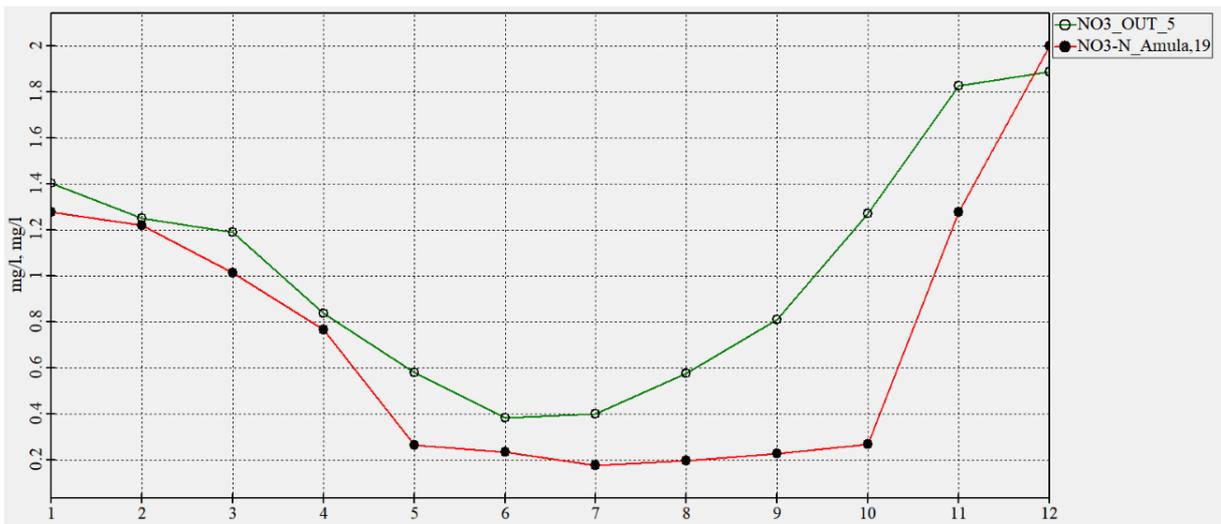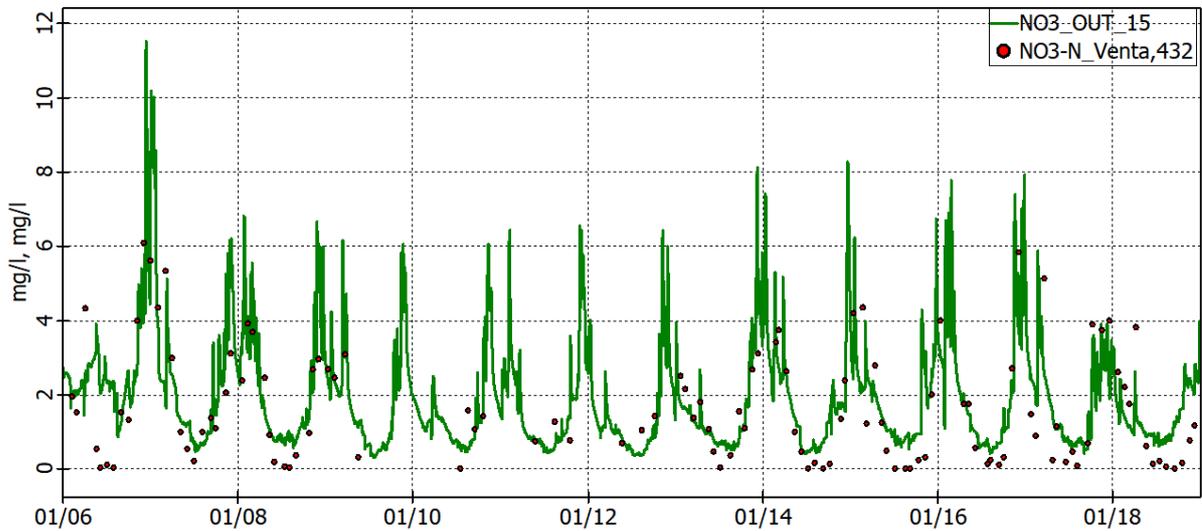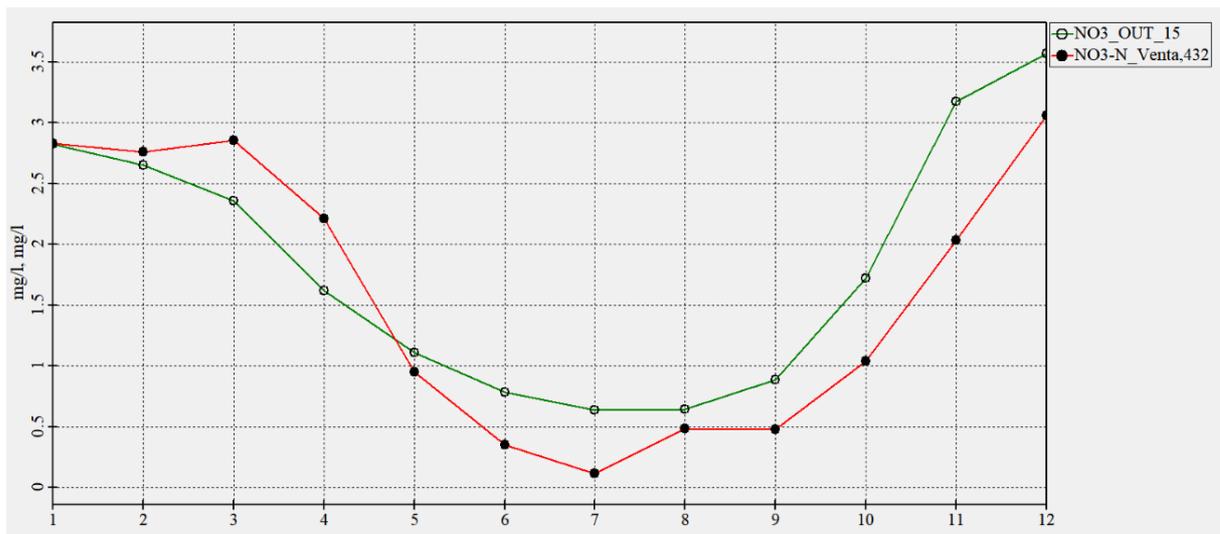Figure 4.21: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Venta-Vendzava.

Figure 4.22: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Venta-Vendzava.

The comparison of the modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.21 and as mean annual cycle of monthly values in Figure 4.22 at the Venta-Vendzava. This station is located some 100 km downstream from previous (Nīgrande), and qualitatively nitrate concentrations are similar, although the nitrate concentrations are slightly lower due the retention.

Figure 4.23: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Bārta, LT-LV border.

Figure 4.24: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Bārta, LT-LV border.

The comparison of the modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.19 and as mean annual cycle of monthly values in Figure 4.20 for the river Bārta, at LT-LV border. The model shows excellent correlation between the observed and modelled N-NO3 concentrations and accurately represents the annual cycle. At the same time, model slightly overestimates the nitrate concentration throughout the year. This comparison purely represents the transboundary inflow from the model of LT water quality, PAIC (2022c).
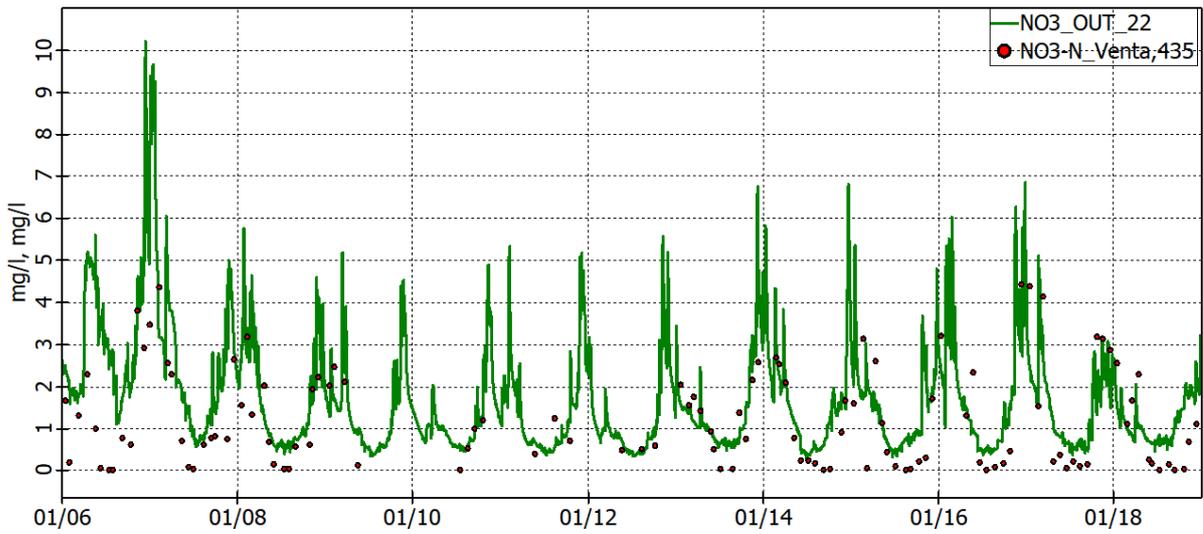
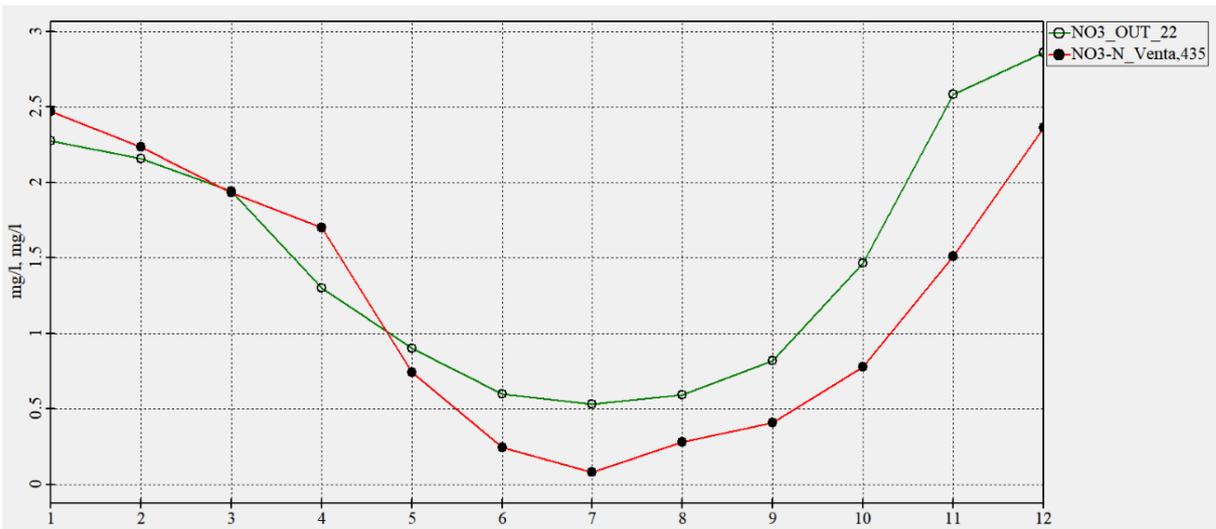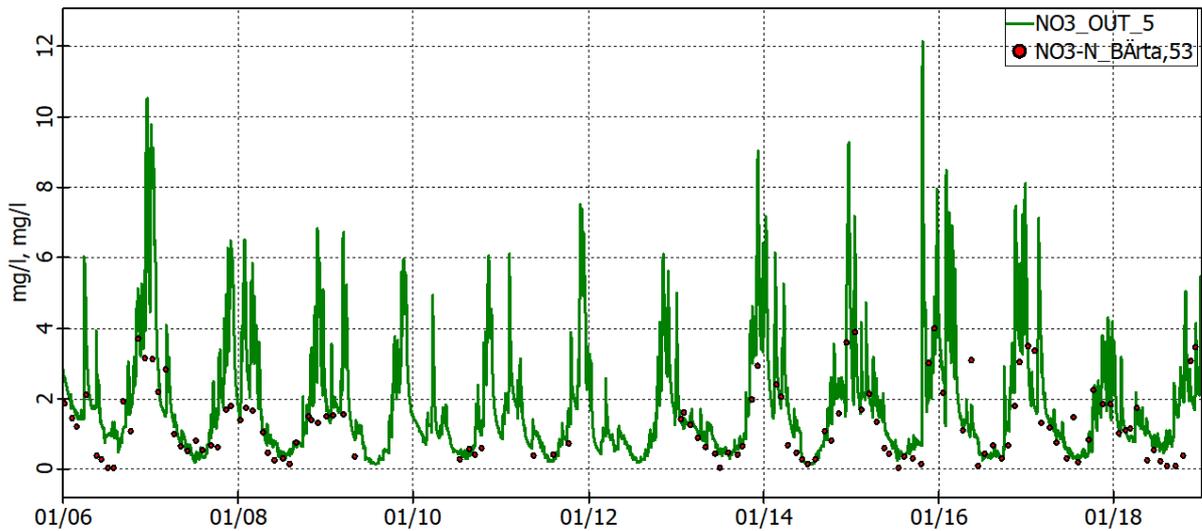Figure 4.25: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Bārta-Dūkupji.

Figure 4.26: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Bārta-Dūkupji.

The comparison of the modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.19 and as mean annual cycle of monthly values in Figure 4.20 for the river Bārta, 0,2 km upstream Dūkupji. The model results are slightly improved in the approximately 20 km long stretch from the previous upstream station.

4.3. Region r3I

The summary of calibration and validation for the Viduslatvija lowland region r3I is provided in Table 4.3. In this table, bold lines correspond to the stations with more than 50 observations, which are analysed further. PBIAS of monthly concentration values are given for all 4 nutrients, while R2 of monthly values for nitrate and total nitrogen concentrations. Green cells correspond to very good or excellent, yellow – to good or satisfactory, while white – for unsatisfactory agreement between the modelling and observation values.

Table 4.3: Results of calibration and validation for region r3I.

STA ID	STANAME	N-NO3		N-TOT		P-PO4	P-TOT	Region
		PBIAS	R2	PBIAS	R2	PBIAS	PBIAS	
54	Bērze, 1.0 km upstr Dobele	0,18	0,86	-0,32	0,95	2,07	0,24	r3
55	Bērze, 1.0 km dwnstr Dobele	0,13	0,45	-0,30	0,63	0,41	-0,11	r3
130	Iecava, mouth	0,52	0,01	-0,31	0,01	0,33	-0,32	r3
255	Misa, mouth	0,08	0,28	-0,44	0,19	0,24	-0,26	r3
260	Mēmele, LT-LV border	0,07	0,82	-0,05	0,66	0,57	-0,05	r3
261	Mēmele, mouth	0,38	0,55	-0,05	0,54	0,89	-0,02	r3
264	**Mūsa, LT-LV border**	**0,11**	**0,80**	**0,18**	**0,93**	**1,40**	**1,33**	**r3**
265	Mūsa, mouth	0,15	0,70	0,26	0,62	2,24	2,13	r3
388	Svitene, mouth	-0,55	0,70	-0,59	0,74	1,15	0,32	r3
411	**Tērvete, upstr Tērvete**	**-0,53**	**0,52**	**-0,65**	**0,81**	**1,49**	**0,96**	**r3**
412	Tērvete, mouth	-0,54	0,82	-0,67	0,92	0,55	0,18	r3
490	Īslīce, mouth	-0,45	0,80	-0,53	0,82	0,01	0,01	r3

Let us consider the 2 stations with more than 50 observations of the water quality. Validation criteria were met for nitrogen, while phosphorus concentrations were overestimated by the model in these stations.

Figure 4.27: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Mūsa, LT-LV border.

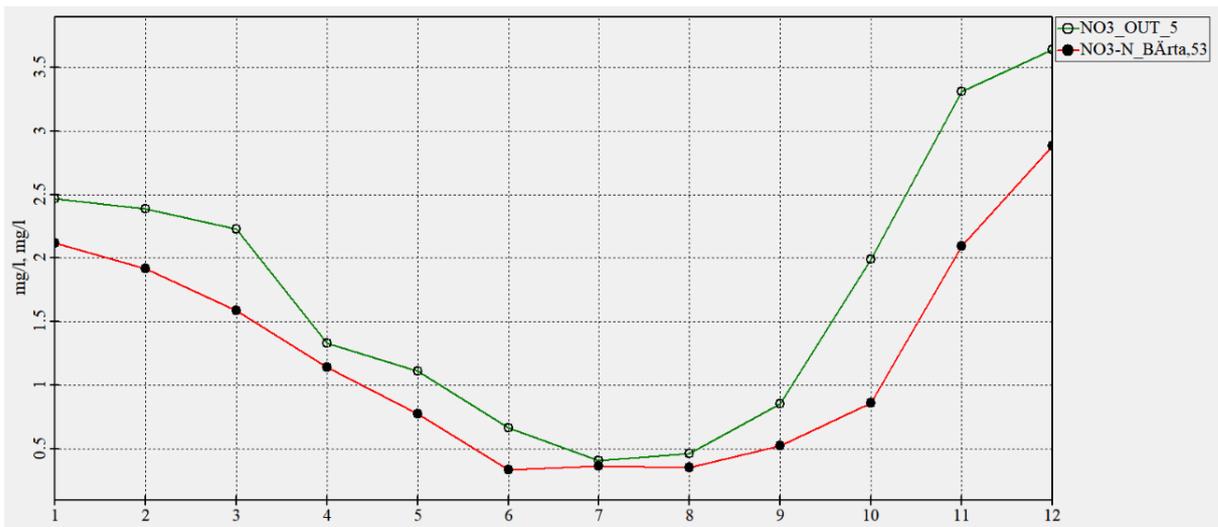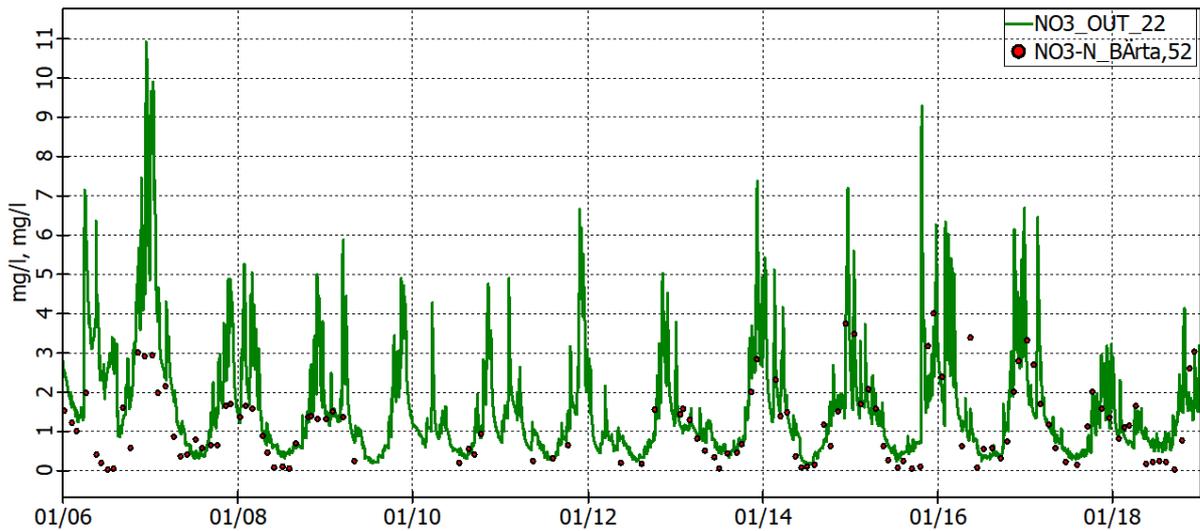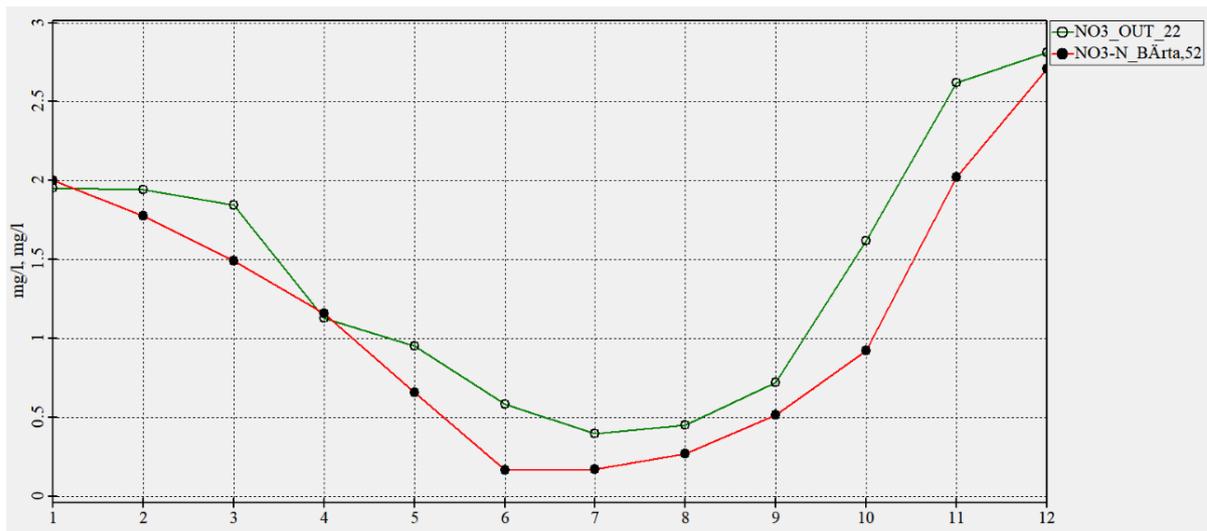
Figure 4.28: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Mūsa, LT-LV border.

The comparison of the modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.27 and as mean annual cycle of monthly values in Figure 4.28 for the Mūsa, LT-LV border. The model has an excellent correlation with the observations. It represents well the annual cycle, however, it underestimates the nitrate concentrations in January-May, and overestimates – in June-December, failing to reach the very low observed values in summer. Model results at this station reflect the transboundary output from the LT water quality SWAT+ model, PAIC (2022c).
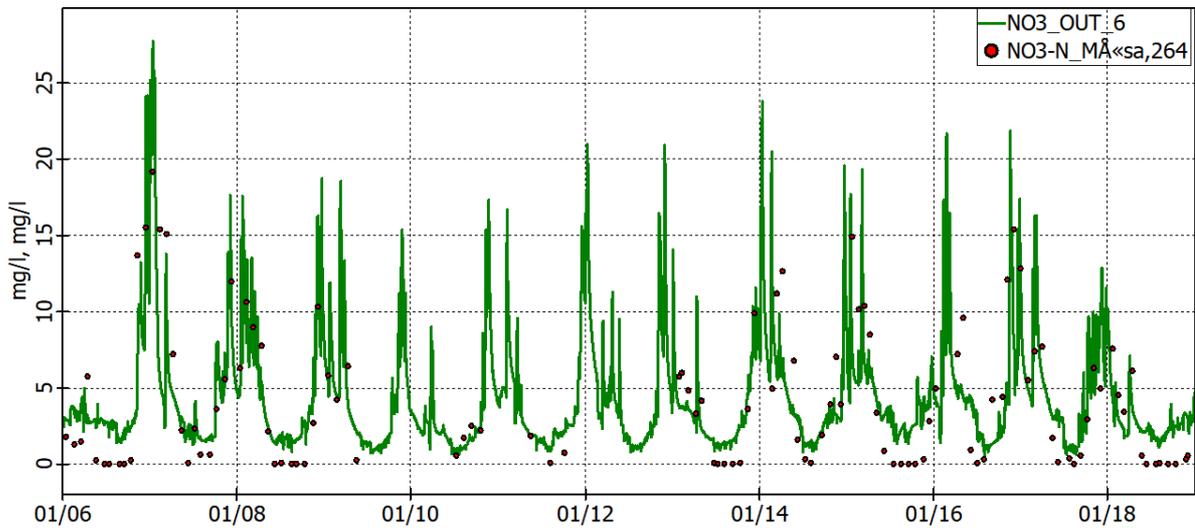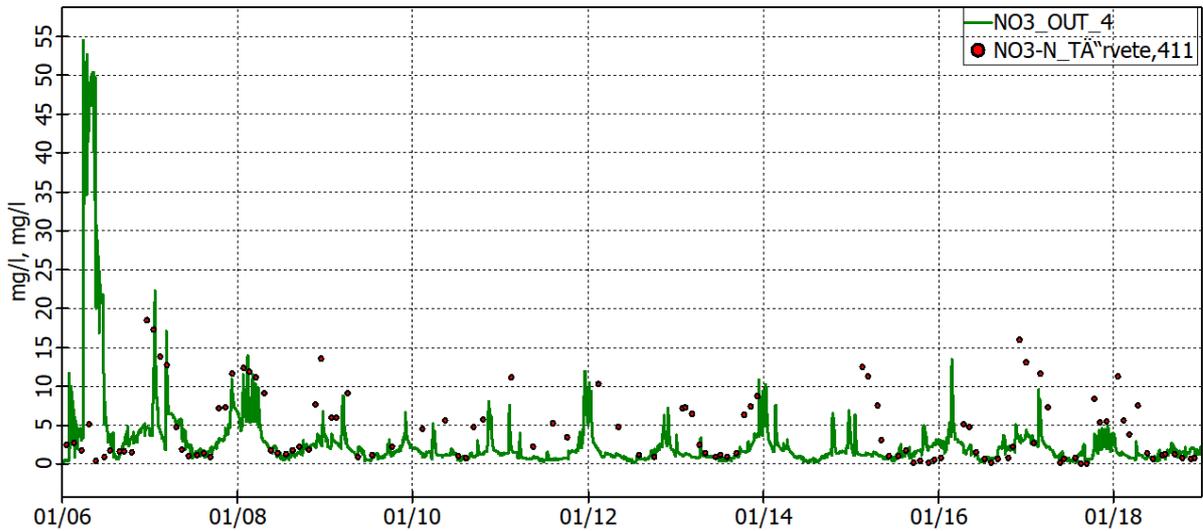
Figure 4.29: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Tērvete-Tērvete.
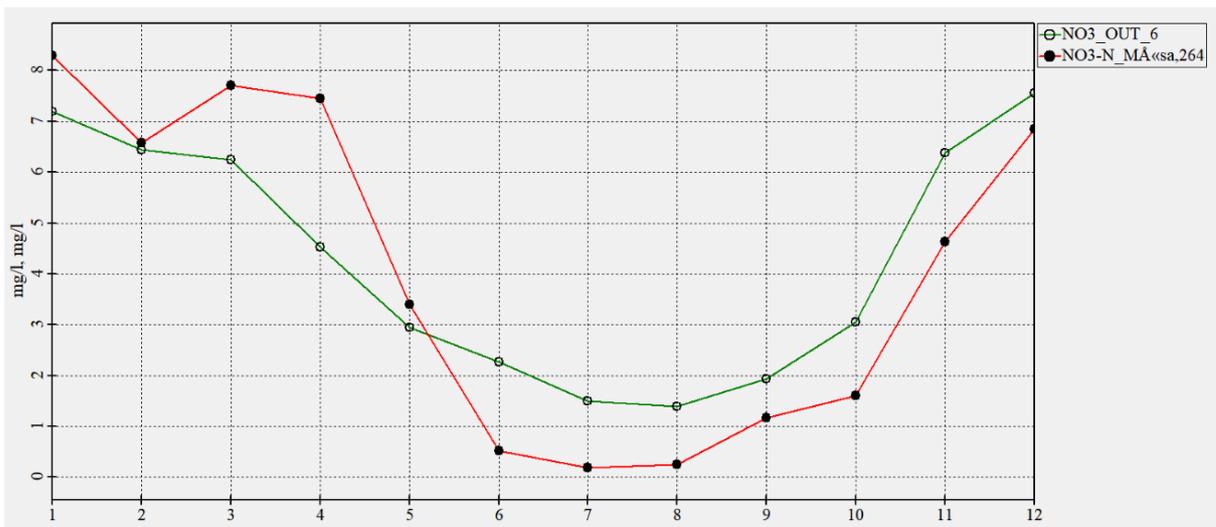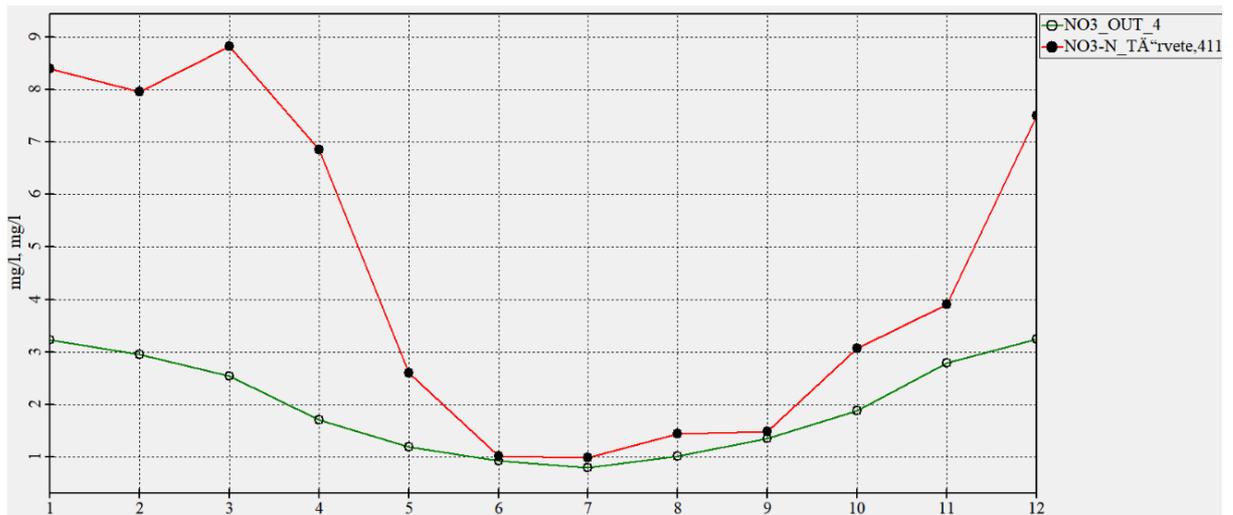

Figure 4.30: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Tērvete-Tērvete.

The comparison of the modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.29 and as mean annual cycle of monthly values in Figure 4.30 for the Tērvete river, upstream Tērvete. The model has a good correlation with the observations. However, although the validation criteria are met, it grossly underestimates the nitrate concentration outside the vegetation season.

4.4. Region r4I

The summary of calibration and validation for the Vidzeme highland region r4I is provided in Table 4.4. In this table, bold lines correspond to the stations with more than 50 observations, which are analysed further. PBIAS of monthly concentration values are given for all 4 nutrients, while R2 of monthly values for nitrate and total nitrogen concentrations. Green cells correspond to very good or excellent, yellow – to good or satisfactory, while white – for unsatisfactory agreement between the modelling and observation values.

Table 4.4: Results of calibration and validation for region r4I.

STA ID	STANAME	N-NO3		N-TOT		P-PO4	P-TOT	Region
		PBIAS	R2	PBIAS	R2	PBIAS	PBIAS	
17	Alūksne lake	3,36	0,30	0,10	0,48	-0,24	-0,04	r4
25	Augstrozes Lielezers lake	4,16	0,64	-0,03	0,02	2,51	0,52	r4
50	Burtnieka lake, Salaca outflow	0,98	0,21	-0,41	0,17	4,55	-0,40	r4
51	Burtnieka lake, middlea	0,51	0,78	-0,44	0,64	1,47	-0,53	r4
75	Dauguļu lake	3,58	0,81	-0,31	0,51	3,67	-0,40	r4
116	Gauja, 1.0 km dwnstr Valmiera	0,67	0,08	-0,28	0,19	0,81	-0,23	r4
380	Stirnezers lake	6,27	0,54	-0,22	0,05	6,38	-0,13	r4
413	**Tūlija, 0.3 km dwnstr Zosēni**	**1,68**	**0,02**	**-0,16**	**0,02**	**3,41**	**-0,09**	**r4**
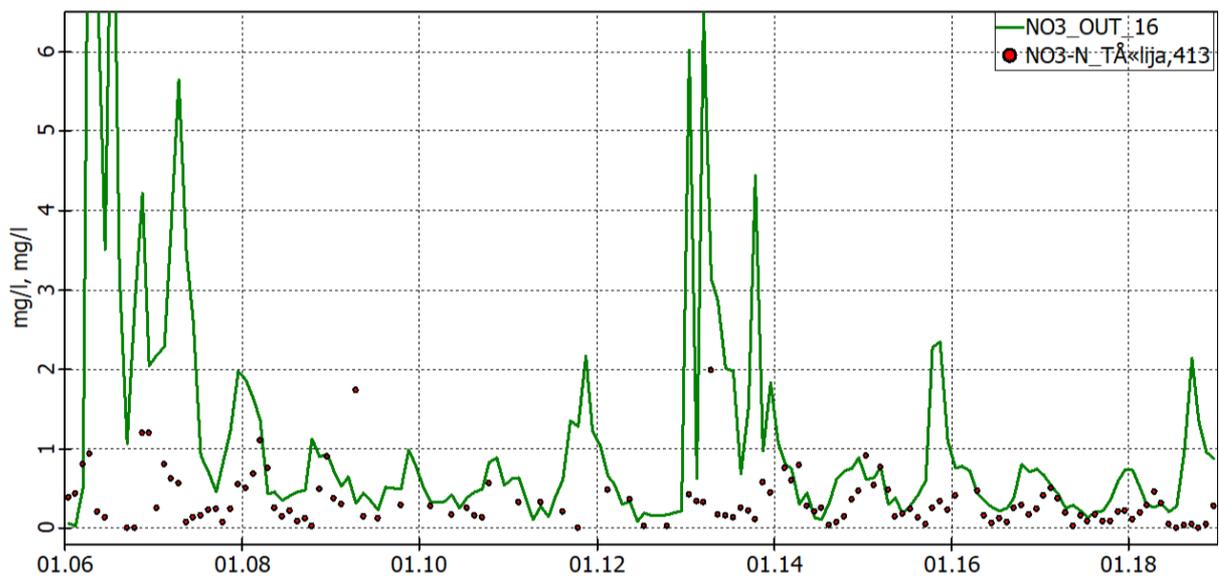
Figure 4.31: Time graph of modelled (green) and observed (dots) N-NO3 concentrations at Tūlija-Zosēni.

Generally, the validation of water quality model was poor in region r4I. Target criteria were met in just 54% - for 26 out of 48 criteria. To a certain extent it may be explained with multiple lake observation stations. Lake parameters are sometimes uncertain and SWAT+ does not detail the parameter distribution within the lakes as well as failing in representing lake processes.

Consequently, the model almost always overestimated the inorganic nutrient concentrations, see Table 4.4.

Let us consider the only station with more than 50 observations of the water quality.

The comparison of the modelled and observed nitrate nitrogen is provided as time graph of concentrations in Figure 4.31 and as mean annual cycle of monthly values in Figure 4.32 for Tūlija, 0,3 km downstream Zosēni. The observed seasonal cycle is rather simple in this river, with distinct spring snowmelt maximum and prolonged minimum during the vegetation season. The model indicates another distinct peak at the end of vegetation season (October) as well as overall overestimation of nitrate concentrations in this very clean river. This may indicate that SWAT+ fails to deliver low values of background pollution.
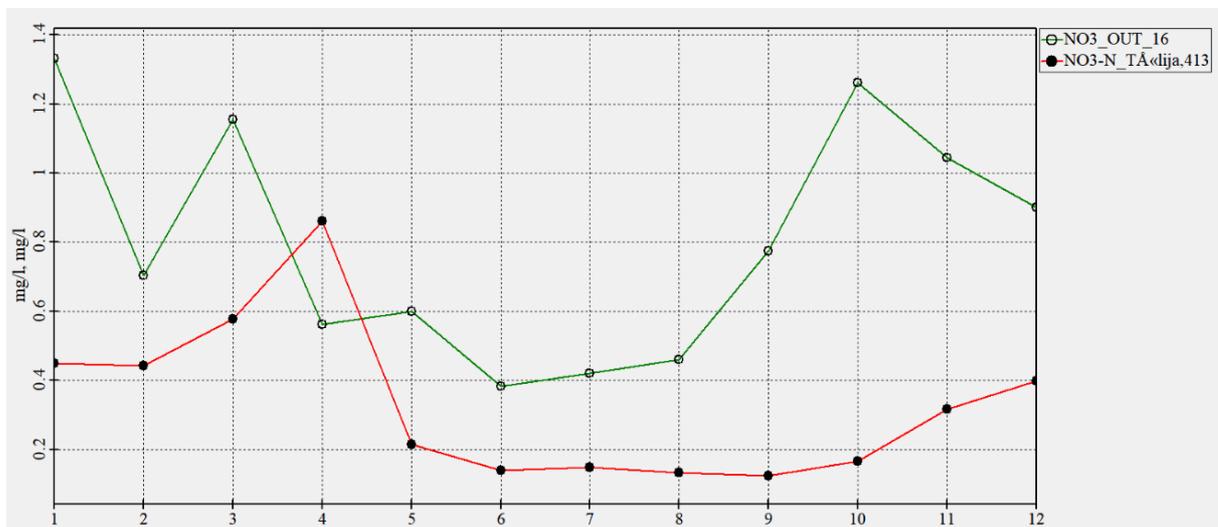

Figure 4.32: Mean monthly values of the modelled (green) and observed (red) N-NO3 concentrations at Tūlija-Zosēni

4.5. Regions r5I-r7I

The summary of calibration and validation for the southeastern regions r5I-r6I is provided in Table 4.5. PBIAS of monthly concentration values are given for all 4 nutrients, while R2 of monthly values for nitrate and total nitrogen concentrations. Green cells correspond to very good or excellent, yellow – to good or satisfactory, while white – for unsatisfactory agreement between the modelling and observation values. There are no water quality stations suitable for calibration or validation in the northeastern region r7I.

Table 4.5: Results of calibration and validation for regions r5I and r6I.

STA ID	STANAME	N-NO3		N-TOT		P-PO4	P-TOT	Region
		PBIAS	R2	PBIAS	R2	PBIAS	PBIAS	
65	Daugava, 1.0 km upstr Jēkabpils	-0,18	0,87	-0,62	0,80	-0,13	-0,59	r5
223	Lubāna lake	-0,19	0,41	-0,54	0,38	0,42	-0,67	r5
341	Rēzekne, 4.0 km upstr Rēzekne	-0,38	0,01	-0,57	0,00	-0,10	-0,43	r5
70	Daugava, LV – BY border	-0,04	0,98	-0,55	0,95	0,02	-0,60	r6
81	Drīdža lake	6,47	0,79	0,25	0,28	0,47	-0,44	r6
360	Saukas lake	3,95	0,45	0,00	0,16	1,41	-0,28	r6

Generally, the validation of water quality model was satisfactory in regions r5I-r6I. Target criteria were met in 80% of cases – 29 out of 36 criteria. One should note that (1) half of the useful stations are located in the lakes and (2) Daugava stations rather reflect the transboundary inflow from Belarus, i.e. the prescribed boundary conditions.

There are no stations with more than 50 observations of the water quality in regions r4I-r7I.

4.6. Overview of water quality model results

The comparison of the observed and modelled nitrate concentrations is given in Figure 4.33 at the observation stations. The size of the markers corresponds to the number of observations, while annotations and colors – monthly PBIAS values at these stations. Most of the unsatisfactory results are found in the clean streams where SWAT+ fails in reproducing the low nitrate values, and in the lakes.
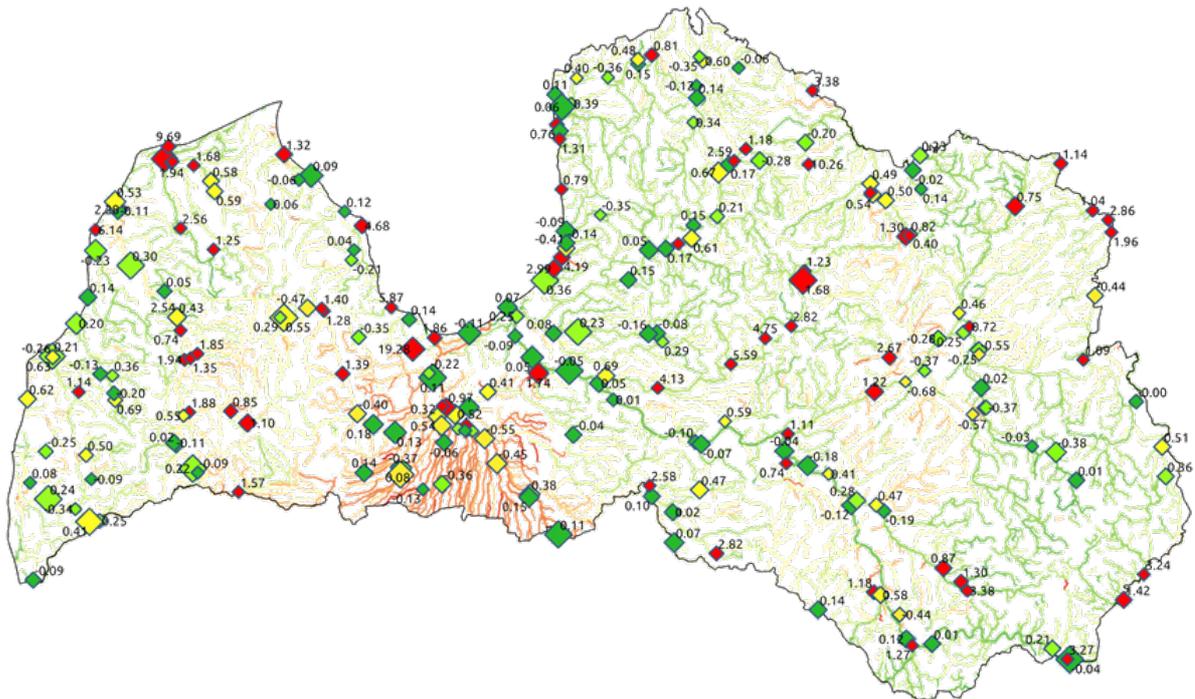

Figure 4.33: Overview of comparison between observed and measured nitrate concentrations. Green color corresponds to PBIAS<0,4; yellow to 0,4<PBIAS<0,7, and red – to PBIAS>0,7.

The mean nitrate concentrations in the reaches are shown in Figures 4.34 for Latvia and combining SWAT+ models of Latvia and Lithuania (PAIC (2022c)) in Figure 4.36.

The highest nitrate concentrations are in the agricultural Zemgale region which receives also significant transboundary pollution from the agricultural lowlands of northern central district of Lithuania. Generally, higher nitrate concentrations are in the lowland reaches. Figure 4.36 shows an excellent compliance with SWAT+ models of Latvia and Lithuania.

The mean density of the nitrate loads from the catchments of the SWAT+ model is shown in the map in Figure 4.35. Besides the higher loads in Zemgale region, one may note the East-West gradient of loads, possibly indicating lower fertilizer use in Latgale.
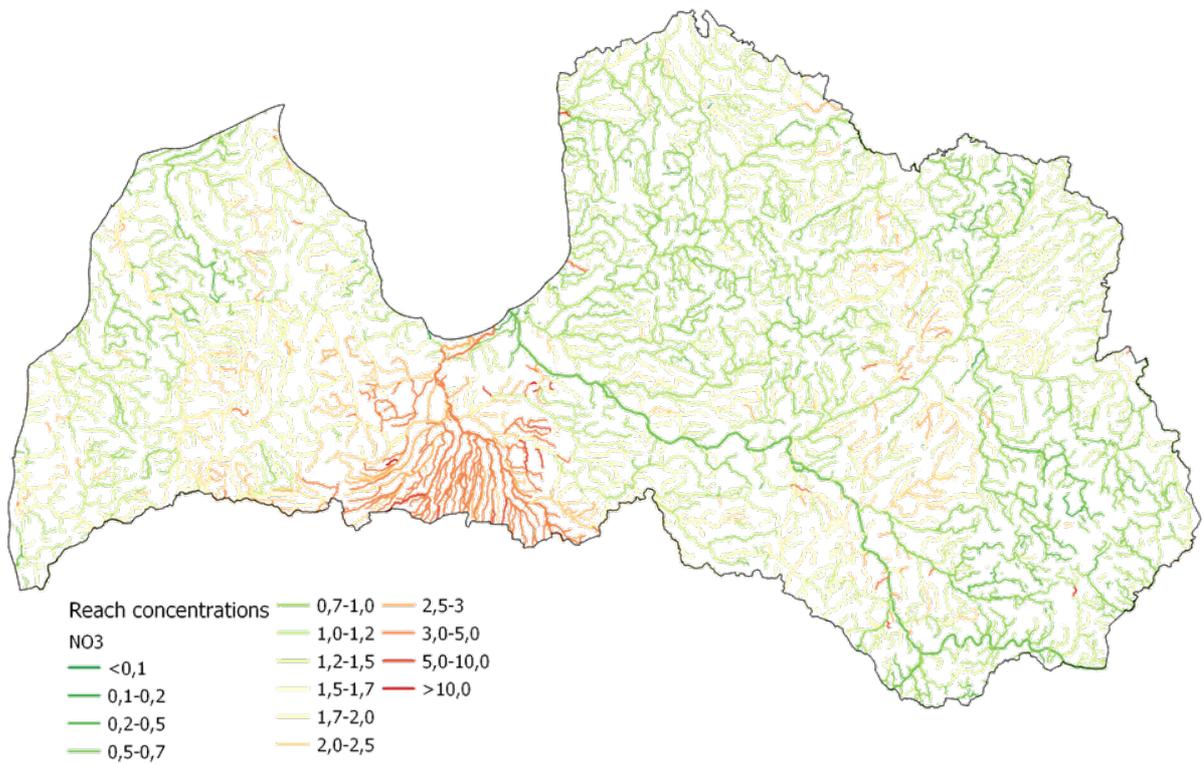
Figure 4.34: Mean nitrate concentrations in reaches according to the LV SWAT+ model.
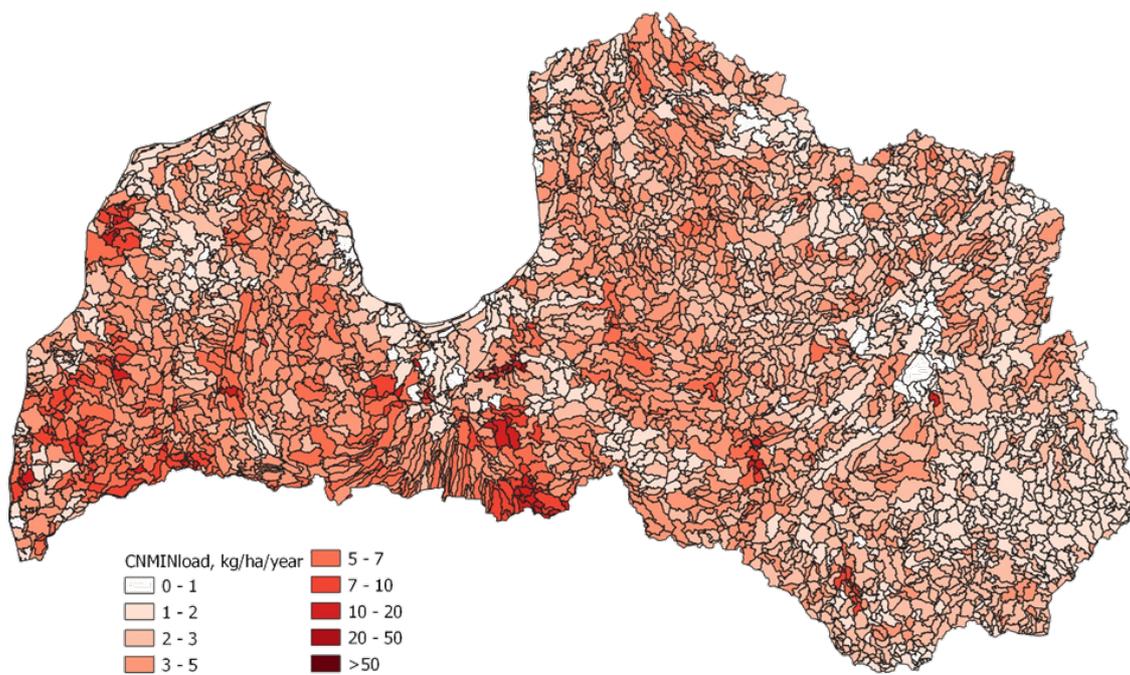

Figure 4.35: Mean nitrate loads from the catchments according to the LV SWAT+ model.

Reach concentrations
NO3
— <0,1
— 0,1-0,2
— 0,2-0,5
— 0,5-0,7
— 0,7-1,0
— 1,0-1,2
— 1,2-1,5
— 1,5-1,7
— 1,7-2,0
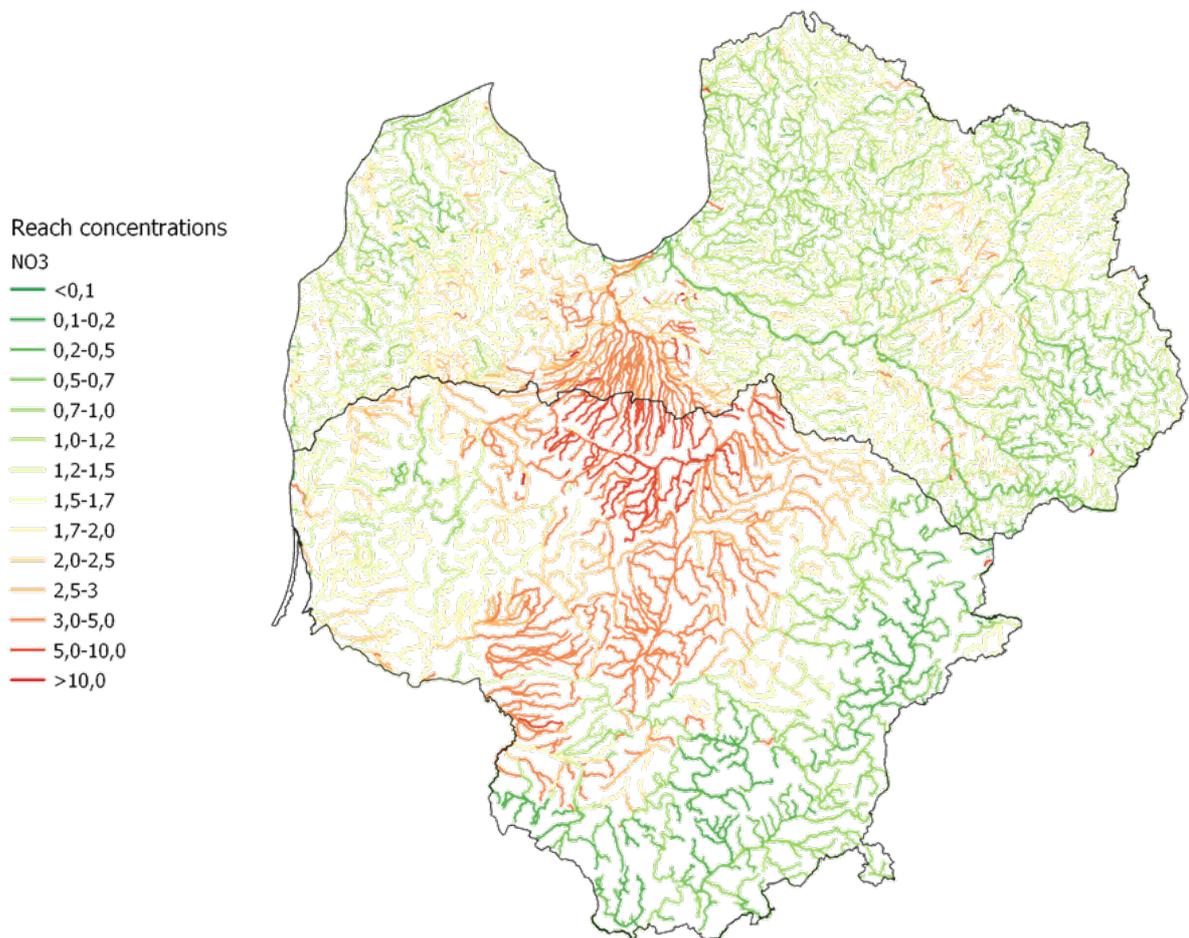— 2,0-2,5
— 2,5-3
— 3,0-5,0
— 5,0-10,0
— >10,0

Figure 4.36: Mean nitrate concentrations in reaches according to the LV and LT SWAT+ models.

References

Bennett, Neil D., et al. "Characterising performance of environmental models."*Environmental Modelling & Software* 40 (2013): 1-20.

Moriasi, D. N., et al. "Model evaluation guidelines for systematic quantification of accuracy in watershed simulations." *Trans. ASABE* 50.3 (2007): 885-900.

PAIC, 2020. DATA BASE FOR MODEL IMPLEMENTATION. LIFE GoodWater IP deliverable R1, Rīga, 31p.

PAIC, 2022a. CALIBRATED AND VALIDATED MODELLING SYSTEM. LIFE GoodWater IP deliverable R2, Rīga, 47p.

PAIC, 2022b. MODELLING RESULTS FOR REFERENCE AND BASELINE SCENARIOS. LIFE GoodWater IP deliverable R3, Rīga, 30p.

PAIC (2022c). Water modelling system of Lithuania upgrade and software support services. 2nd Final report. Riga, September-2022.