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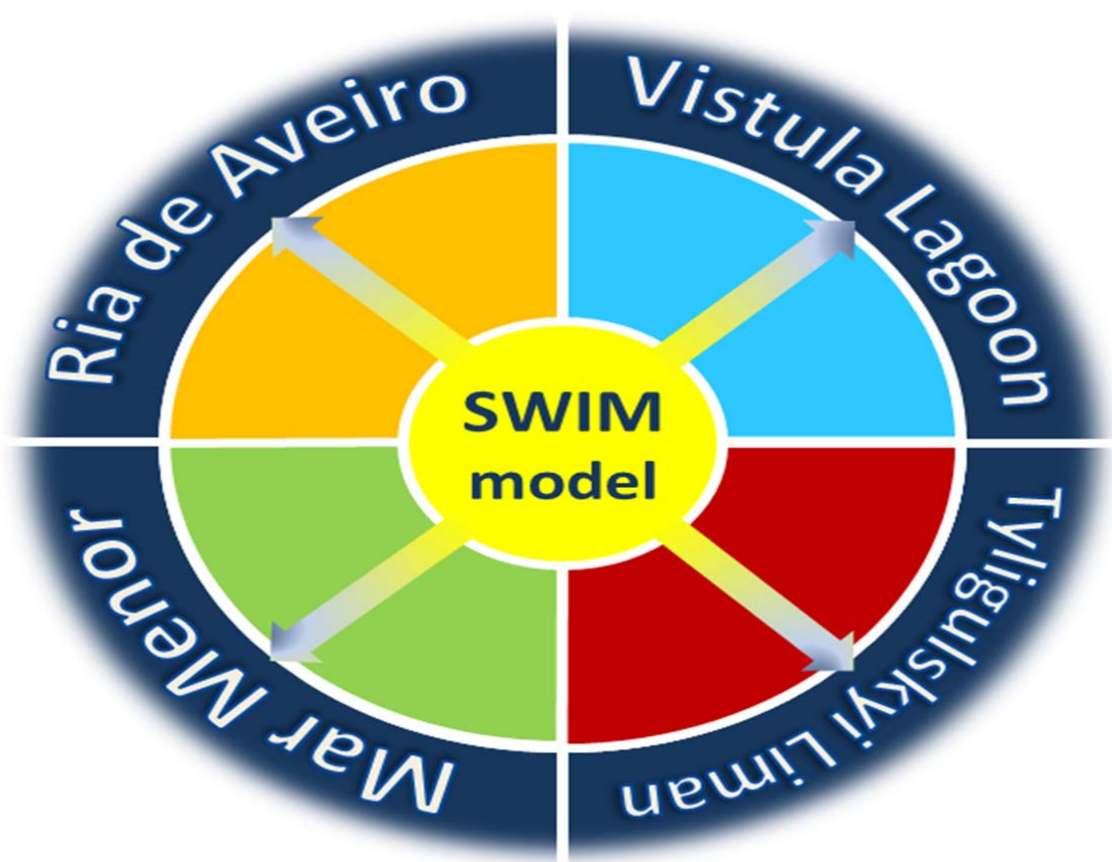
Results of climate impact assessment

Application for four lagoon catchments



Title Results of climate impact assessment – Application for four lagoon catchments
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6. Vistula Lagoon

6.1. Case study description and data preparation

Topography, land use, soils and climate characteristics

Figure 6.1.1 Overview map of the Vistula Lagoon catchment showing the Digital Elevation Model (DEM), national borders, major sub-catchments (numbered), main river courses, discharge gauges with available data, as well as the grid points of WATCH climate data.

The catchment of the Vistula Lagoon covers an area of about 21.000 km^2 containing several single basins of inflowing rivers. It is the largest of four case study catchments in the LAGOONS project. It is a transboundary watershed of which almost 60% belong to Poland, almost 40% to Russia (Kaliningrad oblast) and nearly 1% to Lithuania.

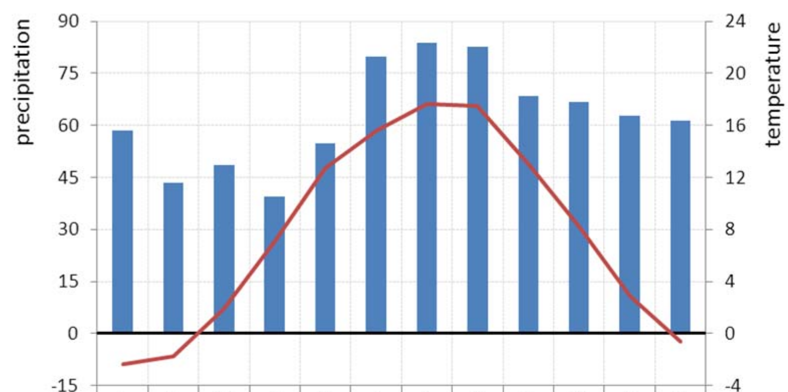
More than 20 rivers are draining to the Vistula Lagoon, among them the largest and most important are Pregolya, Elblag, Pasleka, Nogat and Mamonovka (LAGOONS, 2012b). The main part (41%) of the annual freshwater inflow to the lagoon is coming from the Pregolya river with the catchment of about 15.000 km^2, which is almost equally divided into the Russian and Polish

parts. Average discharge to the lagoon delivered by the Pregolya river is 86 m^3/s. Another quite large river is the Polish Pasłęka river (catchment size of about 2300 km^2) delivering 14 m^3/s on average (LAGOONS, 2012b). Discharge regimes of all rivers are characterized by higher water amounts in winter and lower in summer and a discharge peak in March/April due to snow melting processes. Discharge measurements from 10 different gauges located at several rivers within the catchment of the lagoon were available for various data periods, and were used for hydrological calibration.

According to the Shuttle Radar Topography Mission Data (SRTM) data, altitude in the catchment ranges from -27 to 308 m a. s. l (see Figure 6.1.1). Watershed delineation by the GIS software MapWindow using this Digital Elevation Model (DEM) delivered a map with 442 subbasins, which was used for further set-up of the model.

The density of climate stations with available measured data as well as the continuity of their time series was quite poor with regard to the overall catchment size and the divers time periods with available observed discharge data, which not always overlapped. Therefore it was decided to use the GPCC-corrected data set of the WATCH climate forcing data (WFDEI) for model calibration, covering the period 1979-2009 (Weedon et al., 2011; Schneider et al., 2013). This dataset includes climate time series for the majority of years with available discharge data (important for the model calibration).

Figure 6.1.2 depicts monthly temperature and precipitation averaged over the whole basin and period 1979-2009. According to the data, the highest precipitation occurs in the summer months June to August, simultaneously with the highest temperatures (which do not reach 20°C as average monthly values). The lowest monthly temperatures are measured in January and February, being around -2°C. The average annual precipitation in the catchment is 750 mm per year, and the average temperature is 7.7°C.



	J	F	M	A	M	J	J	A	S	O	N	D
prec [mm]	59	44	49	39	55	80	84	83	69	67	63	61
temp [°C]	-2	-2	2	7	13	16	18	17	13	8	3	-1

Figure 6.1.2
Climate chart for the Vistula Lagoon catchment showing long-term average monthly temperature and precipitation for the period 1979-2009 based on WATCH climate forcing data.

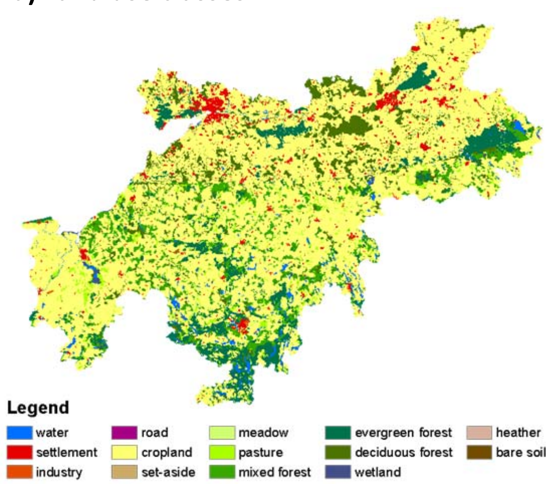
Due to the transboundary location of this case study catchment (which means not only a border between two countries but also between EU- and non-EU areas), it was not possible to use a single source for spatial data on land use and soil type distribution. In both cases two different

sources had to be combined, and this is still detectable when looking on these two additional input maps depicted in Figure 6.1.3.

The land use map for the whole catchment was created by using two different sources: 1) CORINE Land Cover 2000 (CLC2000) for the Polish part, and 2) Kaliningrad oblast territorial planning scheme delivered by our project partners from Kaliningrad for the Russian part. Overlapping areas of these two maps were set according to the Corine2000 parameters. The CORINE land use classes were reclassified to the 15 SWIM land use classes, which are required by the model. After the reclassification the Polish-Russian border is still visible on the map (Figure 6.1.3 a).

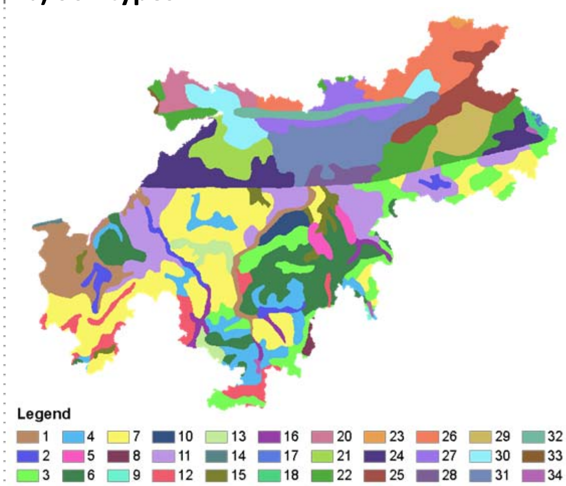
Main land use category within the Vistula Lagoon catchment is cropland covering 67% of the area, followed by forested areas (25%). Grassland as well as settlements cover areas of about 3% of the catchment each.

a) Land use classes



Land use category	[%]
Water	1.7
Settlement	3.1
Industry	0.1
Road	0.01
Cropland	66.5
Set-aside	0.04
Grassland, extensive use (meadow)	0.1
Grassland, intensive use (pasture)	3.1
Forest mixed	6.9
Forest evergreen	8.5
Forest deciduous	9.7
Wetland nonforested	0.3
Heather (grass + brushland)	0.002
Bare soil	0.02

b) Soil types



Main soil type	Soil numbers	[%]
Arenosols	3, 4	11.7
Cambizols	6, 7, 20, 21, 22, 23, 24	37.2
Fluvisols	1, 2, 32	8.7
Gleysols	31	6.7
Histosols	15, 16	2.4
Luvisols	8, 9, 10, 11	9.0
Phaeozems	5	0.9
Podzols	12, 13, 14, 18, 33	4.7
Podzoluvisols	17, 25, 26, 27, 28, 29, 30	18.3
Bog soil	34	0.3

Figure 6.1.3 Spatial distribution of land use classes (a) and soil types (b) within the Vistula Lagoon catchment for the reference conditions as used for setting up the SWIM model and preparation of SWIM input files.

The soil map used for setting up the SWIM model (Figure 6.1.3 b) was derived in a similar way by combining two different data sources: 1) Harmonized World Soil Database (HWSD) and 2) Soil Geographical Database of the European Community (SGDB). Soil parameterisation was performed estimating all necessary soil parameters according to the method described in section 2.2. Names were assigned according to the FAO-90 soil unit symbols.

The main soil types appearing in the study area are cambizol variants (37%), followed by podzoluvisols (18%) and arenosols (12%). The main soil type cambizol is defined to be a good soil for agricultural land and in most cases it is intensively used. Cambizols occur only in temperate and humid climates and are described to be among the most productive soils on the Earth, although they are quite young with beginning soil formation. They have a favourable aggregate structure and high content of weatherable minerals, and their agricultural usefulness can be limited only by unfavourable terrain or climate. The podzoluvisols are characterized by a higher clay content resulting in a good water storage capacity. Arenosols are sandy-textured soils without any structure or soil profile. They are characterized by a high permeability, low water storage capacity as well as low humus and nutrient content. Agricultural use of these soils requires careful management (http://www.britannica.com) to avoid diffuse nutrient loss to the river network. As already mentioned for the land use map, the administrative border crossing the case study area is clearly visible also on the resulting soil map.

By intersection and combination of subbasin, soil and land use maps during the SWIM model set-up a hydrotope map for the Vistula Lagoon catchment was created containing 4469 hydrotopes.

Land and water management (point sources, fertilization and water transfer):

During the water quality modelling it is important to consider nutrient inputs to the catchment by point and diffuse sources. Point sources are usually waste water treatment plants or industrial units, whereas diffuse nutrient pollution originates mainly in fertilized agricultural fields. Therefore, data on point source pollution and data on fertilizer application are needed to set-up the model.

To implement point sources in SWIM for the Vistula Lagoon catchment different sources were used to calculate nutrient inputs to the single river basins. The emissions in kg per day were derived according to the methods described below in a) to c) (coordinates of the settlements and point sources were estimated using GoogleMaps).

a) Pasleka basin:
Rautio et al. (2006) mentioned that 40-50 % of the 78,000 inhabitants of the Pasleka basin are not connected to any sewage system (corresponding to about 35,100 people). As the point sources listed in Mantra-East (2004, Table 5) mainly describe wastewater treatment plants, it was assumed that the nutrient loads originating from this not connected population should be added to the point source emissions. It was done by using the method found in HELCOM (2012), assuming that one inhabitant produces 5.5 g of nitrogen and 1.2 g of phosphorous per day, whereof 76% of nitrogen (148 kg/d) and 88% of phosphorous (37 kg/d) were additionally added to point source emission and introduced to the Pasleka river system.. In total, 341 kg N/d

and 76 kg P/d were estimated to be added by point sources to the Pasleka basin. These values are quite well comparable with those in Rautio et al. (2006), who listed 161 t TN/a (≈ 440 kg/d) and 27 t TP/a (≈ 74 kg/d) to originate from point sources within the Pasleka basin.

b) Mamonovka basin:
For the Mamonovka basin the point source emissions per month listed in HELCOM (2012) were converted to kg/d and then implemented in the model. In total, 71 kg N/d and 14 kg P/d were added in the Mamonovka basin.

c) Remaining part of the Vistula Lagoon catchment:
As no other information about distributed point sources for the remaining area of the whole catchment was available, it was derived using population numbers of the biggest settlements (LAGOONS, 2012b, and internet sources). With this method, altogether 1,102,640 people were counted, which compares quite well to the numbers in literature, where 1,163,000 (Russia – 630,000, Poland – 533,000) people in the Vistula Lagoon catchment are mentioned (Rautio et al., 2006). The rest people of about 60,000 can be assumed to be the population of the Pasleka and Mamonovka basins. Nutrient loads originating from the population were calculated per inhabitant and day (numbers were taken from http://de.wikipedia.org/wiki/Kläranlage). Furthermore, it was assumed that 60% of the population is connected to sewage water treatment plants. According to HELCOM (2012), this finally results in 40% of the total nitrogen and 50% of phosphorous per person per day being emitted to the river system. For the remaining 40% of the population it was assumed that 76% of N and 88% of P enter the river. As a result, in total 6598 kg N/d and 1294 kg P/d were added to the remaining Vistula Lagoon basin (excluding the Pasleka and Mamonovka parts). Comparing the single calculated numbers of produced N and P emissions for the Kaliningrad population (2507 kg N/d, 492 kg P/d) with numbers from the years 1994/95 (4553 kg N/d, 967 kg P/d) delivered by the case study partners, quite large discrepancies are seen. This could be partly explained by an improvement of sewage treatment standards or closure of old industries during the last two decades in this city.

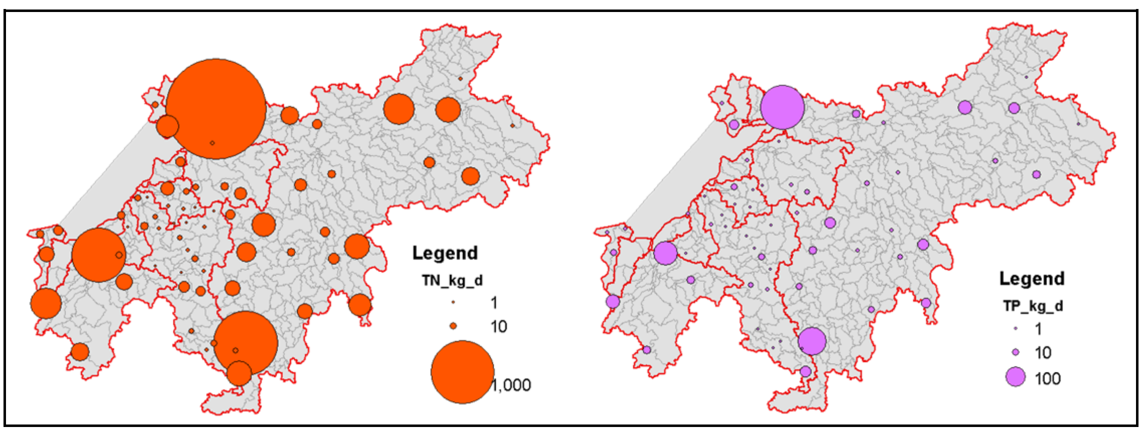


Figure 6.1.4 Point source emissions estimated for the reference conditions for SWIM water quality modelling: location and amounts of introduced total nitrogen (TN) and total phosphorous (TP) per subbasin (in kg/day).

The calculated point source amounts in kg/d were added per subbasin and then introduced to the model as constant values over the whole period (Figure 6.1.4). During the modelling the TN

and TP values were equally divided into nutrient forms (TN/3 → NO_3-N, NH_4-N, N_{org}; TP/2 → PO_4-P, P_{org}).

With regard to diffuse pollution sources in the modelled area it is important to consider agricultural management and fertilizer amounts as close as possible to reality during the water quality calibration. The standard SWIM version uses crop specific fertilization amounts and dates. They are defined in the code for every crop type and are used during the simulation period. Furthermore, the standard SWIM version allows growing only one single crop type on all agricultural areas within the basin and considers only mineral nitrogen (N_{min}), organic nitrogen (N_{org}) and mineral phosphorous (P_{min}) fertilizers.

For the Vistula Lagoon catchment it was decided to grow winter wheat on all fields using fertilization dates and amounts listed in Table 6.1.1. They were estimated based on different sources on fertilization practices in Poland, Warmia-Masuria and Vistula lagoon catchment (Mantra-East (2006); FAO (2003); Burakowska et al. (2005)).

Table 6.1.1
Fertilization dates and amounts (kg ha^{-1}) used for the SWIM modelling in the Vistula Lagoon catchment

Day	N_{min}	N_{org}	P_{min}
95	35	14	16
300	15	8	
Sum per year	**50**	**22**	**16**

Regarding water management measures two different water transfer points were implemented in the SWIM model (Figure 6.1.5): a) water outflow from the Vistula Lagoon basin via the Deyma river, and b) water inflow to the Vistula Lagoon basin via the Szkarpawa and Nogat Rivers.

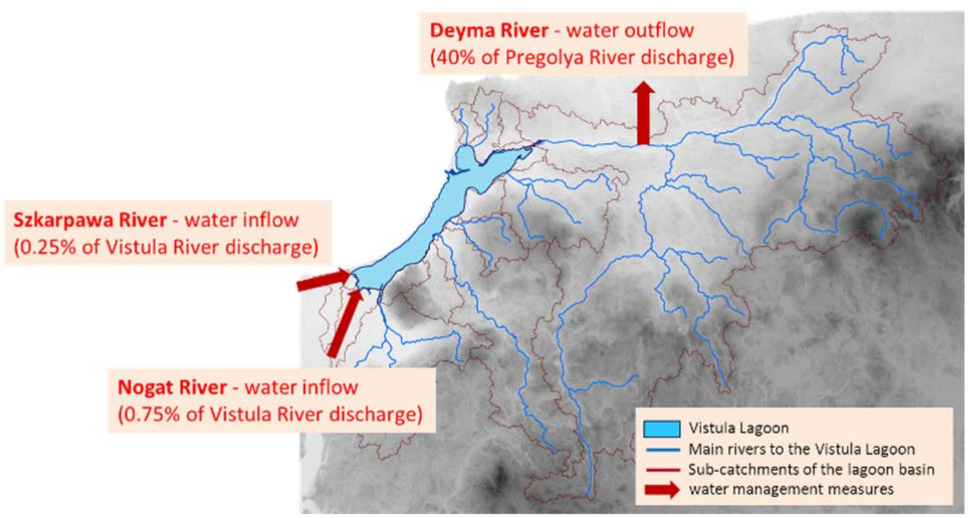


Figure 6.1.5 Water management measures implemented in the SWIM model to simulate water quantity and quality of the rivers within the Vistula Lagoon catchment

The water outflow via the Deyma river was implemented via the assumption that 60% of discharge remain in the Pregolya river, whereas 40% flow out of the catchment (LAGOONS,

2012b). As a constant water outflow to the Courland Lagoon via Deyma River influences river water amount as well as nutrient loads coming with the Pregolya River, the same percentages were assumed for nutrient loads.

Water inflow was implemented according to Robakiewicz (2010), who mentioned that 1-3% of the Vistula river discharge still flows to the Vistula Lagoon. To take this additional water into account during the SWIM modelling, it was assumed that water is flowing via the Szkarpawa (0.25%) and Nogat (0.75%) rivers to the lagoon. Water inflow was calculated on the monthly basis using the long-term (1900-1987) averaged water discharge data of the Vistula River found in the internet (http://www.sage.wisc.edu/riverdata/scripts/station_table.php?qual=32&filenum=2816). The inflowing water from the Vistula River also brings nutrient loads to the Vistula Lagoon. These loads were estimated using information from Dojlido et al. (1994) on the average nutrient concentrations in the Vistula River (years 1989-91). Assuming an improvement of water treatment facilities as well as closure of many industrial units during the last two decades in the Vistula basin, the average assumed nutrient concentrations from Dojlido et al. (1994) were halved.

6.2. Hydrological calibration and validation

Hydrological calibration of the Vistula Lagoon catchment was a challenging task. In addition to the high heterogeneity of spatial input data and inconsistent time series data with many gaps, a non-trivial SWIM modelling strategy was required, as different adjacent river catchments had to be combined within one SWIM model project. Due to the fact, that some sub-catchments of smaller rivers flowing to the lagoon had to be modelled without any information on discharge and/or water quality and could not be calibrated, it was decided to carefully calibrate the two largest sub-catchments Pregolya and Pasleka and then use the calibrated parameter set for the whole catchment. Besides, the Pregolya and Pasleka catchments cover 82% of the total Vistula Lagoon drainage area and have the longest available time series with the measured discharge data. Therefore this choice for the hydrological calibration was quite reasonable.

Figure 6.2.1 illustrates the results of model calibration achieved for the two rivers: Pregolya at the gauge Gvardeysk in the period 1986-1996 (above) and Pasleka at the gauge Lozy in the period 2005-2010 (below). The simulation results for both rivers show satisfactory model performance with the Nash-and-Sutcliffe efficiency above 0.6 with slightly better results for the Pregolya river. Deviations in water balance are lower than ±5%. The long-term average daily discharges as well as seasonal dynamics calculated from the observed and simulated daily values indicate quite good agreement. The snowmelt peaks as well as the level of the low flow discharge could be reproduced quite well with the SWIM model.

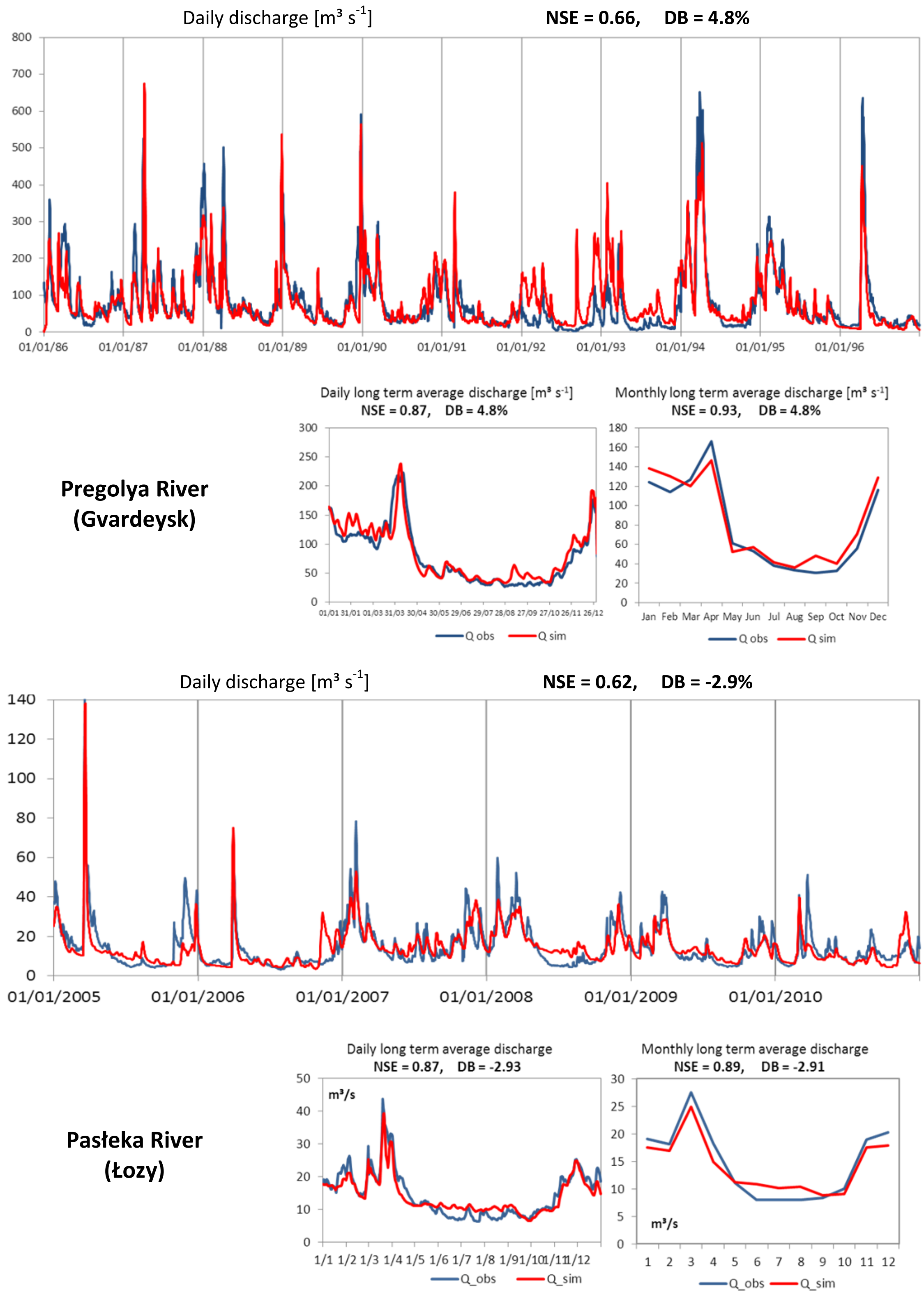


Figure 6.2.1 Hydrological calibration of SWIM for the two main rivers flowing to the Vistula Lagoon: Comparison of simulated and observed discharges as the daily, long-term average daily, as well as long term average monthly dynamics.

After hydrological calibration of the two main rivers flowing to the Vistula Lagoon (Figure 6.2.1) the SWIM model was set up for the entire lagoon basin using WATCH forcing climate data of the period 1979-2009 with a common calibration parameter set. The modelling results were compared with all measured discharge data available at those subbasins, where the gauges are located. Altogether, 10 discharge gauges were taken into account (for location see Figure 6.1.1). The achieved Nash-and-Sutcliffe-efficiencies (NSE) as well as deviations in balance (DB) are listed in Table 6.2.1, and show a satisfactory model performance in the most cases. Still, the best results in terms of NSE could be achieved for the Pasleka and Pregolya river gauges and gauges located at their tributaries, as the calibration parameter set was chosen after calibration of these catchments. But also the discharge in smaller catchments with short periods of measured data could be met quite well.

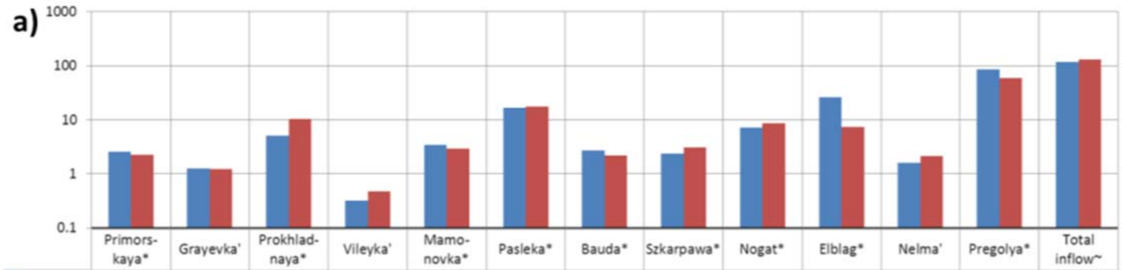
Table 6.2.1 Model performance at 10 discharge gauges located within the Vistula Lagoon basin achieved by using the SWIM project covering the entire basin with a common calibration parameter set.

River	**Pissa**	**Angrapa**	**Pregolya**	**Lava**	**Mamonovka**	**Pasleka**	**Bauda**	**Pasleka**	**Waska**	**Dzierzgon**
gauge	*Zeleny Bor*	*Berestvo*	*Gvardeysk*	*Rodniki*	*Mamonovo*	*Nowa Pasleka*	*Nowe Sadulki*	*Lozy*	*Paslek*	*Bagart*
period	*1995-2000*	*1995-2000*	*1983-1996*	*1995-2000*	*2008-2009**	*1998-2000**	*2009*	*2007-2009*	*2009*	*2009*
NSE	**0.73**	**0.63**	**0.70**	**0.70**	**0.62**	**0.72**	**0.55**	**0.66**	**0.48**	**0.34**
DB	**0.4**	**-23.6**	**0.6**	**-7.3**	**-29.6**	**-9.2**	**-6.8**	**12.9**	**-9.8**	**-7.4**

* monthly values

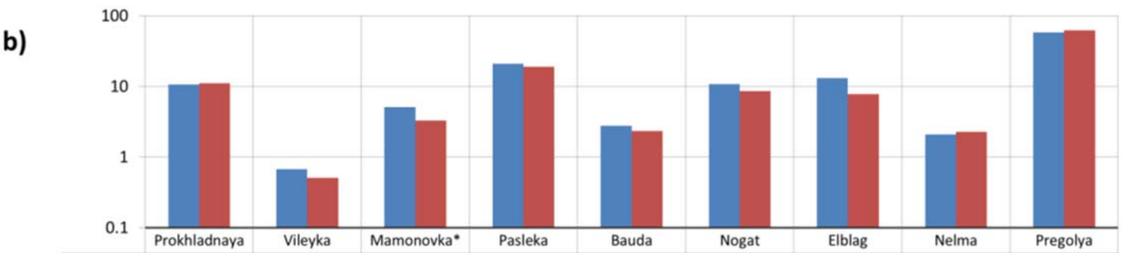
As the last step in hydrological calibration, information about inflowing water amounts coming from different rivers to the lagoon found in literature was compared with the simulated average discharges at the outlets of the twelve most important rivers entering the Vistula Lagoon. The results of this comparison are depicted in Figure 6.2.2. As different sources were found about average discharge of rivers entering the lagoon, two comparisons were conducted covering different observation periods (see a) and b) in Figure 6.2.2). Especially the comparison presented as a) has to be interpreted carefully as different sources with values covering different time periods were combined here.

Some minor discrepancies can be seen in Figure 6.2.2, but in general the results show a good comparison, especially when looking on the total water inflows to the Vistula Lagoon The sum of water discharge for all simulated water courses flowing to the Vistula Lagoon almost perfectly fits to the literature value. Differences are most obvious for the Elblag river, located in the lowest part of the lagoon's catchment area and characterized by intensive water management measures and channelizing, which were not represented by the model. This lowland region was formed by the former delta of the large Vistula river, which is now cut off from the Vistula Lagoon but still has some inflow controlled by water management measures.



	Primors-kaya*	Grayevka'	Prokhlad-naya*	Vileyka'	Mamo-novka*	Pasleka*	Bauda*	Szkarpawa*	Nogat*	Elblag*	Nelma'	Pregolya*	Total inflow~
obs_m³/s	2.5	1.3	5.1	0.3	3.5	16.7	2.7	2.3	7.1	26.2	1.6	86.5	117.0
sim_m³/s	2.2	1.2	10.3	0.5	2.9	17.6	2.2	3.1	8.6	7.3	2.2	59.6	129.0

*Kruk et al. (2011)
` http://www.ebrd.com/pages/project/eia/balkalen.pdf
~Silicz (1975)



	Prokhladnaya	Vileyka	Mamonovka*	Pasleka	Bauda	Nogat	Elblag	Nelma	Pregolya
obs_m³/s	10.5	0.7	5.1	20.9	2.7	10.7	13.1	2.1	57.7
sim_m³/s	11.0	0.5	3.3	18.8	2.3	8.6	7.8	2.3	61.7

* average of the time periods 1998-2000 (MantraEast) and 2008/2009 (HELCOM, 2012)

Figure 6.2.2 Comparison of the observed and simulated water inputs to the Vistula Lagoon per river: a) general mean discharge values found in literature compared with the SWIM-simulated average values for 1980-2009, b) the observed monthly values taken from the Mantra-East-Project averaged for the time period 1998-2000 and compared with the SWIM results for the same period.

The long-term average spatial patterns of water cycle components based on the simulated results for the Vistula Lagoon catchment area can be seen in Figure 6.2.3. The maps show the average model outputs at the hydrotope level for the time period 1980-2009. One can see that the runoff, evapotranspiration and groundwater recharge are correlated with soil, land use and precipitation patterns in the catchment.

The highest precipitation is visible in the northern part of the catchment around the city of Kaliningrad. The lower amounts can be detected in the upstream parts of the catchment as well as in the lowlands close to the former Vistula river mouth. Areas with high precipitation are characterized by higher runoff, especially on agricultural fields and settlements. Forested areas produce lower runoff than surrounding agricultural land.

Besides, runoff generation is visibly coupled to soil properties. Highly permeable soil types with fast seepage show lower values of annual runoff. Maximum evapotranspiration rates can be seen above water bodies, but forested areas also show quite high evapotranspiration values as result of their high leaf area index. Evapotranspiration is high in the lowland, too, due to the high groundwater level in this region. The lowest evapotranspiration amounts are obvious in the settled regions, whereas cropland shows an intermediate amount. The average annual groundwater recharge behaves opposite to runoff and evapotranspiration and is mostly correlated to the soil type distribution, showing the highest recharge amounts on soils with a

good permeability. The lowest groundwater recharge can be seen under forests. Especially on the map illustrating groundwater recharge amounts per hydrotope the administrative border between Poland and Russia is clearly visible, which is caused by the different sources of soil maps.

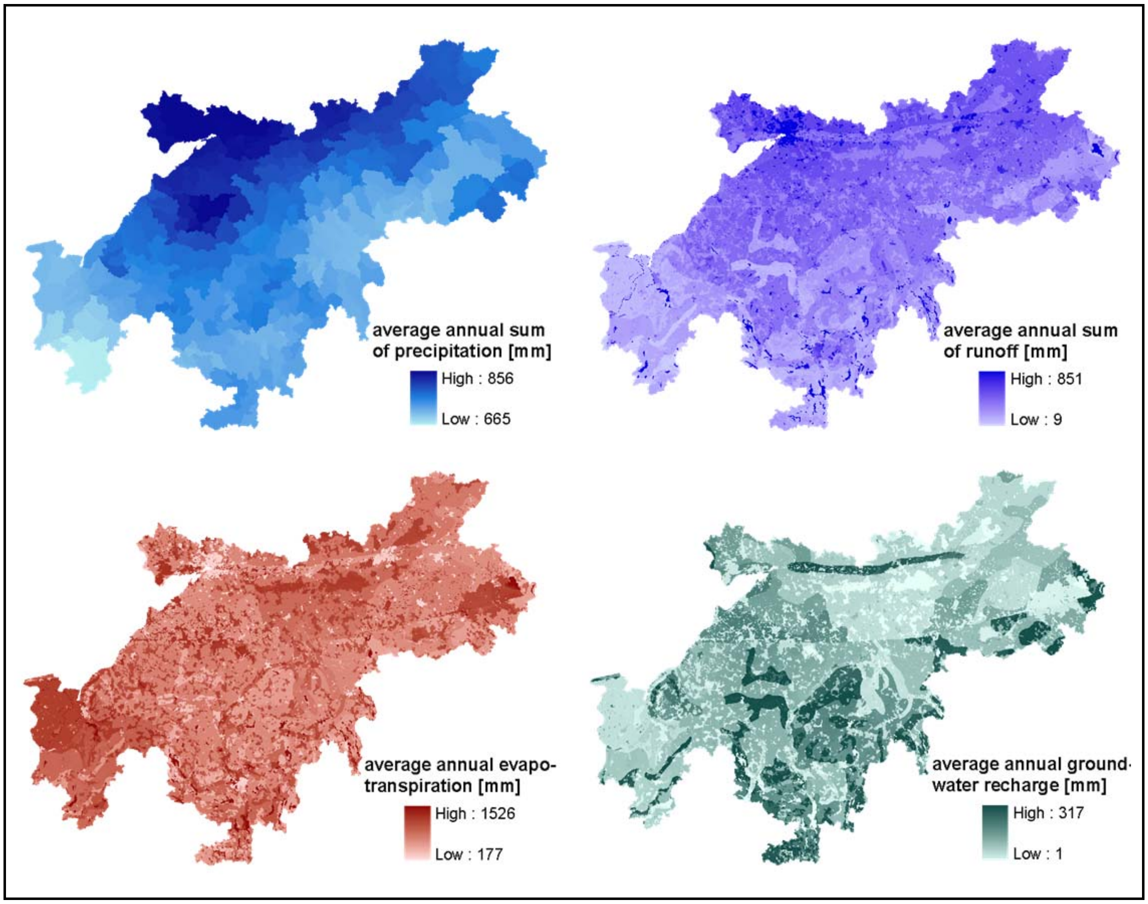


Figure 6.2.3 Spatial patterns of water cycle components in the Vistula Lagoon catchment averaged for the time period 1980-2009.

6.3. Calibration and validation of water quality

Dynamics of water quality parameters (nitrate nitrogen, ammonium nitrogen, phosphate phosphorous, dissolved oxygen and water temperature) were calibrated in detail for the Pasleka river, gauge Nowa Pasleka, due to the best availability of measured data and the longest continuous time series (2005-2010) at this station. Unfortunately, it was not possible to get time series on measured water quality parameters for the most important inflowing river Pregolya, and it could not be included in the calibration. As a result, quite high uncertainty remains regarding nutrient processes in the entire catchment under study. Except the Pasleka basin, there were only some rare measurements on water quality available (mainly for the short period 1998-2000), which were partly real observed values, and partly estimated ones. They could be used only as averages for the spatial model validation regarding water quality.

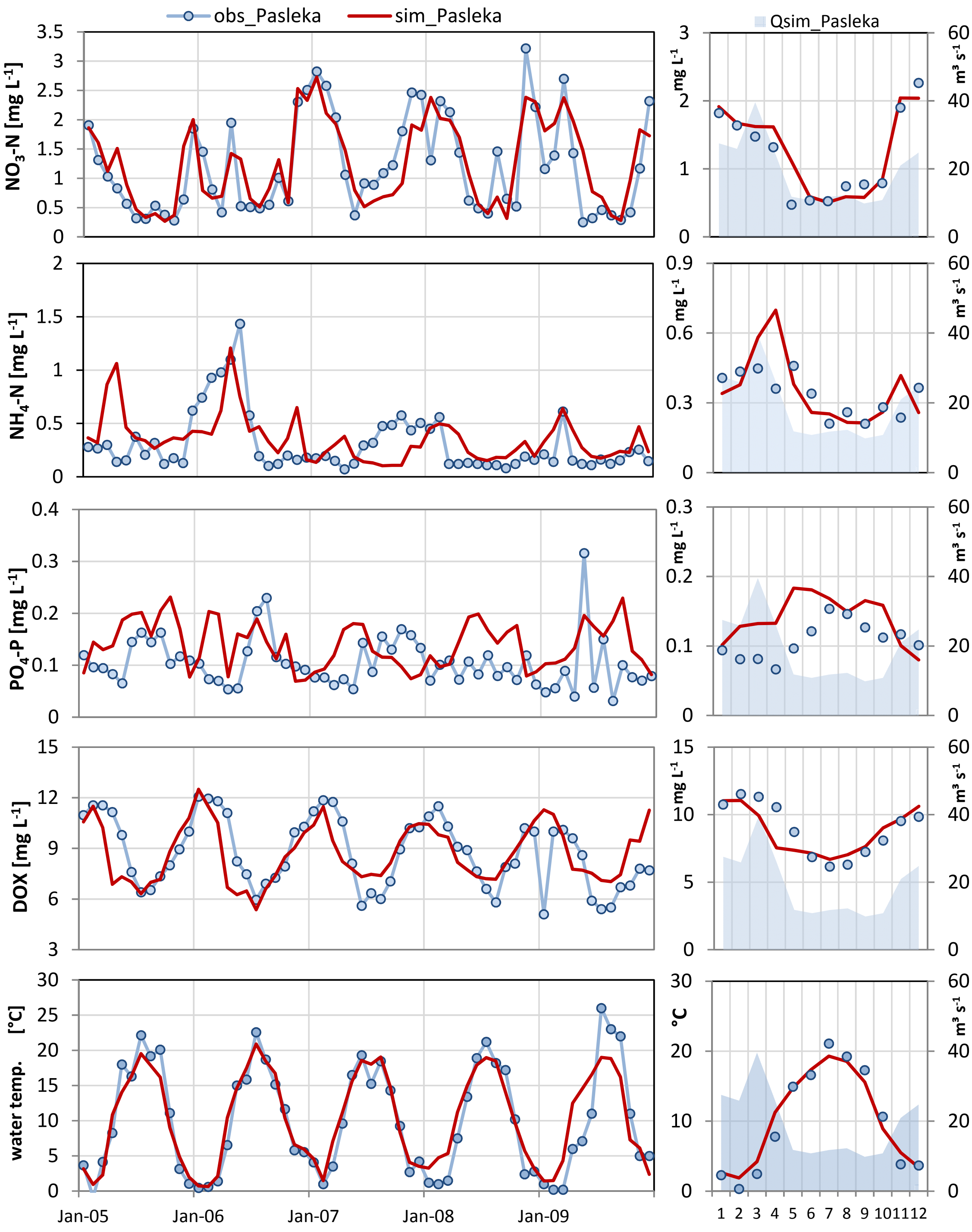


Figure 6.3.1 Observed (obs) and simulated (sim) water quality variables for the Pasleka River (gauge Nowa Pasleka): monthly averages (left) and seasonal dynamics (right) of nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), phosphate phosphorous (PO_4-P), and dissolved oxygen (DOX) concentrations as well as water temperature for the time period 2005-2009; the seasonal nutrient dynamics are compared with the SWIM simulated monthly discharge (Q_{sim}) at the same gauge.

Figure 6.3.1 illustrates results of water quality calibration for the Pasleka river. The monthly observational data are compared with the monthly averages derived from the simulated daily data for the period 2005-2009. A comparison between the observed and simulated data was also done regarding the seasonal dynamics.

In general, the best results could be achieved for water temperature and dissolved oxygen concentrations. The dynamics and levels are almost perfectly matched for these variables, mainly due to the simple physical relationships between these two variables and the air temperature as interpolated to the subbasin centroids.

It is much more complicated to simulate nutrient's behaviour in the catchment and the rivers, as these compounds are not simple conservative substances but are subject to many transformation processes: they may be uptaken by plants, bounded to soil particles (especially ammonium nitrogen and phosphate phosphorous) or degraded by chemical or biological decomposition processes (e.g. denitrification regarding nitrate nitrogen) in the catchment. Besides, the non-conservative transport processes cause retention or loss of nutrients in the catchment which hinders easy simulation of water quality.

In the Pasleka basin, nitrate nitrogen concentrations could be simulated better than other nutrients under observation; the long-term monthly as well as average monthly observed values were reproduced by the SWIM model quite well. The overall dynamic pattern with high concentrations in winter time and low concentrations in the low-flow summer months could be well reproduced by the model. When comparing the seasonal dynamics of nitrate concentrations with the simulated monthly average discharge (high correlation between them) it can be reasoned that nitrate nitrogen in the river originates mainly from diffuse sources.

A similar, but not so strong, pattern can be seen for ammonium nitrogen. Concentrations are higher in winter but lower in summer, so that the prevailing diffuse-source ammonium pollution can be confirmed for the basin. The level of the observed values was matched in the majority of cases but with slight discrepancies during the year. Due to high adsorption potential of the ammonium nitrogen particles in soils, the leaching effect with water flows through the catchment is lower than for nitrate nitrogen.

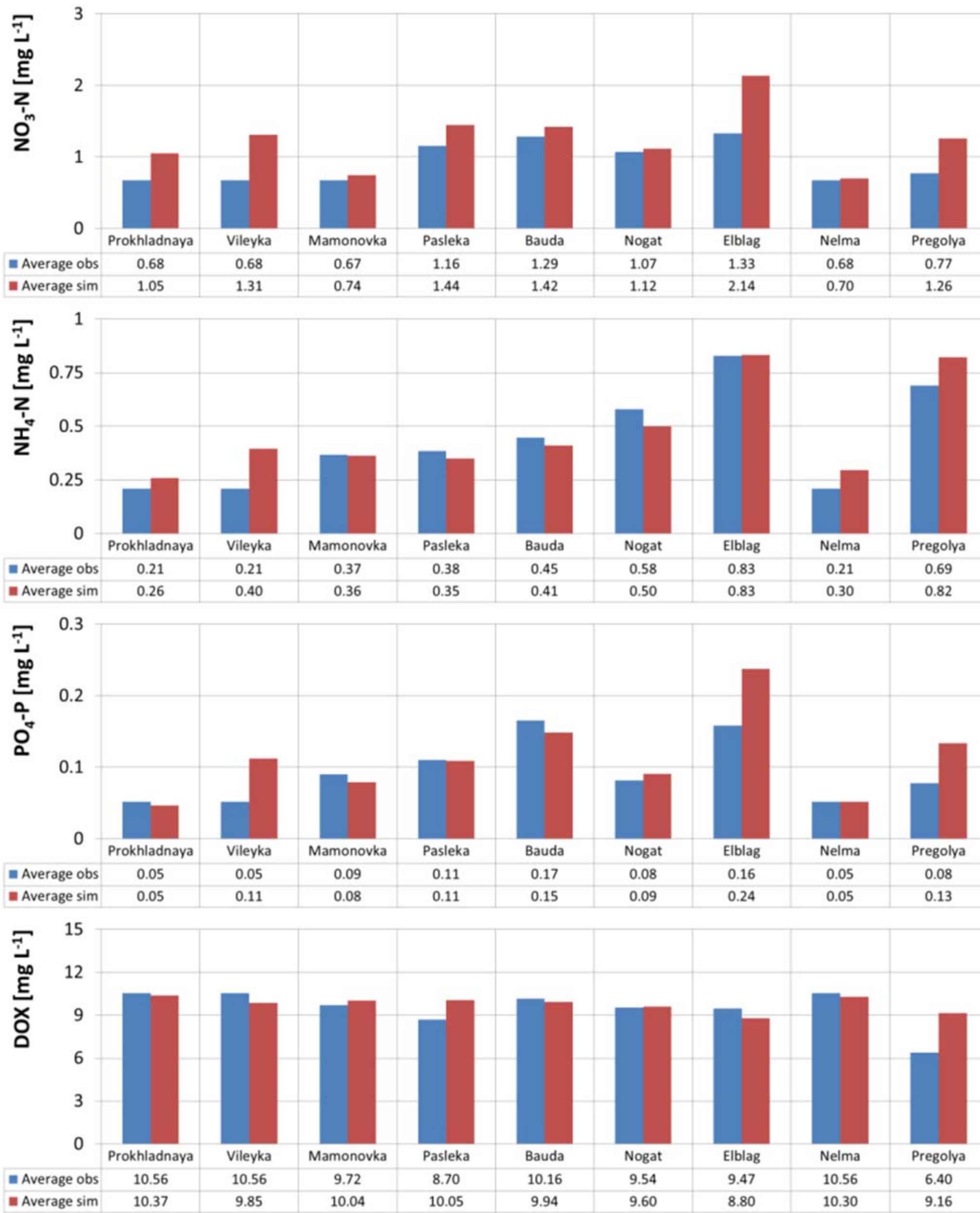
Phosphate phosphorous shows an opposite dynamic behaviour. Looking on the long-term monthly averages the conclusion can be drawn that this substance is coming to river mainly from stable point source emissions leading to higher phosphate concentrations in summer with lower discharge (due to less dilution) than in winter with higher discharge. The monthly averages of the SWIM-simulated results for phosphate phosphorus are not so good comparable with the observations, but the average level and min/max values are captured.

Figure 6.3.2 illustrates the results of spatial model validation regarding water quality. The average nutrient and dissolved oxygen concentration values for the main rivers flowing to the Vistula Lagoon were delivered by our project partners (originating from the Mantra-East project) and compared with the model outputs.

In most of the cases the level of the observed values could be reached, although some discrepancies can be detected as well. The overestimation for the small river Vileyka, bringing only very little loads, should not remarkably influence the total load to the lagoon. Larger

problems can be seen for the Elblag and the Pregolya rivers, where concentrations are mostly overestimated. Regarding the Elblag, the discrepancies can be most probably explained by the discrepancies in the modelled discharge (see discussion above). Regarding the Pregolya, the discrepancies most probably occur due to missing information on pollution sources and uncalibrated nutrient processes for this river basin.

In general, it can be concluded that the ability of SWIM to simulate the spatial distribution of nutrient amounts in the rivers is quite good.



NO_3-N	Prokhladnaya	Vileyka	Mamonovka	Pasleka	Bauda	Nogat	Elblag	Nelma	Pregolya
Average obs	0.68	0.68	0.67	1.16	1.29	1.07	1.33	0.68	0.77
Average sim	1.05	1.31	0.74	1.44	1.42	1.12	2.14	0.70	1.26

NH_4-N	Prokhladnaya	Vileyka	Mamonovka	Pasleka	Bauda	Nogat	Elblag	Nelma	Pregolya
Average obs	0.21	0.21	0.37	0.38	0.45	0.58	0.83	0.21	0.69
Average sim	0.26	0.40	0.36	0.35	0.41	0.50	0.83	0.30	0.82

PO_4-P	Prokhladnaya	Vileyka	Mamonovka	Pasleka	Bauda	Nogat	Elblag	Nelma	Pregolya
Average obs	0.05	0.05	0.09	0.11	0.17	0.08	0.16	0.05	0.08
Average sim	0.05	0.11	0.08	0.11	0.15	0.09	0.24	0.05	0.13

DOX	Prokhladnaya	Vileyka	Mamonovka	Pasleka	Bauda	Nogat	Elblag	Nelma	Pregolya
Average obs	10.56	10.56	9.72	8.70	10.16	9.54	9.47	10.56	6.40
Average sim	10.37	9.85	10.04	10.05	9.94	9.60	8.80	10.30	9.16

Figure 6.3.2 Spatial validation of water quality variables: results for all rivers flowing to the Vistula Lagoon with available water quality measurements comparing the average of all observed values to the average of the according simulated values for different (mostly short) time segments within the period 1980-2009.

6.4. Climate impact on water flows

Average daily dynamics and seasonal changes

Figure 6.4.1 illustrates the impacts of the projected future climate scenarios on total water inflow to the Vistula Lagoon. The long-term average daily discharges as well as seasonal changes of the total water inflow under changing climate are depicted for three future periods with regard to the reference conditions. The averaged discharges of all 15 scenario applications are shown for every future period (black line) and compared to the simulated discharges under reference climate conditions of the period 1971-2000 and also averaged over 15 scenario sets (red line).

The uncertainty bands are included in the graphs as well, showing the min/max corridor, 90/10- and 75/25-percentile ranges of the resulting discharges in different grey colour shades. The dark grey 25/75-percentile band means the range in which water discharge can be expected in future with higher probability. Besides, the simulated discharges under all 15 projected future climate conditions are compared to the average discharge modelled with SWIM under the "best fitting" climate scenario S10 for the same period (blue).

The seasonal changes in water discharge were calculated as the difference between resulting monthly discharges under future climate and monthly water amounts achieved by applying the same climate scenarios in the reference period.

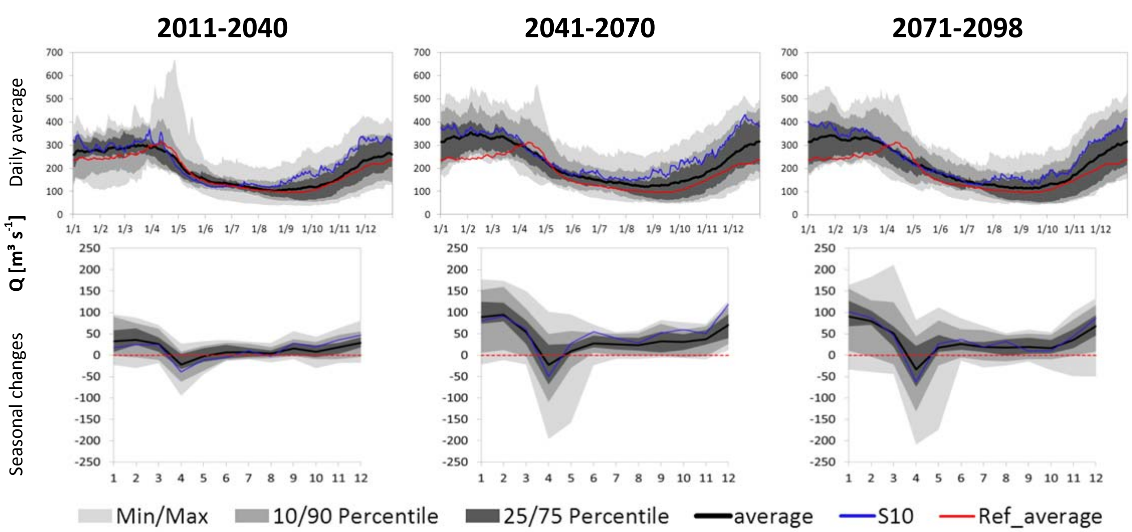


Figure 6.4.1 Dynamics of total water inflow to the Vistula Lagoon averaged for 15 ENSEMBLES climate scenarios: the long-term average daily discharges with percentile bands simulated in future periods compared to the long-term average daily discharge simulated in the reference period (above) and absolute difference in monthly average discharges of three future periods compared to those simulated in the reference period 1971-2000 (below).

Due to a clear increasing trend in precipitation in this region, which was already detected during scenario evaluation, an overall increase in river discharge to the Vistula Lagoon can be seen for all three scenario periods. Positive absolute changes in river discharges are largest in the winter months and lower during the low flow period in summer.

The only negative change can be seen in April, consistently in all three scenario periods. This negative change is probably due to continuously increasing average temperatures in future as expected in all future climate scenarios. Higher temperatures impact snow fall and snow melt processes within the catchment. It seems that snow melt peaks are going to be lowered in the future or even disappear as a result of less precipitation falling as snow in winter. This development is accompanied by higher winter discharges than simulated under reference climate conditions due to higher precipitation (mostly as rain) in the warmer winter months in future.

In general, differences in monthly discharge averages compared to the discharge of the reference period are lowest in the near future (2011-2040) and much higher towards the middle and end of the century with increasing min/max-uncertainty bands, but with quite narrow 25/75-percentile bands. Therefore, an overall increase of future water discharges is quite certain as it is simulated by SWIM driven by the majority of 15 scenario applications.

Changes in water discharges to the Vistula Lagoon simulated with SWIM driven by the "best fitting" climate scenario S10 show similar behaviour and can be interpreted similarly. Higher discharges in autumn and winter as well as a loss of snow melt peak in the spring season seem to be an expectable result of future climate impacts in the Vistula Lagoon catchment.

Changes in water fluxes – average of all 15 scenarios

Climate change impacts on water fluxes were additionally analysed on the hydrotope level with regard to the spatial patterns of water cycle components in the catchment. The average differences in precipitation and three simulated water fluxes: runoff, evapotranspiration and groundwater recharge between the future periods and the reference period were calculated per hydrotope, and results are presented in Figure 6.4.2.

Compared to the reference period, precipitation amounts clearly show an increasing trend in future periods. The increasing trend is less obvious for the first future scenario period (≈ +30 mm); and stronger increase can be seen for the next two future periods (≈ +80 mm). Location of the areas with the highest increase in precipitation differs between the future periods.

All other spatial water cycle patterns are resulting from this precipitation trend, and also influenced by soil type and land use distribution. Runoff increases on areas with higher positive precipitation changes. The runoff increase is lower, or even it is decreasing on highly permeable soil types, where additional precipitation may contribute to groundwater recharge instead.

Due to more available water for transpiration and higher temperatures than in the reference period evapotranspiration amounts mainly increase in the course of the century. The increase is highest over forested areas with large leaf area index and generally lower in the central parts of the catchment, probably as a result of smaller differences in temperature between the reference and the future climate data. The temperature changes could be expected to be buffered by influences of a maritime climate in this part of the catchment. Largest changes in evapotranspiration amounts can be detected above open water bodies, where absolute evaporation values indicate the potential evapotranspiration value, which is supposed to

increase in the future periods by up to 106 mm/y as result of the strong increasing trend in temperature generally projected by all 15 scenarios.

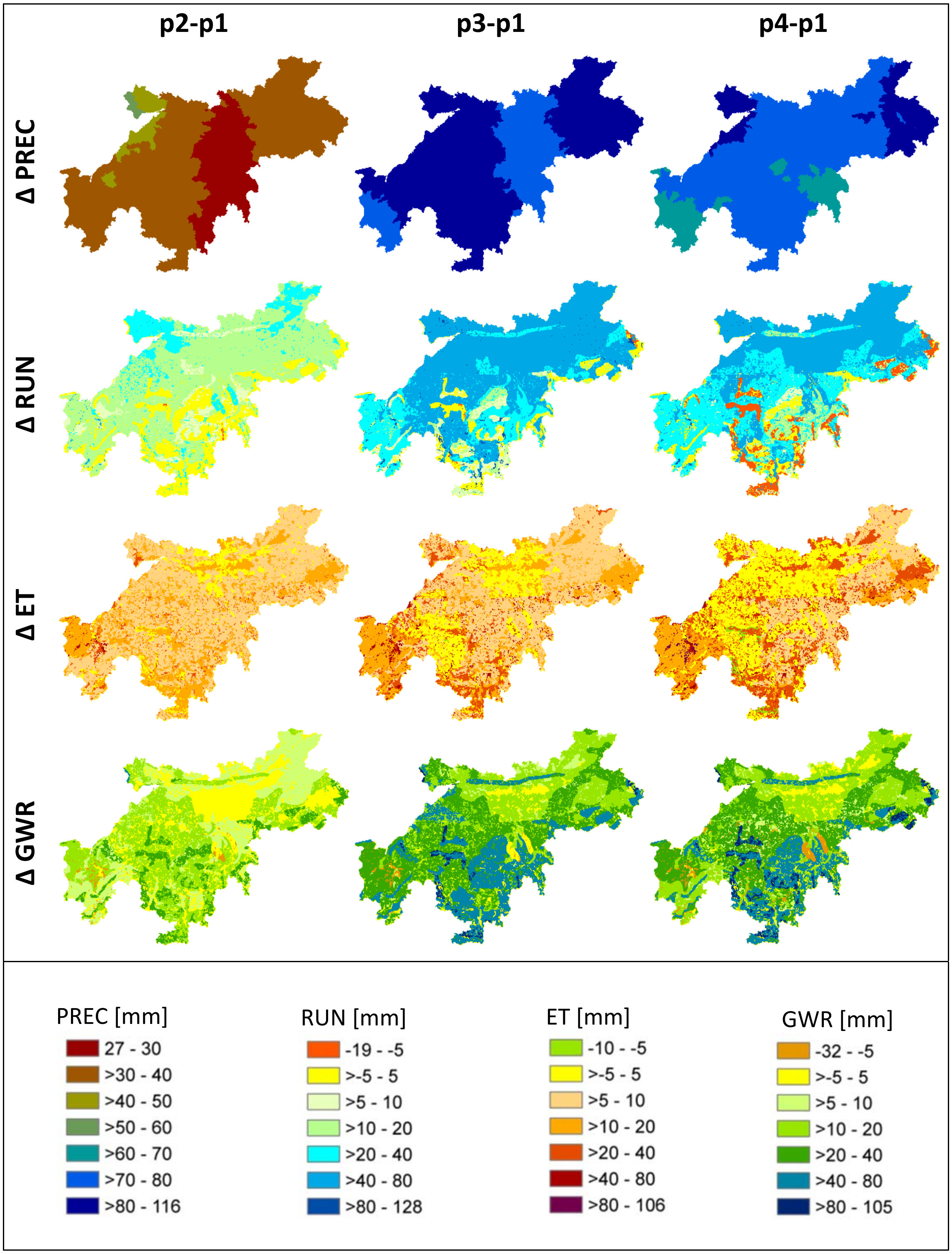


Figure 6.4.2 Spatial patterns of average annual changes in precipitation (PREC), runoff (RUN), evapotranspiration (ET) and groundwater recharge (GWR) in the Vistula Lagoon basin simulated under the set of 15 ENSEMBLES climate change scenarios (results of future periods p2, p3, p4 are compared to those of the reference period p1) . The outputs are averages over all years in the period and all 15 scenarios.

Groundwater recharge is projected to increase on average in future. The highest increase is visible on permeable soil types allowing fast seepage of water to the groundwater aquifer. Under forested areas in the north part of the catchment less changes in groundwater recharge between the different scenario periods were modelled due to specific soil conditions and high evapotranspiration potential.

6.5. Climate impact on water quality

The influence of changed climate on water quality parameters was analysed during climate impact assessment for Vistula Lagoon, too.

Figure 6.5.1 shows the seasonal changes of the average monthly water temperature and dissolved oxygen concentration calculated by comparing SWIM-simulated results for the reference and the future periods driven by 15 ENSEMBLES scenarios. The results are shown as average of simulations driven by all 15 scenarios (black line) together with three uncertainty bands (grey).

A strong increasing trend in the course of the century is obvious for water temperature due to the overall increase in average air temperature, as it was already detected during evaluation of climate scenarios.

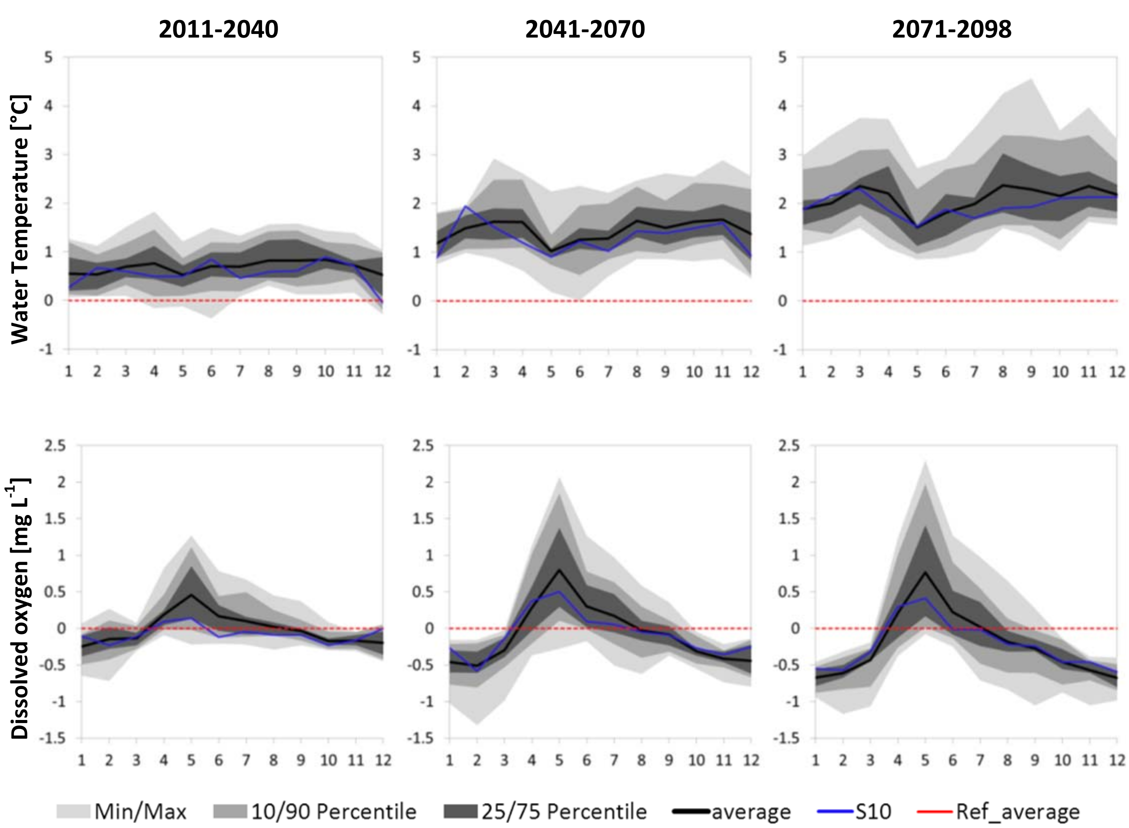


Figure 6.5.1 Changes in seasonal dynamics of water temperature (above) and dissolved oxygen concentrations (below) calculated by comparing average model outputs of the future periods with average model output of the reference period..

Changes in dissolved oxygen concentration can be referred to temperature change in the rivers, and could also be influenced by changes in ammonium nitrogen concentration in the river network. Dissolved oxygen concentrations are expected to decrease in winter months due to higher average water temperature with consequently lower values for saturated concentrations. Higher dissolved oxygen concentrations are simulated by SWIM in the period April to July than during the reference period. This can be explained by lower oxygen consuming ammonium concentrations in the river network during these months (see Figure 6.5.2).

The "best fitting" scenario S10 demonstrates a similar behaviour as the average of all simulations driven by 15 ENSEMBLES scenarios and is almost always located within the 25/75-percentile uncertainty band for both water temperature and dissolved oxygen. Uncertainty of results increases to the end of the century due to the increasing uncertainty of climate scenarios.

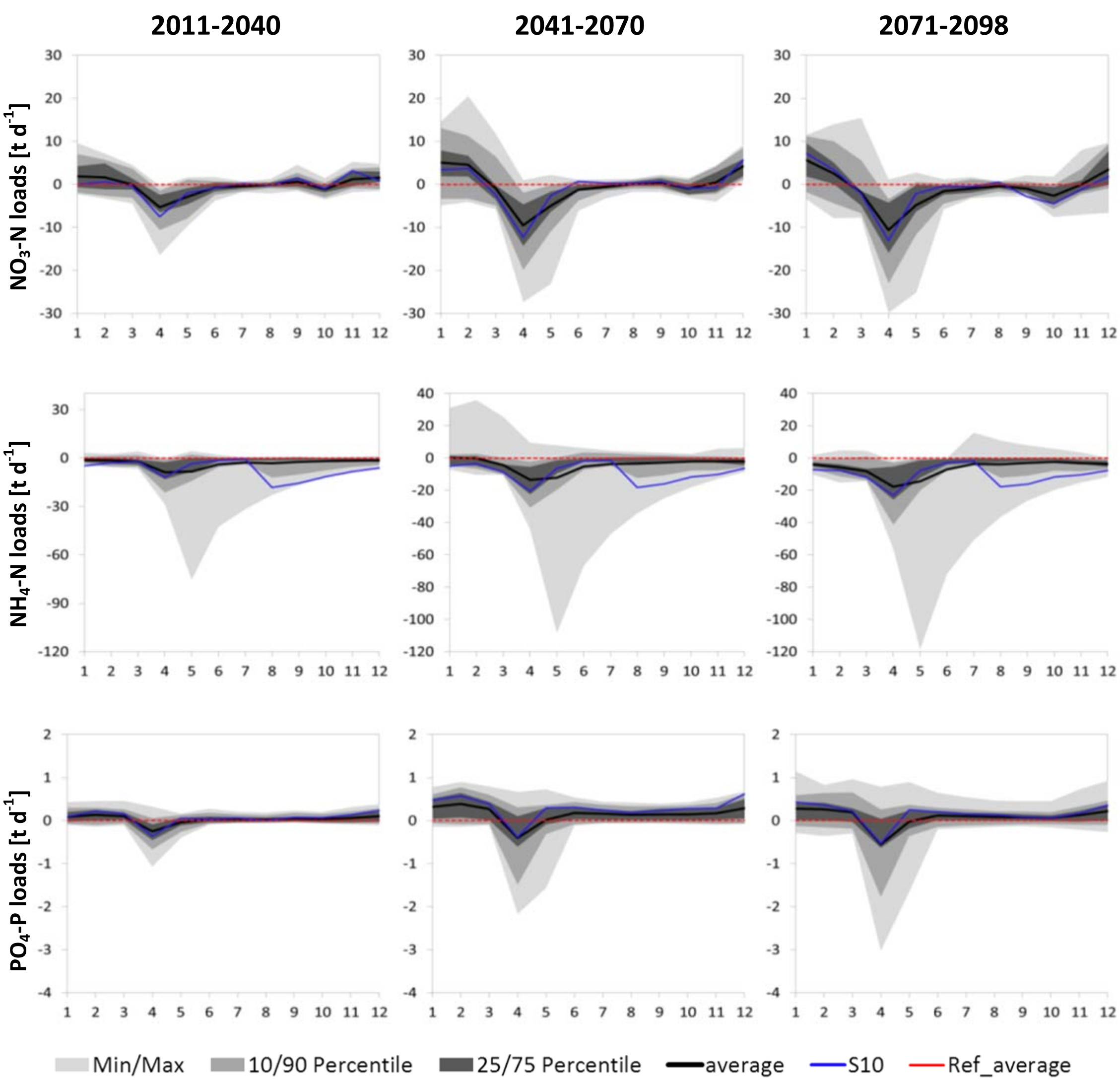


Figure 6.5.2 Impact of ENSEMBLES climate change scenarios on nutrient loads coming to the Vistula Lagoon: average absolute changes in seasonal dynamics of nitrate nitrogen, ammonium nitrogen and phosphate phosphorous calculated as the difference between SWIM-simulated mean monthly nutrient outputs under future climate conditions compared to results achieved under the reference climate.

The changing climate influences nutrient processes in a catchment. Nutrient transformation processes within the soils as implemented in SWIM are often dependent on soil temperature and soil water content, which are directly influenced by air temperature and precipitation amounts. For example, denitrification only occurs in periods when soil water content is approaching saturation, whereas ammonium appears from mineralization of organic matter only under high soil water content or temperatures outside the range between 5 and 40°C. Therefore, changing climate may influence the resulting nutrient loads coming from the catchment.

Figure 6.5.2 illustrates the expected mean monthly changes in nutrient loads entering the Vistula Lagoon under 15 climate scenarios compared to the results achieved by applying the same set of scenarios for the reference period. Changes in nitrate nitrogen loads behave quite similar to the changes in discharge. In winter months (December to February) an increase of loads can be seen followed by a decrease during April/May. During the dryer summer months almost no changes can be detected in the first two periods, and a very slight decrease in summer loads is visible for the last period 2071-2098. This is probably due to changing soil conditions influencing denitrification and mineralization potentials under a wetter and warmer climate. The behaviour of nitrate nitrogen resembles that of discharge due to its nature to be a pollutant mainly coming from diffuse sources. Therefore, increasing precipitation amounts result in higher nitrate nitrogen loads, as higher rates are washed out from the agricultural fields. The changes in loads are lower in the near future period 2011-2040, and reach larger amplitudes in the later periods, which are accompanied by higher uncertainty ranges.

Looking on results achieved for ammonium nitrogen loads under future climate conditions, a decreasing trend can be observed. Maximum decrease is visible during the spring flood season, with minor negative changes throughout the year. This trend seems to be connected mainly to the increasing temperatures in the course of the century, as mineralization processes and emergence of ammonium in soils are temperature related. Ammonium decrease could also be indirectly linked to a rising temperature, because higher temperatures increase evaporation potential in the region, cause lower water contents in soils and inhibit ammonium emergence during mineralization, which is defined to occur at soil water contents above 80%. The min/max-interval shows high amplitude for ammonium loads. This is caused by one outlying future scenario (S14) already detected during climate scenario evaluation. This scenario assumes much lower (winter) temperatures than the other ones in the reference period, resulting in high ammonium occurrence, so that changes in ammonium loads for the future periods can be very high.

Phosphate phosphorous loads show a slightly increasing trend throughout the year, except in April and May, where a decrease can be seen, as snowmelt happens less often in the projected future. The increase in loads is probably connected to increasing leaching processes with higher precipitation amounts, washing some phosphorous from sandy and high permeable soils used for agriculture. The changes are smaller in the first future period due to lower changes in precipitation and higher in the second and third periods with increasing uncertainty.

6.6. Summary and conclusions

Analysis of potential future climate as projected by an ensemble of 15 climate scenarios for the Vistula Lagoon catchment indicates an increasing trend for both temperature and precipitation. While temperature rises steadily from period p1 to period p4, precipitation increase is highest in the second future period p3 (compare data in Table 2.5.3).

Figure 6.6.1 summarizes the effects of projected climate changes on water quantity and quality. After applying a set of 15 climate scenarios to the Vistula Lagoon catchment, percental changes of total inputs to the lagoon were calculated for every scenario and every future period with regard to results achieved under the reference conditions of the same scenario. The average values as well as the uncertainty ranges of the 30-year-average SWIM results driven by these 15 scenarios are presented in the following figure.

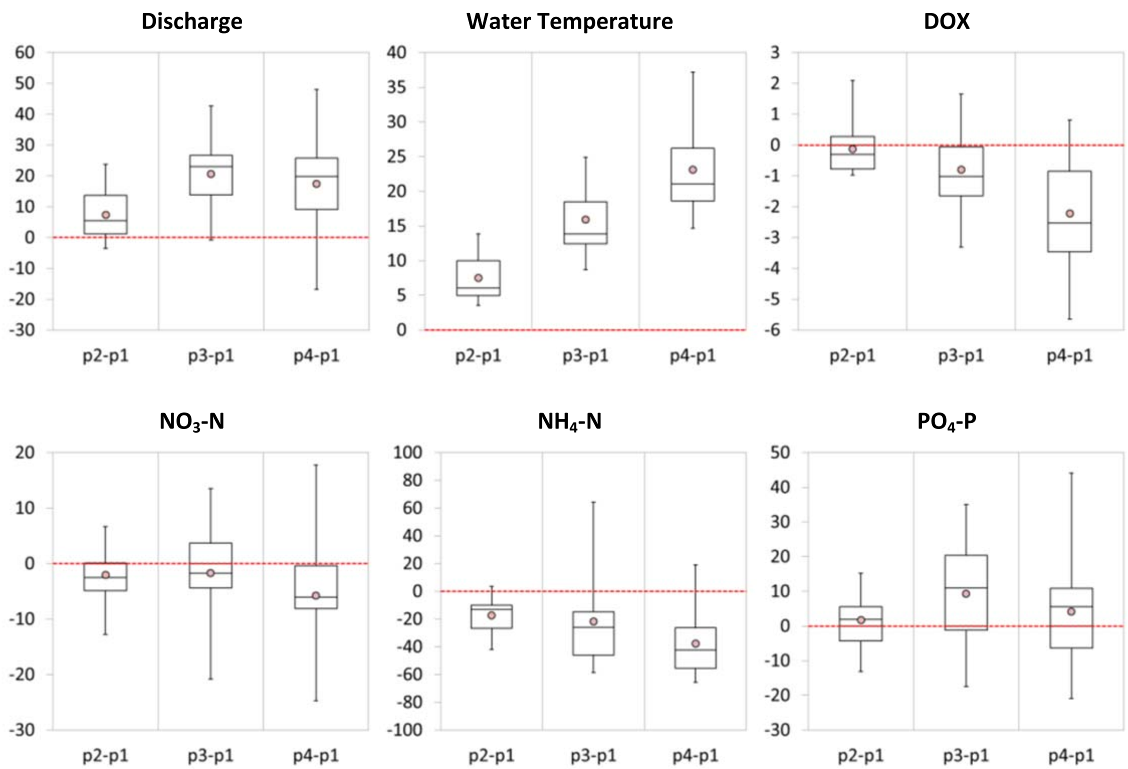


Figure 6.6.1 Ranges of the percental changes of total discharge and nutrient inputs to the Vistula Lagoon as well as of average water temperatures and DOX concentrations simulated with SWIM driven by 15 ENSEMBLES climate scenarios (future periods (p2, p3, p4) compared to reference period (p1) of the same scenario). The box plots visualize the following ranges: min/max, 25/75-percentile, median and average (dots).

The summarized results can be distinguished into two groups:

1) The first group of variables (water temperature, DOX, and NH_4-N) is obviously connected to the increasing trends in temperature even though with different signs. Rising temperatures cause an increase in water temperature, but a decrease in transported ammonium loads, due to inhibited ammonium genesis with warmer soils in

the catchment. Simulated future concentrations of dissolved oxygen in the rivers are mainly resulting from higher temperature (with lower oxygen saturation concentration). Partly increasing oxygen concentrations during the course of the year as a result of lower ammonium content in the rivers do not reverse the overall trend.

2) The second group of variables (water discharge, NO_3-N, and PO_4-P) is mostly related to the precipitation trend projected for the future and increasing water leaching through the catchment soils. For nitrate nitrogen an increase in loads can be observed in the winter months (conforming with the discharge behaviour), but on average a slight decrease can be detected due to the missing snow melt peak. Changes in phosphate phosphorous loads are obviously connected to the projected future precipitation changes.

Model application under assumption of changing climate shows the impacts on water quantity and quality and helps to identify those catchment parts or processes which are most vulnerable to future climate. Climate change impact assessment applied to the Vistula Lagoon catchment revealed clear trends for the future due to unambiguous trends in precipitation and temperature. Impacts seem to be low in the nearer future but will increase in the middle of the century. Therefore it is recommended to think about possible adaptation measures in the medium-term. For this, additional model application and scenario assessment could be useful, in order to estimate the usefulness of possible adaptation measures under changing future climate conditions.

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