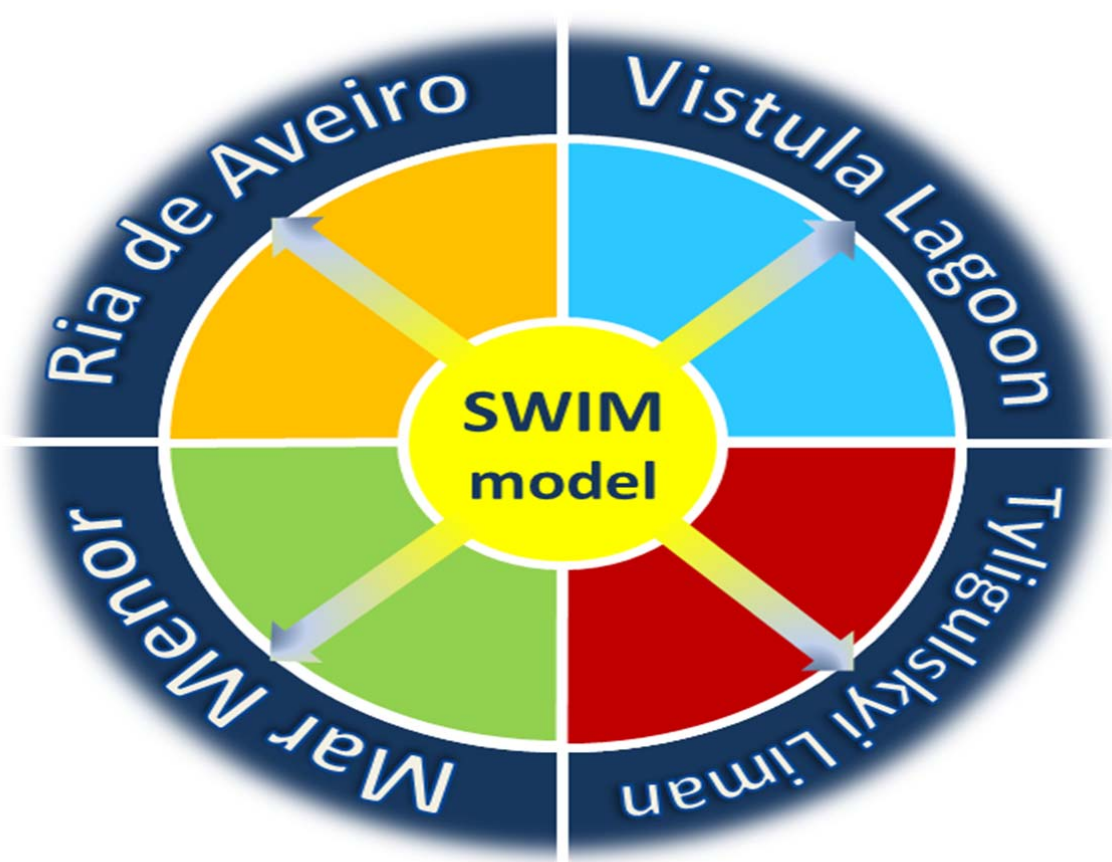
DELIVERABLE D5.1

Results of climate impact assessment

Application for four lagoon catchments



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Title Results of climate impact assessment – Application for four lagoon catchments
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3. Ria de Aveiro

3.1. Case study description and data preparation

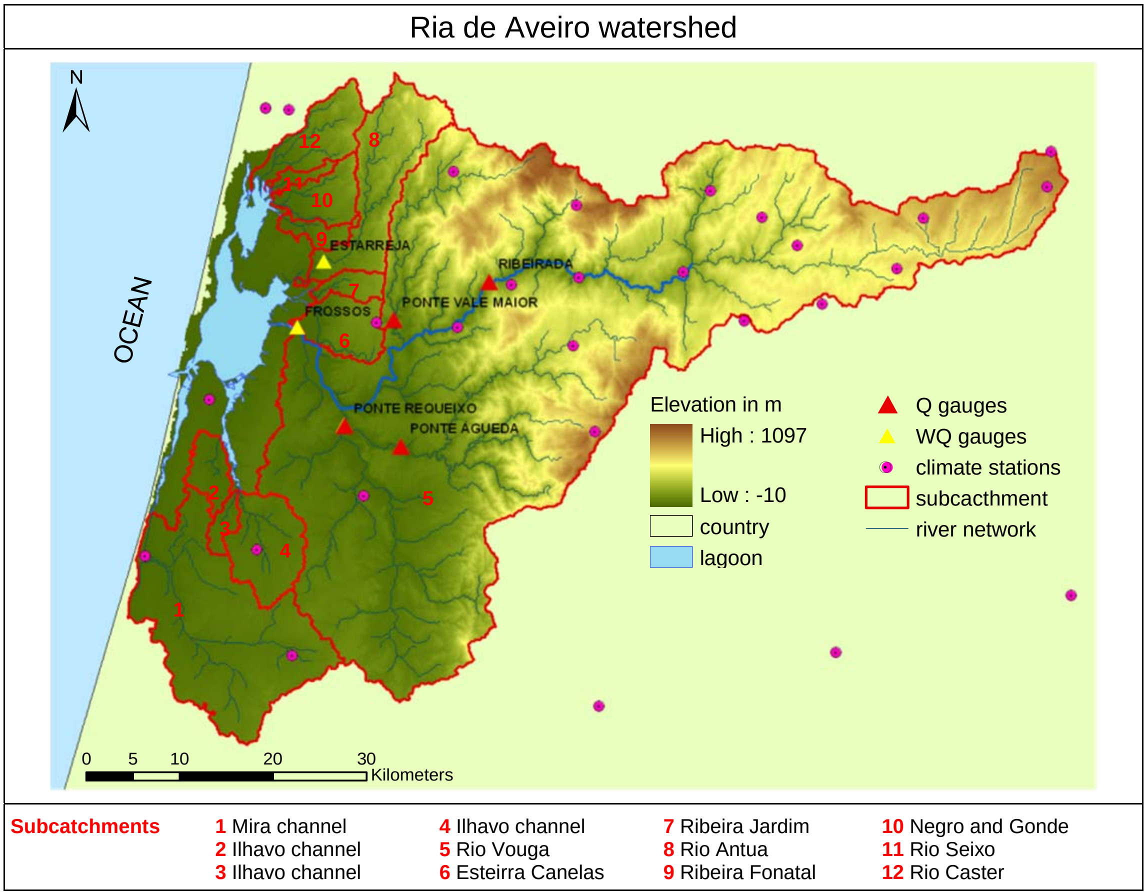
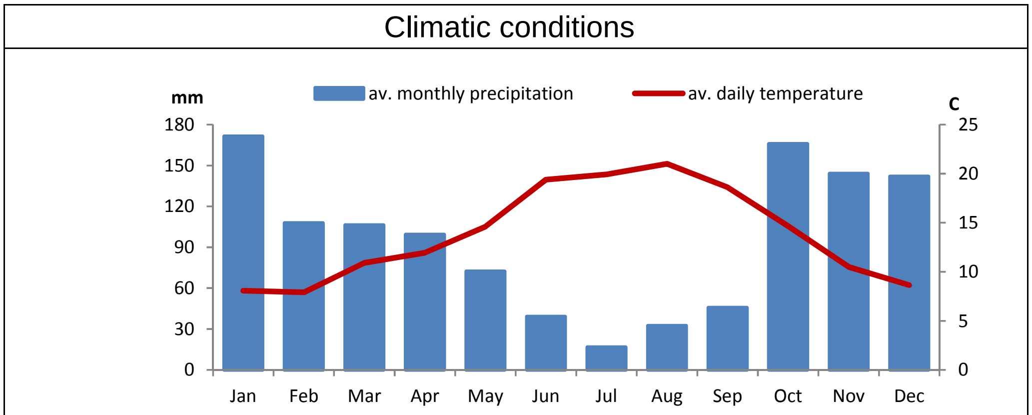


Figure 3.1.1 Overview of Ria de Aveiro lagoon and its catchment, showing topography, the lagoon's boundaries, river network, major sub-catchments (numbered), discharge and water quality gauges and available climate stations.

The total catchment area (see Figure 3.1.1) of the Ria the Aveiro lagoon is about 3600 km^2. The altitude ranges between -10m a.s.l. in the west and southwest and 1097m a.s.l. in the east and northeast part the basin. The average annual precipitation is around 1000mm (see Figure 3.1.2), while most of the rain (70%) falls during winter (October – March). The average temperature is 14°C. Most of the area is occupied by forest (ca. 56%), while arable land (ca. 29%) is mainly located in the lower part of the catchment as well as along the lagoon's boundaries (see Figure 3.1.3). The most dominant soils are Cambisols (ca. 73%).

The major river flowing into the lagoon is the Rio Vouga, with an average daily discharge of 55m^3/s. The Vouga river accounts for 80% of the total freshwater inflow to the lagoon. Most important tributaries of the Vouga are the Águeda river with an average flow of 7m^3/s and the Cértima river with an average flow of 5m^3/s.



precipitation [mm]	171	108	106	99	72	39	17	32	46	166	144	142
temperature [°C]	8.1	7.9	10.9	11.9	14.6	19.4	19.9	21.0	18.6	14.6	10.5	8.6

Figure 3.1.2 Climate chart showing average monthly precipitation and temperature in the Ria de Aveiro catchment based on data from available climate stations.

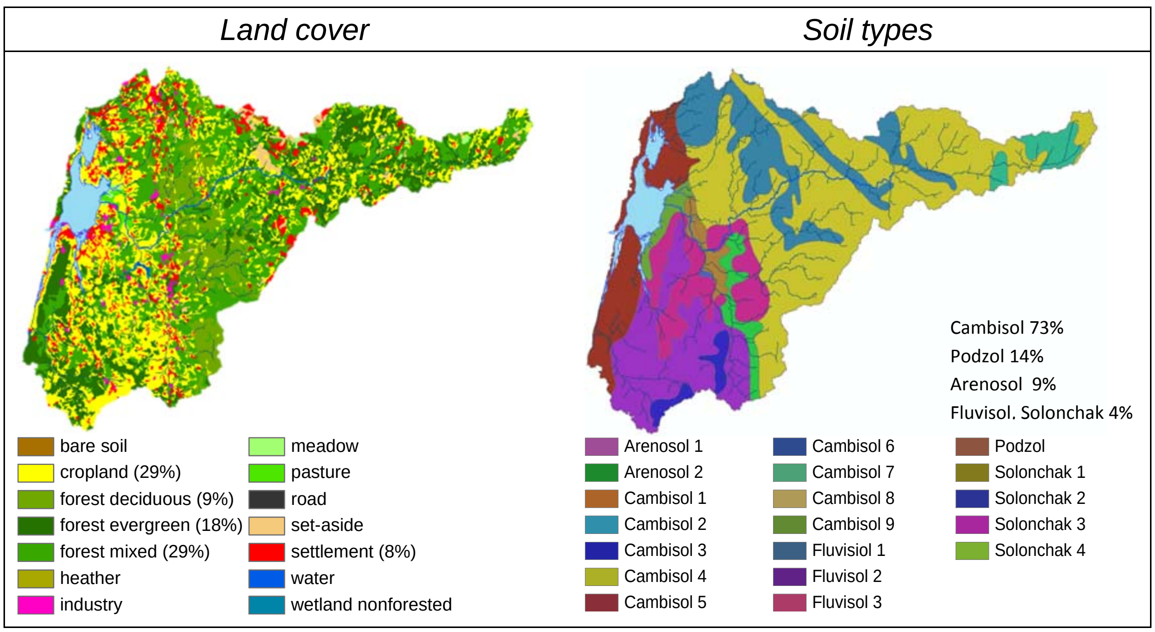


Figure 3.1.3 Spatial distribution of land use classes and soil types within the Ria de Aveiro catchment, as used for the model set up.

Anthropogenic pressures, such as nutrient pollution from urban waste water treatment plants (UWTPs), septic tanks, industries, vineries, piggeries as well as nutrient input via fertilization were included in the model using data from the Portuguese Environment Agency (APA) – former Administração de Recursos Hídricos do Centro (ARH Centro). As visible in the next figure (Figure 3.1.4), most point pollution sources are concentrated around the lagoon, and the northern part of the catchment; the locations of point sources correlate with settlements and industries. Up to 500 tonnes of total nitrogen and 100 tonnes of total phosphorus within one

year are discharged from the largest point source directly into the lagoon, according to the official numbers from APA of the year 2011. Summing up the data on all point sources, we obtain 1213 tonnes of total N and 261 tonnes of total P which are being discharged in the Ria de Aveiro catchment annually.

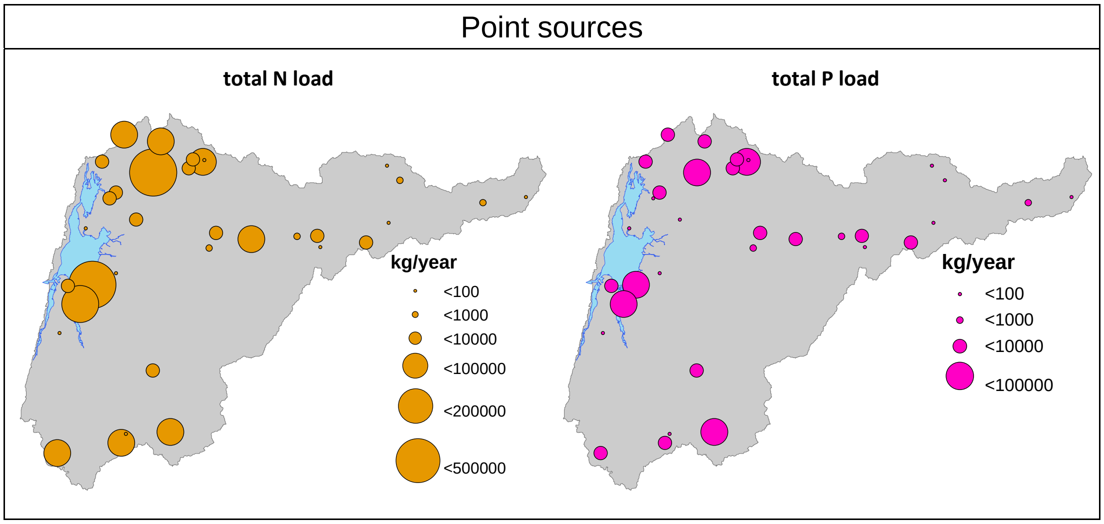
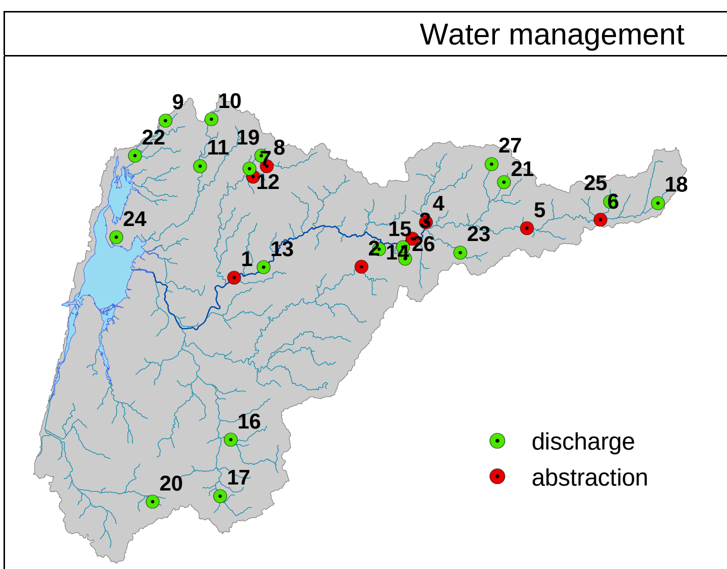


Figure 3.1.4 Locations and amounts of point source emissions of total nitrogen and phosphorus, as implemented in the model.

Water abstraction for drinking water supply from the rivers and water discharge of treated effluents back to the water bodies were also included in the model (see Figure 3.1.5). Water abstraction from groundwater for irrigation purposes could not be included, since relevant information on rates and aquifers was not available.



ID	Mm³/year	ID	Mm³/year
1	20	15	1.58
2	0.22	16	1.14
3	0.06	17	0.95
4	0.22	18	0.002
5	0.16	19	0.005
6	0.19	20	0.69
7	0.06	21	0.06
8	0.41	22	1.48
9	3.78	23	1.80
10	5.77	24	0.009
11	10	25	0.03
12	2.21	26	1.02
13	0.11	27	0.05
14	0.16		

Figure 3.1.5 Locations and amounts of water abstraction and water discharge from/into rivers, as implemented in the model.

On areas categorized as cropland corn was seeded and harvested every year in the model. Corn is the major crop grown on arable land in this area (source: Deliverable D2.1b). Before seeding (4^{th} of March) the crop area is fertilized with 50kg N/ha and 27 kg P/ha. Shortly before the panicles emergence the 2^{nd} fertilizer application of 80kg N /ha and 3 kg P/ha is done. From this stage on until the end of the blooming nitrogen demand of corn is the highest. In total, agricultural areas in the model received 130 kg N/ha and 30 kg P/ha annually during the simulation period (see Table 3.1.1).

Day	N_{min}	N_{org}	P_{min}
64	35	15	27
121	75	5	3
Sum per year	**110**	**20**	**30**

Table 3.1.1
Fertilization dates and amounts (kg/ha) in the Ria de Aveiro catchment as implemented in the model.

The following table (Table 3.1.2) provides an overview of most important data used and implemented in the SWIM model of Ria de Aveiro, as well as their sources.

Table 3.1.2 Data and sources as used and implanted in the model

Data and sources			
Spatial and attributed data	**DEM:** 90x90m raster (SRTM), source: http://srtm.csi.cgiar.org/ **River network, Lagoon boundaries** (source: University Aveiro)	**Landuse:** shape file (CLC2006) , source: http://sia.eionet.europa.eu/CLC2006 **Crop parameters**, source: SWIM database **Crop management**, source: literature review	**Soil:** shape file(ESDB), source: http://eusoils.jrc.ec.europa.eu/data.html) **Soil parameters**, source: SGDBE[4] and German pedological mapping guidelines 2005
Time series	**Climate:** 30 stations (24 in watershed), large gaps in records, especially for precipitation, the missing solar radiation was derived with the Hargreaves – Samani method , total period (2000-2012), sources: http://snirh.pt/ and http://www.tutiempo.net/	**Q gauges**: hourly/quarterly water levels and flow curve equations for 3 gauges for 2002-2005 and 1 gauge for 1991-2000, source: http://snirh.pt/	**WQ gauges**: NO_3-N, NH_4-N, P_2O_5-P and DOX concentrations in mg/l and water temp. in °C for 2002-2009 for 3 gauges; sporadic measurements (on average once per month), not all parameters measured at all gauges, source: http://snirh.pt/
Additional	**Point source pollution**: total N and P loads in t/year with exact location of sources, (source: APA)	**Water abstraction**: - from stream for public water supply in m³/year with exact location, source: APA	**Used water discharge**: - into stream from UWWTP (after treatment) in m³/year with approximate location, source: APA

3.2. Hydrological calibration and validation

Hydrological calibration was performed using data for three discharge gauges (Q gauges): gauge RIBEIRADA on the Vouga river, gauge PONTE ÁGUEDA on the Águeda river and gauge PONTE REQUEIXO on the Cértima river. There are no discharge gauges on any of the remaining small rivers flowing to the lagoon, as well as no estimates on their flows. For water quality calibration three gauges were used; gauge FROSSOS at the outlet of the Vouga river to the lagoon, gauge

ESTARREJA on the Antua river and gauge PONTE REQUEIXO. The period of the hydrological calibration was 2002-2005, while water quality data was available until 2009.

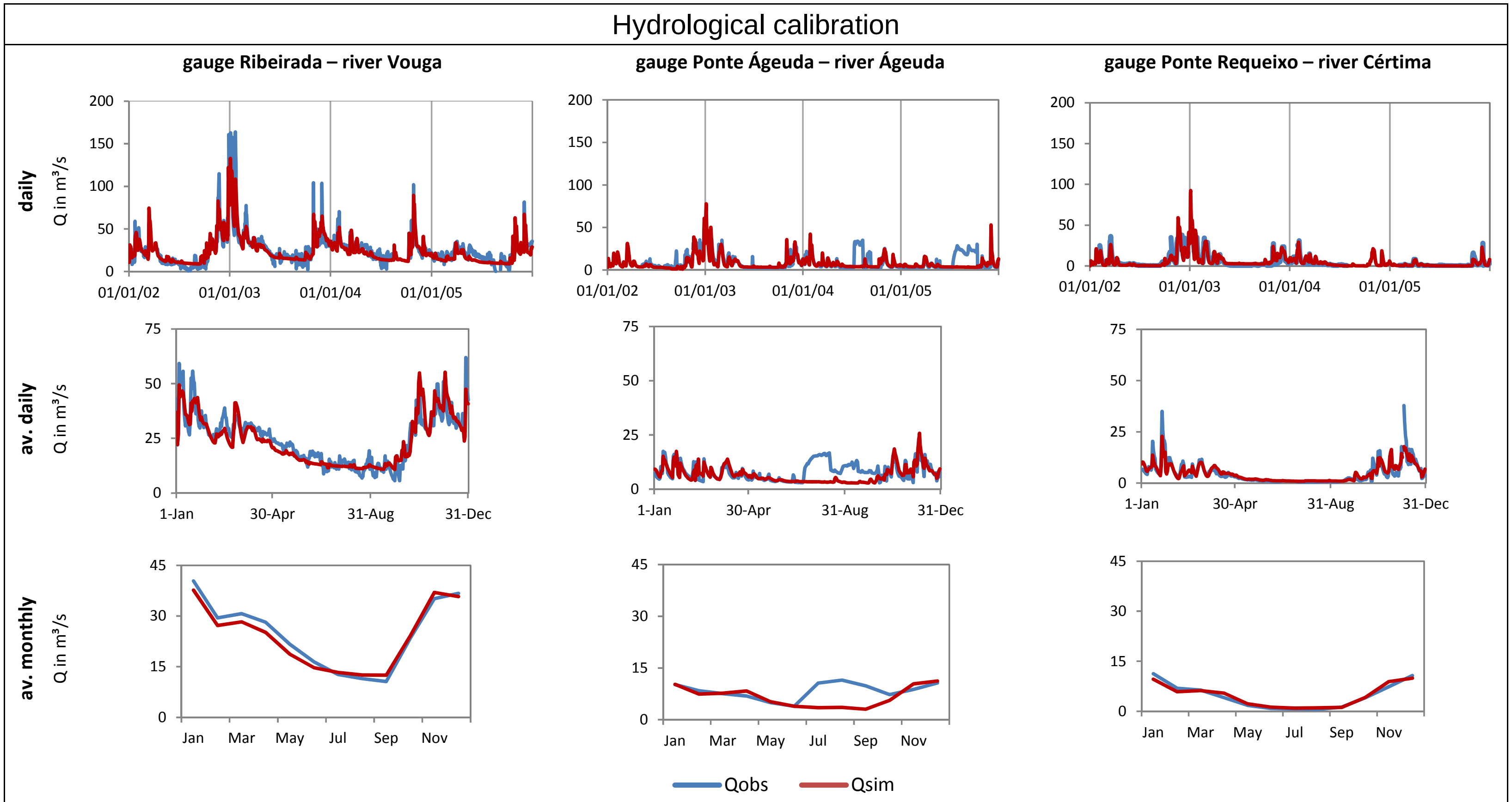
Observed daily discharges were estimated using water levels and a unique flow curve equation for each gauge. Since the equations are valid only within certain boundaries, some recorded values of very low and also very high water levels could not be transformed into daily discharges. In winter 2002/2003 this approach led to additional uncertainty of the observed hydrograph at the gauge RIBEIRADA. Some of the water levels were exactly at the upper limit of equation's range, and resulted in extremely high peak flows, which should be treated as not fully certain.

Another problem related to the observed Q data could be seen at the gauge PONTE ÁGUEDA, where high and relatively constant water levels during summer were transformed into increased flows during the driest months of the year (July – September). However in this case the recorded water levels were caused artificially by a dam and not naturally by an increased water flow. The dam is built in the city of Águeda during summer in order to maintain a minimum water level for recreational purposes, especially canoeing competitions. If the dam, which is a simple sand bar, is destroyed during a strong rainfall event, it is rebuilt again. This explains why sometimes in the observation data the water level drops down, while at the same time the nearest precipitation gauge has recorded very high rainfall intensity, which would lead to the high peak flows in a natural environment.

Additional uncertainties in the hydrological calibration were caused by missing precipitation gauges at high elevations and periods of gaps in meteorological records. In order to overcome underestimation of precipitation at high altitudes a precipitation lapse rate was implemented into the model. In periods of large gaps in records, data from stations located outside the catchment, sometimes at a distance of more than 100 km had to be used for climate interpolation. These uncertainties in input data contributed to difficulties of model calibration, and were translated into uncertainties of modelling results.

Taking into account all uncertainties in input data the hydrological calibration of the model was quite successful, reaching the Nash-Sutcliffe efficiency of 0.76 and the relative deviation in water balance of -3.26% at the gauge RIBEIRADA (see Figure 3.2.1).

Since there is no gauge at the outlet of the Vouga river, it was very important to calibrate discharge additionally at its two major tributaries as good as possible. At the gauge PONTE ÁGUEDA NSE of 0.7 and DB of +9% were achieved. These values are calculated without taking into account the months when the dam is constructed in the city of Àgueda. At the gauge PONTE REQUEIXO NSE was 0.75, and DB was -18%. An overall underestimation of peak flows leads to this notable negative deviation in water balance. In our view, the main reason for that is insufficiently representative climate input data for this subcatchment during the rainy season.



	daily	av. daily	av. monthly	daily	av. daily	av. monthly	daily	av. daily	av. monthly
NSE	0.76	0.85	0.96	0.70*	0.91*	0.96*	0.72	0.80	0.93
DB		-3.26			9.06*			-18	

* efficiency is calculated without days in which dam for summer recreation in the city of Águeda is constructed (July-Sept for 2004 and July-Oct for 2005)

Figure 3.2.1 Graphs of the hydrological calibration for the gauges RIBEIRADA, PONTE ÁGUEDA and PONTE REQUEIXO showing daily, average daily and average monthly results as well as calculated statistics at each gauge.

The following figure (Figure 3.2.2) shows precipitation and three simulated major water fluxes: evapotranspiration, runoff and groundwater recharge in the catchment as average values for the period 2001 – 2012. In general, evapotranspiration is higher in areas in which precipitation is higher and hence more water is available. However evapotranspiration also strongly depends on the land cover. Forests have one of the highest evapotranspiration rates among different land uses. In the Ria de Averio catchment the evapotranspiration rates of 700 mm/year are simulated in the southeast of the catchment, which is mainly covered by forest. The lowest evapotranspiration of ca. 100mm/year was simulated along the lagoon as well as in the southern part of the basin. The runoff distribution in the basin also correlates strongly with the precipitation pattern but it is also dependent on the soil types and their characteristics. The Cambisol along the most western part of the catchment is very sandy (ca. 80%). When rain falls onto this area, water infiltrates into the soil very fast and easily, which leads to low runoff and high groundwater recharge at the same time. On the contrary, soils on the east side of the lagoon have very high clay contents (ca. 60%). This makes them much less permeable; hence less water can infiltrate and reach the aquifer. Most of the water would flow as surface runoff into the lagoon.

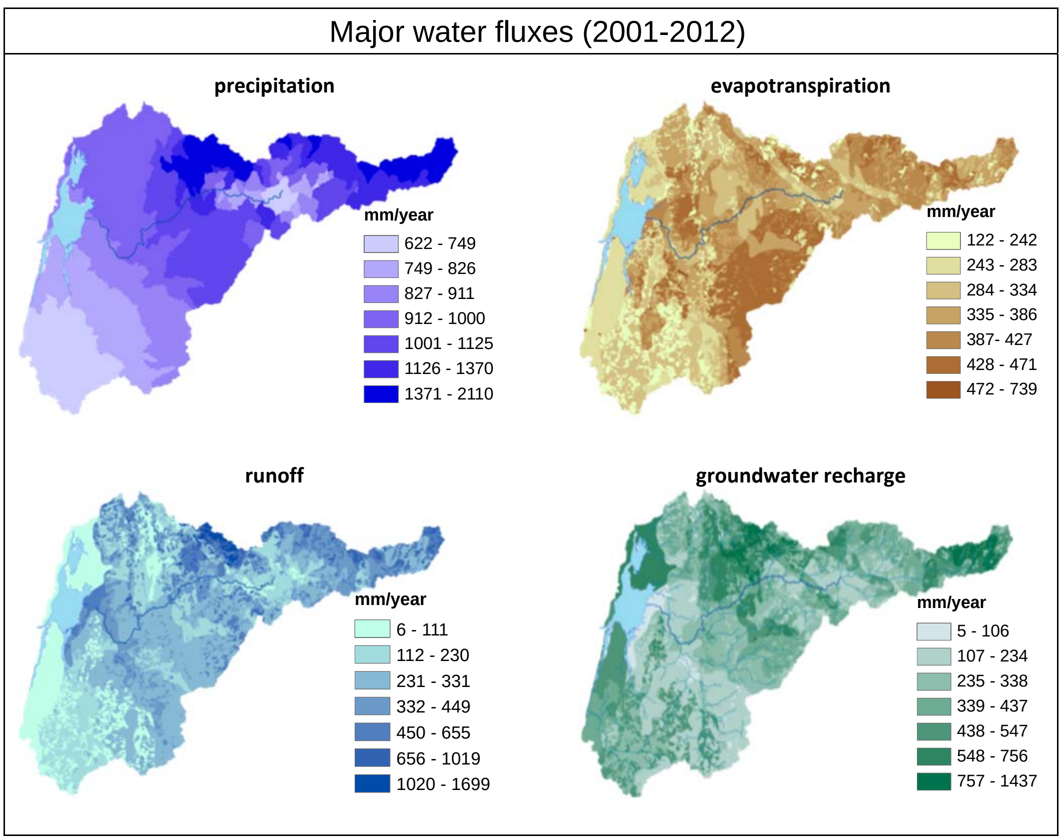


Figure 3.2.2 Spatial patterns of major water cycle components in the Ria de Aveiro catchment averaged over the period 2001 – 2012.

3.3. Calibration and validation of water quality

Water quality was calibrated at two gauges: the gauge FROSSOS at the outlet of the Vouga river and the gauge ESTARREJA at the Antua river, a water course in the north of the lagoon. In addition, ammonium nitrogen was calibrated at the gauge PONTE REQUEIXO, as data at this measuring point was available for a longer time period then in FROSSOS. Five water quality variables were included in the calibration process: orthophosphate phosphorus, ammonium nitrogen, nitrate nitrogen, dissolved oxygen and water temperature. Neither at FROSSOS nor at ESTARREJA it was possible to perform hydrological calibration due of missing data. Therefore, calibration of concentrations at these two gauges was extremely challenging.

Both rivers, Antua and Vouga show very different behaviors regarding concentrations and seasonal dynamics of nutrients. For example, in the Antua river the observed phosphorus concentrations are ten times higher than in the Vouga river (see Figure 3.3.1). The seasonal dynamics of PO_4-P clearly show that point sources are the main reason for water pollution in this river (see Figure 3.3.2). High concentrations during summer when the flow is very low are characteristic for a constant discharge of pollutant into a river. Nitrate nitrogen shows a similar behavior; NO_3-N concentrations in the Antua river are three times higher than in the Vouga river (see Figure 3.3.1), and also concentrations are the highest during summer (see Figure 3.3.2).

On the opposite, concentrations in FROSSOS at the Vouga river increase with higher runoff during winter (see Figure 3.3.2). This phenomenon is characteristic for diffuse pollution, mainly induced by nutrients wash-off from the fertilized agricultural fields. Ammonium nitrogen does not show as clear seasonal dynamics as nitrate and phosphate do (see Figure 3.3.2). Concentrations in ESTARREJA are twice as high as in REQUEIXO (see Figure 3.3.1). The dissolved oxygen and water temperature show similar seasonal behaviors in both rivers. However, during summer oxygen concentrations in Antua drop down stronger than in Vouga, which can be explained by higher nutrient and organic matter concentrations during this period (see Figure 3.3.1).

Water quality parameters were calibrated using the visual “best fitting” method between the observed and simulated values, since the small number of observations was not sufficient to calculate any of the common statistical indicators used for the evaluation of the model performance. Best results were achieved for water temperature and dissolved oxygen concentrations. NO_3-N and PO_4-P dynamics in both rivers also showed acceptable agreement with the observed data. Ammonium nitrogen concentrations were within the same ranges as the measured values at FROSSOS and REQUEIXO, but an explicit seasonal dynamics did not exist and could not be reproduced by the model.

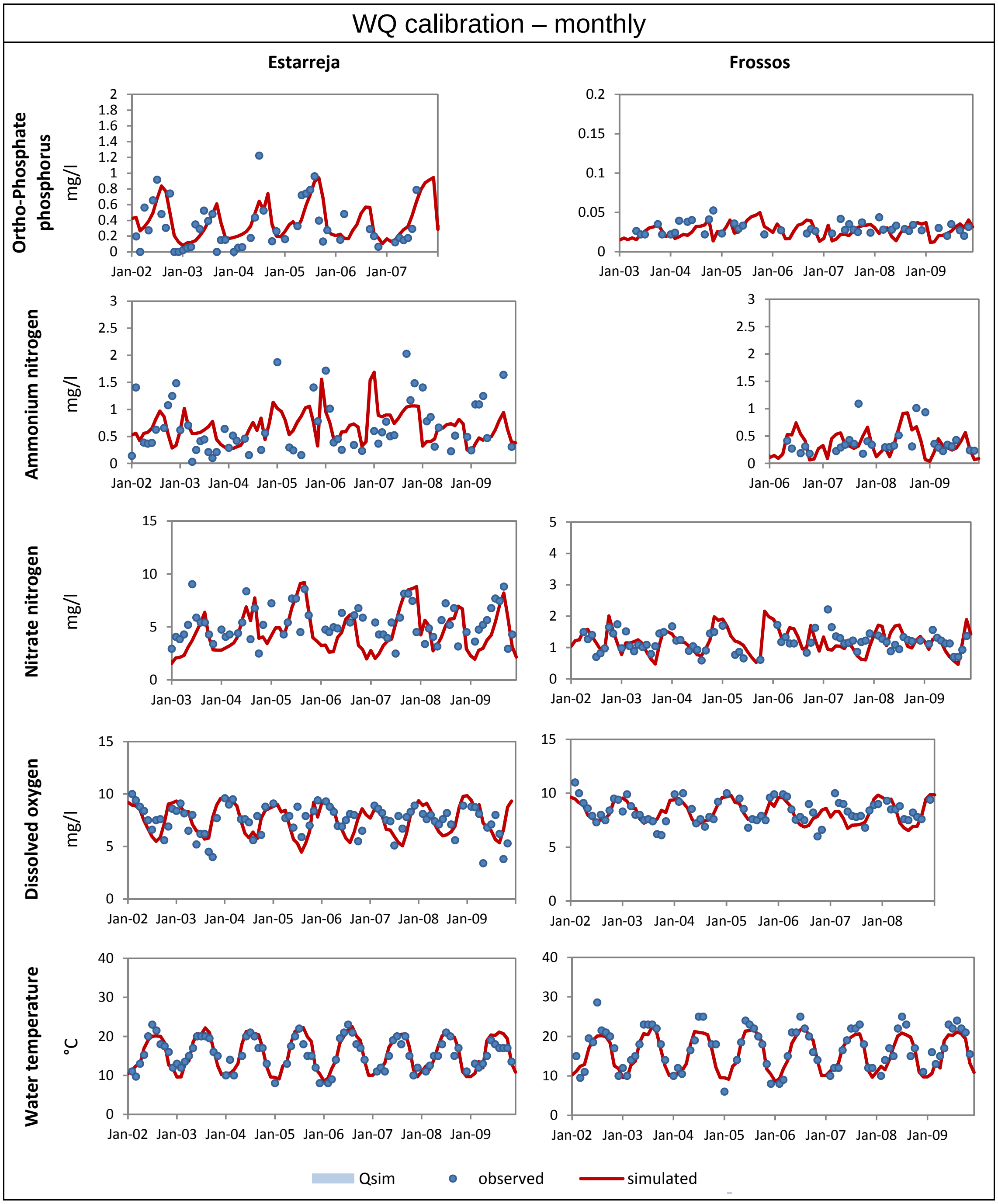


Figure 3.3.1 Graphs of water quality calibration showing monthly averages of simulate variables (red lines) and observed concentrations and water temperature measurements (blue points).

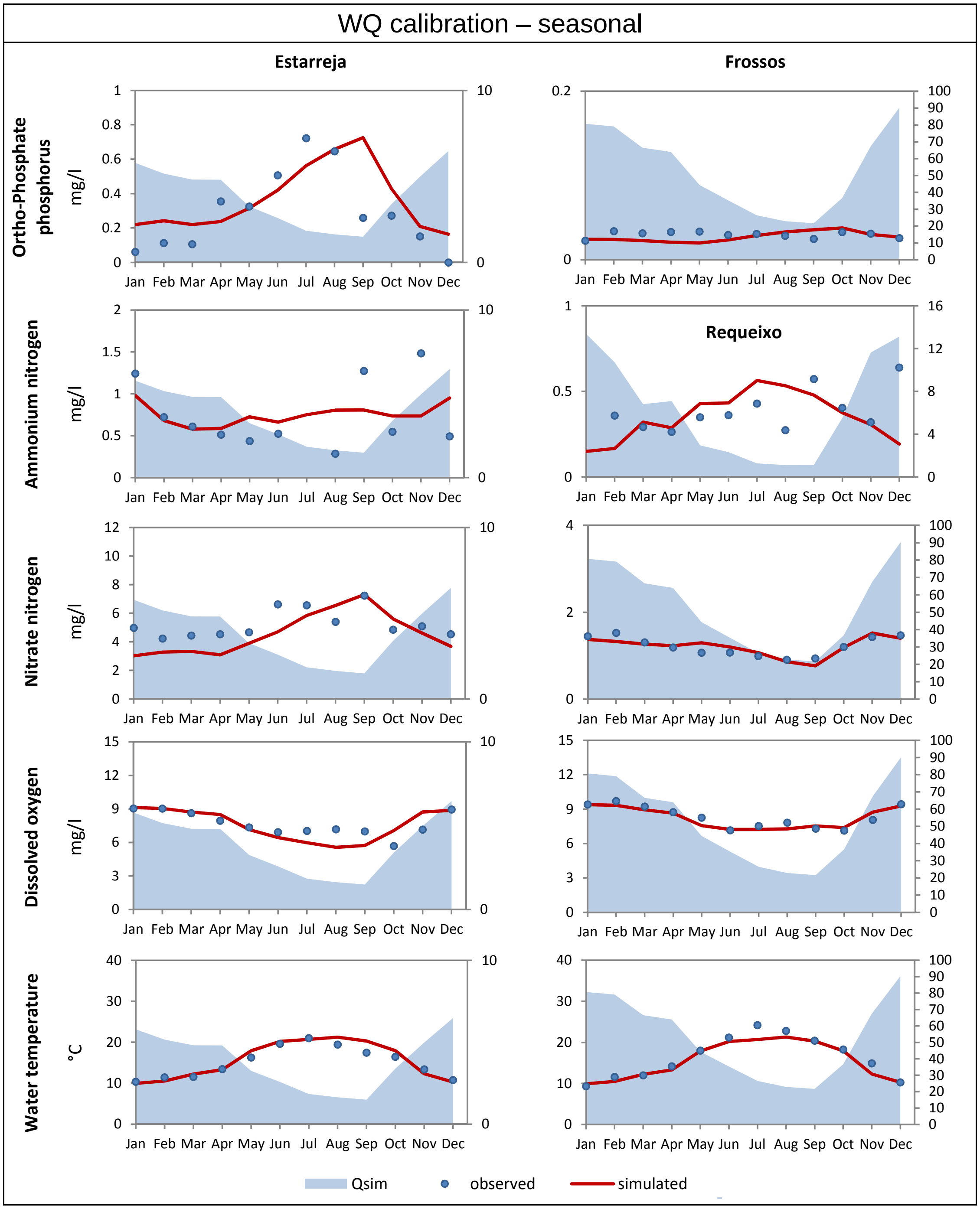


Figure 3.3.2 Graphs of water quality calibration showing seasonal dynamics (long term monthly averages) of simulated and observed water quality parameters as well as of simulated discharge.

3.4. Climate impact on water flows

The following figure (Figure 3.4.1) shows the average daily dynamics of total water discharge to the lagoon in three scenario periods (upper graphs in Figure 3.4.1) and differences in total water discharge between these three periods and the reference period as mean monthly values (lower graphs in Figure 3.4.1). The average values of total discharge from all simulations driven by 15 climate scenarios are shown for three future scenario periods (black lines) and can be compared with the average values of the simulated Q values driven by 15 climate model runs for the reference period 1971-2000 (red lines). The outer uncertainty band (light grey) is defined by the maximum and minimum values of all the results driven by 15 climate scenarios, while the inner range (dark grey) is defined by the 25^{th} and 75^{th} percentiles of all the results.

On average there is only a little reduction in discharge projected for the 1^{st} (2011-2040) and 2^{nd} (2041-2070) future periods and even a slight increase in runoff during Jan-Feb for the 2^{nd} period. Towards the end of the century (2071-2098) the uncertainty range increases but at the same time the trend to reduction becomes stronger. The discharge is reduced by ca. 20 m^3/s while reduction in spring (Mar-May) and autumn (Oct –Nov) is stronger than in summer.

Daily dynamics projected by scenario S3 (blue lines), which is the "best fitting" scenario for this case study, are below the average but within the 25/75 Percentile of all results. Seasonal changes implied by scenario S3 show some deviations from the average trend for the last future period. Discharge simulated with the S3 climate increases in Dec – Jan, while on average it decreases throughout the whole year.

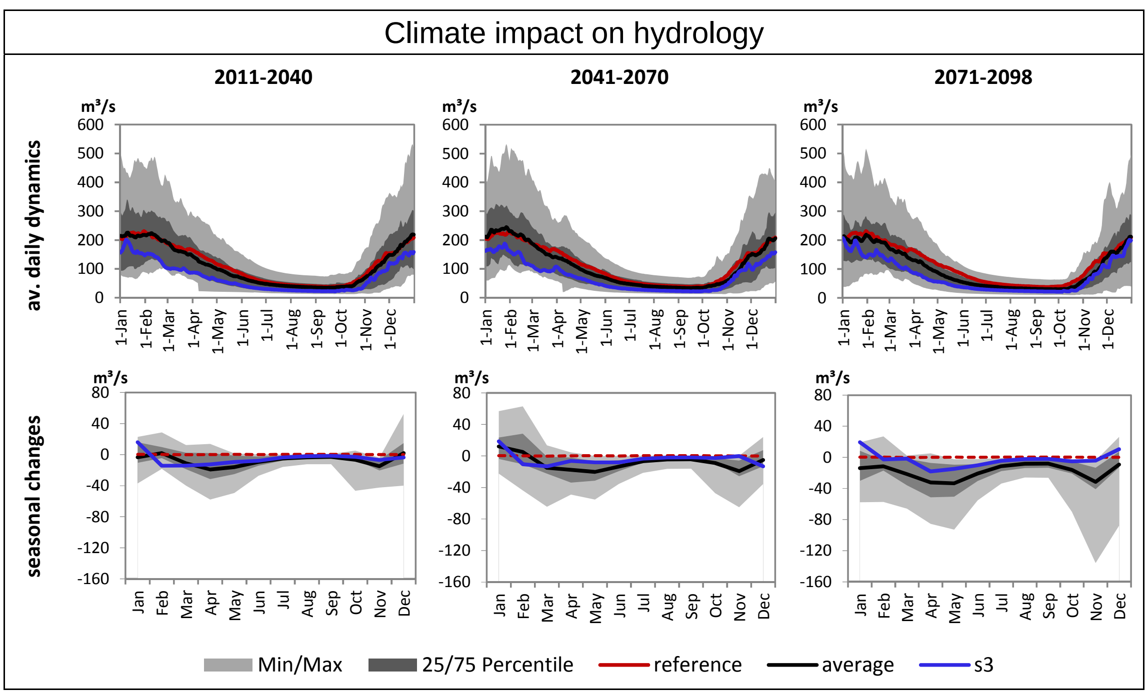


Figure 3.4.1 Average daily dynamics and absolute changes of monthly averages for the total water inflow to the Ria de Aveiro lagoon analysed for all 15 climate scenarios and three future periods compared to the reference period 1971-2000.

The next figure (Figure 3.4.2) shows the spatial patterns of projected changes in precipitation, evapotranspiration, runoff and groundwater recharge in the Ria de Aveiro catchment between the future scenario (p2, p3, p4) and reference (p1) periods. In the first step the model outputs for each scenario (S1 - S15) were averaged over the four simulation periods of 30 years. Next, a mean of all 15 simulation outputs was calculated for the reference and the three future periods. From these, differences in water fluxes between the future periods and the reference period were derived and mapped.

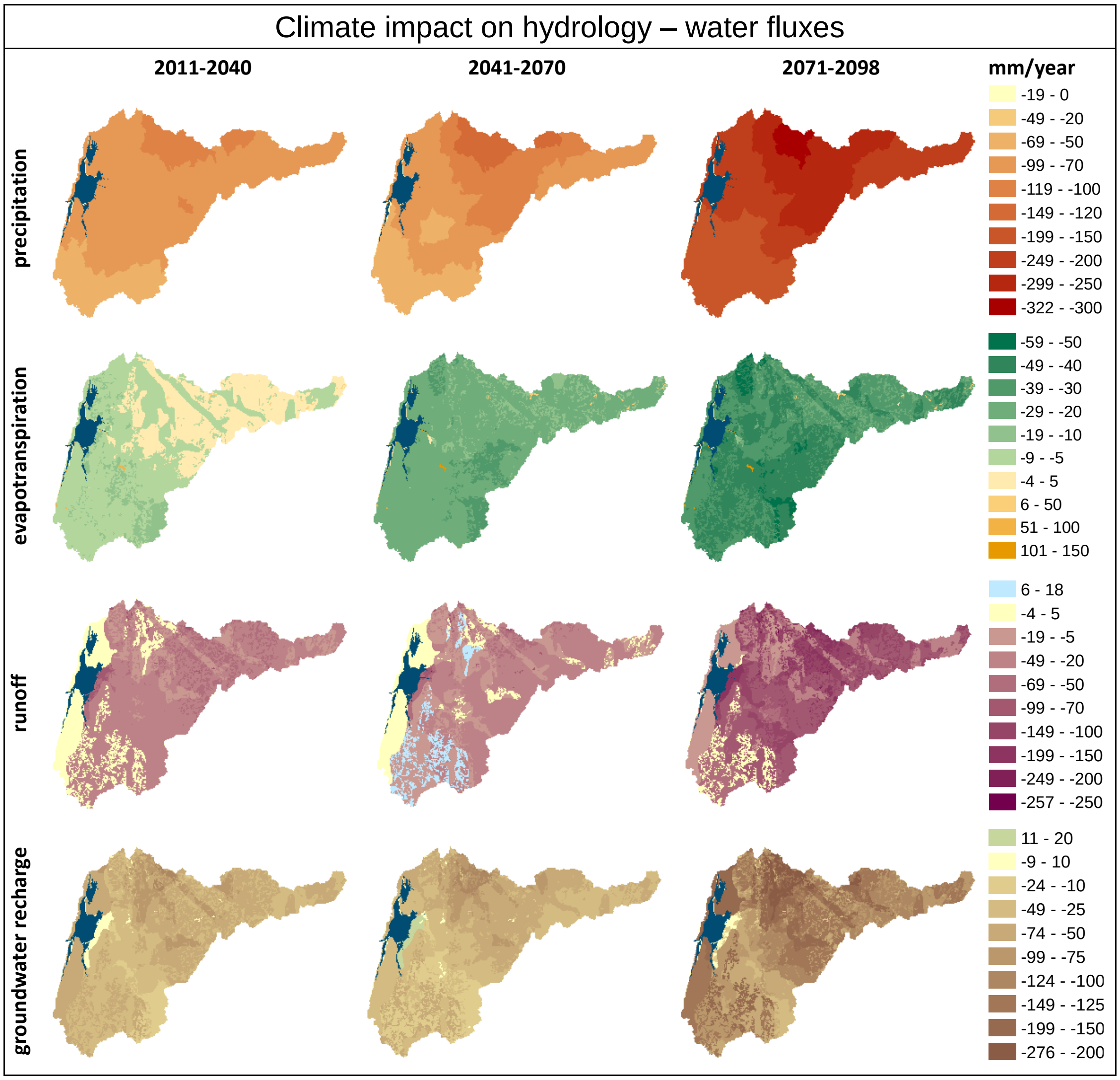


Figure 3.4.2 Average annual differences in major water cycle components in the Ria de Aveiro catchment calculated for the means of all simulations driven by 15 climate scenarios between three future periods and the reference period.

Average annual changes in precipitation show that projected rainfall decreases up to -322mm in some areas for the last future period, while the decrease in the near future is not higher than -100mm. According to the scenarios, rainfall will decrease strongest in the mountainous areas and not so significant in the already dry areas (see Figure 3.4.2).

The overall decrease in precipitation leads to a decrease in evapotranspiration as less water is available in the system. The decrease in evapotranspiration reaches 59mm/year in areas with strong reduction of precipitation and areas covered by forest (southwest), which have the highest evapotranspiration rates under current conditions. Forests react very sensitive to climate change and water availability. Evapotranspiration increases strongly (150mm) above water bodies (e.g. lake Fermentalos) as temperature rises. The lagoon itself was not modelled as a water body within this WP, therefore evapotranspiration rates for the Ria de Aveiro lagoon cannot be shown.

Annual runoff reduction reaches -250mm in some areas. However, during the 2nd future period, some areas show a little increase (6mm). These areas are agricultural land, on which crops are grown. An unfavourable combination of water availability and temperature can damage plant development, which itself influences runoff. Besides land use characteristics, the runoff generation depends also on soil characteristics such as field capacity, porosity, water holding capacity and others. Different soil types and land uses can be clearly identified in the map. Groundwater recharge is expected to decrease even more than runoff until the end of the century (up to -276mm).

3.5. Climate impact on water quality

The results of climate impact assessment on water quality are presented in next figure (Figure 3.5.1) showing the average daily dynamics of total daily nutrient input to the Ria de Aveiro lagoon as well as average DOX concentrations and water temperatures of all lagoon tributaries for three scenario periods.

Average daily dynamics of total nitrate and phosphate input to the lagoon show a similar behaviour as the total water flow to the lagoon. The reason for that is that the major share of nutrient pollution reaching the Ria de Aveiro is transported by the Vouga river. The main input of nutrients in the Vouga river is caused by diffuse pollution (from fertilized fields), hence a reduction in runoff leads to a reduction in nutrient loads. On the other hand, nutrient concentrations in rivers with a high contribution of nutrients from point sources (e.g. Antua river) increase as a results of reduced discharge, while their loads stay practically at the same level.

Lower nutrient loads in some rivers do not lead to notably higher DOX concentrations, which can be expected under the constant water temperatures. In fact, the rising water temperatures cause a decrease in DOX concentrations, and these two factors act in opposite directions.

Figure 3.5.2 shows the average seasonal changes of total monthly nutrient inputs to the Ria de Aveiro as well as changes of average monthly DOX concentrations and water temperatures calculated as means of all lagoon tributaries for three scenario periods compared to the reference period.

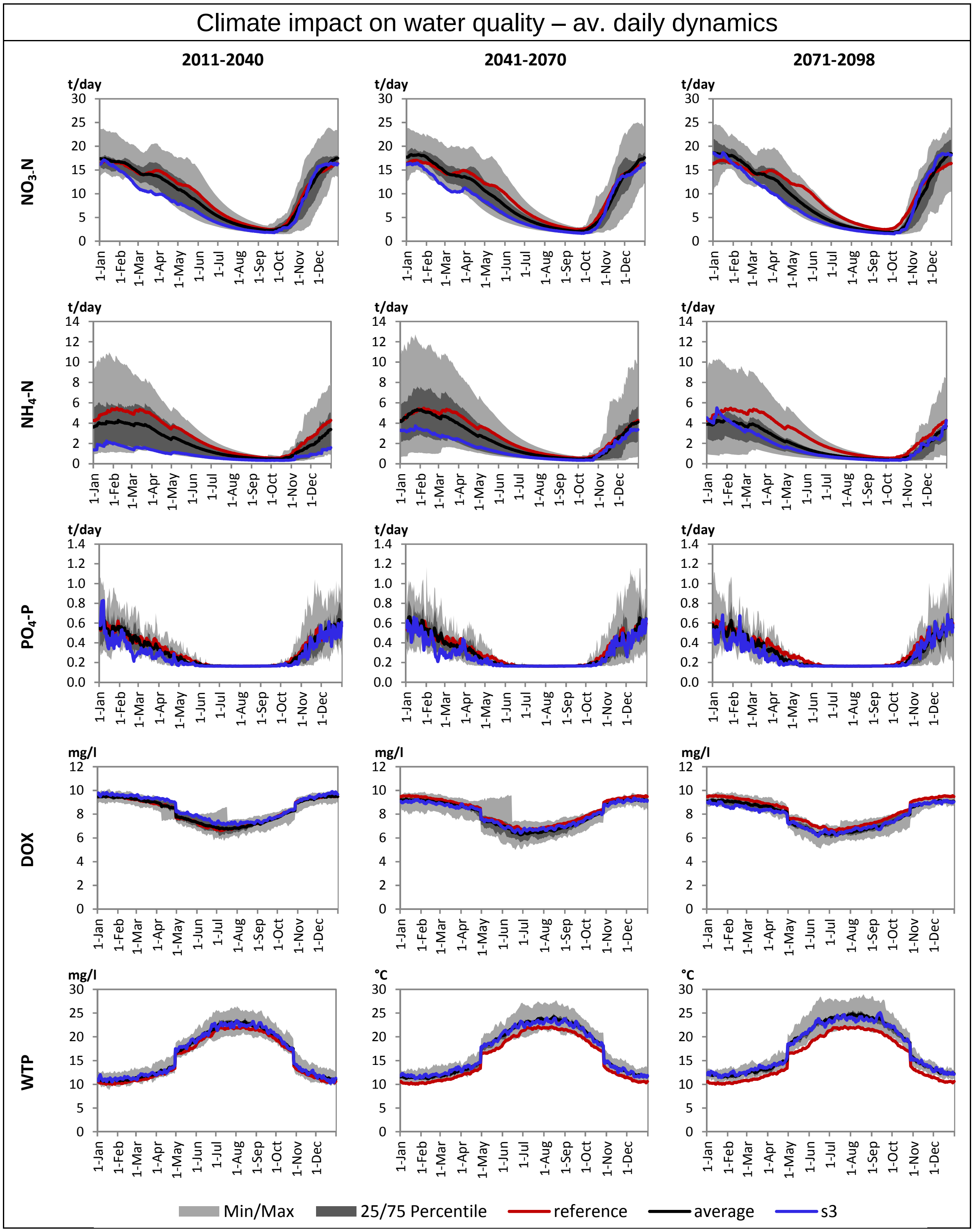


Figure 3.5.1 Average daily dynamics of water quality variables for three future periods based on all simulations driven by 15 climate scenarios, with uncertainty bands as explained above.

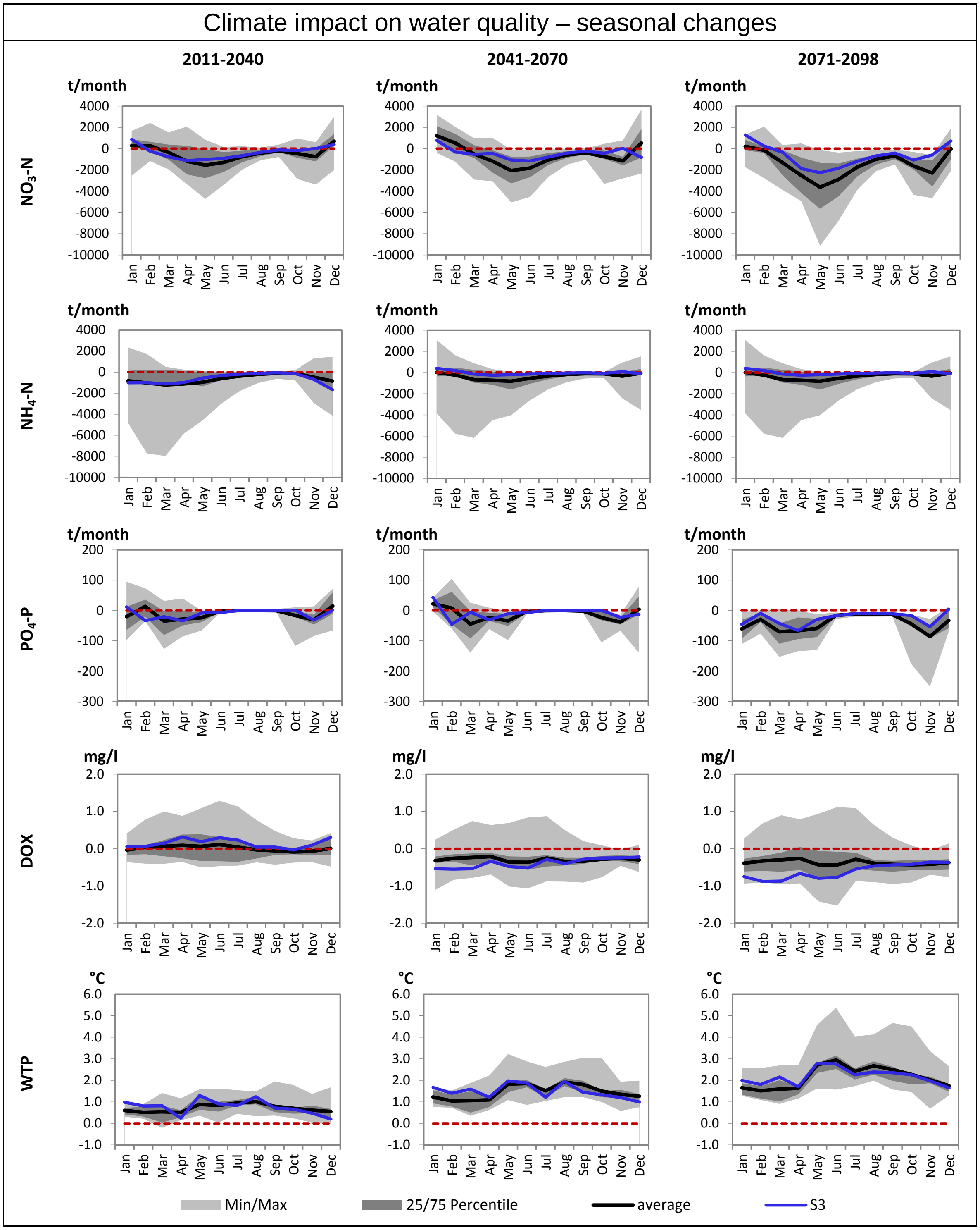


Figure 3.5.2 Average seasonal differences in water quality variables between the future scenario periods and the reference period.

Seasonal changes of nitrate nitrogen load show the strongest decrease in loads during spring (Mar-May), while for runoff the most notable reduction was observed from October to November. In the model fertilizers are applied in the beginning of March, when corn is seeded, and about four weeks later in the beginning of April. The hydrological impact assessment showed a clear decrease in runoff for exactly this period, thus NO_3-N loads are reduced during this period. Ammonium loads show in 75% of all cases the same behaviour (see dark grey bands in 2nd row in Figure 3.5.2). However some scenarios also project very strong decrease during February and March (see light grey bands in 2nd row in Figure 3.5.2). Changes in Phosphorus loads are also driven by changes in runoff. Dissolved oxygen concentrations stay nearly constant during the 1st future period and then clearly decrease. Water temperature increases in each of the three future periods, while the increase from April to June is the strongest.

3.6. Summary and conclusions

In conclusion we can state that the projections for Aveiro (Figure 3.6) show a moderate decrease of average daily discharge to the lagoon by 15% (-20m^3/s) during the last three decades of the century. For the near future (1st and 2nd future periods) most scenarios agree on a reduction between -5 to -7%, while for the 3rd future period the uncertainty becomes higher and most scenarios project a reduction of -6 to -21%. Although the decreasing trend is very clear when average results driven by 15 climate scenarios are analysed, the uncertainty is high, and some scenarios show a slight increase of daily discharge in the first two scenario periods.

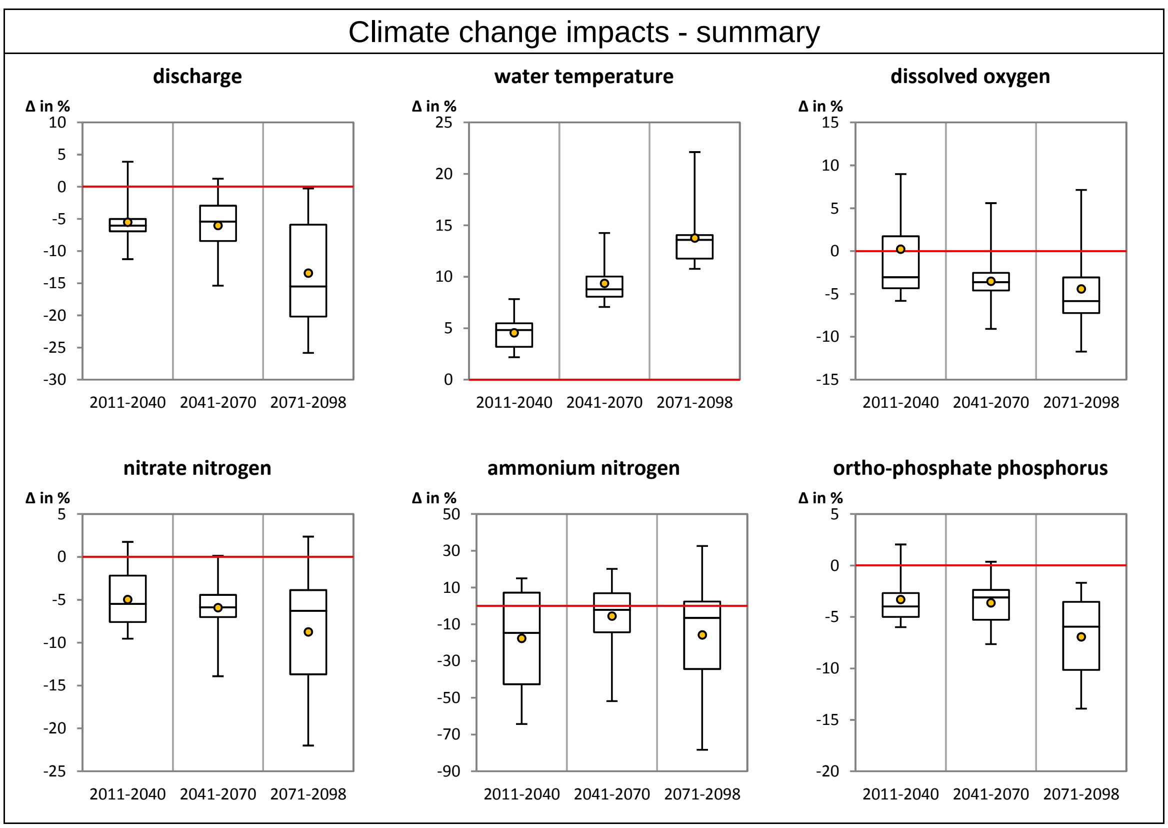


Figure 3.6 Relative changes of average daily total discharge and nutrient inputs to the lagoon, as well as of average water temperatures and DOX concentrations for three future scenario periods compared to the reference period.

The trend in water temperature is even clearer. All scenarios agree on increasing temperatures. Towards the end of the century an average increase of ca. 2°C is projected.

Dissolved oxygen concentrations show a decreasing trend. The range of +/- 10% means in real values a change of +/- 0.8mg/l.

Average daily NO_3-N loads also follow a decreasing trend of ca. -6% (ca. 500kg/day) for all future periods. There is a strong agreement among most scenarios (-4 to -7%) for the 2nd future period but a higher disagreement (-4 to -14%) for the last period.

On average, ammonium nitrogen is getting reduced by -2 to -27% (-35 to -300kg/day), although some scenarios project a slight increase of daily loads. Here the disagreement between scenarios is higher than for any other parameter. The reason is that ammonium loads are influenced not only by water discharge, but also by soil temperature, which varies strongly among scenarios, the same as air temperature does.

Phosphate phosphorus shows a similar trend as NO_3-N. All scenarios agree on a reduction of PO_4-P for the last period. Average daily loads are reduced by -6% (16kg/day) towards the end of the century.

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