DELIVERABLE D6.3

The Vistula Lagoon, the Ria de Aveiro Lagoon, the Mar Menor Lagoon and the Tyligulskyi Lagoon

Results of combined climate and ecosystem processes: Report describing results of combined climate and ecosystem processes

Deliverable 6.3

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CO Confidential, only for members of the consortium (including the Commission Services)

Contents

Common introduction

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Coastal lagoons are highly productive ecosystems, producing a number of essential services of vast ecological, social and economic importance, being at the same time classified as high vulnerability zones due to human activities. In addition, the Millennium Ecosystem Assessment working group (www.maweb.org) recognized climate change as an additional pressure to coastal lagoons.

Coastal lagoons constitute important buffering zones between catchments and sea or ocean with respect to water quantity and quality. Due to this fact, they are subject to multiple stressors and have to cope with all loads that come from catchments (nutrients, pollutants, floods), but also with severe weather events (precipitation, air temperatures, winds, solar radiation) and sea/ocean conditions (storm surges, tides, changes in salinity and water temperatures, as well as nutrients and pollutants). No wonder that so many different stressors upon one water basin may result in many ecological concerns in the lagoon area, and require careful mitigation measures in order to ensure its good water quality and quantity.

LAGOONS used scenario-building and modelling approaches to test and simulate the combined state of the four case study lagoons and its drainage basin, taking into account observed and anticipated changes in climate. Results of how the lagoons may cope with multiple stressors originating from the climate change impacts and socio-economic and environmental changes in the catchment are presented here, based on results of numerical modelling of all four lagoons (i.e. Ria de Aveiro (Portugal), Mar Menor (Spain), Tyligulskyi Liman (Ukraine) and Vistula Lagoon (Poland/Russia).

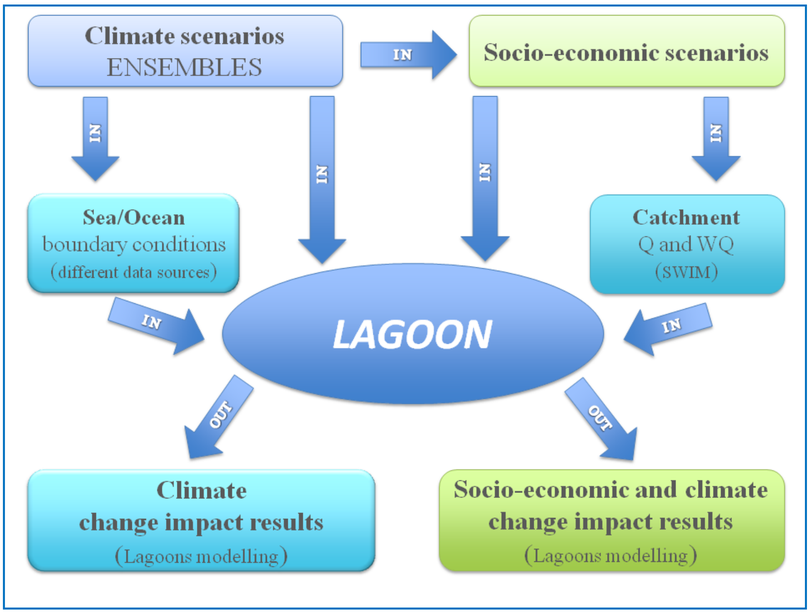

Figure 1 Scenarios modelling concept

In essence, the specific approach of scenarios in the LAGOONS project was based on the creation of alternative water and environmental scenarios (including climate change) that combined input from the various scientific disciplines, as summarized in D6.1 (available at http:/lagoons.web.ua.pt).
The LAGOONS description of work included the following sequential steps:

- The creation of mutual knowledge base and a basic understanding of all scientific approaches (WP2&3);
- The definition of ~~3~~ 4 qualitative story-line scenarios jointly with stakeholders (WP4);
- The translation of the qualitative story-line scenarios into quantitative form (WP5&6);
- The modelling of the water and environmental conditions in the river basin (WP5) and in the lagoon (WP6);
- Analyses of the policy and socio-economic implications of the modelling results (qualitative scenario impacts), including an analysis of the value of scenarios from an information perspective (WP4).

Foreseen the integrated water resources and coastal zone management in European lagoons in the context of climate change, a common procedure for selecting climate change and four socio-economic and environmental scenarios was used in all lagoons. In case of the climate change scenarios the procedure will be described in this report. However, methodology for formulating the socio-economic and environmental scenarios was in detail described in previous reports (i.e. D4.1 and D4.2 and D5.1 and D5.2) for all case study areas. Models of all four lagoons were run with the same set of socio-economic and environmental scenarios, with story lines specific for the area and described in the Deliverable D4.2. All socio-economic and environmental scenarios were developed for the year 2030, using a typical year from the period 2011-2040 as the climatic input to the models. In case of the climate change scenarios all CSA selected 3 typical years representing following periods: 1971 – 2000, 2011 – 2040, 2071 - 2098 (with one difference for Ria de Aveiro – 1981 -2010, described in the Chapter 2) and in addition, each of the CSA defined their own specific extreme scenarios relevant for the area and of high importance for the stakeholders. They will all be depicted in relevant Chapters concerning each of the CSA.
A set of 15 climate scenario data (s1-s15) was provided by the ENSEMBLES project (van der Linden and Mitchell, 2009) and analysed. The reference period was 1971-2000 (p0), and climate impacts were evaluated for three future scenario periods 2011-2040 (p1), 2041-2070 (p2) and 2071-2098 (p3). Before application of climate scenarios for impact assessment, they were analysed and evaluated comparing long-term average monthly and annual temperature and precipitation in three future periods to those in the reference period. By that, so called climate change signals were estimated. Detailed procedure on selection of one climate scenario out of the set of 15 is described in the Deliverable D5.1 (LAGOONS.2013).
In order to run lagoons models under different climate change scenarios it was necessary to limit model computations to one year (as mentioned above), due to computation and results analysis time restrictions. In ideal situation lagoon models should have been ran for all considered climate periods (p0, p1, p2, p3) and next the modelling results would have been analysed with respect to typical and extreme climatic and hydrodynamic situations. However such approach was not possible to follow in approximately a year time that remained for the lagoons modelling, therefore some less time consuming solution was adopted. It based on selection of typical years from each climatic period, as well as extreme ones. Next, along with

the application of the relevant for the selected years climate forcing, river discharges and nutrient loads modelled by SWIM, sea/ocean boundary conditions for water temperature, salinity, water level, nutrients concentrations (provided by different regional models or based on some assumptions discussed later on in the report), lagoon models were run for these specific years. They provided results of one complete year including all climatic seasons (Fig. 1).

Below the common methodology for selecting typical years in each of the climate period in all CSAs is presented.
The methodology was based on statistics. It was assumed that:

N - total number of years in one data set (N=30)
i - year number (i=1, 2,..., 30)
k – month number (k=1,..., 12)
m – number of data in a month

The procedure to select a single climatic parameter x (e.g. daily precipitation) was as follows:

Step 1 - calculation of mean value for each year (i) and month (k) according to following formulae:

$$\overline{x}_{i,k} = \frac{1}{m}\sum_{s=1}^{s=m} x_{i,k,s}$$

Step 2 - calculation of mean value for the whole N-year period for month (k) according to:

$$\overline{x}_{k} = \frac{1}{N*m}\sum_{i=1}^{i=N}\sum_{s=1}^{s=m} x_{i,k,s}$$

Step 3 - bias calculation for each year (i) and month (k) according to:

$$b_{i,k} = abs\left(\frac{\overline{x_k} - \overline{x_{i,k}}}{\overline{x_k}}\right)$$

Step 4 - calculation of total yearly bias according to:

$$b_i = \sum_{k=1}^{k=12} b_{i,k}$$

Choice of the “typical” year was based on (n) parameters therefore for each parameter steps 1 – 4 had to be repeated. Each CSA defined the most important parameters relevant for their climatic area and selected monitoring stations which had to be considered to define properly the typical climatic years.
Two methods were proposed in order to make a final choice of the typical year. They are presented below.

CHOICE 1

The joint bias for year (i) for (n) parameters using weights (equal or diversified, depending on their importance or impact on processes to be modelled; such approach – required some justification and/or explanation why certain weights were used) was calculated according to the following formulae:

$$b_{tot,i} = w_1 * b_{i,1} + w_2 * b_{i,2} + \ldots + w_n * b_{i,n} \qquad \text{where } \sum_{s=1}^{s=n} w_s = 1$$

Final choice of the "typical" year was made based on selection of year with the minimum $b_{tot, i}$.

In case two or more years have the same result, i.e. the total bias, additional steps should be taken as described below.

Step 5 - calculation of standard deviation for each year (i) and month (k) for all parameters (only for years with minimum $b_{tot, i}$)

$$s_{i,k} = \sqrt{\frac{1}{m}\sum_{s=1}^{m}\left(x_{i,k,s} - \bar{x}_{i,k}\right)^2}$$

Step 6 - calculation of total standard deviation for year (i) for each parameter (only for years with minimum $b_{tot, i}$)

$$s_i = \sum_{k=1}^{k=12} s_{i,k}$$

CHOICE 2

Calculation of joint standard deviation for n parameters according to following formulae:

$$s_{tot,i} = w_1 * s_{i,1} + w_2 * s_{i,2} + \ldots + w_n * s_{i,n} \qquad \text{where } \sum_{s=1}^{s=n} w_s = 1$$

Final choice of the "typical" year was based here on selection of the year with the minimum $s_{tot, i}$ (and $b_{tot, i}$).

Details on results of scenarios application into the lagoons models and final modelling results are described in next chapters.

References

van der Linden, P. and Mitchell, J. F., editors (2009): ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project. Met Office Hadley Centre

LAGOONS 2013. Results of climate impact assessment – Application for four lagoon catchments. LAGOONS Report D5.1, 107 pp.

Chapter 1

The Vistula Lagoon - Results of combined climate and ecosystem processes: Report describing results of combined climate and ecosystem processes

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1. Scenarios

1.1 Climate change scenarios

There were two types of climate change scenarios defined: the typical ones and extreme.
The ***typical scenarios*** VL-p0, VL-p1 and VL-p3 – referred later as to p0, p1, p3 - (Tab. 1.1) were chosen according to the procedure described in the Common Introduction.
'Typical' year was selected in each period (i.e. 1971 - 2000, 2011 - 2040, 2071 – 2098) by choosing the year with the lowest combined bias from each of the 30-years averaged total annual temperature and annual precipitation in five locations around the lagoon (i.e. Elblag, Frombork, Krynica Morska, Kaliningrad and Baltiysk). However, in case of unclear selection (e.g. in the five locations different years were selected according to the lowest combined bias) the final choice was based on the annual temperature distribution analysis with the focus on summer temperatures. Summer temperatures play an important role for biological processes and it was decided not to select years with unusual/extreme summer temperatures.
Main assumptions for selection of the ***extreme scenarios*** VL-p01 and VL-p31 (referred later as to p01, p31) called "**Hot summer**" (Tab. 1.1) were to find years in which winter temperatures do not drop below 0 C and in summer period average temperature is relatively high with few days of extreme temperatures close to 25 C. The purpose of it was to find out if a warm winter without ice cover may affect summer primary production in the lagoon. So even though this scenario was called "Hot summer", it was more focused on warm winter then hot summer. From possible candidates the years with the highest winter and summer temperatures were selected.
In the **p01** scenario river discharges (Pregola – 99,1 m^3/s, Pasleka – 29,4 m^3/s) were slightly higher than average for this 30 year period (Pregola – 95,7 m^3/s, Pasleka – 26,7 m^3/s), and in April some moderate extremes were observed (Pregola – 280 m^3/s, Pasleka – 89,4 m^3/s), however they are typical for this period of the year. Therefore the response of the lagoon to high temperatures in winter 1973 and summer 1973 was be mainly affected by the temperature pattern.

Table. 1.1. Climate change scenarios description.

Scenario ID	Climate periods	Selected year	Description of scenario	Atmospheric forcing/river input	Ocean boundary
VL-p0	1971 - 2000	1990	Typical reference year	M10/SWIM	ECOSUPPORT project, model ERGOM
VL-p01	1971 - 2000	1973	Extreme event (hot summer)	M10/SWIM	ECOSUPPORT project, model ERGOM
VL-p02	1971 - 2000	1981	Extreme event (cold winter)	M10/SWIM	ECOSUPPORT project, model ERGOM
VL-p03	1971 - 2000	1992	Storm (extreme wind velocity, selected wind direction, extreme precipitation, high river discharges)	M10/SWIM	ECOSUPPORT project, model ERGOM
VL-p04	1971 - 2000	1997	Extreme event for wind action resulting in salt wedge intrusion upstream the Pregola River (16.12.1997 21:00 + 192 hours)	M10/SWIM	ECOSUPPORT project, model ERGOM
VL-p1	2011 - 2040	2039	Typical year for the near future	M10/SWIM	ECOSUPPORT project, model ERGOM
VL-p11	2011 - 2040	2014	Extreme event (cold winter)	M10/SWIM	ECOSUPPORT project, model ERGOM
VL-p12	2011 - 2040	2024	Storm (extreme wind velocity, selected wind direction, extreme precipitation, high river discharges)	M10/SWIM	ECOSUPPORT project, model ERGOM
VL-p3	2071 - 2098	2081	Typical year for far future	M10/SWIM	ECOSUPPORT project, model ERGOM
VL-p31	2071 - 2098	2088	Extreme event (hot summer)	M10/SWIM	ECOSUPPORT project, model ERGOM

List of abbreviations:

M10 – best fitting climate scenario ECHAM 5-r3 chosen from 15 GCM/RCM combinations of climate scenarios (results from ENSEMBLES project)

SWIM – Soil and Water Integrated Model applied for climate assessment for the catchment area of Vistula Lagoon

ECOSUPPORT – results from the EU-BONUS founded project ECOSUPPORT - Advanced tool for scenarios of the Baltic ECOsystem to SUPPORT decision making (2009-2011) coupled with physical-biogeochemical model ERGOM

In the **p31** river discharges (Pregola – 128 m^3/s, Pasleka – 39 m^3/s) were slightly higher than average for this 30 year period (Pregola – 110,5 m^3/s, Pasleka – 31,5 m^3/s), and in winter some moderate extremes were observed (Pregola – 270 m^3/s on, Pasleka – 84 m^3/s), however they are typical for this period of the year in case of mild winter. Therefore the response of the

lagoon to high temperatures in winter 2087/2088 and summer 2088 were be mainly affected by temperature pattern, the same as in previous scenario.

The both selected extreme years (1973 and 2088) were very similar with respect to temperatures and river discharges.

Main assumptions for selection of the ***extreme scenarios*** p02 and p11 called "**Cold winter**" (Tab. 1.1) were to find years in which winter temperatures stay below 0 C for a longest possible period resulting in long term ice cover of the lagoon and in summer period average temperature is relatively mild, without heat extremes. The purpose of it was to find out if long period of ice cover on the lagoon may result in an improvement of the lagoon water quality.

For the scenario **p02** year 1981 was selected as the representative one. That year had a very cold winter with temperatures remaining below 0 C for 5 months and constant ice cover. Following summer was rather average with respect to temperatures. River discharges in that period (Pregola – 94 m^3/s, Pasleka – 27 m^3/s) were nearly the same as the average for a 30 year period (Pregola – 95,7 m^3/s, Pasleka – 26,7 m^3/s), and in April some extremes were observed (Pregola – 626 m^3/s on 25.04.1981, Pasleka – 227 m^3/s on 02.04.1981). This could have some impact on nutrient concentrations in the lagoon later in summer.

For the scenario **p11** year 2014 was selected. It had relatively cold winter with temperatures below 0 C lasting for nearly 4 months and nearly continuously. River discharges in that year (Pregola – 89 m^3/s, Pasleka – 28 m^3/s) were slightly lower (in case of Pregola) and the same for Pasleka than average for a 30 year period (Pregola – 100,8 m^3/s, Pasleka – 28 m^3/s), and in April a very high extreme was observed (Pregola – 802 m^3/s on 22.04.2014, Pasleka – 327 m^3/s on 16.04.2014). This was an unusually high discharge which could affect nutrients distribution in the lagoon during spring and early summer. Such high river discharges in spring time resulted mainly from melting of the snow which had accumulated during long winter period.

Scenarios **p03** and **p12** describe storm events on the lagoon, when wind velocity over the Vistula Lagoon was higher than 10 m/s and reaching 18 m/s for a period of approximately 72 hours.

Scenario **VL-p04 (p04)** describes the situation in the past (1997), when wind velocity over the Vistula Lagoon was mainly higher than 12 m/s during 192 hours (with short breaks), mean and maximum wind velocities were 14.5 and 18.7 m/s, mean and maximum discharges of the Pregola River were 52.3 and 54.4 m^3/s. It is a reference event for the wind action resulting in deep salt wedge intrusion upstream the Pregola River.

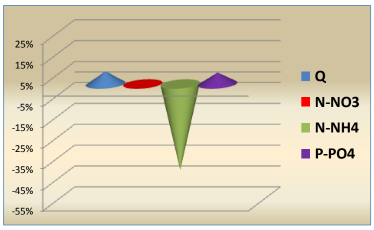
1.2 Socio-economic and environmental scenarios

A set of four socio-economic and environmental scenarios (i.e. BAU – Business as Usual, CRI - Crisis, MH – Managed Horizons, SET – Set Aside) was defined for the Vistula Lagoon study area (Tab. 1.2). A description of the story lines and the assumptions made for each of these scenarios can be found in the LAGOONS Deliverable 4.2 and 5.2. They describe projected changes in land uses and water management that were included in the catchment model SWIM, resulting in variations in freshwater discharges and nutrient inputs entering the lagoon, which were used as input data for the lagoon model.
The atmospheric forcing and the conditions at the ocean boundary were applied as those of the 'typical' year for the 2011-2040 period (p1; Tab. 1.1) in all four cases.

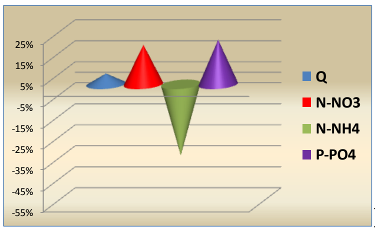
Table. 1.2. Socio-economic and environmental scenarios description.

Scenario ID	Climate periods	Selected year	Description of scenario	Atmospheric forcing/river input	Ocean boundary
VL-BAU	2011 - 2040	2039	BAU combined with climate change	M10/SWIM	ECOSUPPORT project, model ERGOM
VL-CRI	2011 - 2040	2039	CRISIS combined with climate change	M10/SWIM	ECOSUPPORT project, model ERGOM
VL-MH	2011 - 2040	2039	MANAGED HORIZONS combined with climate change	M10/SWIM	ECOSUPPORT project, model ERGOM
VL-SET	2011 - 2040	2039	SET ASIDE combined with climate change	M10/SWIM	ECOSUPPORT project, model ERGOM

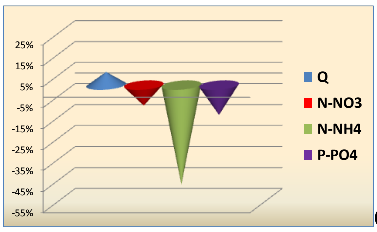
The basic difference between the scenarios concerned modified volume and quality of riverine waters due to changes in land use in the drainage basin (Fig. 1.1).



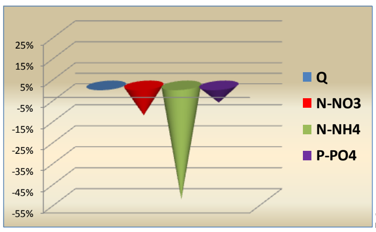
BAU



MH



CRI



SET

Figure 1.1. Combined climate change and land use impact on river discharges and water quality in four scenarios – percental changes between scenario p1 and the socio-economic and environmental scenarios.

2. Climate change impact on the lagoon

2.1 Climate forcing

The Vistula Lagoon is a shallow water body characterised by wind driven currents modified by inflow of numerous rivers, as well as water exchange with the South Baltic Sea through the Baltiysk Strait (Fig. 2.1).
Atmospheric forcing plays an important role in dynamics of water movement; it has also a direct influence on intensity of processes on-going in the lagoon.
To assess the impact of long-term changes in atmospheric forcing, i.e. climate change, on the lagoon, an analysis of historical and future climate characteristics being the main drivers is presented below. For this purpose, all scenarios are divided into three groups, i.e. (1) - typical years in the past (scenario p0), in the near- (p1) and far-future (p3); (2) years with hot summers in the past (p01) and in the future (p31); (3) years with cold winters in the past (p02) and in the future (p11).

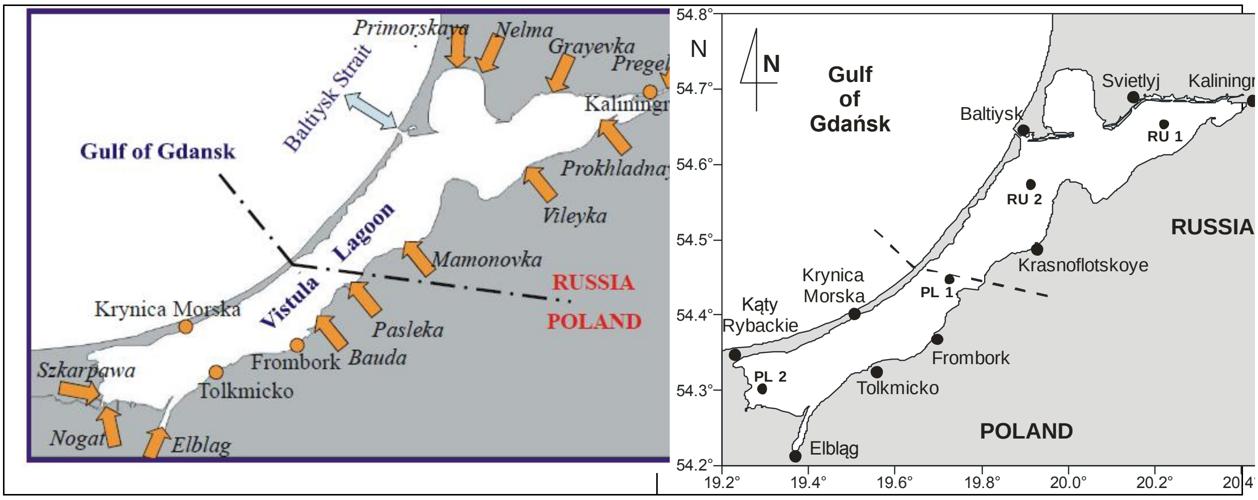


Figure 2.1. The Vistula Lagoon – location of river discharges and cities.

Comparison of wind magnitude and direction for all scenarios defined above is given in Fig. 2.2 (except short-term scenario VL-p04). Diagram shows minimum, maximum, average, median, 25 and 75 percentile values of velocity magnitudes in division into 8 main wind directions. In addition, frequency of wind direction is incorporated (bold crosses).
It is characteristic that average wind velocity is very close to its median; only occasionally average value exceeds the median by more than 0.5 m/s. For all scenarios the minimum value is close to 0 m/s; the maximum value varies in the range of 7-18 m/s in typical years, 6-15 m/s in years with hot summer, and 7-19 m/s in years with cold winters. The highest values are usually encountered in the historical period (1970-2000).
The range of velocity variation between 25 and 75 percentiles is broader for N, W and NW wind directions in comparison with other directions.
Frequency of wind direction is quite similar for typical years; much bigger variations are observed in years with extreme seasons.

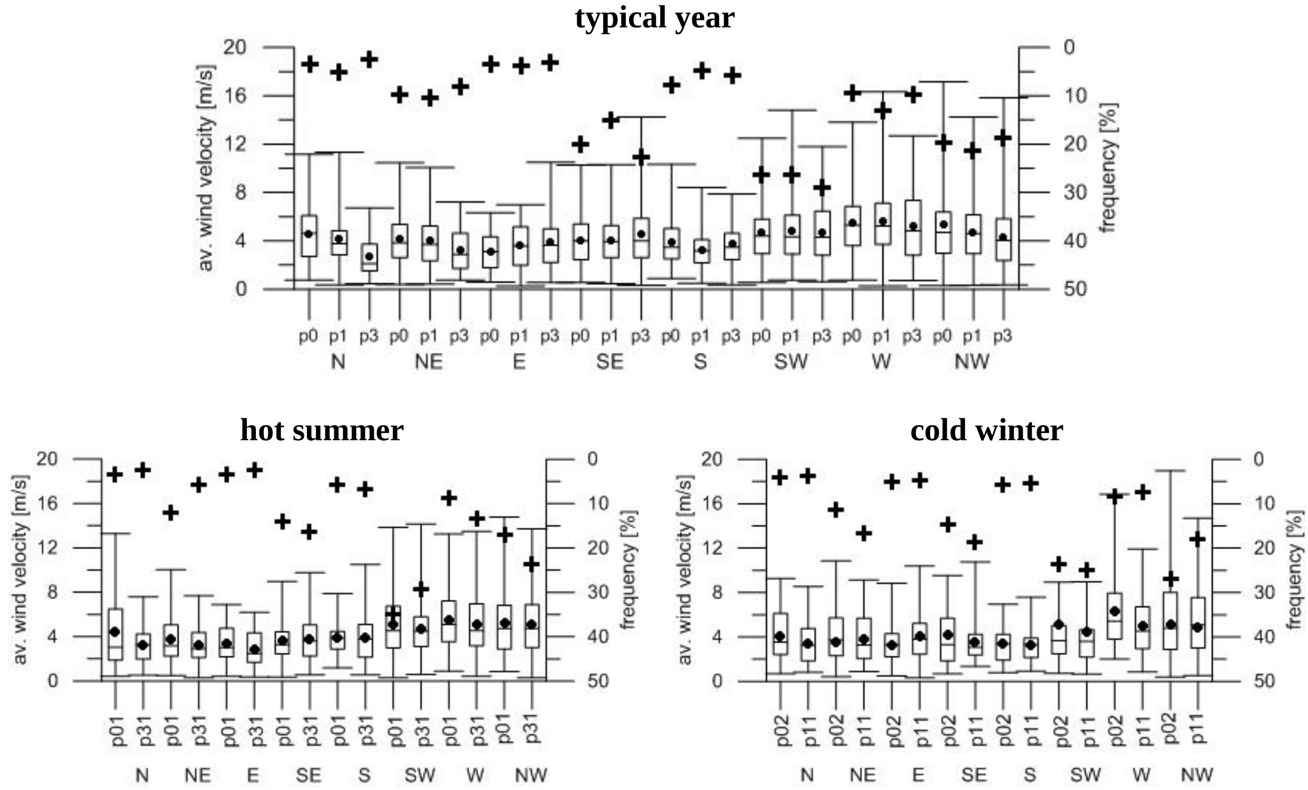


Figure 2.2. Comparison of yearly wind variability in typical years (top), years with hot summers (bottom left) and years with cold winters (bottom right) in division into 8 directions – data for Baltiysk station.

The yearly average wind speed has a tendency to decrease in typical and extreme years (see Tab. 2.1); however, situation is more complex in terms of the division into wind directions. The relative change of velocity magnitude given in Tab. 2.2 confirms a lack of the same tendencies in analysed groups.

From the point of view of storm surges in the Polish and Russian part of lagoon, we should focus on chosen wind conditions. For the Polish part, especially the Elbląg region, the most dangerous is strong wind from NE direction, i.e. wind along the main axis of the lagoon. From the statistics presented for typical years, frequency of wind from this direction will be similar in all scenarios, whereas the average and maximum velocity magnitude will have a tendency to decrease. Storm surges in the Russian part are caused mainly by wind from SW and W directions. These directions are relatively frequent, and the maximum predicted velocities reach 18 m/s. It follows from the comparison of unfavourable conditions for the storm surges occurrence that the Russian part of the lagoon is exposed more to flooding and salt wedge intrusion upstream the Pregola River.

Tab. 2.1. Comparison of average wind speed [m/s] in division into typical years (p0, p1, p3), years with extremely hot summer (p01, p31) and extremely cold winter (p02, p11)

	N	NE	E	SE	S	SW	W	NW	YEAR
p0	4,53	4,21	3,10	4,03	3,88	4,72	5,50	5,34	4,41
p1	4,18	4,00	3,56	4,03	3,23	4,79	5,68	4,74	4,28
p3	2,60	5,91	5,00	3,92	3,25	3,90	4,02	5,77	4,38
p01	5,23	6,13	4,28	4,21	3,10	3,72	5,38	5,68	4,61
p31	3,23	4,67	4,98	5,05	3,37	4,39	3,79	4,68	4,47
p02	5,60	5,69	4,48	3,35	3,09	3,49	4,52	6,28	4,67
p11	6,34	4,27	3,76	3,03	3,76	4,20	4,53	4,93	4,18

Tab. 2.2. Comparison of relative change of average wind speed [%]

	N	NE	E	SE	S	SW	W	NW	YEAR
(p1-p0)/p0	**-7,85**	**-4,89**	14,67	**-0,09**	**-16,65**	1,45	3,30	**-11,25**	**-3,13**
(p3-p0)/p0	**-42,71**	40,43	61,22	**-2,89**	**-16,33**	**-17,52**	**-26,81**	8,21	**-0,85**
(p31-p01)/p01	**-38,20**	**-23,81**	16,48	19,86	8,76	17,98	**-29,52**	**-17,63**	**-2,97**
(p11-p02)/p02	13,11	**-24,90**	**-16,14**	**-9,64**	21,64	20,46	0,27	**-21,49**	**-10,66**

Vistula Lagoon has a single connection with the Baltic Sea via the Baltiysk Strait. In the model set-up this connection is described by the open boundary, where water level and salinity change in time. Values of those parameters, coming from the external data source (Baltic Sea model ERGOM applied in the ECOSUPPORT project) are incorporated into the lagoon model. Comparison of monthly average water level variations at the open boundary (Fig. 2.3) shows a rather chaotic picture in all analysed cases.

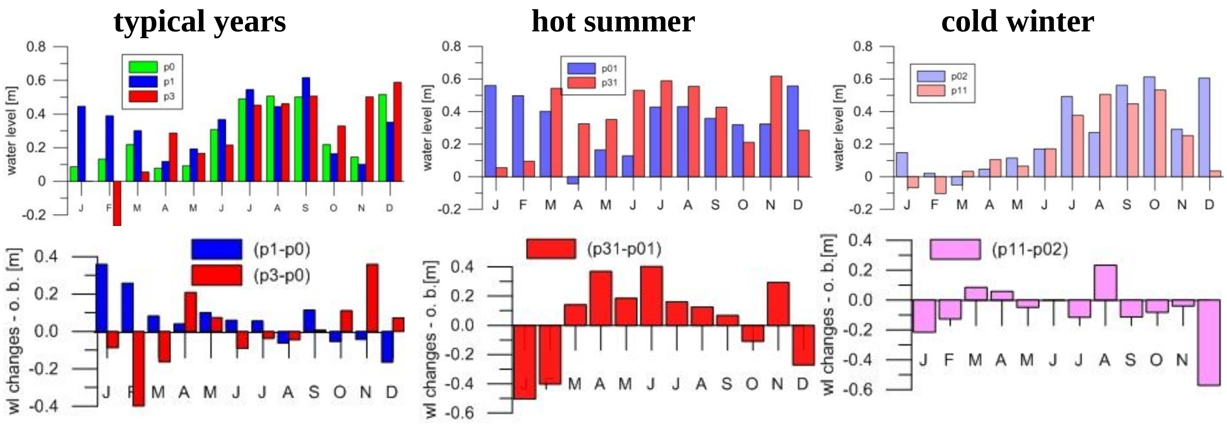


Figure 2.3. Monthly average water level changes at the open boundary (upper panels) and relative water level changes (lower panels) in division into scenario groups.

Monthly average salinity values at the connection between the lagoon and the Gulf of Gdańsk (Baltiysk Strait) show a decrease in all years in the future in comparison with the reference years of each group (typical and extreme; Fig. 2.4). The highest relative decrease (up to 40%) can be seen in typical years in the future, while in years with cold winters the relative decrease does not exceed 15%.

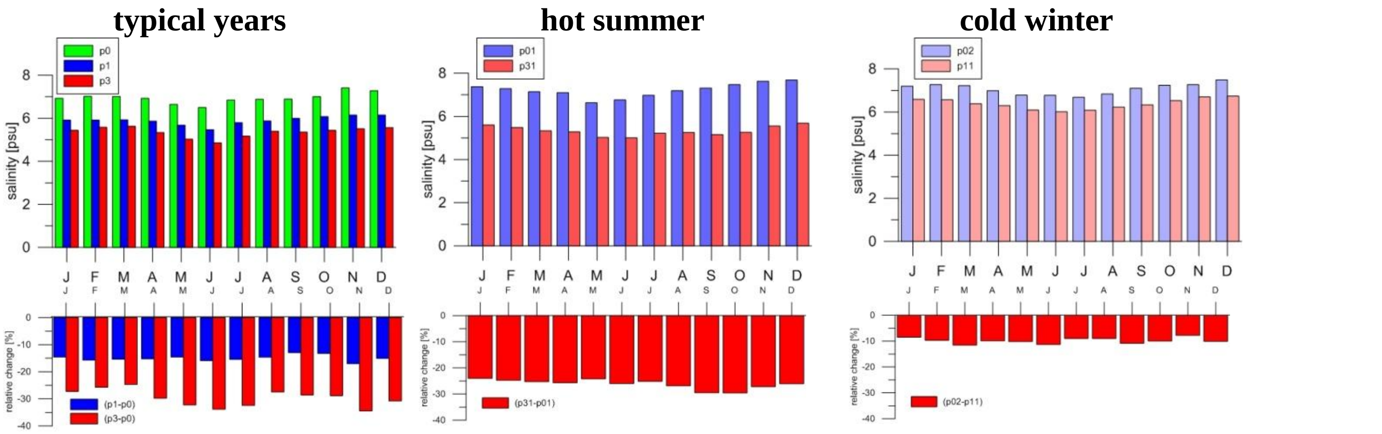


Figure 2.4. Monthly average salinity changes at the open boundary (upper panels) and relative salinity changes (lower panels) in scenario groups.

In typical years the average water temperature has a general tendency to increase in the whole year; the highest relative increase is observed in winter months, namely January, February and March (Fig. 2.5). In years with hot summer, water temperature mostly increases in winter time; in winter time temperature in the reference period is higher than in typical years. The same tendency is observed in the summer time. In years with cold winter, water temperature is lower than in the previously discussed periods. In winter months, water temperature is expected to decrease (up to 50%), however in absolute values those differences reach approx. 1^{o}C. Years with cold winter are characterized by colder summers.

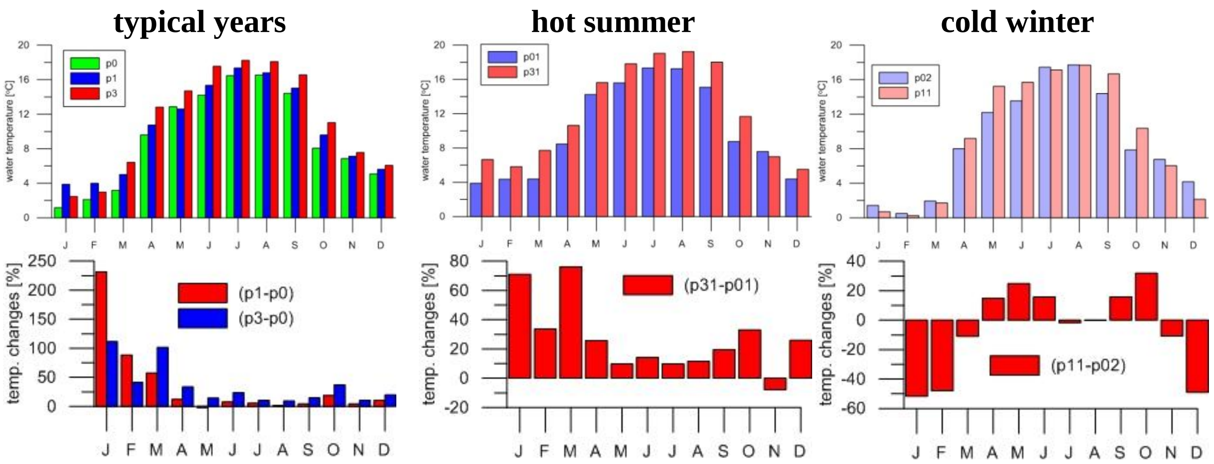


Figure 2.5. Monthly average water temperature (upper panels) and relative temperature change (lower panels) in groups, in division into months.

In typical years in the future, mean annual discharge for most rivers will either increase or be very similar; some bigger relative decrease (up to 10%) can be expected for Mamonovka and Nelma in the far future (p3). In years with hot summers the average annual discharge is expected to increase in the future (up to 50% for Bauda and Elbląg), while in years with cold winter the discharge decrease (up to 20%) is expected for all but Nelma River (Fig. 2.6).

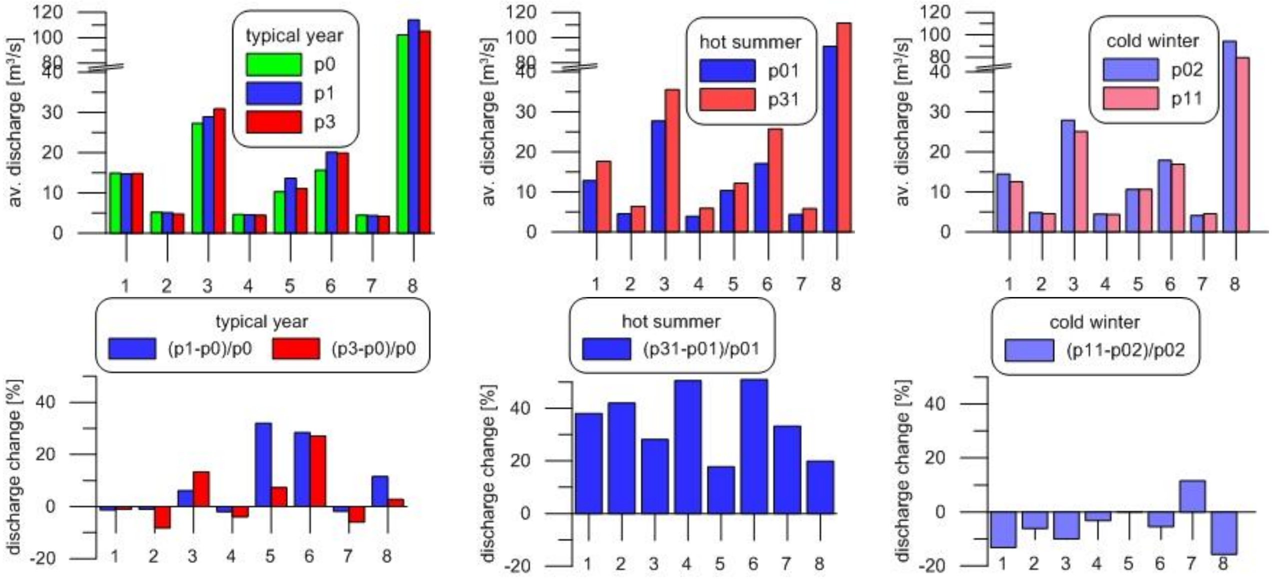


Figure 2.6. Mean yearly average discharge for the main rivers in the Vistula Lagoon drainage basin in chosen groups of years (1-Prokhladnaya, 2-Mamonovka, 3-Pasleka, 4-Bauda, 5-Nogat, 6-Elbląg, 7-Nelma, 8-Pregola)

Amount of water discharged into the lagoon has an influence on its ecological status. However, knowledge of the annual average value may not be sufficient to explain processes occurring in the lagoon. A closer analysis of discharge variation in the scale of months (Fig. 2.7) shows big differences between months. It is very characteristic that in typical years the biggest variations are observed in the period November - April; during the remaining part of year the range of variations is usually much lower. Those variations are probably associated with snow melting. When we compare years with cold winters, small range of discharge variation is observed in the whole year but April. This is the specific month when, after a longer period of reduced discharge due to ice cover, we can observe rather dynamic outflow of water from the drainage basin. In extreme cases, as seen in p11 scenario, such a huge discharge can 'flush out' the lagoon.

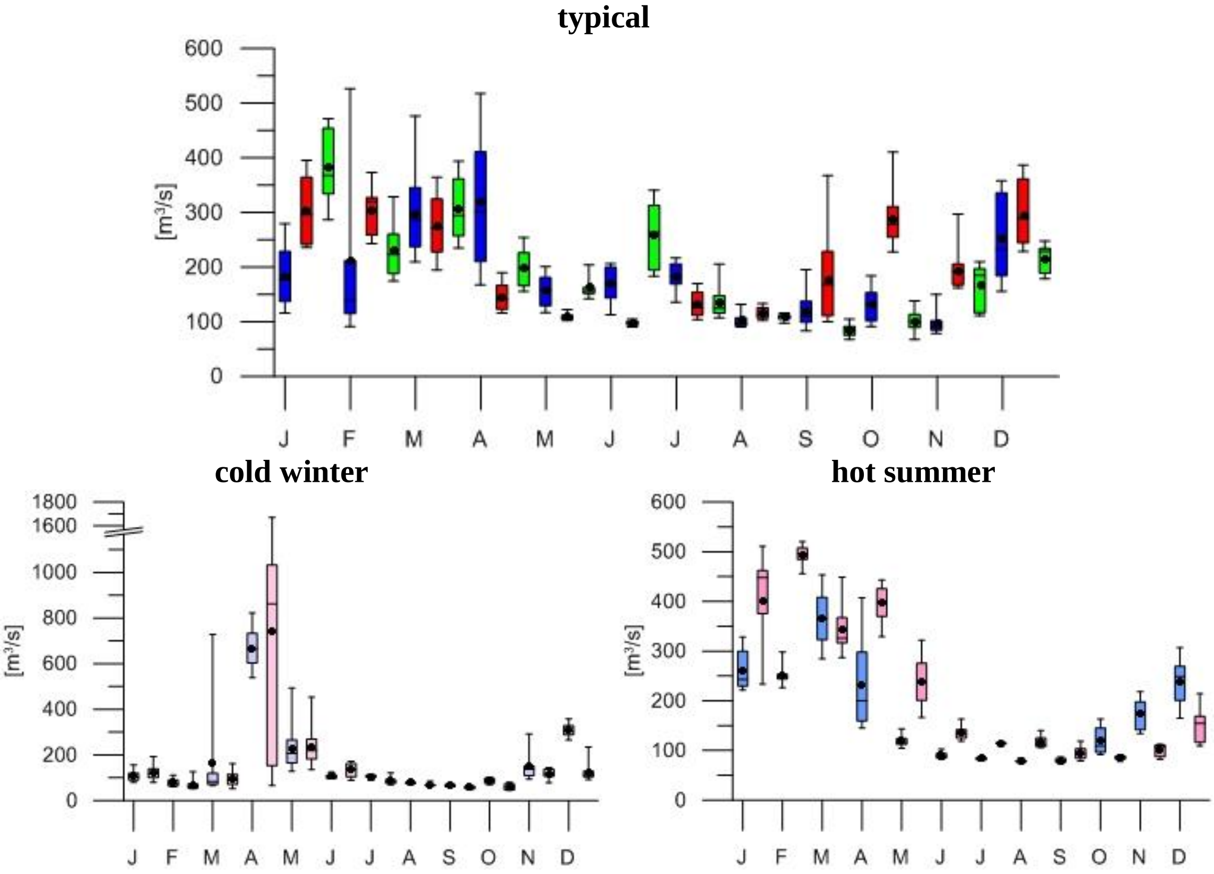


Figure 2.7. Variation of discharge from all rivers in division into months, in all scenario groups.

typical years **hot summer** **cold winter**

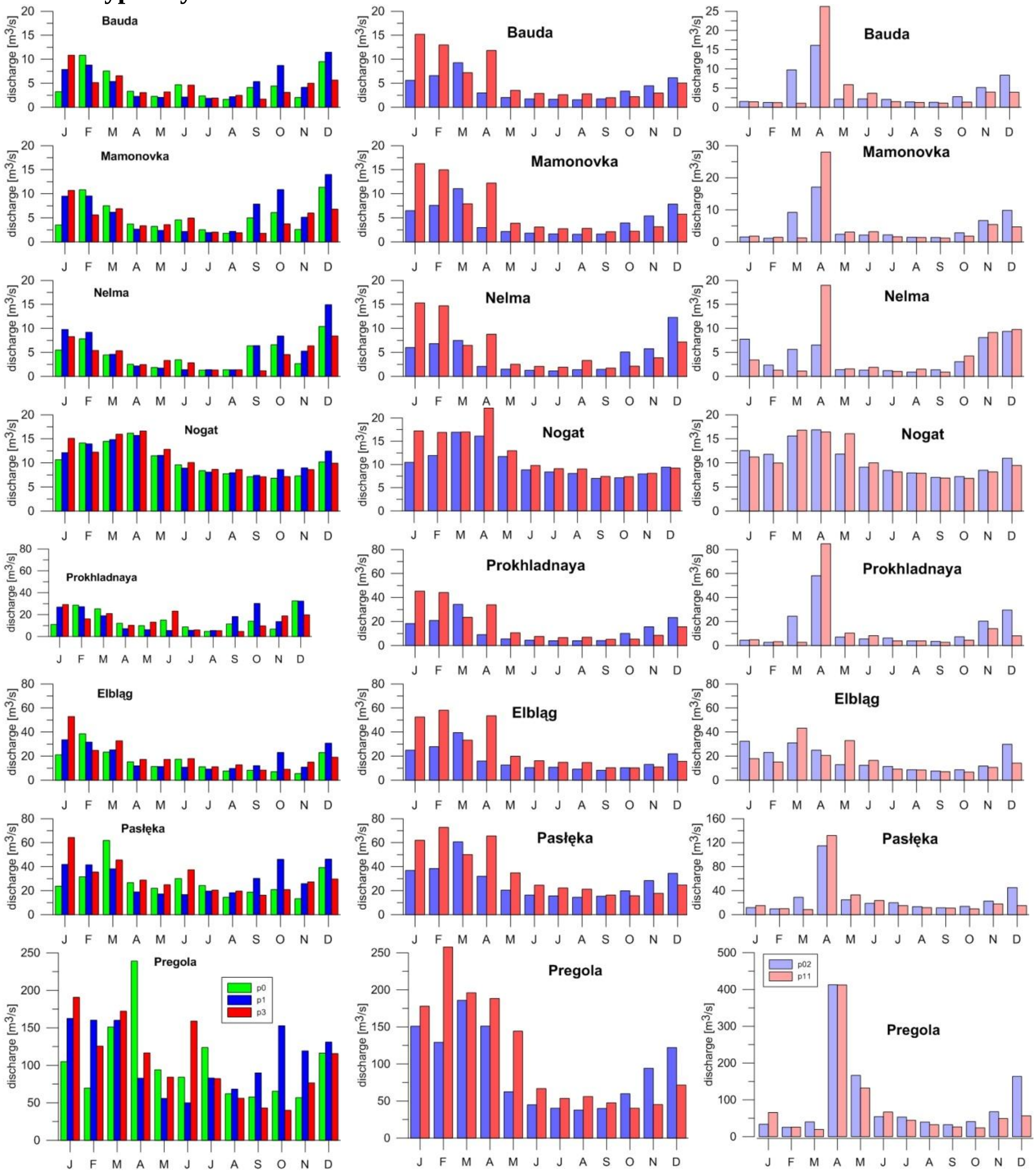


Figure 2.8. Monthly average discharge values for the main rivers in the Vistula Lagoon drainage basin in chosen groups of years: left – typical year p0, p1, p3; middle – years with hot summer p01, p31; right – years with cold winter p02, p11.

2.2 Loads from the catchment

As mentioned in Chapter 2.1, climatic conditions play a decisive role in riverine water inflows into the Vistula Lagoon from its catchment. Thus, climatic conditions shape hydrological conditions, which in turn have a great impact on nutrient leaching from soil profile (diffuse outflow). Hydrological conditions shape and modify nutrient loads reaching the Vistula Lagoon.

“Typical years”

In the case of scenarios for so called “typical years”, the annual pattern of nutrient load discharges into the Vistula Lagoon shows elevated loads in the period between October and April, and significantly reduced loads of N-NH_4, N-NO_3 and P-PO_4 between May and September. Such an annual nutrient load pattern overlaps annual variability in riverine water outflow (Figs. 2.9, 2.10 and 2.11, see Chapter 2.1).

The Pregola River (Russian part of the Lagoon) and the Pasleka River (Polish part of the Lagoon) are the greatest sources of nitrogen and phosphorus in the region studied. Comparison of scenarios for “typical years” (p0, p1, and p3) shows that largest N-NH_4 and N-NO_3 loads reach the Lagoon in scenario p0, whereas in scenarios p1 and p3 they show a declining tendency in the years ascribed to particular scenarios (see to Chapter 1.1; Fig. 2.12). As to phosphorus and its loads in the form of P-PO_4, the largest annual loads were observed in scenario p1, whereas smallest in scenario p3 (Fig. 2.12). As the Pregola River is characterized the by highest water outflows in the region studied, this river is the largest contributor to overall N and P loads discharged into the Vistula Lagoon (for details see Chapter 2.1).

“Hot summers”

In “hot summers scenarios” (p01 and p31), the main part of monthly loads of N-NH4 reach the Lagoon over the period January-May (Fig. 2.9). In the case of N-NO_3, the monthly dynamics of loads discharged into the Vistula Lagoon is very similar to that defined for “typical years”. Over the period June-September N-NO_3 the loads are lower as compared to values observed in the remaining part of the year. On top of this observation, the loads of N-NO_3 are higher in scenario p31 than in scenario p01 in the first half of the year, and the situation is just opposite in the second half of the year (Fig. 2.10). Although the annual pattern of P-PO_4 loads shows a declining tendency over the entire calendar year, P-PO_4 loads in scenario p31 are higher than in scenario p01 (Fig. 2.11, Fig. 2.12). In “hot summer’s scenarios”, the annual loads of N-NH_4 and N-NO_3 remain on a comparable level in all rivers but Pregola. In Pregola River, a slight decline in annual loads of N-NH_4 and N-NO_3 are observed between scenarios p01 and p31 (Fig. 2.12).

“Cold winters”

The annual dynamics of variability in N-NH_4, N-NO_3 and P-PO_4 loads in scenarios defined as “cold winters” differs from the annual dynamic of relevant parameters in two other scenario groups (“typical years” and “hot summers”). In “cold winters scenarios”, the inflows of N-NH_4, N-NO_3 and P-PO_4 to the Lagoon are distinctly limited at the beginning of the year (January-March), and such a situation is observed nearly in all rivers subjected to studies in our model. The exception are the Elbląg and Nogat Rivers, whose nutrient discharges remain on the level similar to those observed in “typical years” and “hot summer scenarios”. Most probably, such a situation is generated by a direct impact of municipal nutrient loads from the city of Elbląg; this point source pollution adds to diffuse nutrient outflows by these rivers (Figs. 2.9, 2.10 and 2.11). Over the period May-December, the variability in loads of nitrogen and phosphorus (N-NH_4, N-NO_3 and P-PO_4) is similar to that found in scenarios “typical years” and “hot summers” (Figs. 2.9, 2.10 and 2.11).

“typical years” “hot summer” “cold winter”

Figure 2.9. Monthly loads of N-NH_4 [tonnes month^{-1}] from the main rivers to the Vistula Lagoon in chosen groups of years: left – “typical years” (p0, p1, p3); middle - years with “hot summer” (p01, p31); right - years with “cold winter” (p02, p11).

Figure 2.10. Monthly loads of N-NO_3 [tonnes month^{-1}] from the main rivers to the Vistula Lagoon in chosen groups of years: left – "typical years" (p0, p1, p3); middle - years with "hot summer" (p01, p31); right - years with "cold winter" (p02, p11).

“typical years” “hot summer” “cold winter”

Figure 2.11. Monthly loads of P-PO_4 [tonnes $month^{-1}$] from the main rivers to the Vistula Lagoon in chosen groups of years: left – “typical years” (p0, p1, p3); middle - years with “hot summer” (p01, p31); right - years with “cold winter” (p02, p11).

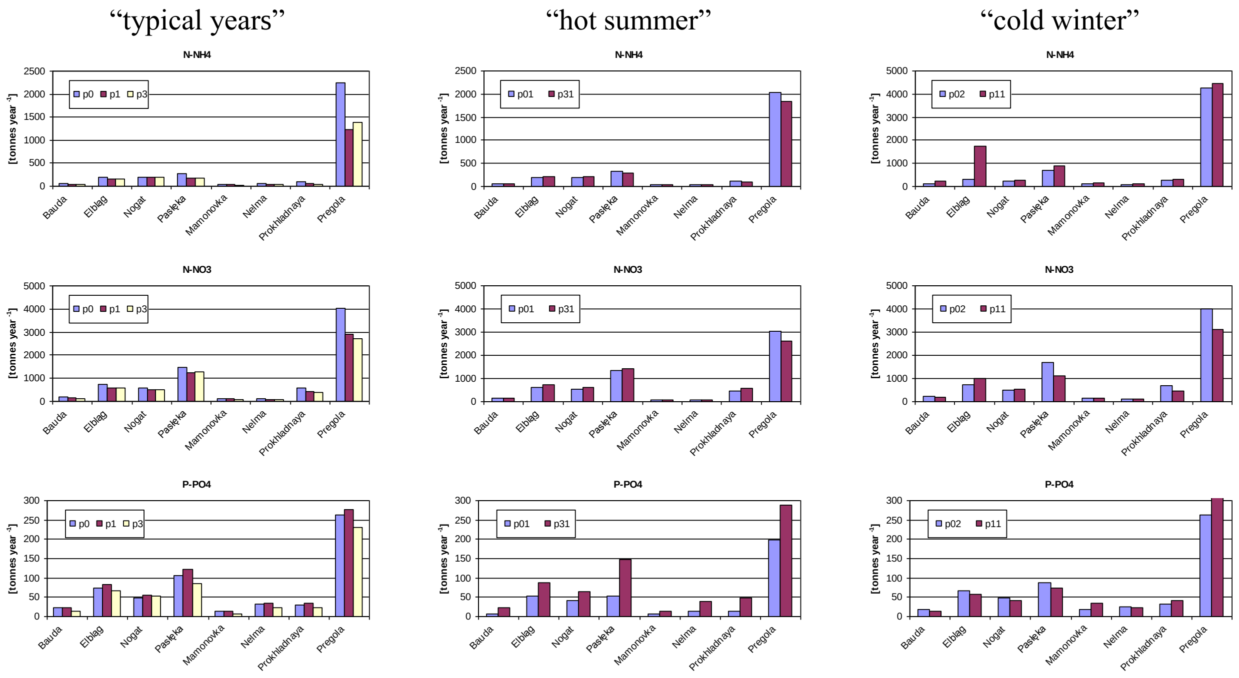


Figure 2.12. Yearly loads of N-NH_4, N-NO_3 and P-PO_4 [tonnes year^{-1}] from the main rivers to the Vistula Lagoon in chosen groups of years: left – "typical years" (p0, p1, p3); middle - years with "hot summer" (p01, p31); right - years with "cold winter" (p02, p11).

Extremely high loads of nitrogen and phosphorus in April (with some small fluctuations in the case in of the Elbląg River) are a characteristic feature in scenarios „cold winters" (Fig. 2.12; see Chapter 2.1). Comparison of annual loads of N-NH_4, N-NO_3 and P-PO_4 in all the scenarios shows that there is a two-fold increase in annual loads of N-NH_4 in the scenario defined as "cold winters", whereas loads N-NO_3 and P-PO_4 remain on comparable levels in all the climatic scenarios studied (Fig.2.12).

2.3 Lagoon's response and discussion

As a consequence of time varying hydro-meteorological conditions, hydrodynamic conditions change in space and time. From the point of view of potential ecological changes, salinity and temperature are the most important parameters. In this study, water temperature was assumed to be uniform in space, but varying in time (see Fig. 2.5, Chapter 2.1).
Here, the variability of salinity patterns in space and time is discussed based on four chosen locations RU1, RU2, PL1, PL2, see Fig. 2.13 (in Deliverables 6.1 and 6.2 the following nomenclature was applied: RU1 - v2/AN2; RU2 – v7/AN6; PL1- p2/MIR5; PL2 – p8/MIR12).

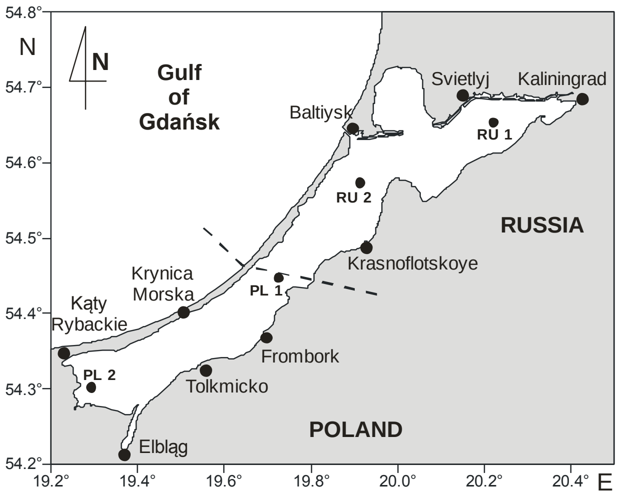


Figure 2.1.3 Location of characteristic points used for the analysis.

In typical years (Fig. 2.14, 2.15) the salinity in the lagoon will have a general tendency to decrease in the future due to the salinity decrease in the area of open boundary (source of salt water for lagoon), despite the fact of temporal increase of discharge for some rivers. Based on 4 locations representing the characteristic features of lagoon, we can notice that the range of salinity variation in a historical year is bigger than that expected in the near- and far-future for all analysed characteristic points. This is true on the scale of months as well as on the scale of years.

Monthly salinity variations in years with cold winter (Fig. 2.16) depict quite a different pattern compared to typical years. In those years we can expect a rather dramatic salinity change during spring time, especially in the region located close to Pregola River (location RU1). This picture is well correlated with river discharges (Fig. 2.6, 2.8). This phenomenon is not well seen in yearly average values (Fig. 2.17). Yearly salinity averages in years with cold winter are expected to decrease in the future, similarly as in typical years.
In years with hot summer (Figs. 2.18, 2.19) it is expected that salinity will decrease on the scale of a year, however this decrease should be rather associated with the salinity decrease in the area of the open boundary, not due to a discharge. Only small differences in river discharge in the summer months are expected in the future.

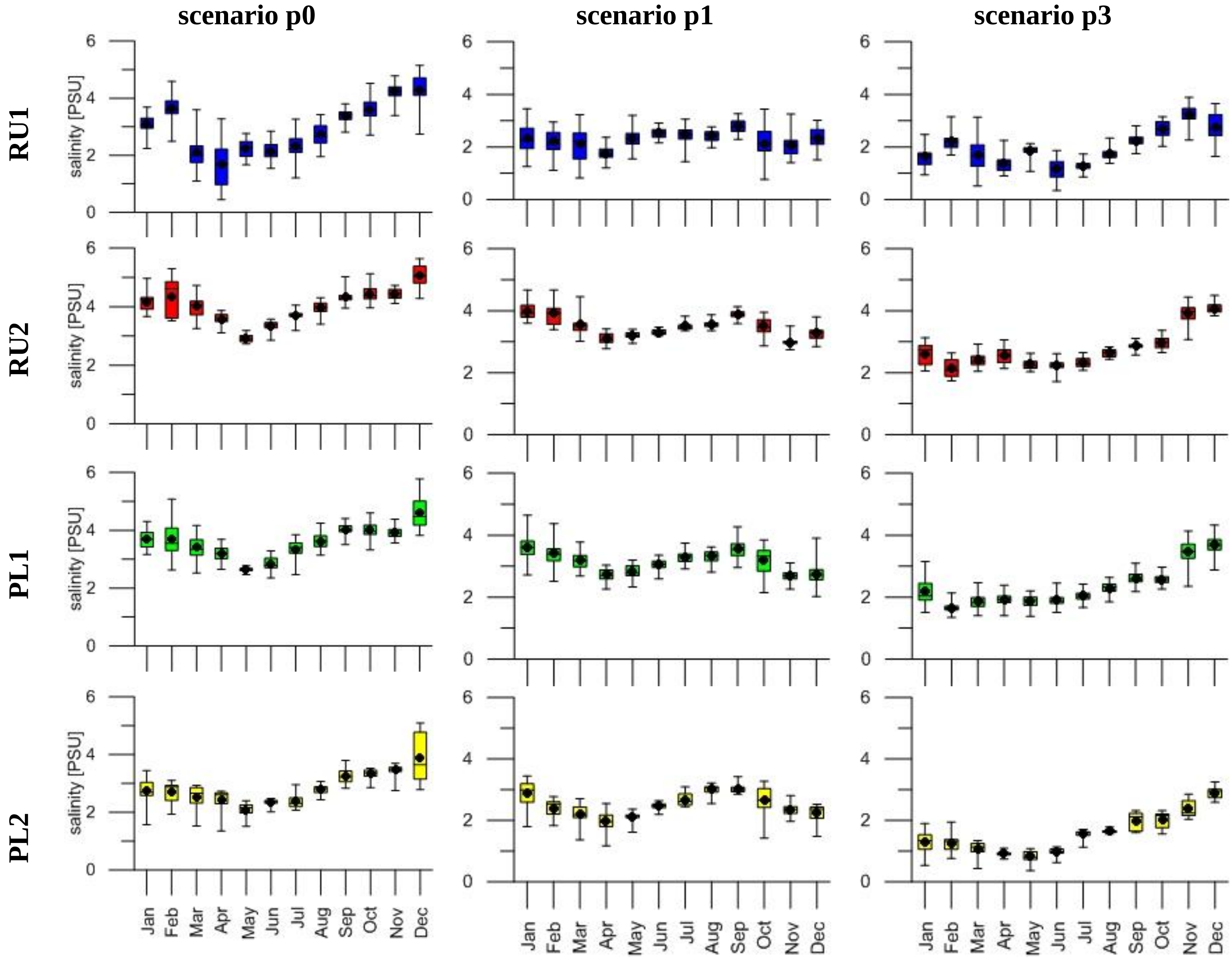


Figure 2.14. Monthly average salinity variation in chosen locations in typical years in past (p0), in the near-future (p1), and in the far-future (p3).

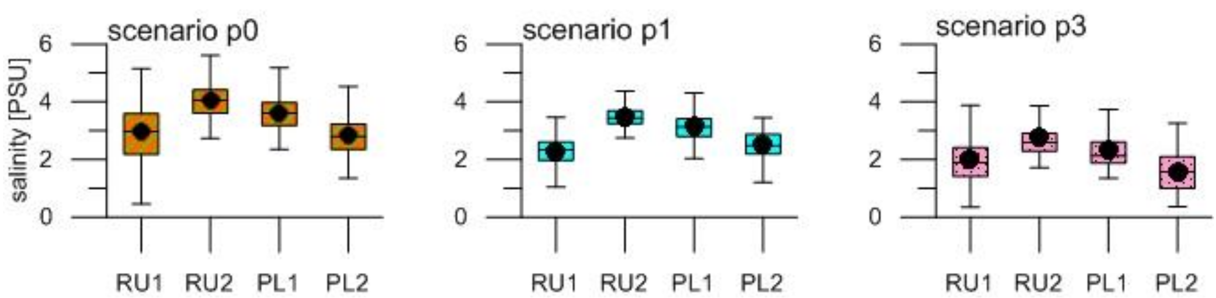


Figure 2.15. Yearly average salinity variation in chosen locations (RU1, RU2, PL1, PL2 in typical years p0, p1, p3.

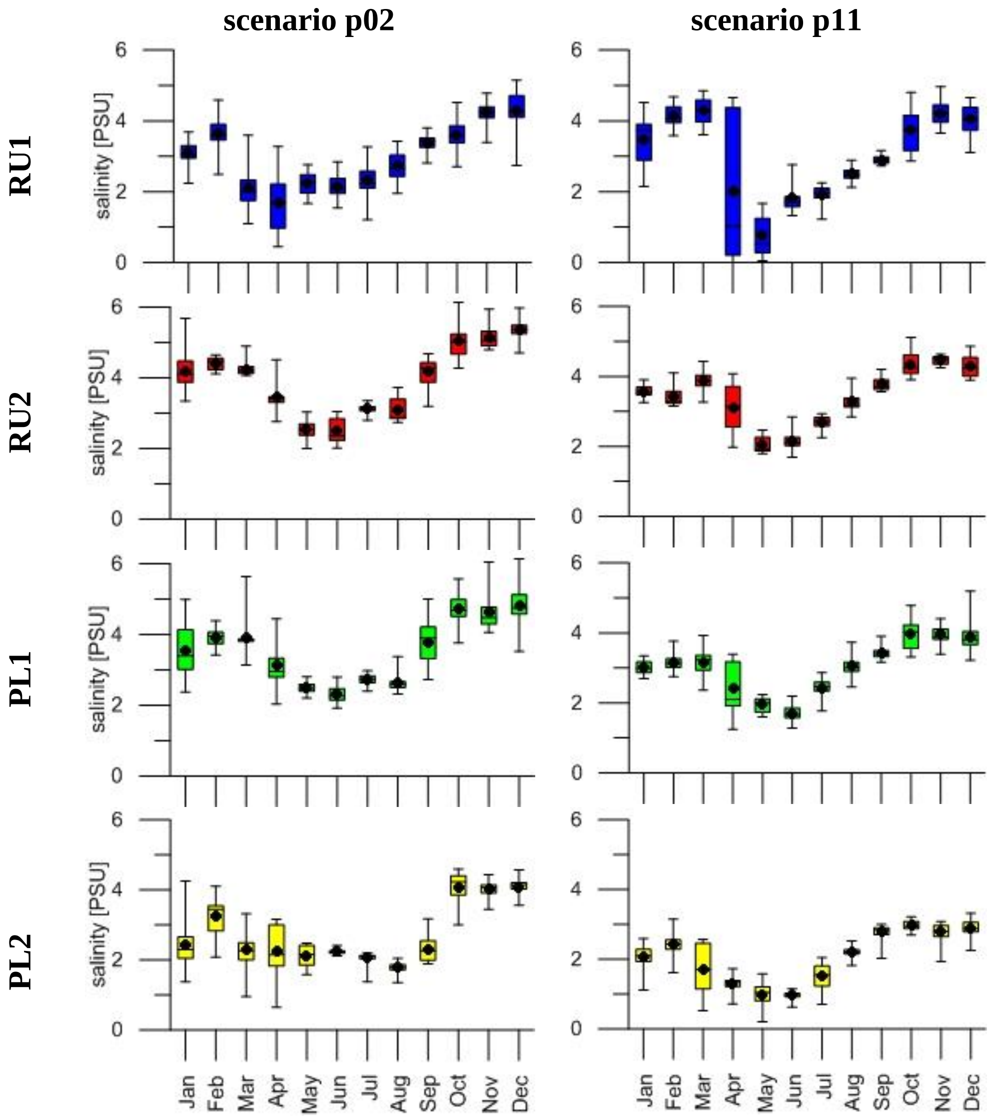


Figure 2.16. Monthly average salinity variation in chosen locations - years with cold winter.

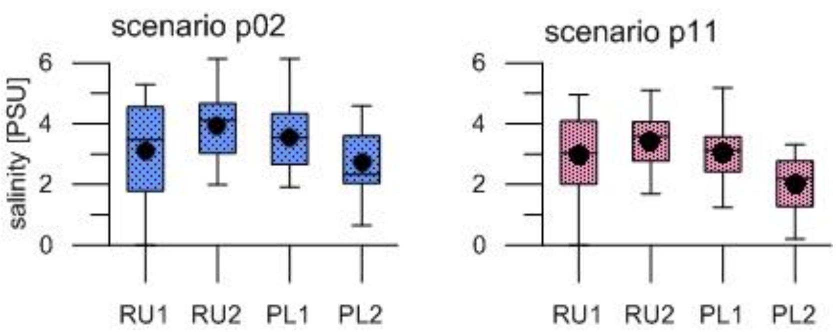


Figure 2.17. Yearly average salinity variation in chosen locations - years with cold winter.

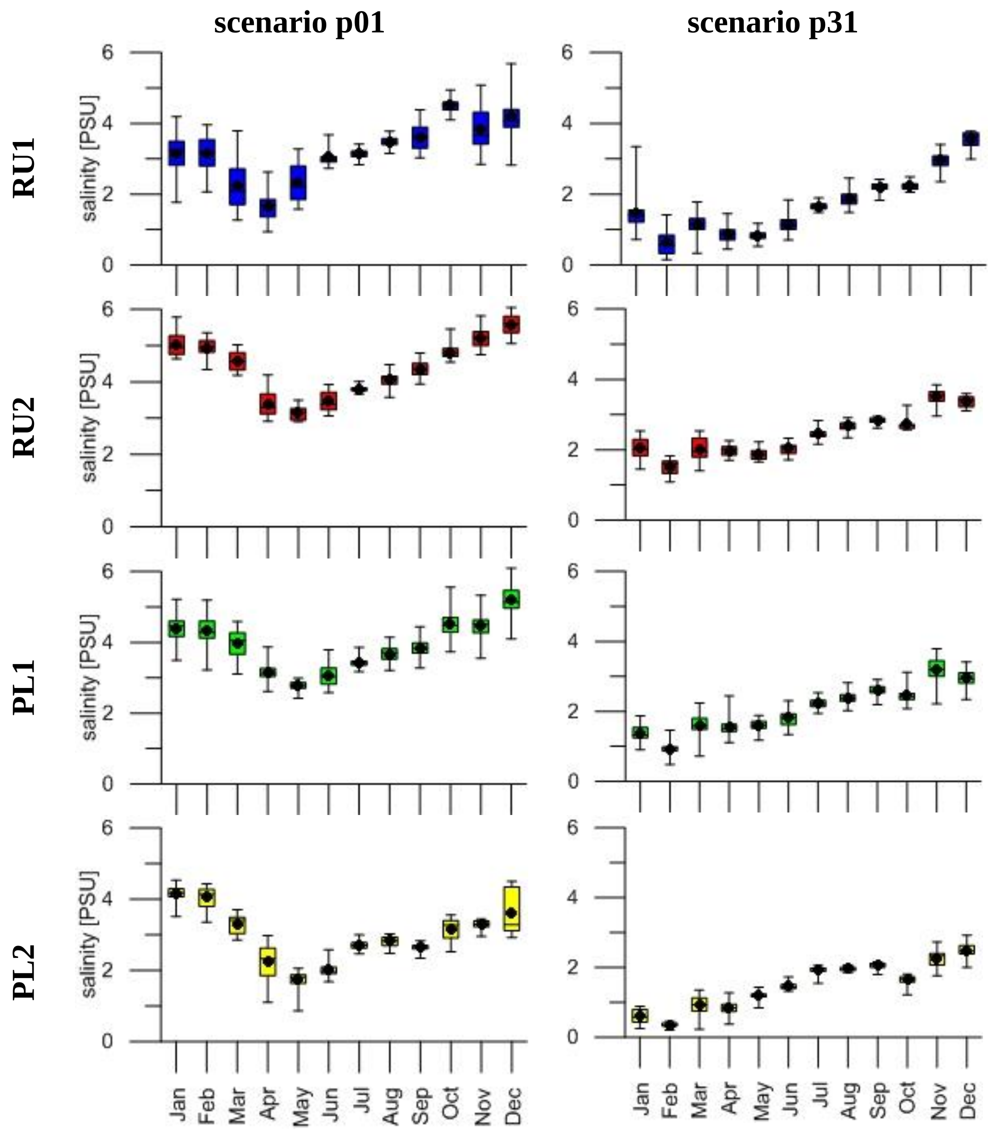


Figure 2.18. Monthly average salinity variation in chosen locations - years with hot summer.

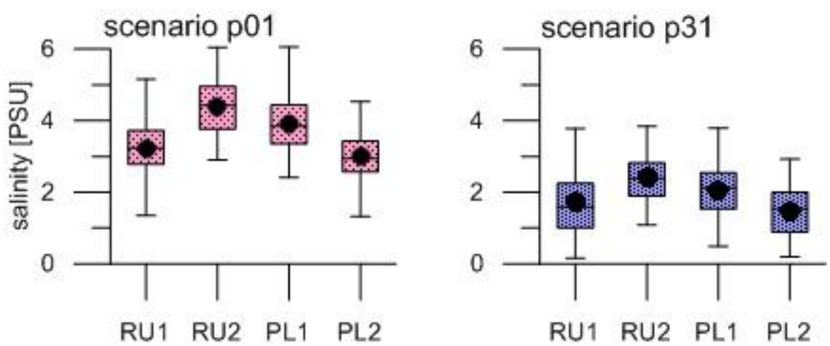


Figure 2.19. Yearly average salinity variation in chosen locations - years with hot summer.

Similarly to the analysis of hydrodynamic parameters in the Vistula Lagoon, the analysis of parameters responsible for water quality is based on the data from 4 observation points

(Fig. 2.13). The water quality analysis encompasses the following parameters: content of chlorophyll-a (Chl-a), concentrations of nitrates ($N-NO_3$), ammonium ($N-NH_4$), and phosphates ($P-PO_4$). Scenarios describing an impact of climate change were divided into three groups, i.e. "typical years" (scenarios p0, p1, p3), years characterized by "hot summers" (p01 and p03), and years characterized by "cold winters" (scenarios p02 and p11).

„Typical years"

Scenarios elaborated for "typical years" (p0, p1, p3) show that nitrates and ammonium concentrations will decrease (taking into account medians and the average values as indicators), whereas phosphate concentrations will increase over the entire area of the Vistula Lagoon (Figs. 2.20, 2.21, 2.22 and 2.23).

The most pronounced increase in phytoplankton biomass (expressed as concentration of chlorophyll-a) is expected at station PL2. Less visible changes in phytoplankton biomass are expected in the remaining parts of the Lagoon (Figs. 2.20 and 2.24). Phytoplankton development depends on environmental conditions in a given region. Although temperature may have a stimulating impact on chlorophyll-a concentrations (phytoplankton) in the case Vistula Lagoon (see to Chapter 2.1), the appearing liming role of nitrogen in phytoplankton development cannot be neglected in analysis of our results. The expected decline in concentration of mineral forms of nitrogen ($N-NH_4$ and $N-NO_3$) leads to imbalanced utilization of phosphorus in the ecosystem, which in turn results in P accumulation in water column expressed as an increase in P concentrations (Figs. 2.20, 2.21, 2.22, 2.23 and 2.24).

The Vistula Lagoon is not uniform with respect to water quality parameters. The "typical years scenarios" show a decrease in daily concentrations of all nutrients studied, as well as in chlorophyll-a content in the central part of the region (stations RU2 and PL1), and an increase in values of these parameters at stations RU1 and PL2, located at the edges of the Lagoon (Figs. 2.20, 2.21, 2.22, 2.23 and 2.24). Comparison of the results obtained in all the scenarios for "typical years" shows that daily concentrations of nutrients remain on a comparable level, and this means that nutrient loads reaching the Lagoon are also comparable (Figs. 2.21, 2.22, 2.23 and 2.24).

"Hot summers"

Scenarios representing extremely "hot summer" seasons (p01, p31) indicate an increase in riverine water inflows to the Vistula Lagoon, followed by a decline in salinity, and an increase in water temperature in this region (see Chapter 2.1). Simulations taking into account "hot summers" point to maintenance of declining tendencies in ammonium and nitrate concentrations, and to increasing trends in the case of phosphate and chlorophyll-a concentrations. It seems that an increase in water column temperature is a driving force in the system and becomes a main factor affecting nutrients and chlorophyll-a (Figs. 2.20, 2.21, 2.22, 2.23 and 2.24). Generally, the predicted changes expected in the Vistula Lagoon ecosystem are very similar to the results obtained for the "typical years" scenarios.

"Cold winters"

In scenarios representing extremely "cold winter" seasons (p02, p11), riverine water inflows to the Vistula Lagoon will diminish, whereas water temperature will increase. However, the increase in water temperature will not be as high as in the case of scenarios for "typical years" (see to Chapter 2.3). Concentrations of ammonium, nitrates, and phosphates, as well as content of chlorophyll-a (the latter two parameters presented only for scenario p11) in "cold winter" scenarios will strongly deviate from values obtained for "typical years" scenarios. The deviations are particularly visible in the case of daily values of parameters modelled; they are less pronounced in the case of medians and average values of subjected parameters (Figs. 2.20, 2.21, 2.22, 2.23 and 2.24).

Riverine water inflows in “cold winter” scenarios p02 and p11 require comments that are more detailed. The assumed annual volumes, as well as the seasonal water discharge dynamics, are substantially different in these scenarios. Both scenarios generate reduced riverine water discharge into the Vistula Lagoon at the beginning of the year, namely from January to March. Scenario p11 assumes extremely high water flows in rivers in April, exceeding the average values even by 10 times. Such an assumption resulted in flushing of the Vistula Lagoon and, in practice, replacing the lagoon water with the riverine water. Nitrogen and phosphorus loads, which had been discharged into the Lagoon were in this scenario washed out from the ecosystem due to extreme riverine water inflow in April (see Chapter 2.2 and 2.3; Figs. 2.21, 2.22 and 2.23). There was also flushing of phytoplankton/chlorophyll-a, as it was assumed that riverine waters contain 10 times lower concentrations of chlorophyll-a (phytoplankton). Load of nitrogen ($N\text{-}NH_4$ and $N\text{-}NO_3$) that remained in water column was not sufficient to restore phytoplankton biomass (chlorophyll-a). Under the circumstances, nitrogen becomes a limiting factor in phytoplankton development, and that fact creates conditions for diminished phosphorus uptake, leading to its accumulation in the water column. Situation returns to typical in September-October, when loads of $N\text{-}NH_4$ and $N\text{-}NO_3$ become higher. Still, high P concentrations and increasing N concentrations create good conditions for phytoplankton growth (see Chapter 2.3; Figs. 2.21, 2.22, 2.23 and 2.24).

Summing up all the results obtained in the climatic group of scenarios for the Vistula Lagoon, it can be stated that there is predicted an increase in content of chlorophyll-a (increase in phytoplankton biomass) and an increase in phosphate concentrations at parallel decline in ammonium and nitrate concentrations. It is expected that nitrogen will become a factor limiting for phytoplankton growth in the entire vegetative period. At present, phosphorus is a limiting factor in phytoplankton growth in spring, whereas nitrogen plays a limiting role in the remaining part of the vegetative season (Witek et al., 2010). A switch of the Vistula Lagoon ecosystem into a liming state for phytoplankton growth by nitrogen may initiate an increase in intensity of blue-green algae, because some pool of phosphorus will be available in the ecosystem and blue-green algae are able to take up N from the atmosphere.

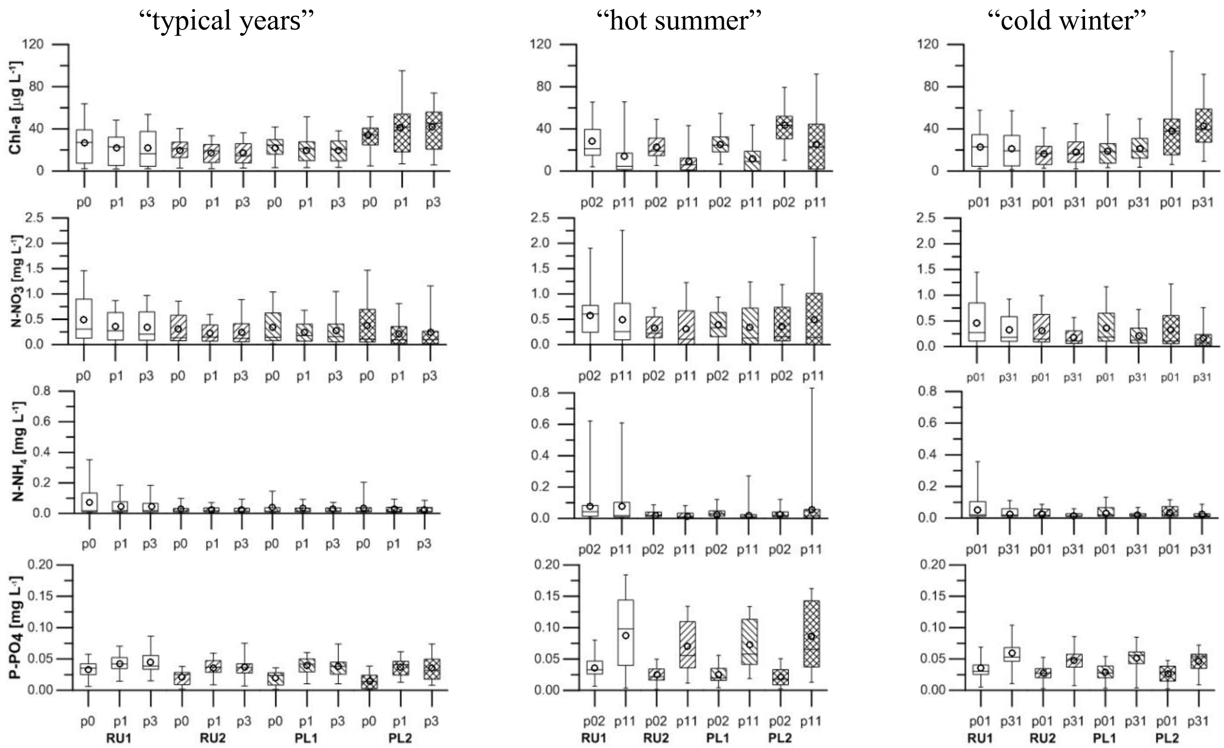


Figure 2.20. Results of water quality modelling in the Vistula Lagoon for three climatic scenarios. The presented data encompass 4 observation points: RU1, RU2, PL1 and PL2. The following parameters are shown in graphs: min/max values, percentile 25/75, median (horizontal line), and average value (circle) of parameters simulated in the following scenarios: "typical years" (p0, p1, p3), years with "cold winters" (p02, p11), years with "hot summers" (p01, p31).

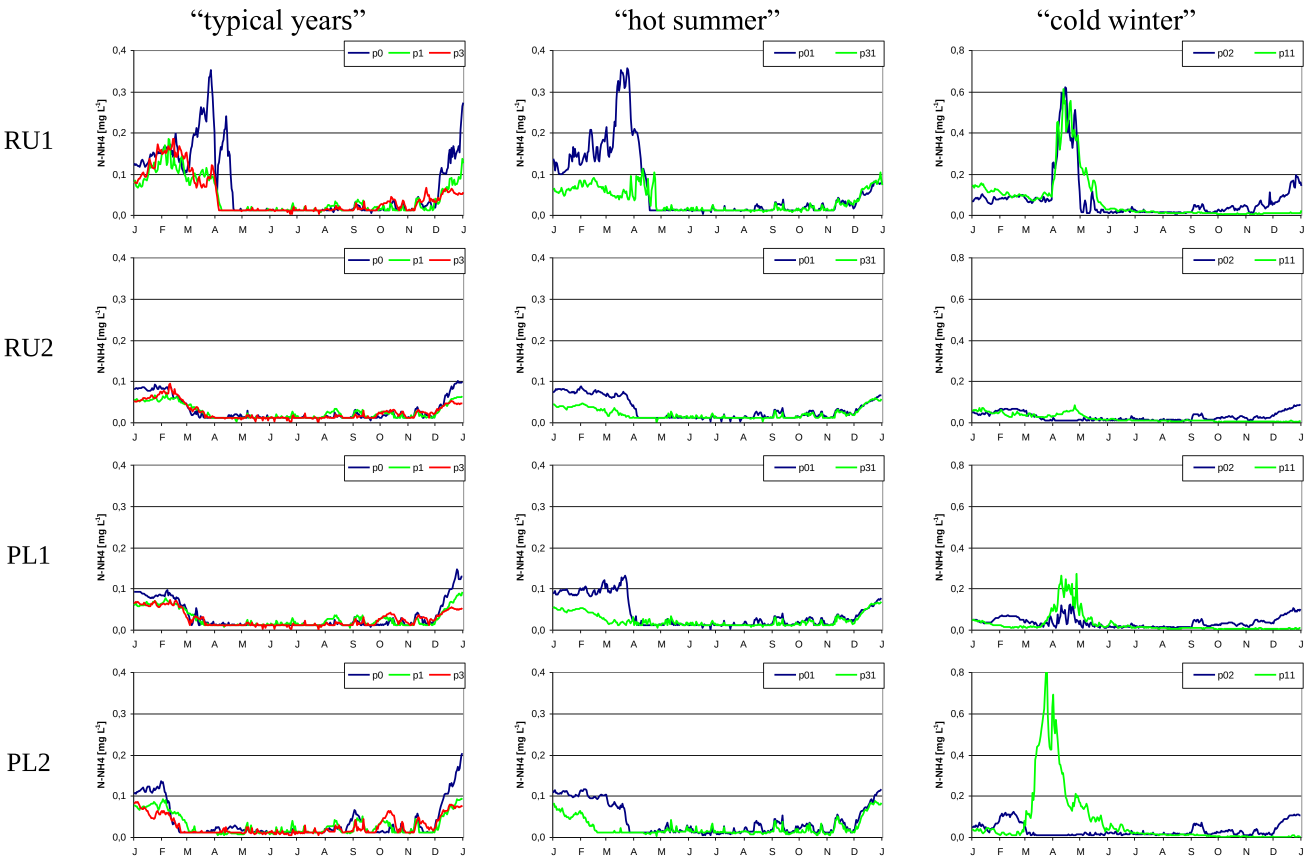


Figure 2.21. Daily variations of N-NH$_4$ [mg L^{-1}] in locations RU1, RU2, PL1 and PL2 in model calculations carried out for "typical years" (p0, p1, p3), "hot summer" (p01, p31) and "cold winter" scenarios (p02, p11).

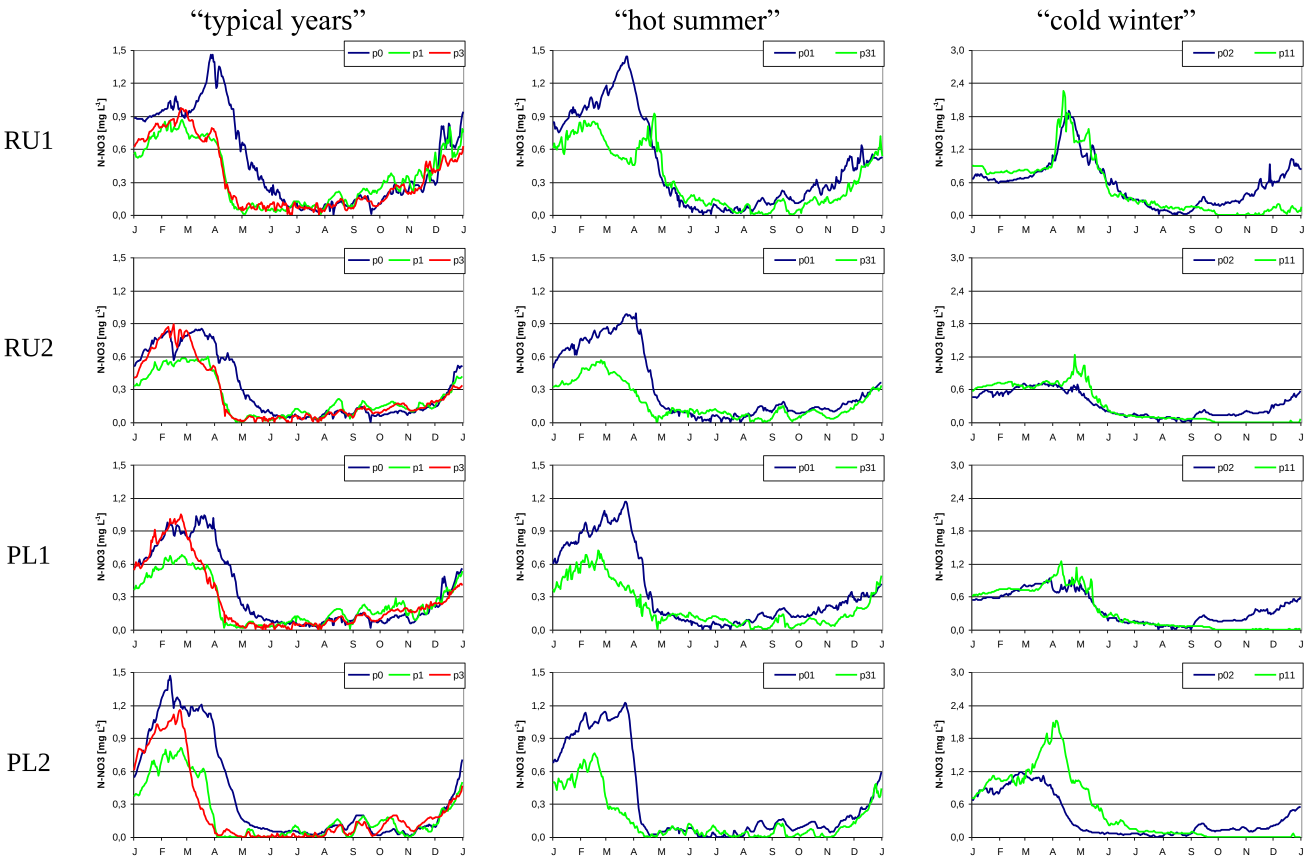


Figure 2.22. Daily variations of N-NO_3 [mg L^{-1}] in locations RU1, RU2, PL1 and PL2 in model calculations carried out for "typical years" (p0, p1, p3), "hot summer" (p01, p31) and "cold winter" scenarios (p02, p11).

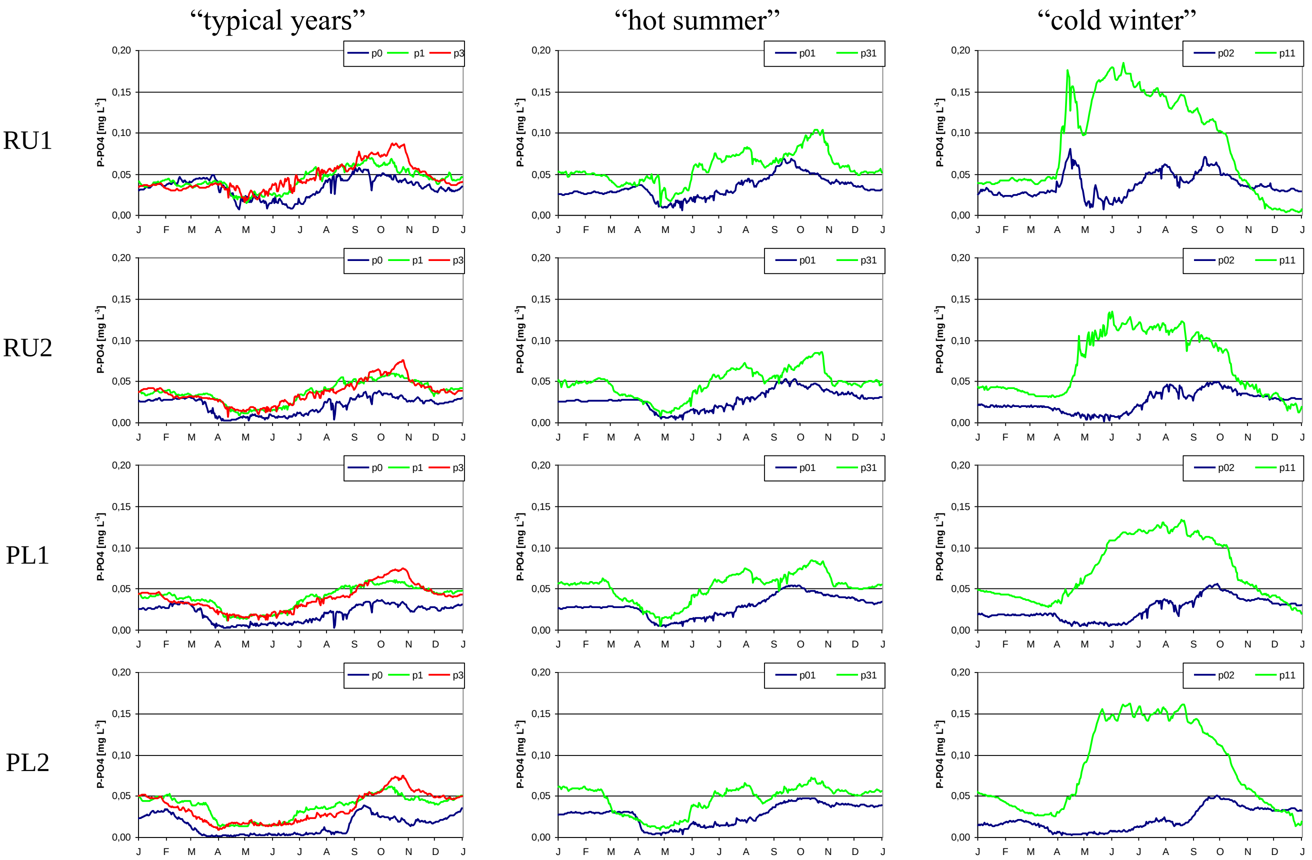


Figure 2.23. Daily variations of P-PO_4 [mg L^{-1}] in locations RU1, RU2, PL1 and PL2 in model calculations carried out for "typical years" (p0, p1, p3), "hot summer" (p01, p31) and "cold winter" scenarios (p02, p11).

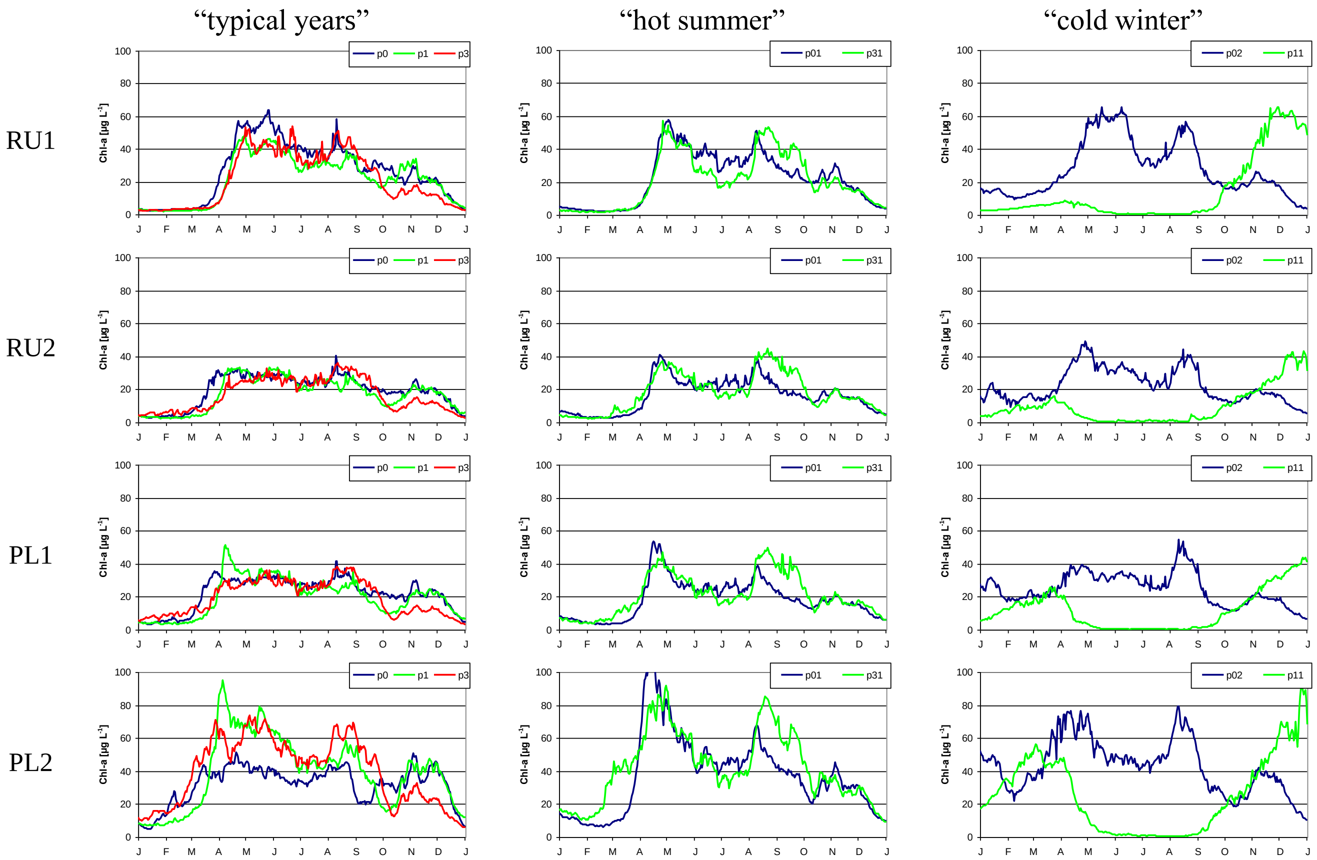


Figure 2.24. Daily variations of chlorophyll-a [µg L^{-1}] in locations RU1, RU2, PL1 and PL2 in model calculations carried out for "typical years" (p0, p1, p3), "hot summer" (p01, p31) and "cold winter" scenarios (p02, p11).

The results obtained in climatic scenarios can be referred to the Order of the Minister of Environment (*), and waters of the Vistula Lagoon can be classified as follows (Table 2.3):

- Based on forecasted chlorophyll-a concentrations, there is no expected change in water quality class or in ecological state (water quality class III, ecological state –moderate);
- Based on forecasted N-NO_3 concentrations, there is expected improvement with respect to water quality class and a change from moderate to good ecological state;
- Based on forecasted N-NH_4 concentrations, water quality remains unchanged (water quality class I, ecological state – very good);
- Based on forecasted phosphate concentrations, there is expected change from water quality class I to class II.

The presented classification of water quality and ecological state are based on average values calculated for the observation points RU1, RU2, PL1 and for PL2 for the "typical years" scenarios.

Tab. 2.3. Average values of chlorophyll-a concentrations and nutrients ($N\text{-}NO_3$, $N\text{-}NH_4$ and $P\text{-}PO_4$) with reference to Polish administrative law (average values for typical scenarios and water quality classifications)

Parameter/scenario	**p0**	**p1**	**p3**	**Remarks**
Chlorophyll-a [µg/l]	24.98	24.56	24.53	Water class III (23.2-31.3); ecological status – moderate
Nitrates $N\text{-}NO_3$ [mg/l]	0.38	0.26	0.28	Water class III (>0.3) and II (0.2-0.3); ecological status – moderate than good
Ammonium $N\text{-}NH_4$ [mg/l]	0.04	0.03	0.03	Water class I (<0.1); ecological status – very good
Phosphate $P\text{-}PO_4$ [mg/l] *)	0.022	0.039	0.039	Water class I (<0.03) and II (0.03-0.045) ecological status – very good than good

(*) Following Order of Minister of Environment of 09 Nov. 2011, Law Gazette Nr 257, Item 1545, it was assumed that given numbers on phosphates refer to pure phosphorus and not to phosphorus ion (PO_4^{-3}).

2.4 Impact of extreme climate events on VL hydrodynamics

Vistula Lagoon is a water body where water levels change continuously in time. During the majority of time uniform or nearly uniform water levels in the whole lagoon can be observed. This pattern is correlated with low and medium wind velocities. However, occasionally winds with extremely high velocities occur, leading to significant water level difference between north-eastern and south-western parts of the lagoon.
Such situations were observed in the past, and can be expected in the future. To assess possible changes in intensity of such phenomena, two extreme events, i.e. long-lasting events when wind velocity exceeded 10 m/s from NW-NNW direction are presented below. Those events can be defined as follows:

p03 - extreme event from the historical period (autumn 1992),
p12 – extreme event from the near-future (autumn 2024).

For comparison of water level changes in the two extreme scenarios (p03, p12), results from four locations (RU1, RU2, PL1, PL2, see Fig. 2.1) were chosen (Fig. 2.25). It can be seen that extreme water level differences are observed between locations RU1 and PL2 in both cases.

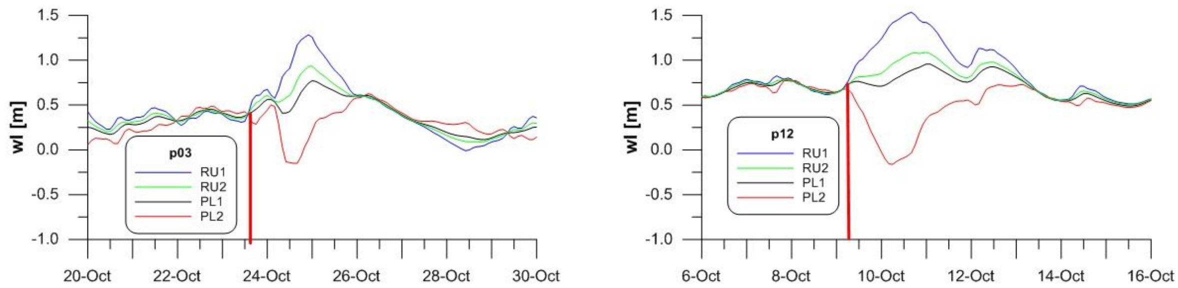


Figure 2.25. Comparison of water level extreme events: left – historical period; right - near-future period.

For the purpose of this analysis, as the starting point of the development of an extreme event is taken the moment when water levels in locations RU1 and PL2 are equal, and then they start to bifurcate (denoted by the red line – Fig. 2.25). The starting point in case of p12 event is very clear, whereas in case of p03 event the starting point is not so obvious.
To enable comparison of the two extreme situations, they are presented on the relative time scale, with the starting point located 3 days before the bifurcation point (Fig. 2.26).
A gradual increase of water level difference started at a moment when in both scenarios (p03, p12) the wind velocity reached ~9 m/s. In the preceding period the latter was permanently increasing. The maximum velocity of 17-19 m/s was reached after ~36 hours. A decrease of wind velocity has a similar dynamics, however due to higher maximum value in case of p12 scenario, this process was longer. In the same time wind was directed from NNW – NW/N.
More intensive and longer-lasting wind conditions expected in the future resulted in a more extreme phenomenon. As shown, the maximum water level difference for the historical event reached 1.44 m; whereas the difference for the future event was found as 1.69 m.
Based on the analysis presented above it can be concluded that in the future we can expect more dynamic wind conditions, leading to bigger variations in the free surface of the lagoon.

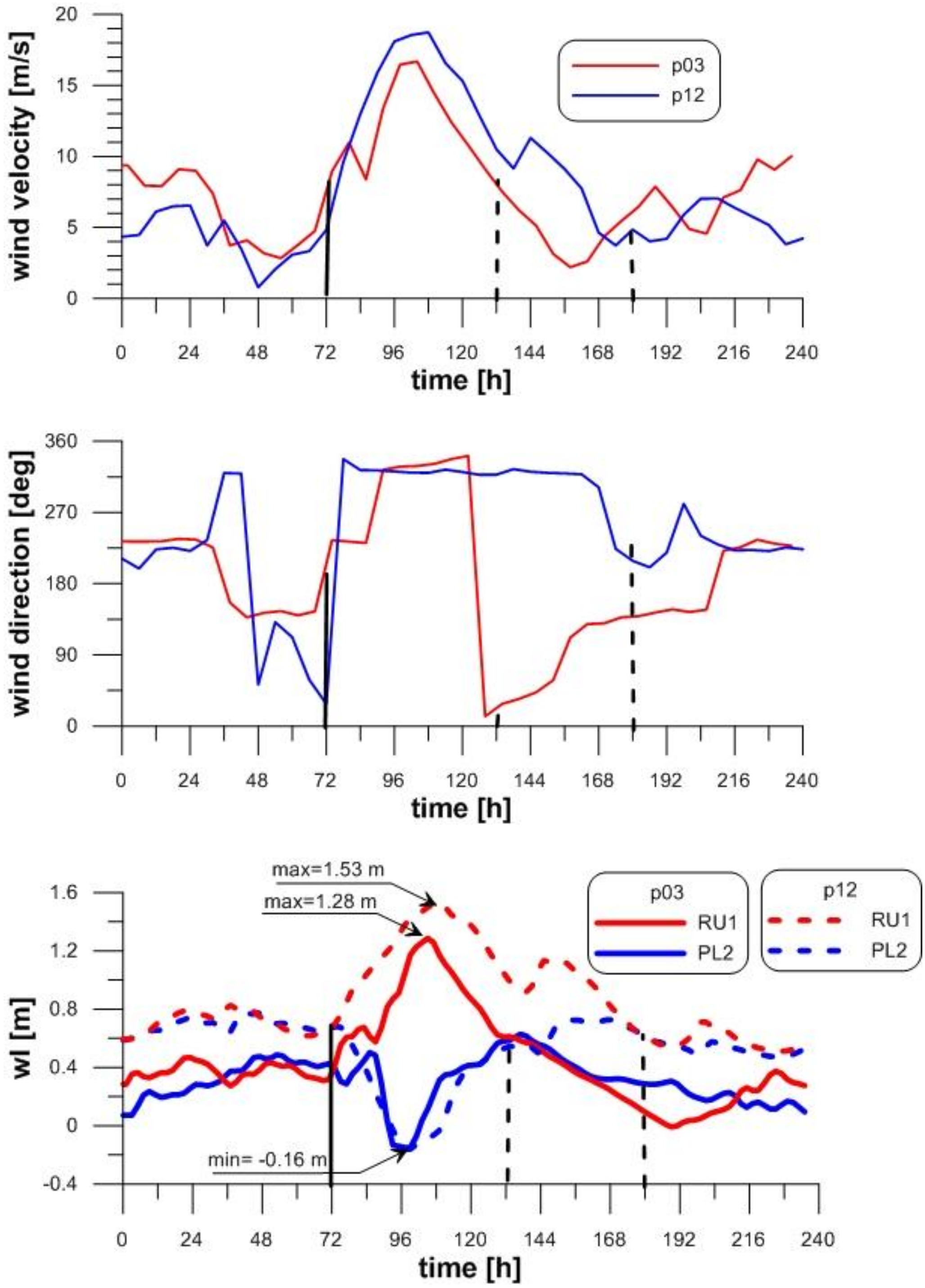


Figure 2.26. Wind velocity (top), wind direction (middle) and water level (bottom) variations before, during and after the extreme event in two scenarios (p03 – historical, p12 – future).

2.5 Salt wedge intrusion upstream the Pregola River.

There is a regular salt-wedge intrusion upstream the Pregola River. Saline (brackish) water from the Vistula lagoon penetrates upstream every autumn and reaches the centre of the urban part of the Kaliningrad City. During strong western and south-western winds these brackish waters penetrate deep upstream and salt wedge intrusion occupies the area in which intakes of Kaliningrad Drinking Water Supply System are located (Fig. 2.27). During these unfavourable conditions, Kaliningrad is supplied with drinking water from an artificial emergency reservoir, which has limited capacity. Time of release of stored water depends on: (a) duration of wind surge, and (b) consumption by citizens and city infrastructure (including enterprises), which in turn depend on season and weather conditions.

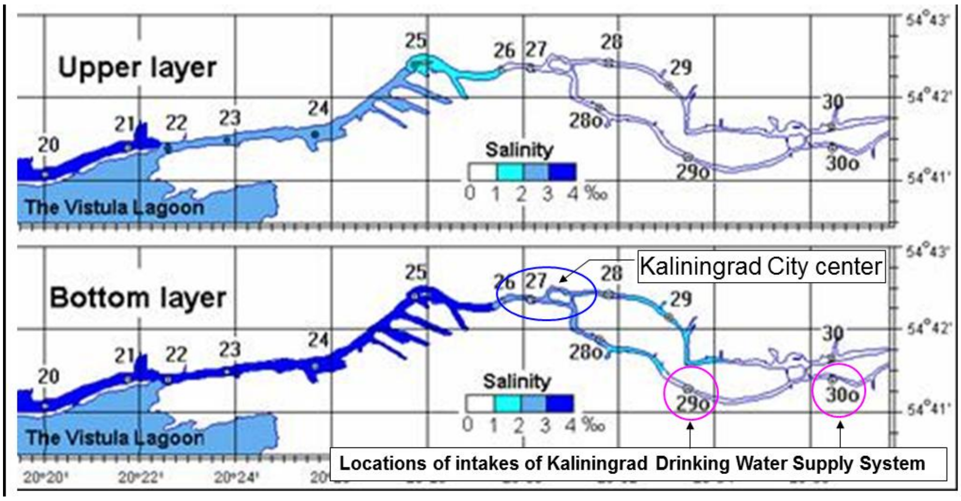
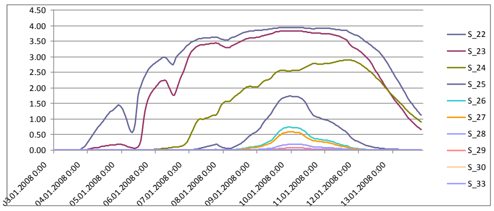
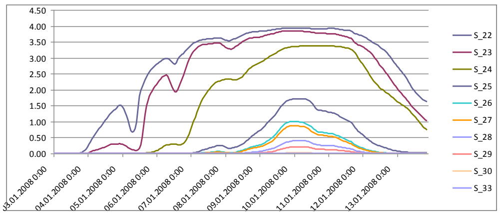


Figure 2.27. Scheme of the most probable location of brackish water on the eve of the autumn storm period in surface and bottom layers of the Pregola River. Monitoring points are indicated by numbers (20-30, 28o-30o). Intakes of the Drinking Water Supply System are located at the monitoring points 29o and 30o.

An example of episode of the longest wind influence (03.01– 13.01.2008), wind from W-SW (200-280º), with a speed in a range of 4-16 m/s for nearly a week time, modelled in 2D and 3D modes, shows the dynamics of salt-wedge intrusion upstream the Pregola River. The simulations were carried out by applying MIKE21 and MIKE 3 FM models, using the same initial (average December salinity distribution) and boundary conditions (Pregola River discharge, and water level variations). At the very mouth of the river (monitoring points 22 and 23 in the Fig. 2.27), salinity increased till reaching nearly 4 PSU in both modelling runs (2D and 3D). Even for point 25, the salinity variations obtained in both modelling modes are very similar. Differences between 2D and 3D solutions occur at more upstream points – in general the 3D solution predicts more deep penetration of the saltish water, by up to 1-2 km, depending on the location along the river stream (Fig. 2.28), as it follows from comparison of salinity time variations at the points of monitoring stations 25 and 26. Point 29 marks the location of the downstream intake of the city water supply system, and salinity at this point increased up to 0.3 PSU in maximum.



a)



b)

Figure 2.28. Salinity temporal variations at monitoring points in the Pregola River (upper layer); results obtained by running the model in 2D (a) and 3D (b) modes.

Local wind and the Pregola River discharge are the main driving forces for the upstream deep salt wedge intrusion. Local wind acts in two ways. First, it generates a direct wind shear stress acting on the river water surface, and, second, its most significant effect is that it causes the wind surge in the Vistula Lagoon and related water level set up at the river mouth. Except for these direct driving forces, an actual effect of deep upstream salt wedge intrusion depends on the salinity stratification conditions before the wind action, i.e. on the initial conditions. These initial conditions are formed during seasonal variations of the salinity field. Thus, the short-term effect of deep upstream salt wedge intrusion depends not only on short-term actual wind action and river discharge, but also on seasonal history of salt wedge formation in the Pregola River mouth.

Thus, we have three factors which determine the effect of deep upstream salt wedge intrusion in the Pregola River, namely, two instant factors (actual wind and river discharge), and one factor, the initial salinity stratification pattern in the river mouth, which is not instant, and depends on seasonal history. Modelling of various events (January 04 of 2008, October 10 of 2077, December 24 of 2083) shows that intensity of salt wedge intrusion depends mostly on initial conditions rather than on wind action and river discharge.

A modelling scenario for the Pregola River and the Vistula Lagoon dynamics (see beginning of this chapter) showed that future possible climate changes will not bring drastic changes in the behaviour of coupled Vistula Lagoon-Pregola River system. Seasonal formation (autumn period) of initial conditions favourable for deep intrusion of salt wedge will be always expected. Therefore among three factors mentioned above, only the wind action and the Pergola River discharge should be analysed against the changes in the local climate.

To analyse the combinations of “wind forcing - discharge” conditions, the following parameters were introduced for each event of wind forcing:

- cumulative W-E ‘wind impulse’, [m], equal to Σ (W^a_i*dt_i);
- cumulative discharge, [m^3], equal to Σ (Q^{riv}_i*dt_i);

where i – number of sub-periods of quasi-steady wind and river discharge conditions, dt_i – duration of i-th sub-period, W^a_i – W-E component of wind speed during this sub-period, Q^{riv}_i – discharge of the Pregola River during this sub-period, Σ – summation over “i” through all sub-periods to cover duration of an event.

The events of considerable wind forcing (wind speed higher than 12 m/s, with duration longer than 12 hours and a break not longer than 12 hours between sub-periods of such a wind) were analysed using the data set for wind from the climate projection M10. There were found 994

sub-periods with the wind stronger than 12 m/s for the whole period of 1961 – 2100. Only 339 of them had duration of more than 12 hours. And only for 224 of them the wind blew from the direction of 215-295º, i.e. may produce a storm-surge in the eastern corner of the Vistula Lagoon. The diagram in Fig. 2.29 shows that, according to the climate projection M10, the number of such events will slightly decrease at the end of the 21st century.

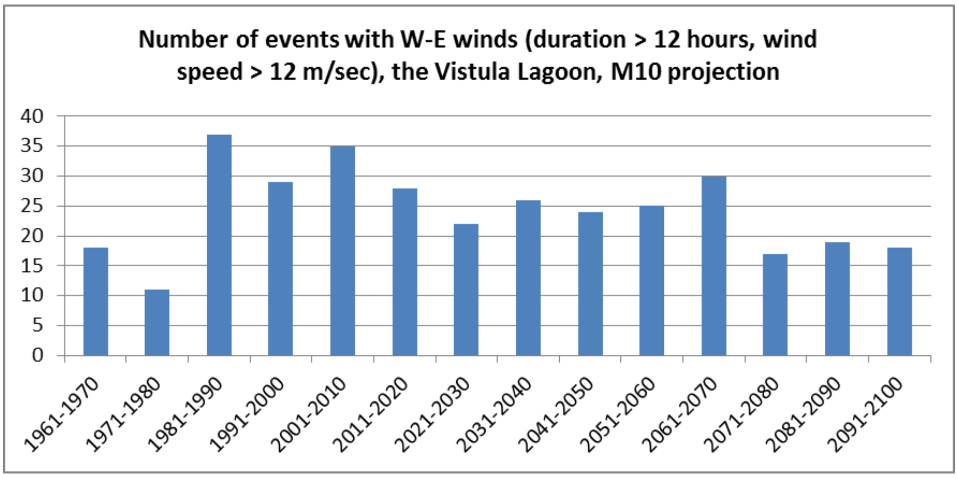


Figure 2.29. Number of wind events (M10 projection data set) per each 10 years interval for the period of 1961-2100. Each event is characterized by a wind of duration longer than 12 hours, wind speed - greater than 12 m/s, breaks - not longer than 12 hours.

Any combination of "wind forcing – discharge" for selected events may be presented as a dot in the 2-dimensional diagram (Fig. 2.30), in which the x-axis corresponds to cumulative W-E wind impulse, whereas the y-axis corresponds to cumulative discharge.

An analysis of all selected events from the period 1971-2000 shows the characteristic ranges of cumulative wind impulse and discharge (Fig. 2.30a, dashed rectangular). As for the events for the period 2000-2050 (Fig. 2.30b), there are a number of them which do not fit to those ranges due to a high river discharge. There are also a number of events (Fig. 2.30c) which do not fit to these ranges for the period of 2050-2100 due to both the river discharge and the wind action. While a high river discharge resists the wind action, the probability of deep upstream salt wedge penetration is increasing only during the second half of this century.

Once the lagoon is covered by ice during winter time and, therefore, a wind surge does not occur in its eastern part in winter season, only autumn situations have to be considered (Fig. 2.30d). And as for the autumn season, the only possible event (Fig. 2.30d) is out of the range we have found for the historical period of 1971-2000. It means that there are no considerable changes in the combination "wind forcing – discharge" in the future projection, and climate changes will not bring an increase of risk of deep upstream salt wedge intrusion in the Pregola River.

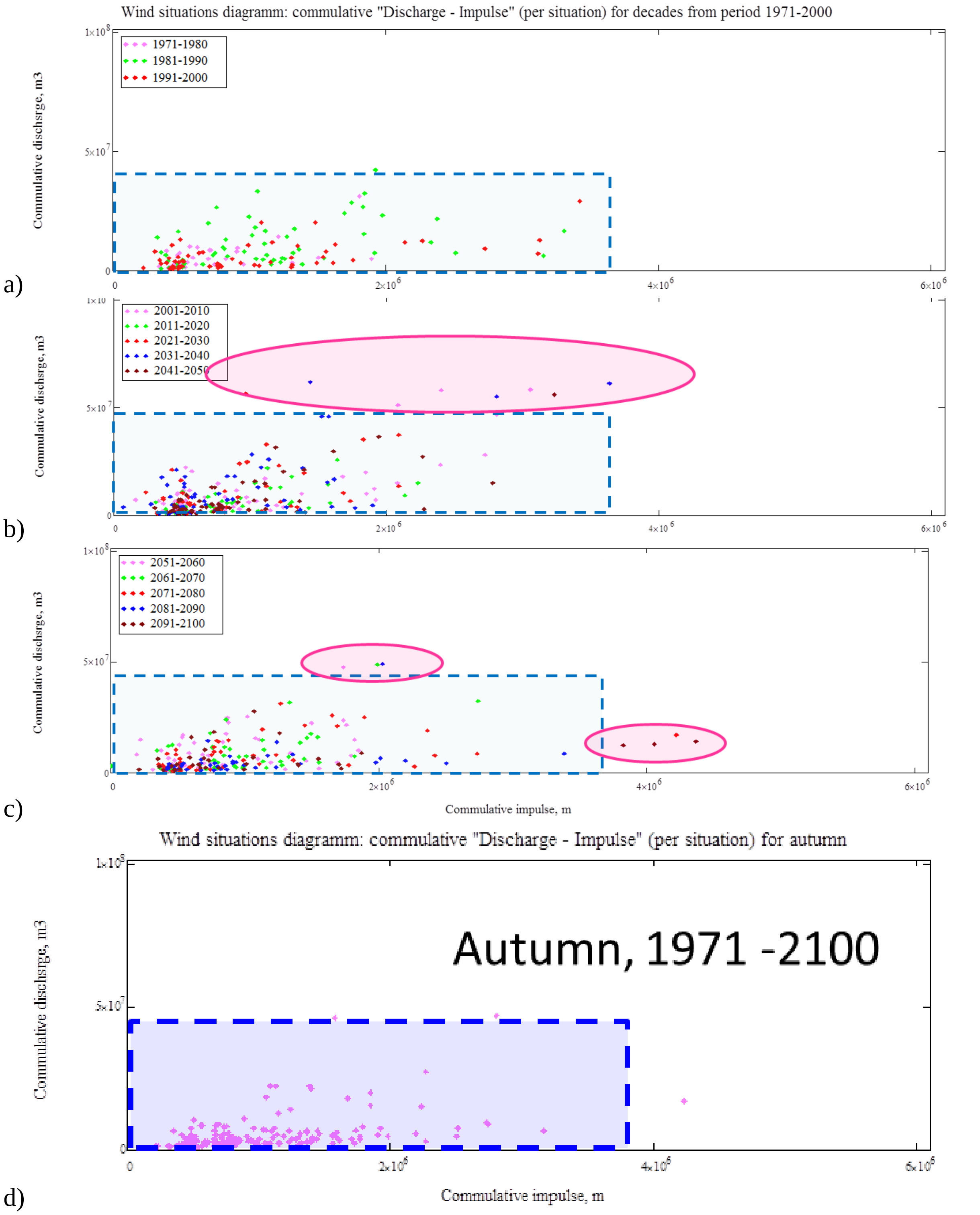


Figure 2.30. Diagrams “wind forcing – discharge” for (a) three decades of 1971-2000, (b) five decades of the first half of 21st century (2001-2050), and (c) five decades of the second half of 21st century (2051-2100), as well as (d) the only autumn event for the whole period (1971-2100).

3. Combined socio-economic and climate change impact on the lagoon

3.1 Climate forcing

Changes in hydrodynamics and ecological status of the Vistula Lagoon can be due to climate and socio-economic changes expressed by changes in land use. In Chapter 2 the impact of climate changes was discussed in detail; here the analysis concentrates on joint influence of the climate change together with four possible land use scenarios discussed in detail in Deliverable 5.2. Figure 3.1 is a good summary of land cover distribution in the scenarios to be discussed in this chapter.

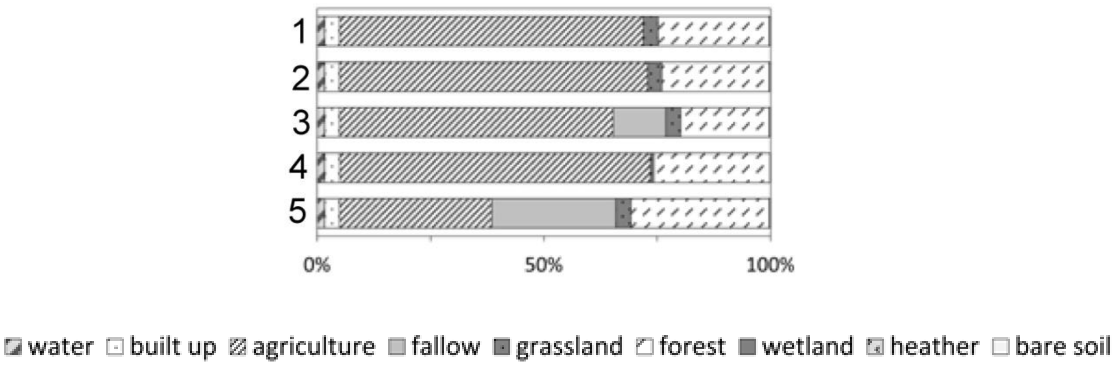


Figure 3.1. Land cover distribution for the reference conditions (1-p1) and four scenarios (2 -BAU: Business as usual, 3 - CRI: Crisis, 4 - MH: Managed horizons, 5 - SET: Set-aside) for the catchment of the Vistula Lagoon (based on Deliverable 5.2, Lagoons 2014).

The analysis presented below is based on predicted climate change in a typical year in the near-future (p1) and four scenarios of socio-economic changes in the region expressed by changes in the land use. Taking those assumptions, salinity and water level variations at the connection with the Baltic Sea, as well as water temperature in the lagoon, were all assumed to be the same in all analysed scenarios as in scenario p1. The basic difference between scenarios concerns modified volume and quality of water discharged into the lagoon due to changes in the land use in the drainage basin.

Similarly as in the climate change impact assessment, let us compare river discharges in analysed socio-economic scenarios. Comparison of yearly average discharge for all rivers (Fig. 3.2) does not show big differences between scenarios, both with regard to range of variation and mean values. Only in case of the SET scenario a discharge decrease can be seen.

Comparison of mean yearly average discharges for the main rivers (Fig. 3.3) shows quite a diverse situation. In case of the Pregola River the discharge decreases in all scenarios in relation to the reference period p1; a similar situation is observed for Nogat and Elbląg Rivers. The opposite situation was found for Nelma, Mamonovka and Bauda. In case of Prokhladnaya and Pasleka Rivers, the discharge increase in all scenarios except the SET was found.

The most detailed information comes from mean monthly discharges in all main rivers and all scenarios, see Fig. 3.4. It is very characteristic that the minimum discharge is encountered in

the summer months (July, August). The maximum discharge does not appear so regularly, usually it occurs in early spring.

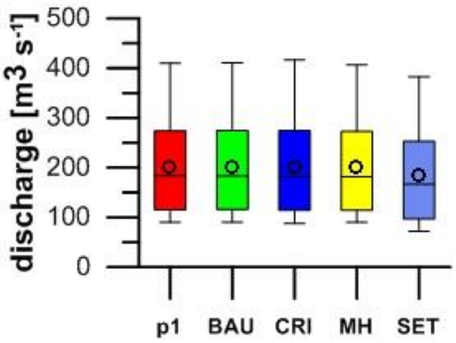


Figure 3.2. Yearly average discharge for all rivers in scenarios p1, BAU, CRI, MH, SET.

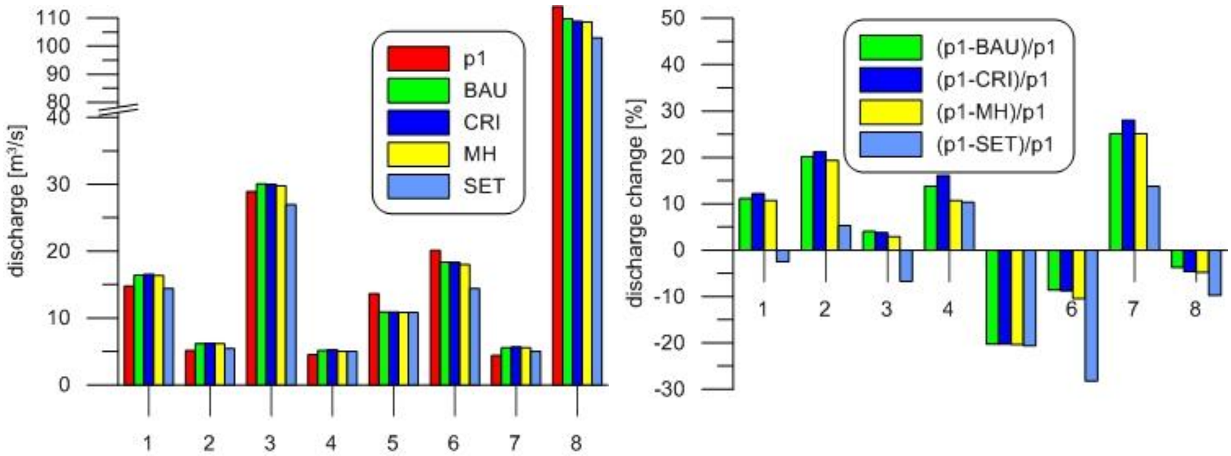


Figure 3.3. Mean yearly average discharge for the main rivers in the Vistula Lagoon drainage basin in chosen groups of years (1-Prokhladnaya, 2-Mamonovka, 3-Pasleka, 4-Bauda, 5-Nogat, 6-Elbląg, 7-Nelma, 8-Pregola).

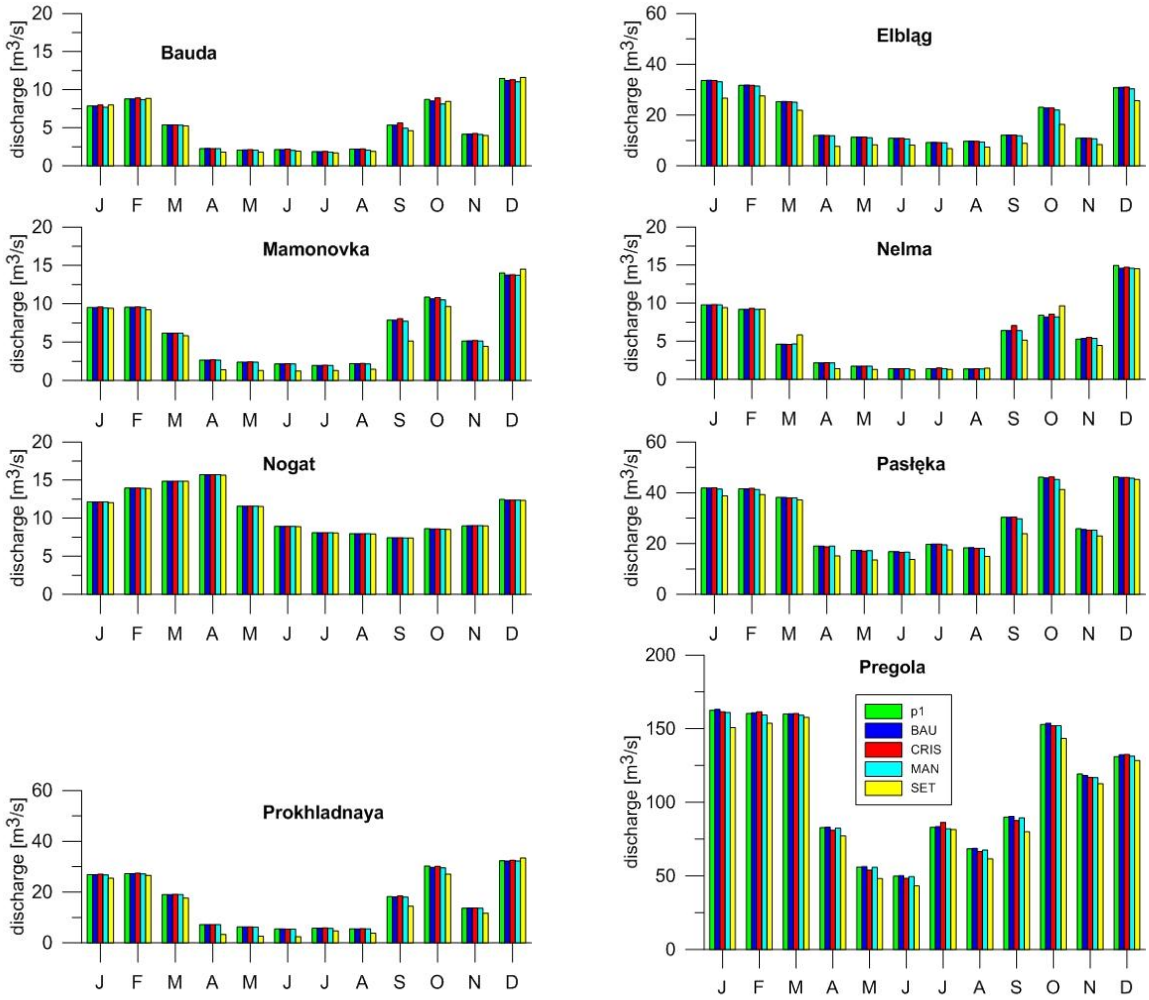


Figure 3.4. Mean monthly river discharge in rivers: comparison between p1, BAU, CRIS, MH and SET scenarios.

3.2 Loads from catchment

Scenario **p1** (defined as "typical year" in the period 2011-2040) with its assumptions, and four socio-economic scenarios which took into account changes in land use in the catchment, were used to estimate nutrient emission into the Vistula Lagoon (for detailed information see Deliverable 5.2). The details concerning hydrodynamic conditions are presented in Chapter 3.1. Combination of the "typical year" scenario with any of the four socio-economic scenarios gave the nutrient discharges exclusively determined by changes in land use. It can be further concluded that all the catchments which are assumed to have inconsiderable changes in land use will generate similar loads of nitrogen and phosphorus.

The following three scenarios: p1, BAU and MH belong to a group of scenarios with similar structure of land use, characterized by comparable contribution of arable land and forested areas to the overall agricultural area. The scenarios „Crisis" (CRI) and „Set Aside" (SET) assume lower contribution of arable land and an increased area of fallow land (Fig. 3.1, Chapter 3.1).

Changes of monthly loads of N-NH_4, N-NO_3 and P-PO_4 showed similar dynamics, with the highest discharges at the beginning of a year, the lowest loads in summer, and an increase in loads in autumn, though the autumn discharges are not as high as the winter/spring ones (Fig. 3.5; Fig. 3.6; Fig. 3.7). The River Nogat is characterized by (i) the lowest annual variability in N-NH_4, N-NO_3, P-PO_4 loads in comparison with those observed in other rivers studied, and (ii) similar discharges in all the socio-economic scenarios. Such a situation can be explained by insignificant differences in water discharges by the Nogat River. This fact remains in contrast to what is observed in the remaining rivers, which show visible changes in water outflows and, in consequence, in loads of nitrogen and phosphorus. The assumed socio-economic changes, leading to the changes in land use, seem to be responsible for changes in water outflow (for detailed information see Deliverable 5.2, Chapter 3.1, Fig. 3.5, Fig. 3.6, Fig. 3.7, Fig. 3.8 and Fig. 3.9).

Comparison of annual loads of nitrogen and phosphorus introduced into the Vistula Lagoon allows concluding that the Pregola River (Russian part of the lagoon) and the Pasleka River (Polish part of the lagoon) are the greatest contributors to N and P loads to the lagoon (Fig. 3.8).

Comparison of the outcomes of all the socio-economic scenarios point to the fact that the lowest annual loads of nitrogen and phosphorus are observed in the „Set Aside" and „Crisis" scenarios, whereas the highest loads of N (N-NH_4 and N-NO_3) and P (P-PO_4) are forecast in the „Managed Horizons" (MH) scenario, which assumes the most intensive agricultural activity (Fig. 3.9).

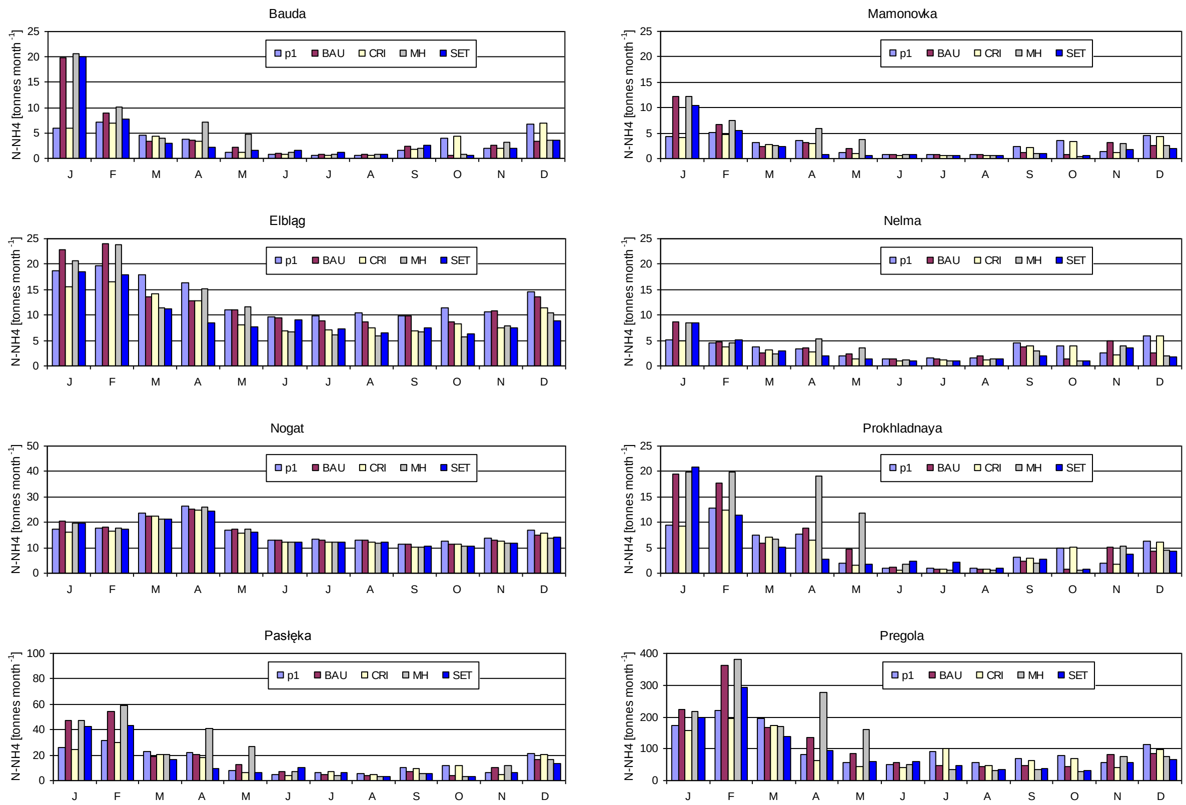


Figure 3.5. Monthly loads of N-NH$_4$ [tonnes month^{-1}] from the main rivers to the Vistula Lagoon for chosen scenarios: p1 - “typical year”, BAU - “Business as Usual”, CRI - “Crisis”, MH - “Managed Horizons” and SET - “Set Aside”.

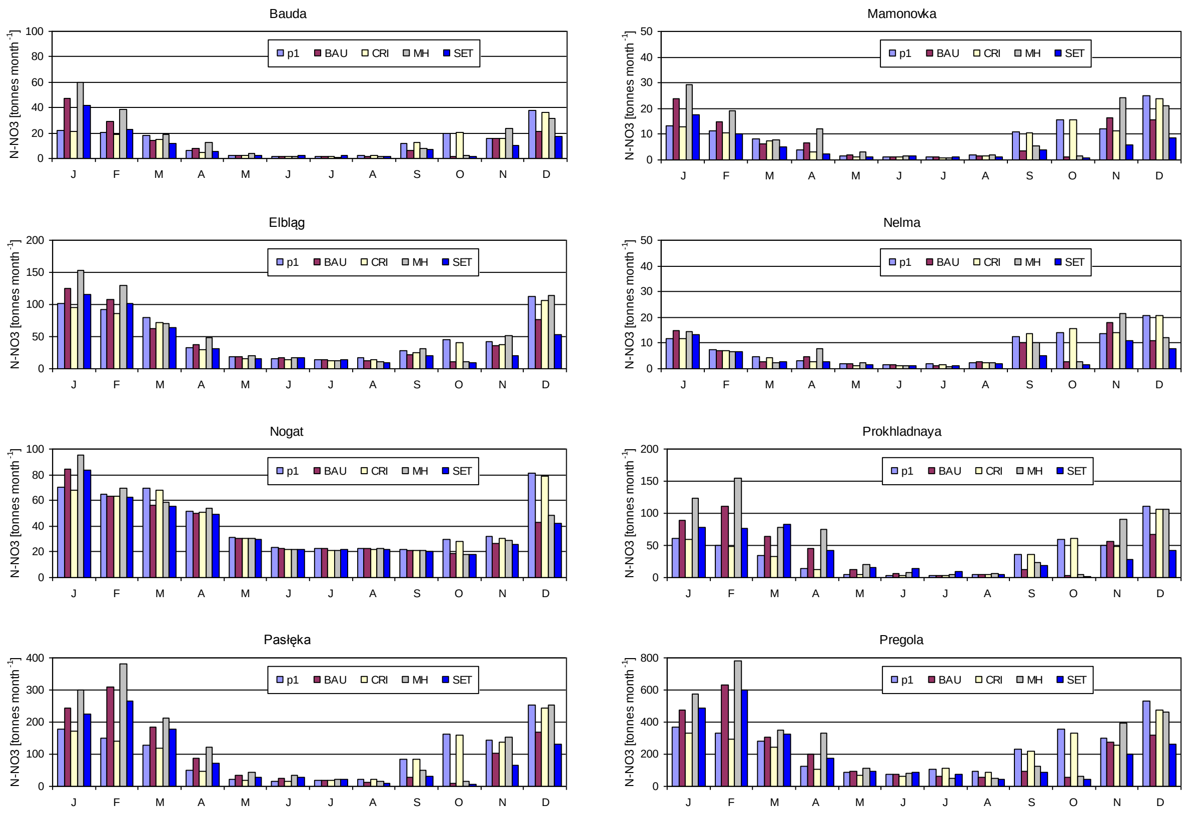


Figure 3.6. Monthly loads of N-NO_3 [tonnes month^{-1}] from the main rivers to the Vistula Lagoon for chosen scenarios: p1 - "typical year", BAU - "Business as Usual", CRI - "Crisis", MH - "Managed Horizons" and SET - "Set Aside".

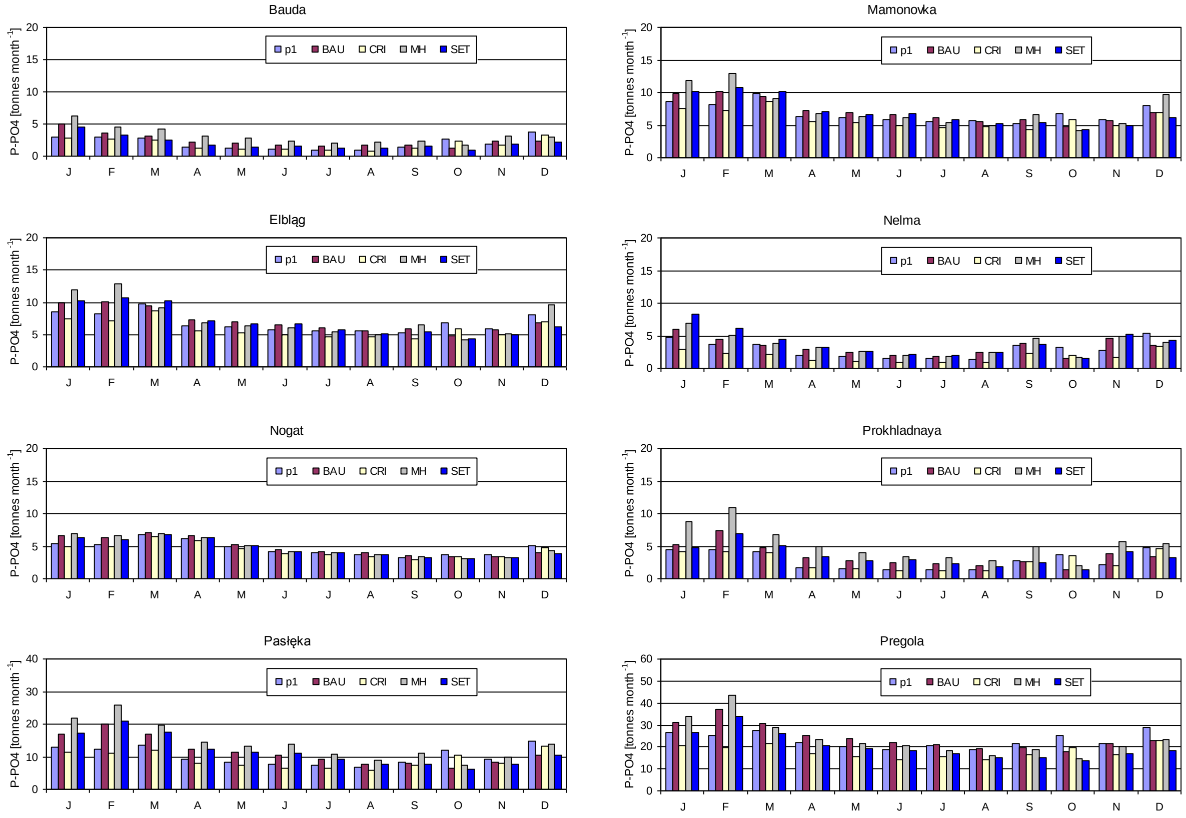


Figure 3.7. Monthly loads of P-PO$_4$ [tonnes month^{-1}] from the main rivers to the Vistula Lagoon for chosen scenarios: p1 - “typical year”, BAU - “Business as Usual”, CRI - “Crisis”, MH - “Managed Horizons” and SET - “Set Aside”.

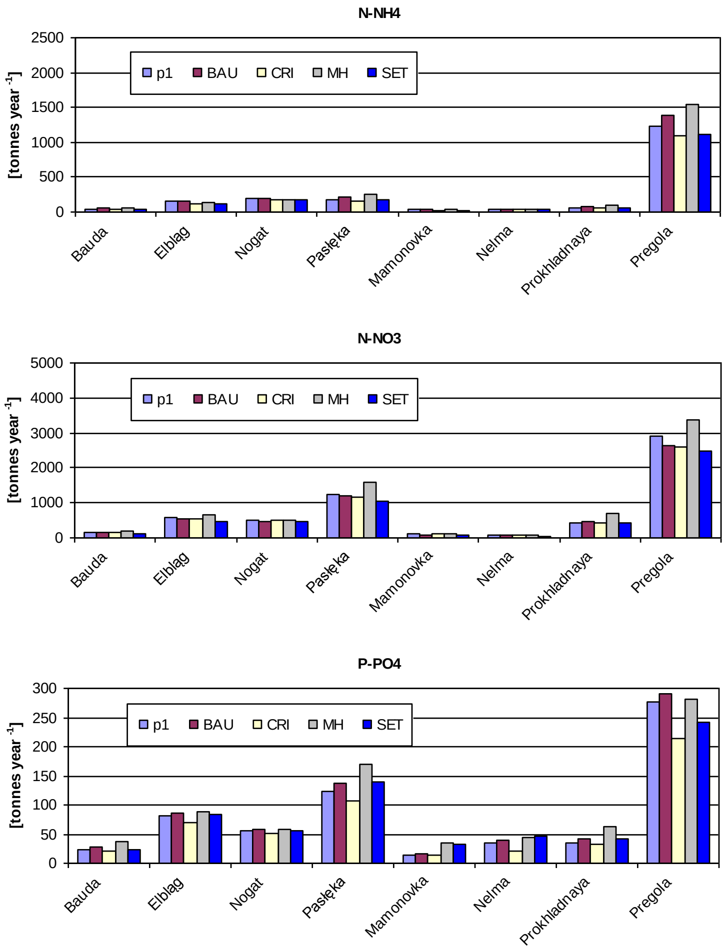


Figure 3.8. Yearly loads of N-NH_4, N-NO_3 and P-PO_4 [tonnes year^{-1}] from the main rivers to the Vistula Lagoon for chosen scenarios: p1 - "typical year", BAU - "Business as Usual", CRI - "Crisis", MH - "Managed Horizons" and SET - "Set Aside".

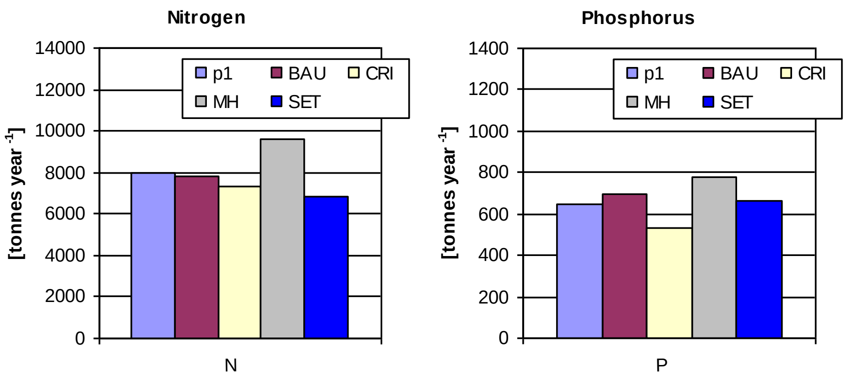


Figure 3.9. Yearly loads of nitrogen (sum of N-NH_4 and N-NO_3) and phosphorus (P-PO_4) [tonnes year^{-1}] from all of the rivers (taken into account for modelling calculations) to the Vistula Lagoon for chosen scenarios: p1 - "typical year", BAU - "Business as Usual", CRI - "Crisis", MH - "Managed Horizons" and SET - "Set Aside".

3.3 Lagoon's response

Similarly to the analysis of the climate change impact on the lagoon's ecosystem, also an influence of combined socio-economic and climate changes is presented, using chosen parameters, i.e. salinity, P-PO4, N-NH4, N-NO3, Chl-a.

Salinity changes on the scale of a year (Fig. 3.10) in chosen locations do not show big differences between analysed scenarios. The most pronounced differences can be seen in case of the SET scenario, parallel to changes in land use and discharge.

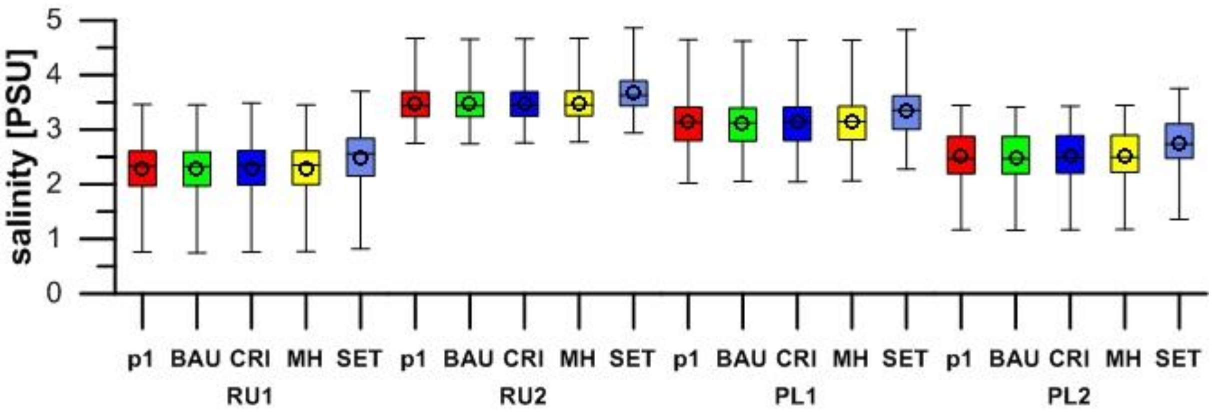


Figure 3.10. Annual salinity variation at chosen locations for socio-economic scenarios.

More detailed information comes from an overview of monthly variations of salinity in chosen locations (Fig. 3.11). It is well seen that in location v2, close to Pregola River inflow into the lagoon, the range of salinity variation (min-max) is within the range 1-4 psu for all the scenarios, while the monthly average values are mostly in the range 2-3 psu. Higher salinity values are expected in locations v7 – located in the area influenced by water exchange with the Gulf of Gdańsk, and v2 – located in the central part of the lagoon. In case of location v7, salinity can vary in the range 2.9-5 psu, with the average in the range 3-4 psu. In location p2 the range of variation is wide and equals 2-5 psu, with the average in the range 2.9-4 psu. Location p8, situated in the southern part of the lagoon, is under the influence of smaller rivers (Nogat, Elbląg), and is much further from the Baltiysk Strait. As a consequence, the range of salinity variation is close to location v2, and is in the range 1-3.9 psu, with the average in the range 2-3 psu.

It is very characteristic that the lowest salinity can be expected in the spring time (March – April), while the maximum in the winter time (usually in January). The smallest variations in discharge are expected in the summer time.

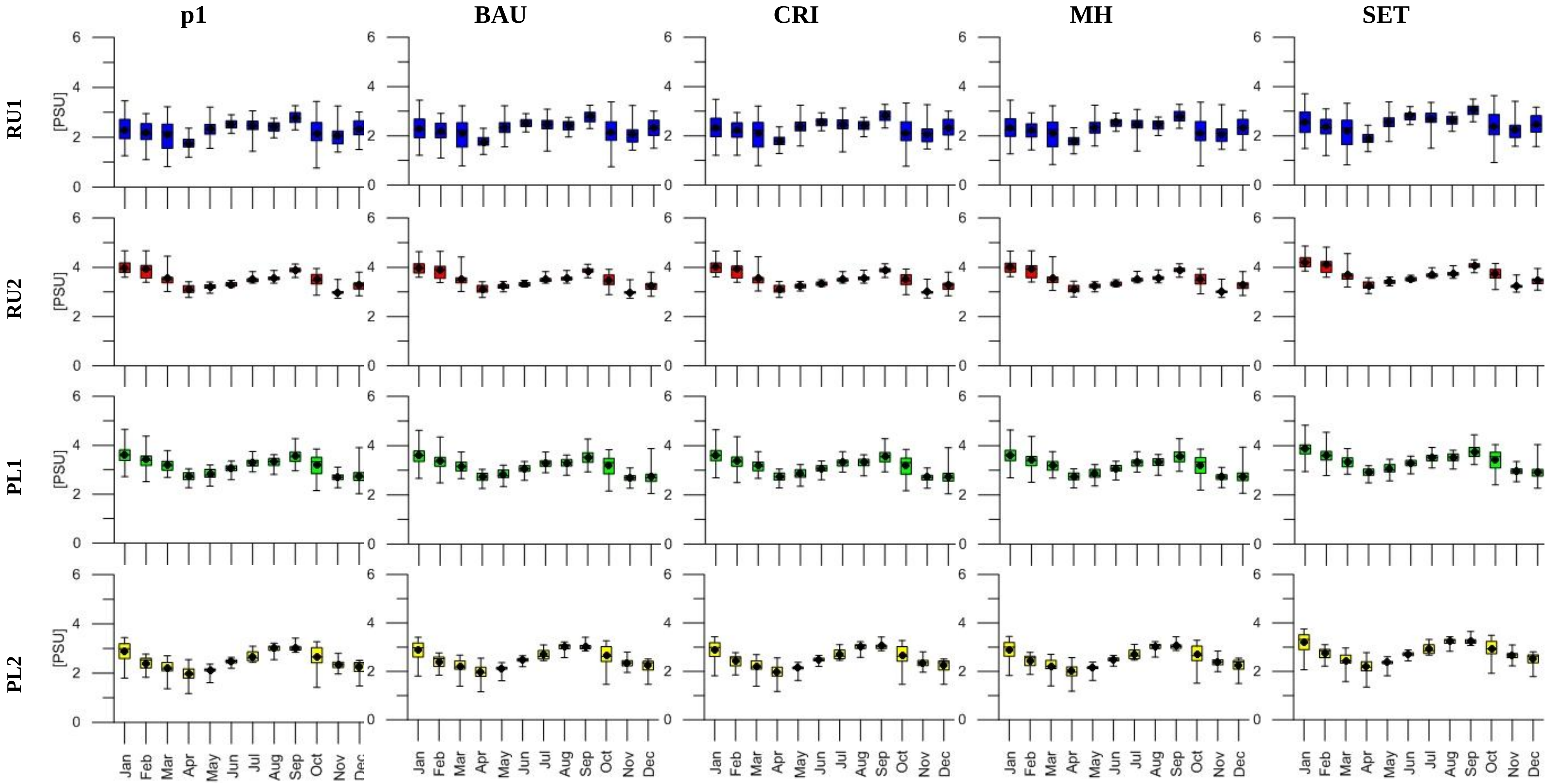


Figure 3.11. Monthly variations of salinity at chosen locations (RU1, RU2, PL1, PL2) and for chosen scenarios (p1, BAU, CRI, MH, SET).

An estimation of a potential impact of socio-economic, as well as environmental (climatic) changes, on the ecosystem of the Vistula Lagoon was made by combining four socio-economic scenarios (land use) with the climatic scenario **p1 – „typical year"**, which estimates climatic changes in the near future. The analysis results are based on four observation points (Fig. 2.13), and provide information on the following parameters: concentrations of chlorophyll a, (Chl-a), nitrates (N-NO_3), ammonium (N-NH_4), and phosphates (P-PO_4) in the Vistula Lagoon.

Variability of salinity and water level at the open boundary of the model (Baltiysk Strait), and variability of temperature in the water column, were assumed the same in all the scenarios. The main difference among the scenarios considered results from modified volumes of riverine water inflows and from nutrient concentrations in waters drained from the Vistula Lagoon catchment.

The scenario **BAU** – „Business as Usual" – preserving the present structure of land use, is in its assumptions similar to the scenario prepared for the reference year (**p1**), and this explains why concentrations of modelled parameters remained on similar levels. It is expected that concentrations of phosphates (P-PO_4) will show greatest changes. Further, it is expected that concentrations of N-NO_3 and N-NH_4 will show a slight decline, whereas concentrations of P-PO_4 will demonstrate an increase (for detailed information see Deliverable 5.2; Fig.3.12, Table 3.1).

In the **CRI** – „Crisis" scenario the arable land (relative change in its area – 10%) and forests (relative change their area – 20%), which are located in close vicinity to municipal areas, will be converted into fallows. Such a situation will insignificantly affect N-NO_3, N-NH_4 and P-PO_4 concentrations and inflows of riverine waters to the Vistula Lagoon. The predicted changes of parameters in the water column point to a possible improvement of water quality, thus improving the functioning of the lagoon's ecosystem. At the model simulated limited agricultural and industrial activity, the greatest relative change in concentrations will be shown by phosphates (for detailed information see Deliverable 5.2, Fig. 3.12, Table 3.1).

In the **MH** – „Managed Horizons" scenario, which reflects an intensive development of economy, including agriculture, the fallow grounds will be converted into arable land (relative change in area – 2%), or the forested area (relative change in area – 5%). These changes will have an insignificant impact on water outflows to the Vistula Lagoon, but nutrient concentration will increase. The greatest increase is expected in the case of N-NO_3. These facts may result in an increase in phytoplankton abundance, evidently much more intensive than predicted in the case of other socio-economic scenarios. Enhanced phytoplankton blooms may negatively affect the whole ecosystem of the Vistula Lagoon (for detailed information see Deliverable 5.2, Fig. 3.12, Table 3.1).

The **SET** – „Set Aside" scenario, by its nature – without excessive anthropogenic pressure – is characterized by the greatest changes in the structure of land use and the greatest decline in riverine inflow to the lagoon. It is forecast that concentrations of parameters related to water quality will decline, in particular nitrate concentrations. Out of four scenarios analysed, the „Set Aside" scenario gives the most favourable ecological conditions in the Vistula Lagoon. It has to be stressed here that the above conclusions are drawn based on the present available input data. Taking into account the time span, one must be aware of the fact that environmental parameters may undergo some modifications due to expanding the data base and feeding it with new measurements made in the catchment (for detailed information see Deliverable 5.2, Fig. 3.12, Fig. 3.13, Fig. 3.14, Fig. 3.15, Fig. 3.16, Table 3.1).

One of the features of the Vistula Lagoon is a differentiation in spatial distribution of nutrient concentrations and chlorophyll-a content. The central part of the lagoon (observation points

RU2 and PL1) is characterized by the lowest modelled medians and averages, and also by their increase in the direction towards observation points RU1 and PL2). This situation is also reflected in graphs showing the variability in nutrient and chlorophyll-*a* daily concentrations (Fig. 3.12, Fig. 3.13, Fig. 3.14, Fig. 3.15, Fig. 3.16).

It is worth mentioning that in each of the socio-economic scenarios, all the parameters, which are essential in qualitative classification of uniform water bodies, remain within the same class of water purity (according to Act of the Minister of Environment of 09 Nov. 2011 on the qualification of the state of uniform surface water bodies and environmental quality norms for substances given priority; Law Gazette No 257, Item. 1545; Table 3.2). These facts point to the conclusion that the process of environmental changes in the Vistula Lagoon ecosystem will be slow as referred to life-time of a human being, and will follow the statement “Natura non facit saltus” (Nature does not make leaps) by Aristotle.

Table 3.1. Relative changes [in %] of discharge and concentrations of Chl-a, NO3-N, NH4-N, PO4-P in water column of the Vistula Lagoon and in each of the scenarios compared to the period p1 (2011 – 2040). Data presented in the table are the averages calculated for 4 observation points: RU1, RU2, PL1 and PL2.

Scenario	Water discharge	Chl-a	N-NO_3	N-NH_4	P-PO_4
BAU	0.26	-2.31	4.44	2.92	7.12
CRI	-0.33	-0.18	-9.51	-6.27	-14.73
MH	-0.71	5.08	24.82	2.77	13.19
SET	-7.63	-5.25	-23.60	-5.52	-7.63

Table 3.2. Classification of Vistula Lagoon Water with a reference to concentrations of chlorophyll-a (Chl-a) and nutrients (N-NO_3, N-NH_4, P-PO_4) in analysed scenarios (data presented in the table are the averages calculated for 4 observation points: RU1, RU2, PL1 and PL2).

Scenario	Chl-a		N-NO_3		N-NH_4		P-PO_4 *)	
	[µg L^{-1}]	Water class	[mg L^{-1}]	Water class	[mg L^{-1}]	Water class	[mg L^{-1}]	Water class
p1	24.56	III	0.26	II	0.031	I	0.039	II
BAU	23.99	III	0.27	II	0.032	I	0.041	II
CRI	23.95	III	0.24	II	0.030	I	0.035	II
MH	25.16	III	0.30	II	0.031	I	0.040	II
SET	23.84	III	0.23	II	0.029	I	0.037	II

*) Following Order of Minister of Environment of 09 Nov.2011, Law Gazette No 257, Item. 1545, it was assumed that given numbers on phosphates refer to pure phosphorus and not to phosphorus ion (PO_4^{-3}).

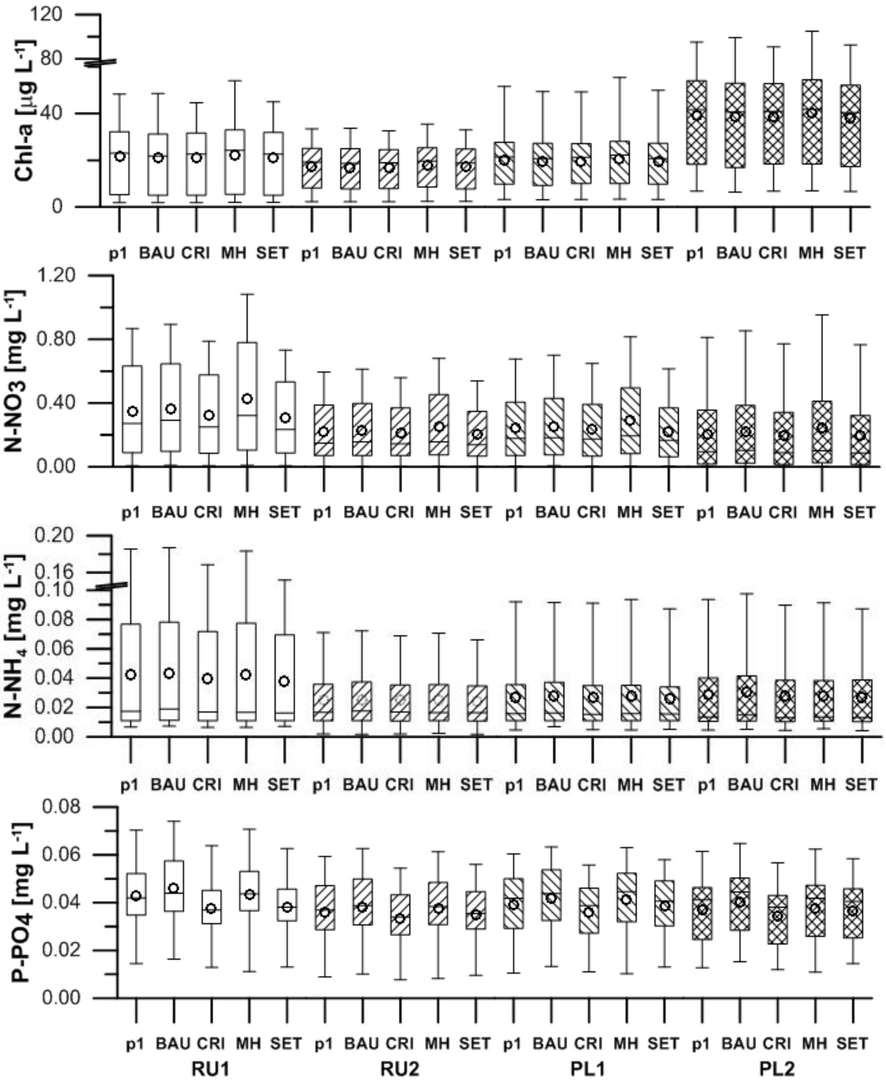


Figure 3.12. Concentrations of chlorophyll-a and nutrients ($N-NO_3$, $N-NH_4$ and $P-PO_4$) estimated for socio-economic scenarios at four observation points (RU1, RU2, PL1 and PL2) in the Vistula Lagoon. Plots show the following data: min/max, percentile 25/75, median (vertical lines), and average values (circles) of simulated parameters in particular scenarios: p1 - “typical year”, BAU - “Business as Usual”, CRI - “Crisis”, MH - “Managed Horizons”, and SET - “Set Aside”.

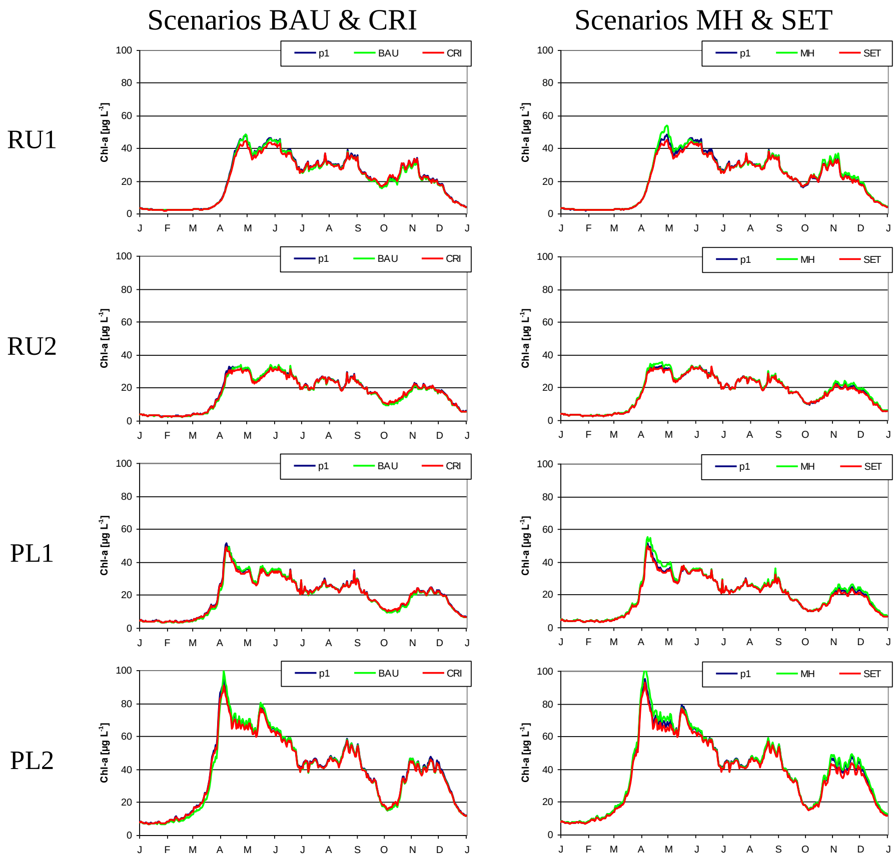


Figure 3.13. Daily variations of chlorophyll-a [µg L^{-1}] at locations RU1, RU2, PL1 and PL2 in model calculations carried out for combined socio – economic scenarios: p1 - “typical year”, BAU - “Business as Usual”, CRI - “Crisis”, MH - “Managed Horizons” and SET - “Set Aside”.

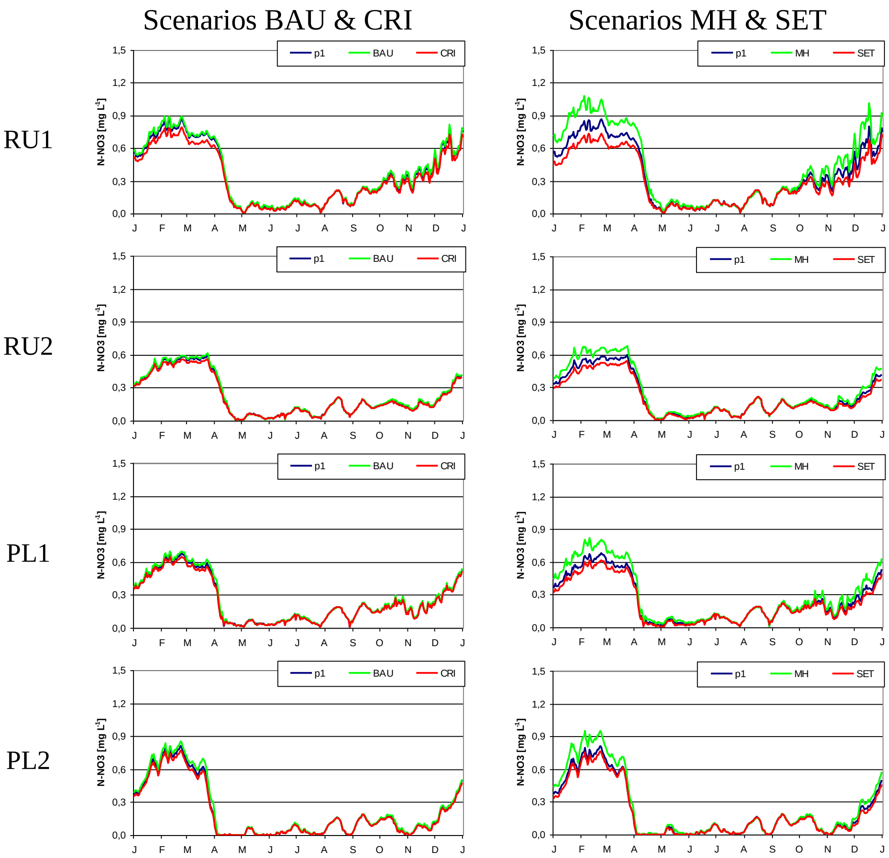


Figure 3.14. Daily variations of N-NO_3 [mg L^{-1}] at locations RU1, RU2, PL1 and PL2 in model calculations carried out for combined socio – economic scenarios: p1 - “typical year”, BAU - “Business as Usual”, CRI - “Crisis”, MH - “Managed Horizons” and SET - “Set Aside”.

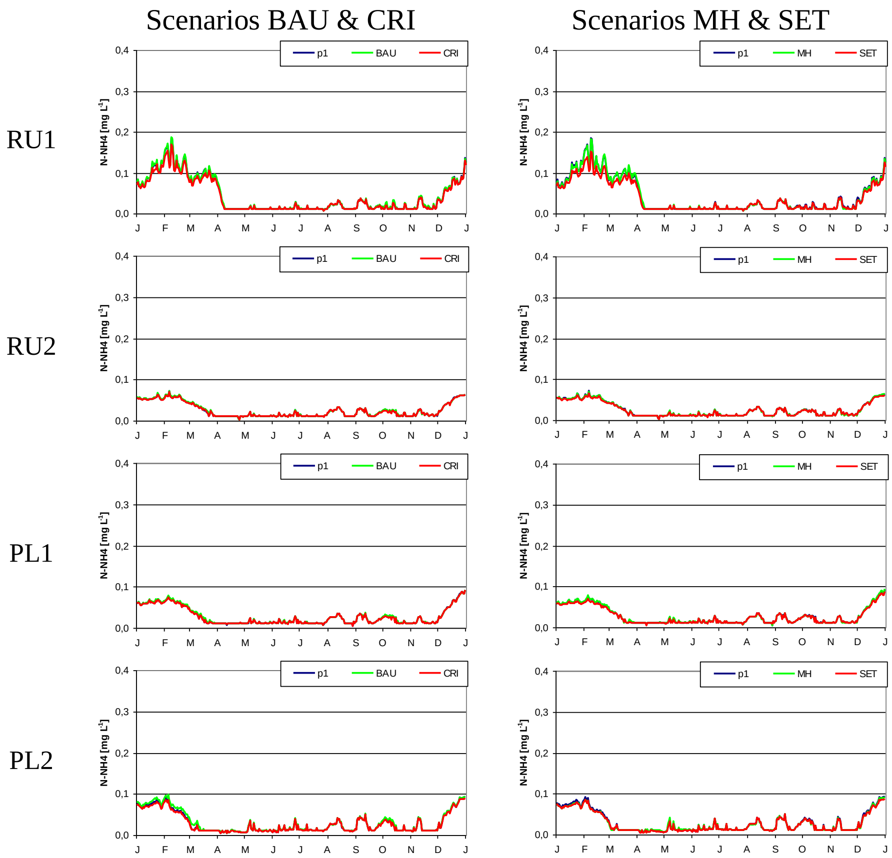


Figure 3.15. Daily variations of N-NH_4 [mg L^{-1}] at locations RU1, RU2, PL1 and PL2 in model calculations carried out for combined socio – economic scenarios: p1 - "typical year", BAU - "Business as Usual", CRI - "Crisis", MH - "Managed Horizons" and SET - "Set Aside".

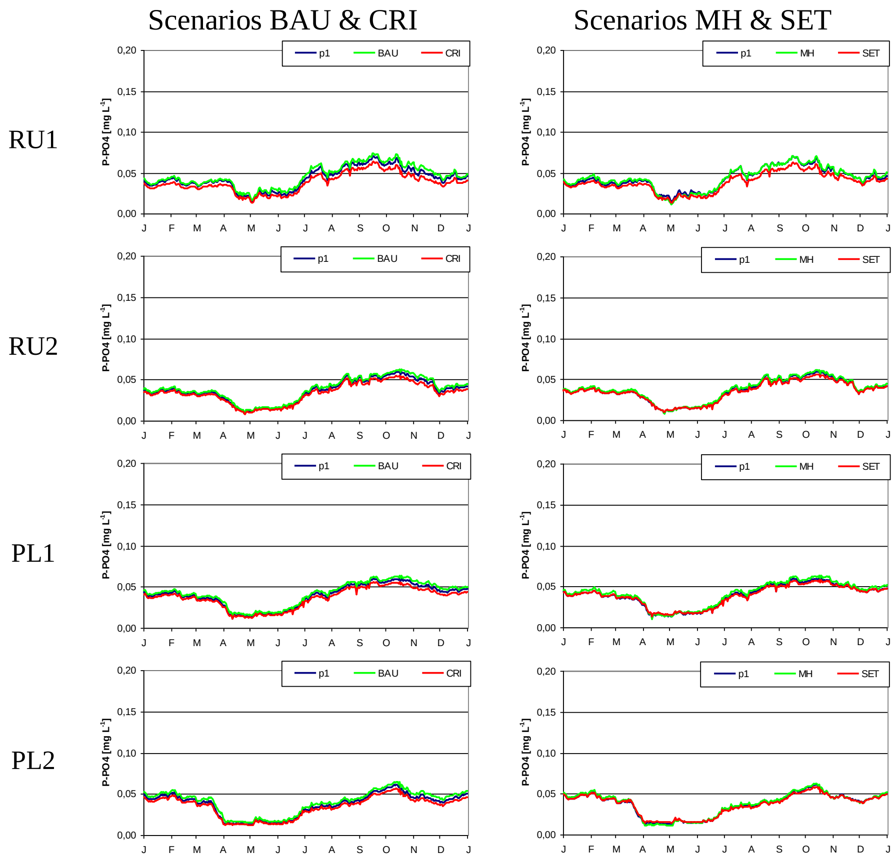


Figure 3.16. Daily variations of P-PO_4 [mg L^{-1}] at locations RU1, RU2, PL1 and PL2 in model calculations carried out for combined socio – economic scenarios: p1 - "typical year", BAU - "Business as Usual", CRI - "Crisis", MH - "Managed Horizons" and SET - "Set Aside".

4. Conclusions and recommendations

In case of the Vistula Lagoon, as a result of the expected climate change, a cumulative effect of an increase of fresh water discharge and a salinity decrease in the Baltic Sea will lead to a considerable drop in both the annual average value and the annual range of salinity in the Vistula Lagoon. This tendency will be observed in the whole lagoon, while desalinisation of the Baltic waters governs the salinity dynamics only in the central part of the lagoon, in the vicinity of the lagoon inlet, whereas an increase of freshwater inflow results in a salinity reduction at the remote parts of the lagoon. A general decrease in salinity in the Vistula Lagoon will lower the threat of both salinity water intrusion upstream the Pregola River and blocking of the intakes of Kaliningrad City drinking water supply system. Also the changes in wind forcing and the Pregola River discharge due to the climate change will not increase this threat. With regard to water quality in the future, concentrations of chlorophyll *a* and phosphate are expected to increase, while nitrate nitrogen and ammonium are expected to decrease. In addition, it is expected that nitrogen will be the limiting factor for phytoplankton growth during the whole vegetation season.

Phosphorous in the Vistula Lagoon requires special attention. The foreseen increase in phosphorous concentration in the water column (especially due to the climate change), resulting from an increased load from the drainage basin, will play an important role in:

- transitioning a system, from a present situation where phosphorus is a limiting factor in phytoplankton growth in spring, whereas nitrogen plays a limiting role in the remaining part of the vegetative season, into a system in which nitrogen will become a factor limiting phytoplankton growth during the entire vegetative period;
- intensification of algae blooms in the summer time due to expected temperature increase and high concentration of phosphorous in the water column, as well as the ability of algae to uptake atmospheric nitrogen.

Eutrophication is presently the most important issue for the Vistula Lagoon. In this context all the changes leading to reduced concentration of nutrients is desirable. From this point of view, the Set Aside scenario will have the most positive impact on the lagoon in comparison with other scenarios being analysed. Also the Crisis scenario shows a positive impact on the lagoon. The worst scenario for the lagoon appeared to be the Managed Horizon, for which a significant increase in nitrate and phosphate concentrations, along with an increase of Chl-a concentrations, was predicted. As a result, more intensive algal blooms should be expected if such scenario happens.

Based on the results achieved, it should be recommended to modify the land use composition so as to increase natural retention as well as to reduce fertilization of fields. All environment friendly agriculture should be promoted in the Vistula Lagoon drainage basin. All those technical activities, leading to a reduction of nitrogen and phosphorous loads from diffusive sources into the Vistula Lagoon, should be advised.

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Chapter 2

The Ria de Aveiro Lagoon - Results of climate and ecosystem processes: Report describing results of climate and ecosystem processes

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1. Scenarios

1.1 Climate change scenarios

To address the changes brought about by changes in the climate forcing four different scenarios were simulated for each 30-year time interval: (i) a typical year scenario, serving as reference for that time interval; (ii) a hot summer scenario; (iii) an extreme flood at the end of the dry summer season; and (iv) an extreme winter storm surge.

Water quality was simulated using the Delft3D suite for all four scenarios. For further description of this setup please see Deliverables D6.1 and D6.2. In order to gauge the effect of the flood and surge on the inundation and navigability inside the lagoon, the ELCIRC model (Zhang *et al.*, 2004) was used. This model uses an unstructured mesh resolving the finer details of the lagoon's morphology needed for a correct assessment of the inundation and navigability. The current application of the ELCIRC model was developed and improved in Picado *et al.* (2010) and Lopes *et al.* (2013).

The hot summer scenario consisted in the modelling of a full hydrological year. In order to determine the year in which the summer had exceptionally high temperatures, for each of the 30-year interval first the monthly mean temperatures were calculated, then, for each year, the monthly mean temperatures were averaged to find the summer mean of each year. For each 30-year interval, the 95-percentile threshold of summer mean temperatures was determined to yield 2 years above it. The year closest to the threshold was chosen, provided that it contained no extreme precipitation or draught. Otherwise, the less anomalous year with respect to precipitation was chosen.

In terms of the water quality, the purpose of the extreme flood and surge scenarios was to gauge the lagoon's resilience to: (i) extreme floods at the end of the dry months when concentrations in the catchment are high; and (ii) storm surges at winter time with their associated high river flow but lower concentrations of nutrients and organic matter. For this, a 3-day perturbation was created from the typical year condition, and its development was observed for 3 months.

Extreme river flows were calculated for 6 river inputs by fitting a distribution to each 30-year period, and extracting the 100-year return flow (Q_{100}). The mean 30-year flow for the months October to April was also calculated for each of the periods (Q_{wet}). Concentrations in the rivers were kept from the typical year scenario of each of the periods in order to reflect the

loading increase, higher for autumn conditions. The perturbation in river flow was modelled as a 3-day linear interpolation between Q_{wet} on the first day, Q_{100} on the second day, and back to Q_{wet} on the last day.
Extreme sea surface elevation was adopted with a 100-year return period from analysis of historical data (Picado *et al.*, 2013). The mean sea surface level was perturbed using a sine wave with period of 3 days and amplitude of 1.12 m.
For both autumn and winter conditions, the peak flow was synchronised with the largest tidal amplitude of the season which was less than 0.1 m from the 30-year largest equinoctial tide. For winter conditions, the peak of the surge was also synchronised with the peak of the flow and the largest tidal amplitude.
For the assessment of the navigability and inundation during the extreme flood and surge scenarios, the river runoff and surge were adopted the same as those used in the water quality runs. In addition to using a different model, these runs used the maximum equinoctial tide for each of the 30-year period instead of the largest seasonal spring tide. The runs of the ELCIRC model were carried out for 7-days after the start of the extreme event. Table 1.1 lists the climate change scenarios and their atmospheric and ocean forcing.

Table1.1. Climate change scenarios description.

Scenario ID	Climate periods	Description of scenario	Atmospheric forcing/river input	Ocean boundary
RA-A1	1981 – 2010	Typical reference year	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT
RA-A11	1981 – 2010	Extreme year (hot summer)	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT
RA-A12	1981 – 2010	Extreme event (flood)	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT
RA-A13	1981 – 2010	Extreme event (storm surge)	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT
RA-A2	2011 – 2040	Typical year for the near future	RACMO-KNMI/SWIM	HYCOM/WOA 2009/CERSAT
RA-A21	2011 – 2040	Extreme year (hot summer)	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT
RA-A22	2011-2040	Extreme event (flood)	RACMO-KNMI/SWIM	HYCOM/WOA 2009/CERSAT
RA-A3	2071 – 2098	Typical year for far future	RACMO-KNMI/SWIM	ROMS/WOA20 09/CERSAT
RA-A31	2071 – 2098	Extreme year (hot summer)	RACMO-KNMI/SWIM	ROMS/WOA20 09/CERSAT
RA-A32	2071-2098	Extreme event (flood)	RACMO-KNMI/SWIM	ROMS/WOA20 09/CERSAT
RA-A33	2071-2098	Extreme event (surge)	RACMO-KNMI/SWIM	ROMS/WOA20 09/CERSAT

List of abbreviations:
RACMO-KNMI – Regional Atmospheric Climate Model, Royal Netherlands Meteorological Institute.
SWIM – Soil and Water Integrated Model, Potsdam Institute for Climate Impact Research
HYCOM – Hybrid Coordinates Ocean Model
ROMS – Regional Ocean Model System
WOA2009 – World Ocean Atlas 2009
CERSAT - Centre ERS d'Archivage et de Traitement

1.2 Socio-economic and environmental scenarios

The socio-economic and environmental scenario runs incorporated all of the changes made at the catchment by using the corresponding SWIM model outputs. In addition to this, a decrease in infrastructure maintenance was included in the RA-B2 and RA-C2 scenarios by simulating a 10% leakage in the flow of the interceptor component of wastewater, which will connect to the S. Jacinto marine outfall pipeline. For this, up-to-date 2013 values provided by the utilities company SIMRIA (SIMRIA, 2014) for BOD5 were used to calculate People Equivalents (PE, Arceivala 1998). Once PE was found, Arceivala's (1998) method was used to calculate nutrient and organic load, and 5% was leaked to the lagoon at each of the sources shown in Figure 1.1, by using the flow data for 2013 from SIMRIA (2014). This amounted to 0.1 m^3s^{-1}, 31.2 mgL^{-1} of SPM, 1.4 mgL^{-1} of total nitrogen, and 0.4 mgL^{-1} of total phosphate.

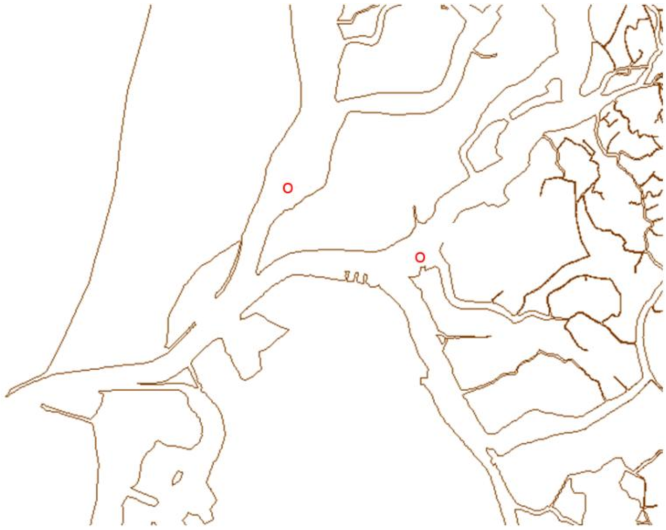

Figure 1.1. Location of chronic leakage in the interceptor component of S. Jacinto marine outfall pipeline.

Given that the management scenarios did not result in river flow differences relevant for the hydrodynamics with respect to the typical scenario, only the RA-B4 scenario was run for the ELCIRC model.

Run RA-C5 is defined as the same conditions of A23, but with the inclusion of the Baixo Vouga Lagunar dike.

In the inundation/flooding simulations using the ELCIRC model, the dike was included for the RA-B4. These results can be applied to the RA-B3, RA-C3 and RA-C4 scenarios representing the *Set-aside* and *Managed Horizons* storylines.

No bathymetry change scenarios were included in either the Delft3D suite or the ELCIRC model runs due to: (i) the unavailability of reliable measurements to quantify and project natural and anthropogenic changes in the bathymetry; and (ii) the current consensus which does not envisage large maintenance dredging operations, restricting those to very localised operations in small harbours and marinas with negligible impacts on the hydrodynamics (Dias *et al.*, 2012).

Table 1.2. Socio-economic and environmental scenarios description.

Scenario ID	Climate periods	Description of scenario	Atmospheric forcing/river input	Ocean boundary
RA-B1	1971 - 2000	BAU	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT
RA-B2	1971 - 2000	CRISIS	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT
RA-B3	1971 - 2000	SET-ASIDE	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT
RA-B4	1971 - 2000	MANAGED HORIZONS	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT
RA-C1	2011 - 2040	BAU combined with climate change	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT
RA-C2	2011 - 2040	CRISIS combined with climate change	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT
RA-C3	2011 - 2040	MANAGED HORIZONS combined with climate change	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT
RA-C4	2011 - 2040	SET ASIDE combined with climate change	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT
RA-C5	2011 - 2040	Same as RA-A23 with the BVL dike	RACMO-KMNI/SWIM	HYCOM/WOA 2009/CERSAT

2. Climate change impact on the lagoon

2.1 Climate forcing

Both the Delft3D-FLOW and the Delft3D-WAQ models used the ENSEMBLES RT2B experiments for their atmospheric boundary condition. From among of all the models used in the ENSEMBLES RT2B experiment, Soares *et al.* (2012) point to the KNMI-RACMO model as the most suitable for the projecting of climate related change within the study area.

For the ocean boundary, salinity and temperature was extracted from a solution of the operational model HYCOM (Cummings, 2005), for the 1981-2010 and 2011-2040 simulation intervals. Given that there was no available solution for these parameters for the mesoscale in the 2011-2040 period and that this solution was applied in the calibration and validation phases with good results, the inclusion of additional unwanted variability was prevented by using the same boundary conditions for both the present and mid-century intervals. The projected effects of climate change at the ocean boundary increase in pace towards the end of the 21st century. Therefore, a ROMS solution from Miranda *et al.* (2013) was chosen as the boundary condition for salinity and water temperature in the 2071-2098 runs. This solution is expected to be more extreme than the A1B storyline adopted for the LAGOONS project, since it uses the more adverse A2 IPCC storyline.

Primary production was forced at the ocean boundary resorting to the CERSAT ocean colour product (CERSAT, 2014). This remote sensing product had good results during the calibration and validation phases. As with salinity and water temperature, in the absence of future projections of chlorophyll-a for this study area, the same series was used for all simulation intervals.

For the prescription of nutrients at the ocean boundary, the World Ocean Atlas of 2009 climatology (Garcia *et al.*, 2010) was used for all simulation intervals.

Tide was forced at the ocean boundary following the same methodology as in the calibration and validation phases (LAGOONS 2014). For the A3 scenario family the 0.34 m mean sea level rise projected by Lopes *et al.* (2013) was included.
At the catchment-lagoon interface, the Delft3D-FLOW and Delft-WAQ models used flows and nutrient concentration from the SWIM model. There were no results for suspended solids from the SWIM, therefore this parameter was modelled based on an empirical function as explained in the D6.2 report (LAGOONS, 2014). For the ELCIRC model used in extreme event simulation, the freshwater flow was synthesised from the flow statistics as described above.
The typical years for the A1 and A2 families have very similar atmospheric forcing. The A3 simulation family was forced by higher air temperature and solar radiation and a drier atmosphere. Table 2.1 shows the minimum, average and maximum values for relative humidity, air temperature, net solar radiation and wind speed and direction for 3 typical years.

Table 2.1. Statistics for boundary forcing.

	Salinity	**Temperature (ºC)**	**Chl-a (mg/l)**	**NO_3-N (mg/l)**	**PO_4-P (mg/l)**	**DOX (mg/l)**
Typical 1981-2010 and 2011-2040	34.90 35.59 36.01	11.20 15.40 0.90	0.00053 0.00106 0.00259	0.007 0.013 0.042	0.001 0.003 0.006	7.21 7.69 8.05
Typical 2071-2098	35.58 35.68 35.73	10.75 12.90 15.15	“	“	“	“

For salinity and water temperature at the ocean boundary, there are clear differences between the A1, A2 runs and the A3 runs. For the end of the century (A3 runs) the water temperature is lower, and salinities have a smaller range due to the stronger and more persistent coastal upwelling (Miranda *et al.*, 2013).

2.2 Loads from catchment

For the full set of ENSEMBLE models, and including all years of each time interval, the input from the catchment showed a moderate decrease in freshwater discharge for the A1 family (-5 to -7%), becoming more pronounced for the end of the century (A3 family, approximately -15% on average). Nutrient load for all nutrients also decreased on average between -5% and -9% for NO_3-N loads, -6% and -18% for NH_4-N, and -3% and -7% for PO_4-P. However, the level of the uncertainty is high within each period and for all 15 driving climate models taken into account. The uncertainty is also shown to increase towards the end of the century.
All nutrient loads increase at the beginning of the hydrological cycle and decrease towards the end as the catchment is flushed, reaching its minimum at the end of the summer. This is common for the three time intervals considered, and for the calibration and validation intervals. Further analysis of the characteristic load of each tributary and their change through the hydrological year is made in the LAGOONS (2014).

2.3 Lagoon's response and discussion

Comparing the typical year of the 1981-2010 interval (RA-A1) with the future typical years (RA-A2, RA-A3), chlorophyll-a has a moderate increase (< 50%) for both the near future and the end of the century. For this last interval, the models project a moderate decrease in DIN. No conclusive change was found for phosphate in either future interval. Figure 2.1 presents the spatial distribution of the changes in chlorophyll-a and nitrates for the RA-A3 scenario, showing that chlorophyll-a increases more in the central part of the lagoon and Ílhavo channel, but decreases in the Mira channel and Laranjo Basin. On the other hand, nitrate decreases rather uniformly throughout the lagoon. A moderate drop in water temperature (2-3 ºC) and a rise in salinity (1 – 5) are projected for the RA-A3 scenario.

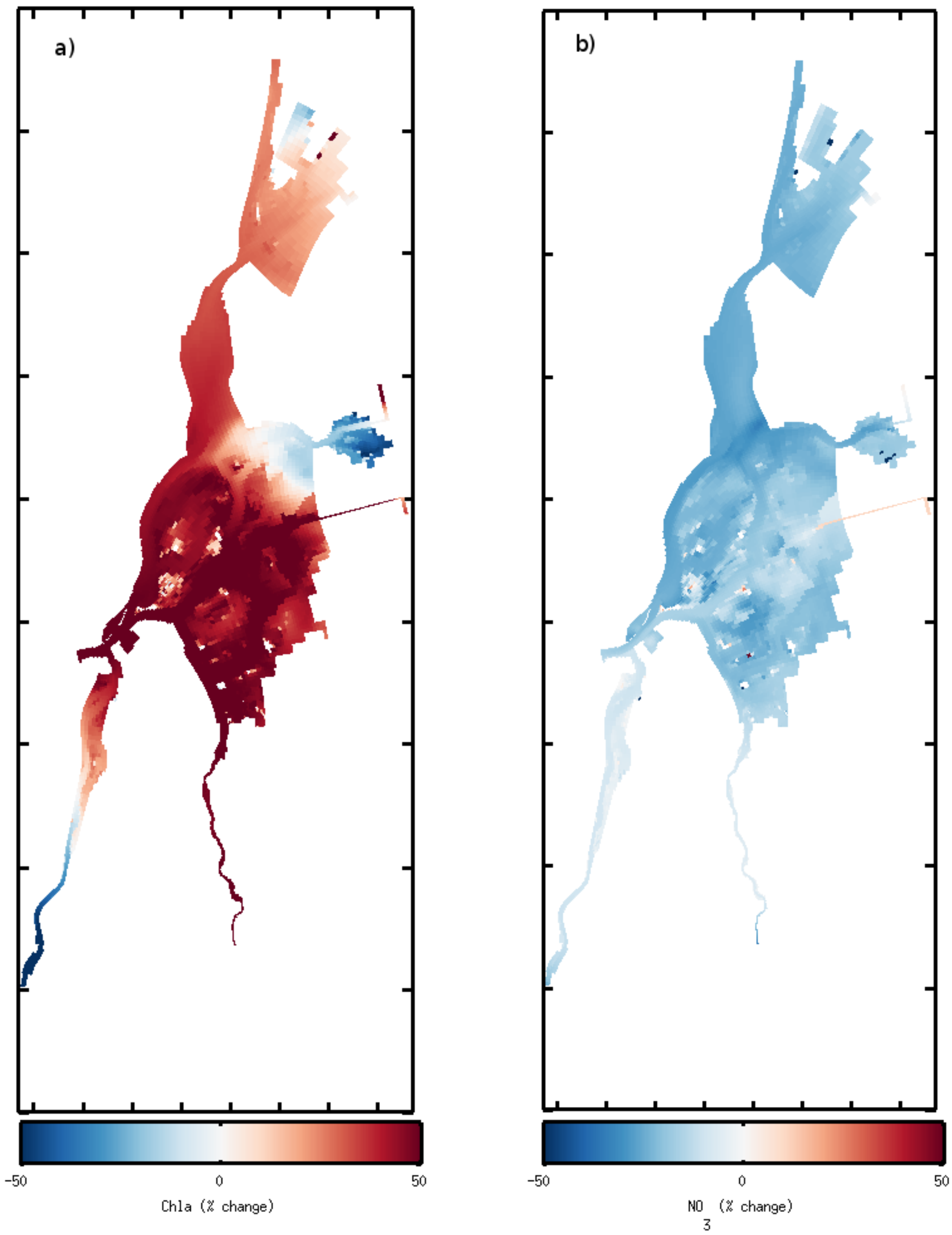

Figure 2.1. Spatial distribution of the difference in chlorophyll-a and NO_3N between RA-A2 and RA-A1 in percent change: (a) chlorophyll-a, (b) NO_3-N.

The hot summer scenarios projects minor inconclusive differences for the present and near future (RA-A11, RA-A21) when comparing with the respective typical year (RA-A1, RA-A2). For the end of the century, the hot summer scenario (RA-A31) projects a moderate increase in salinity and a moderate drop in DIN in comparison with the typical year for the interval (RA-A3). No relevant differences were found between RA-A31 and RA-A3 with respect to water temperature, chlorophyll-a and phosphate. Figure 2.2 shows that salinity rises at the head of the channels where the main freshwater inputs are located.

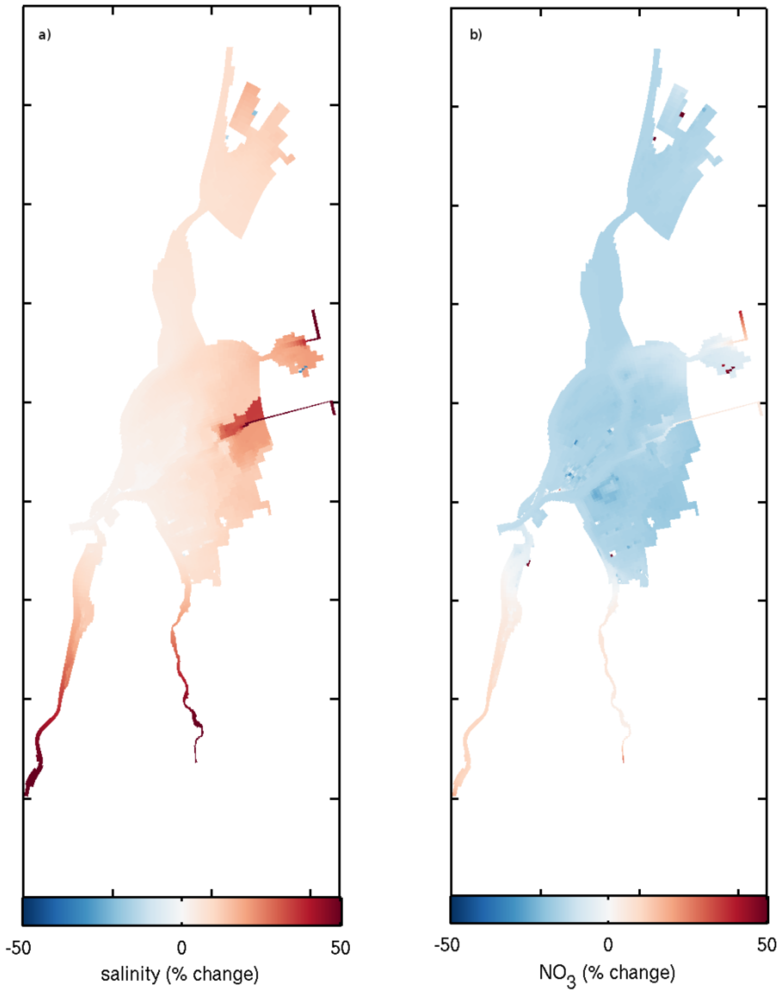

Figure 2.2. Spatial distribution of the difference in salinity and NO_3N between RA-A31 and RA-A3 in percent change: (a) salinity, (b) NO_3-N.

For the extreme flood at the end of the dry summer season, results show an extreme increase in nutrients (Figure 2.3) and a drop in salinity inside the lagoon, with no increase in chlorophyll-a. These river-borne nutrients are quickly flushed from the lagoon by tidal action, converging with the reference scenario within a month after the event (Figure 2.3).

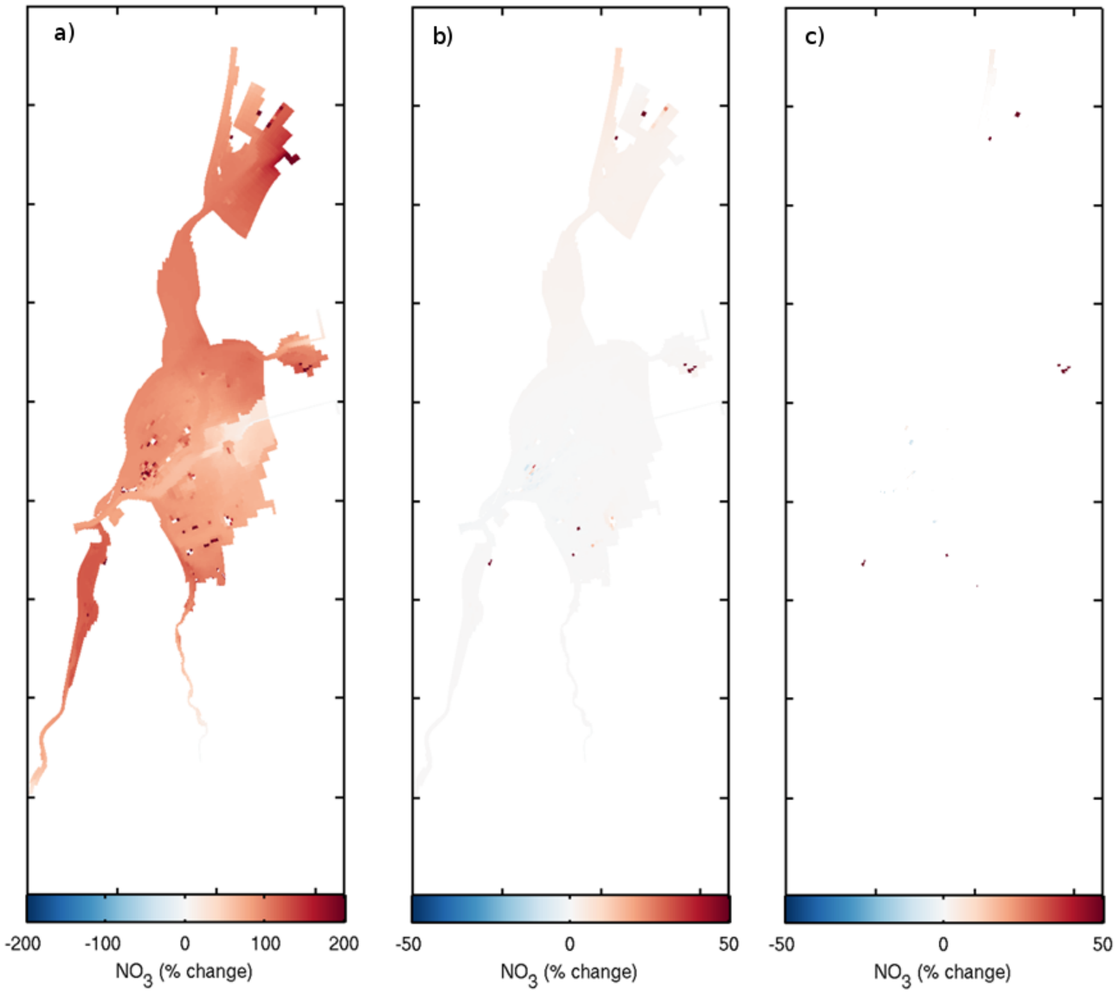

Figure 2.3. Spatial distribution of the difference in NO_3N between RA-A22 and RA-A2 in percent change for the 3 months of the experiment: (a) 1 month after the event, (b) 2 months after the event, (c) 3 months after the event.

For the storm surge event, nutrient concentrations in the lagoon did not increase due to the low winter concentrations in the catchment. The extreme increase in volume through the combined action of the storm surge, the extreme spring tide, and the extreme river flow, leads to a very fast flushing of the freshwater and the incorporation of coastal water soon after the surge relaxation. This fast flushing of the lagoon leads to a drop in chlorophyll-a for both the near future and the end of the century scenarios (RA-A23, RA-A33), which persists until the end of the experiment (Figure 2.4).

With respect to the navigability inside the lagoon, no changes are projected between the present and the near future, given that no differences were applied to the bathymetry between these intervals and the rise in mean sea level is negligible. However, for the end of the century, minor changes are projected due to the rise in mean sea level.

As for the marginal inundation resulting from the tide and an average river flow, the area flooded between the present and the end of the century increases, with special relevance for the area of the Baixo Vouga Lagunar and the Laranjo Basin. For all the intervals analysed, inundation is exacerbated by the flood and storm surge extreme scenarios, with the storm surge leading to a larger inundated area.

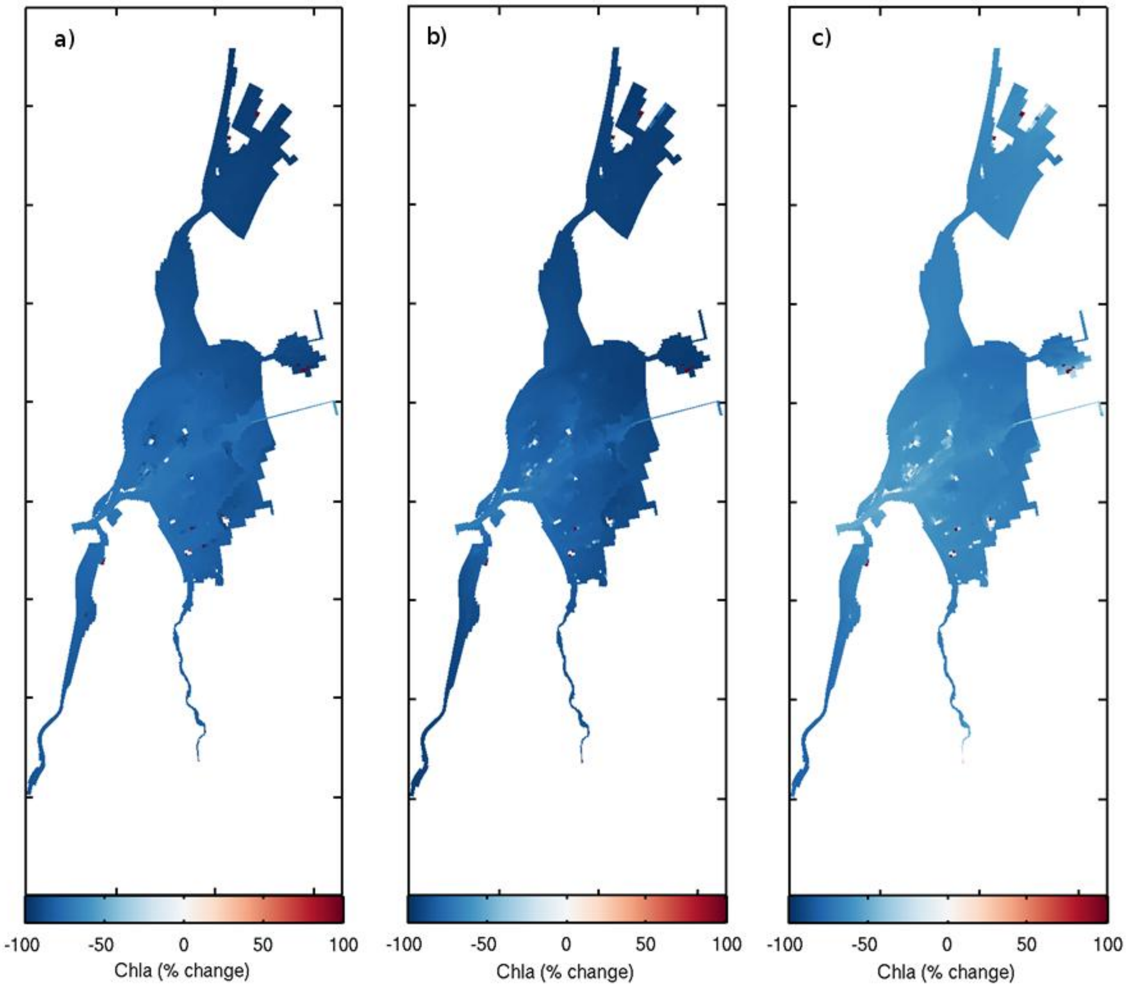

Figure 2.4. Spatial distribution of the difference in chlorophyll-a between RA-A23 and RA-A2 in percent change for the 3 months of the experiment: (a) 1 month after the event, (b) 2 months after the event, (c) 3 months after the event.

3. Combined socio-economic and climate change impact on the lagoon

3.1 Climate forcing

The climate used for the socio-economic runs was the same as the one used for the mid-century runs when the expected socio-economic changes take place. This climate is very similar to the reference scenario 1981-2010. Differences between these mid-century scenarios and the typical year for the 1981-2010 period contain more inter-annual variability than differences attributable to climate change. Hence, the analysis and discussion focus only on the changes produced by the mid-century socio-economic scenarios in comparison to the typical year for the same time interval. The statistics of this forcing are presented in Table 2.1.

3.2 Loads from the catchment and lagoon's response

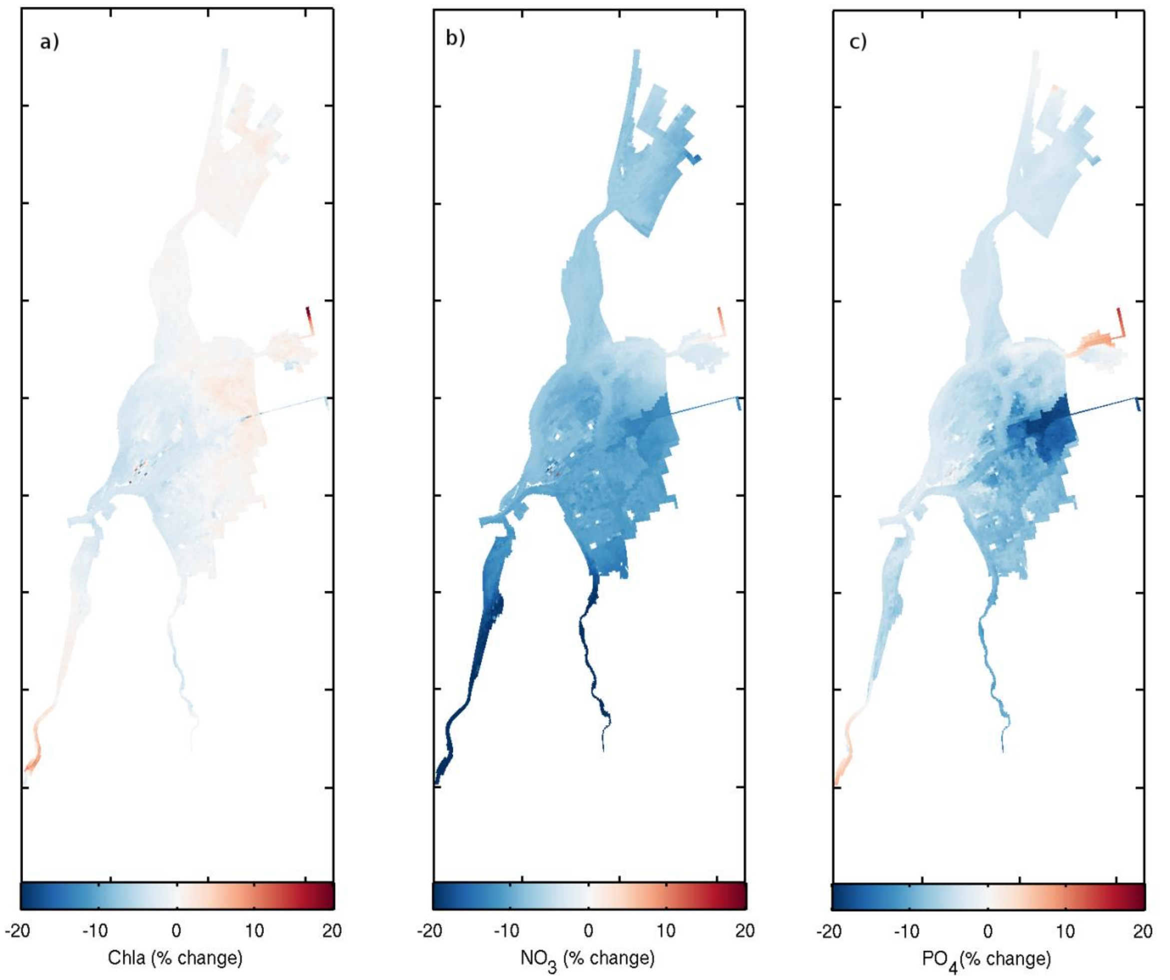

Figure 3.1. Spatial distribution of the difference in chlorophyll-a, NO_3N and phosphate between RA-C2 and RA-A2 in percent change: (a) chlorophyll-a, (b) NO_3N, c) PO_4-P.

Changes in land use in the catchment led to minimal differences in freshwater flow input in the lagoon. These small changes in freshwater flow resulted in negligible changes in the salinity of the lagoon.

For the BAU scenario (RA-C1), the socio-economic storyline projects the present land use trend to the mid-century interval. This leads to a reduction in nutrient input to the lagoon of less than 3%. As a consequence, these changes in the catchment did not produce visible changes in nutrients or chlorophyll-a in the lagoon.

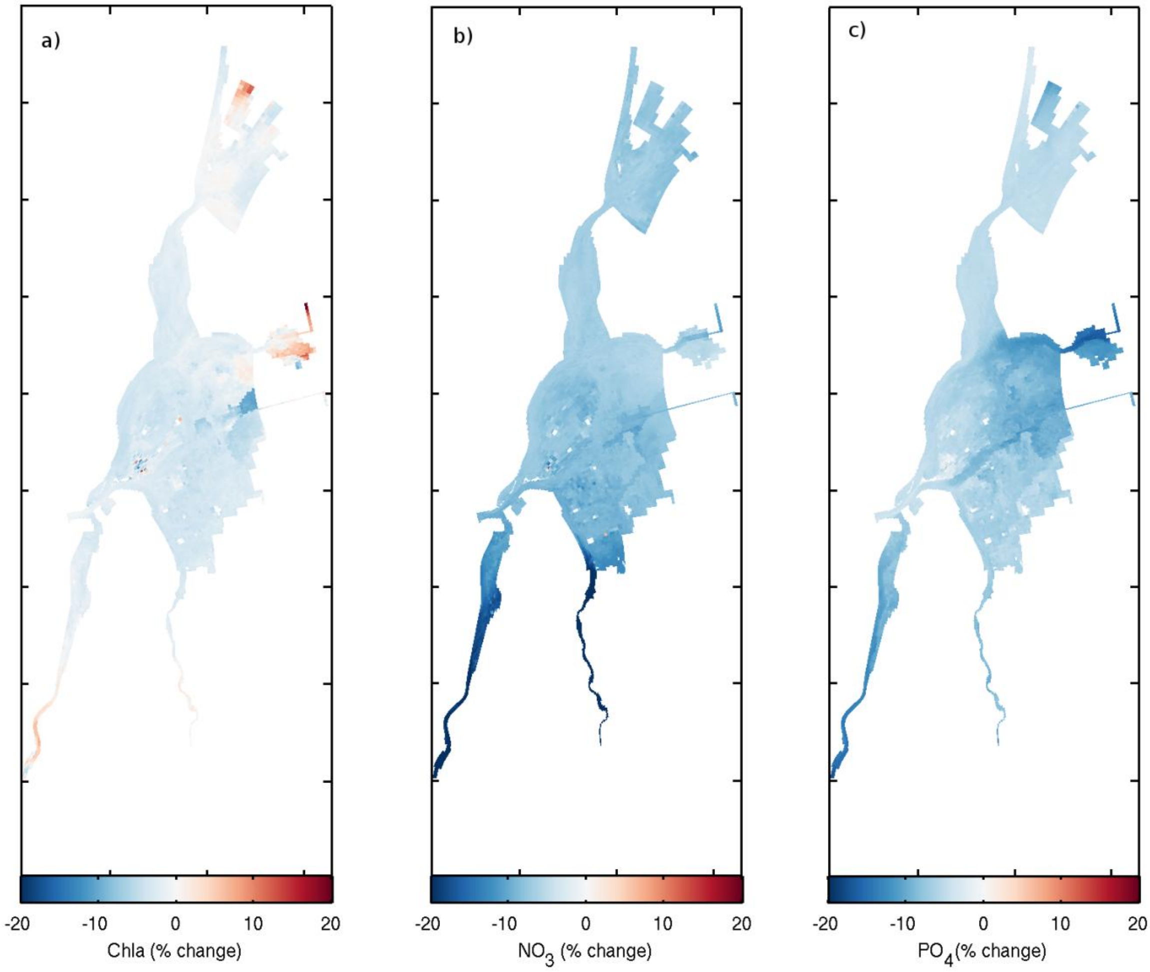

Figure 3.2. Spatial distribution of the difference in chlorophyll-a, NO_3N and phosphate between RA-C2 and RA-A2 in percent change: (a) chlorophyll-a, (b) NO_3N, (c) PO_4-P.

For RA-C2, the economic crisis scenario projects the abandonment of 50% of agricultural land and a 20% decrease in the catchment’s population. These changes in land use lead to a drop of approximately 12% in nitrates, and 7% in phosphates. The results for the lagoon show that this drop has the consequence in a reduction in nitrates of the same order of magnitude, with no relevant overall changes projected for phosphates or chlorophyll-a. Figure 3.1 shows that there is a general drop in nitrate throughout the lagoon for the RA-C2 scenario, with special incidence in the Mira and Ílhavo channels. Despite the overall negligible change in phosphate in most of the volume of the lagoon, in this scenario there is an increase in phosphate at the head of the Mira channel and the Antuã mouth, and a decrease at the head of the Espinheiro channel. The inclusion of the chronic leakage in the S. Jacinto outfall did not produce any changes in water quality in the RA-C2 scenario.

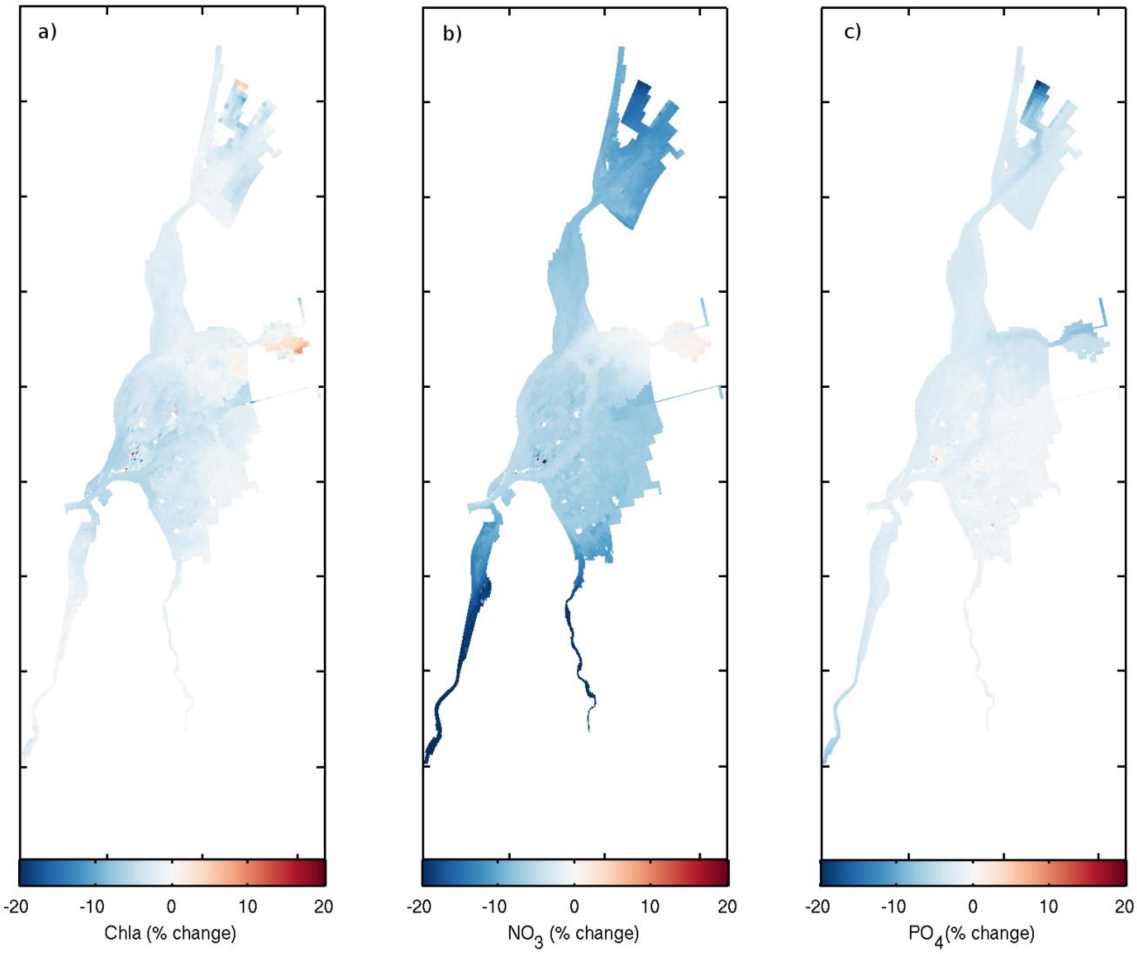

Figure 3.3. Spatial distribution of the difference in chlorophyll-a, NO_3N and phosphate between RA-C2 and RA-A2 in percent change: (a) chlorophyll-a, (b) NO_3N, (c) PO_4-P.

The RA-C3 is based on the set-aside economic scenario which projects a 20% increase in forest area, a 50% decrease of livestock, and a conversion of 50% of agricultural area to fallow land. In terms of practices, heavy impact industries are reduced by 75%, and organic farming increases by 75%. As a whole, these socio-economic changes project a moderate decrease in nutrient load from the catchment: 12% for nitrates and 14% for phosphates. This decrease leads to a general drop of the same order of magnitude in nutrients throughout the lagoon. This drop in nutrient concentration does not lead to a drop in chlorophyll-a.

Table 3.1 - Ranges of relative changes [in %] in Ria de Aveiro compared with RA-A2: salinity and concentration of chlorophyll-a, NO_3-N, NH_4-N, PO_4-P (* - value between -1 and 1).

	Salinity	Chl-a	NO_3-N	NH_4-N	PO_4-P
RA-C1	[*, *]	[*, *]	[-3, 3]	[*, 2]	[-2, -1]
RA-C2	[*, *]	[-2, *]	[-17, -2]	[-5, *]	[-5, 3]
RA-C3	[*, *]	[-3, -1]	[-21, -8]	[-13, 2]	[-15, -6]
RA-C4	[*, *]	[-2, *]	[-13, -2]	[-4, *]	[-10, -1]

The storyline behind the RA-C4 scenario adopts an environmentally managed future, prescribing an increase of 125% in organic farming, and 50 % in irrigation and cereal crops,

keeping the total agricultural area unchanged. In this scenario, heavy impact industries decrease by 20%, and population increases by 10%. When this setup is applied at the catchment, the SWIM model projects small changes in the nutrient load, showing a decrease in nitrates of approximately 8%, and a rise of 4% in phosphates. This variation is not enough to change qualitatively the nutrient balance inside the lagoon, with an exception of the Mira channel, which shows a moderate decrease in nitrate (Figure 3.3). Table 3.1 shows the range of change for each of the scenarios and variables considered.
The conclusion of the Baixo Vouga Lagunar in the RA-C3 and RA-C4 scenarios shows that this structure prevents the flooding of agricultural land by lagoonal water, even during extreme events.

4. Conclusions and recommendations

The short flushing times of Ria de Aveiro, combined with the moderate changes in freshwater and nutrient inputs from the catchment, lead to limited variations in nutrients and chlorophyll-a between the present and the future scenarios, subjected to a different climate. Hence, the differences between typical years for each of 30-year intervals tend to reflect more the inter-annual variability inside those intervals rather than the trend due to the climate change.
A clear conclusion from this study is that the effect of the climate change in the lagoon is mainly felt at the end of the century. The climate forcing differences between the reference climate and the mid-century climate are small. Concurring to this is the usage of the same ocean boundary conditions for both present and mid-century scenarios. The difference in the climate and the justified usage of a different model for ocean boundary conditions lead to larger changes at the end of the century only due to climate forcing.
Exposure to climate forced changes at the shelf will increase with the sea level rise, which in turn leads to an increased water exchange between the lagoon and the adjacent ocean. The projected rise in salinity and the drop in water temperature inside the lagoon, despite the increase in solar radiation, is an example of this exposure to the shelf. The projections for the end of the century for the Northwest Iberian coast (Miranda *et al.*, 2013) show a rise in coastal upwelling caused by increased southward winds, which will lead to the incorporation of deeper, colder and saltier water into the lagoon.
The scenarios derived from the socio-economic storylines yielded mild changes in the nutrient loads discharged from the catchment into the lagoon. The mesotidal semidiurnal and fortnightly cycles of water level and currents inside the Ria de Aveiro lead to a short flushing time. This tidal regime, together with the estuarine circulation, equalises nutrient concentration promoting flushing when river-borne nutrients are discharged in the lagoon and at the same time maintaining a base level of nutrient concentration by tidal resuspension of the benthic nutrient sources.
Apart from the short-lived nutrient peak in the extreme early autumn flood scenarios, the changes in the lagoon were below 50%. Climate scenarios for the end of the century did show higher values than the ones caused by the land use changes in the catchment. With an exception of the flood scenarios, the Water Framework Directive classification of the five water masses of the Ria de Aveiro is not expected to change due to nutrient and chlorophyll-a, for both climate and land use driven scenarios.

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Chapter 3

The Mar Menor Lagoon - Results of combined climate and ecosystem processes: Report describing results of combined climate and ecosystem processes

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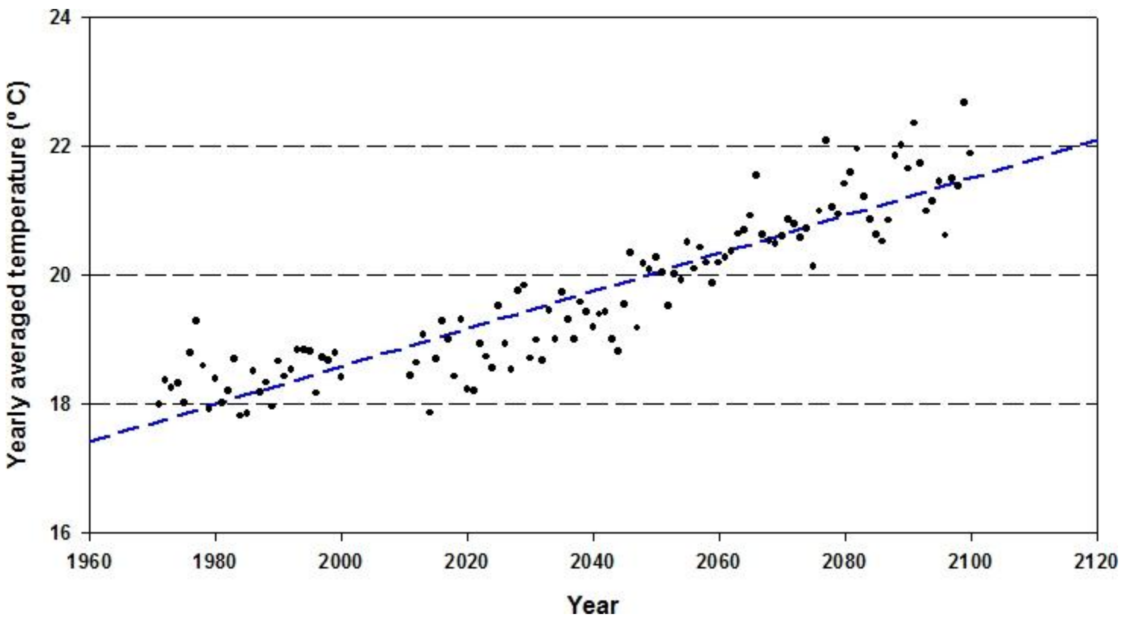
1. Scenarios

1.1 Climate change scenarios

The Mar Menor lagoon is located in a semiarid region of south-eastern Spain. The climate there is characterized by hot summers, mild winters and scarcity of precipitation (below 300 mm/yr) that mainly occurs torrentially during the autumn and winter seasons. Climate change predictions for this particular area highlight an increase in atmospheric temperatures (up to 4 ºC by the end of the century) as well as a clear decrease in precipitation (up to 100 mm by the end of the century) (Figure 1.1.1).

Both, temperature and precipitation, are considered as key climatic variables for the functioning of the Mar Menor lagoon, and are responsible, not only for major hydrodynamic features in this particular area, but also for the observed variations in nutrient concentrations and productive cycles of phytoplankton and benthic macroalgae, determining lagoonal ecosystem functioning.



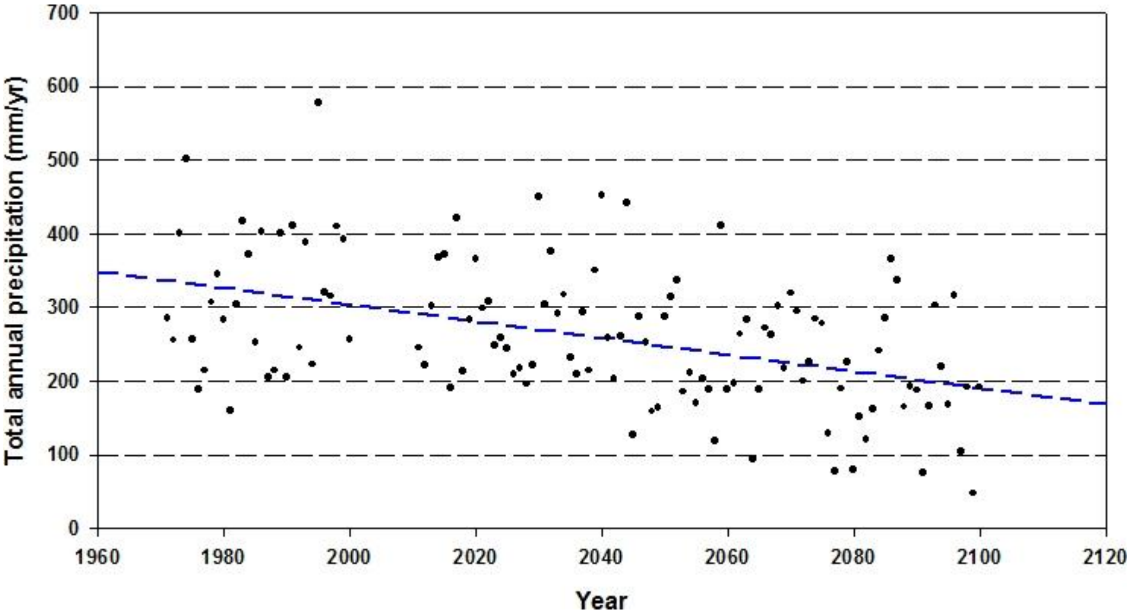


Figure 1.1.1. Evolution of yearly averaged atmospheric temperatures and total annual precipitations from 1970 to 2098 as predicted by M10-ENSEMBLES model for the Mar Menor area. Dashed blue lines represent linear regressions of data.

Precipitations, although scarce, are ultimately responsible for the amount of freshwater inputs entering the lagoon, which mostly occur during storm events. Freshwater inputs are generally low and seem to have little influence on lagoonal water salinity, mostly governed by water exchanges with the adjacent Mediterranean Sea and evaporation rates within the lagoon. Inputs, however, can carry important amounts of nutrients and particulate material that are delivered into the basin and can have a significant effect on lagoonal ecosystems, particularly in the areas located close to the mouth of the wadis (Velasco et al., 2006). Total annual precipitation was therefore selected as one of the main drivers for the selection of climate change scenarios.

Temperatures in the area are generally high, particularly during the summer season, and are expected to continue increasing. Summer temperatures usually reach values above 30 ºC, causing a significant increase in evaporation rates and therefore in lagoonal salinities. Furthermore, water temperatures can reach values as high as 31 ºC during the summer, temperatures that have demonstrated to be critical for benthic primary producers and overall ecosystem functioning (Lloret et al., 2008). Averaged summer temperatures were also selected as a second driver for the selection of climate change scenarios.

On each of the three periods selected for the definition of our climate change scenarios, p0 (1971-2000), p1 (2011-2040) and p3 (2071-2098), a total of five scenarios were defined. First, a ‘typical’ year was chosen in each period by selecting the year with the lowest combined bias from each of the 30-year averaged total annual precipitation and summer temperature. Four ‘extreme’ years were also defined in each period by analysing the distribution of annual precipitation and summer temperature data and selecting the years corresponding to the 5% and 95% percentiles of each distribution to represent the most extreme values of those variables (Table 1.1.1).

Table 1.1.1. Climate change scenarios description.

Scenario ID	Climate periods	Selected year	Description of scenario	Atmospheric forcing/river input	Ocean boundary
MM-p0	1971 - 2000	1980	Typical reference year	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p01	1971 - 2000	1999	Extreme event (hot summer)	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p02	1971 - 2000	1972	Extreme event (cold summer)	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p03	1971 - 2000	1995	Extreme event (wet year)	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p04	1971 - 2000	1976	Extreme event (dry year)	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p1	2011 - 2040	2018	Typical reference year	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p11	2011 - 2040	2035	Extreme event (hot summer)	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p12	2011 - 2040	2014	Extreme event (cold summer)	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p13	2011 - 2040	2040	Extreme event (wet year)	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p14	2011 - 2040	2016	Extreme event (dry year)	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p3	2071 - 2098	2090	Typical reference year	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p31	2071 - 2098	2077	Extreme event (hot summer)	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p32	2071 - 2098	2075	Extreme event (cold summer)	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p33	2071 - 2098	2087	Extreme event (wet year)	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-p34	2071 - 2098	2091	Extreme event (dry year)	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b

List of abbreviations:
M10 – ENSEMBLES M10 model.
IEO – Instituto Español de Oceanografía (Spanish Oceanographic Institute).

1.2 Socio-economic and environmental scenarios

A set of four socio-economic and environmental scenarios were defined for the Mar Menor study area. A description of the story lines and the assumptions made for each of these scenarios can be found in the LAGOONS-Deliverable 4.2. The application of these assumptions allowed us to determine changes in land uses and water management that were fed into our watershed models, resulting in variations in freshwater discharges and nutrient inputs entering the lagoon that were used as input data for our lagoon model.
The atmospheric forcing and the conditions at the ocean boundary were applied by making the same assumptions as those of the 'typical' year for the 2011-2040 period (p1) in all four cases. No other changes were assumed.
Major differences between the various scenarios regard mainly freshwater discharges and nutrient inputs. Compared to the total lagoonal volume, freshwater discharges are extremely

low, and possible future variations in discharges are expected to have little to no effect on lagoon's hydrodynamics and salinity. In contrast, nutrient inputs ultimately determine the relative growth of both phytoplankton and macroalgae in the lagoon. Input variations will, in turn, be reflected in lagoonal concentrations of nutrients, and subsequently, in chlorophyll concentrations and macroalgal biomasses, determining the overall ecosystem functioning and ecological status.

Table 1.2.1. Socio-economic and environmental scenarios description.

Scenario ID	Climate periods	Selected year	Description of scenario	Atmospheric forcing/river input	Ocean boundary
MM-BAU	2011 - 2040	2018	BAU combined with climate change	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-CRI	2011 - 2040	2018	CRISIS combined with climate change	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-MH	2011 - 2040	2018	MANAGED HORIZONS combined with climate change	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b
MM-SET	2011 - 2040	2018	SET ASIDE combined with climate change	M10/SWIM	IEO, Marcos & Tsimplis, 2008a,b

2. Climate change impact on the lagoon

2.1 Climate forcing

Climate forcing on each of the modelled scenarios was defined by the use of ENSEMBLES-M10 daily data for all climatic variables used as inputs in our lagoon model (See LAGOONS-Deliverable 6.2 for a complete list). Differences between the various scenarios clearly represent the main trends of increasing temperatures and decreasing precipitations along the three selected climatic periods for the study area (Figure 2.1.1).

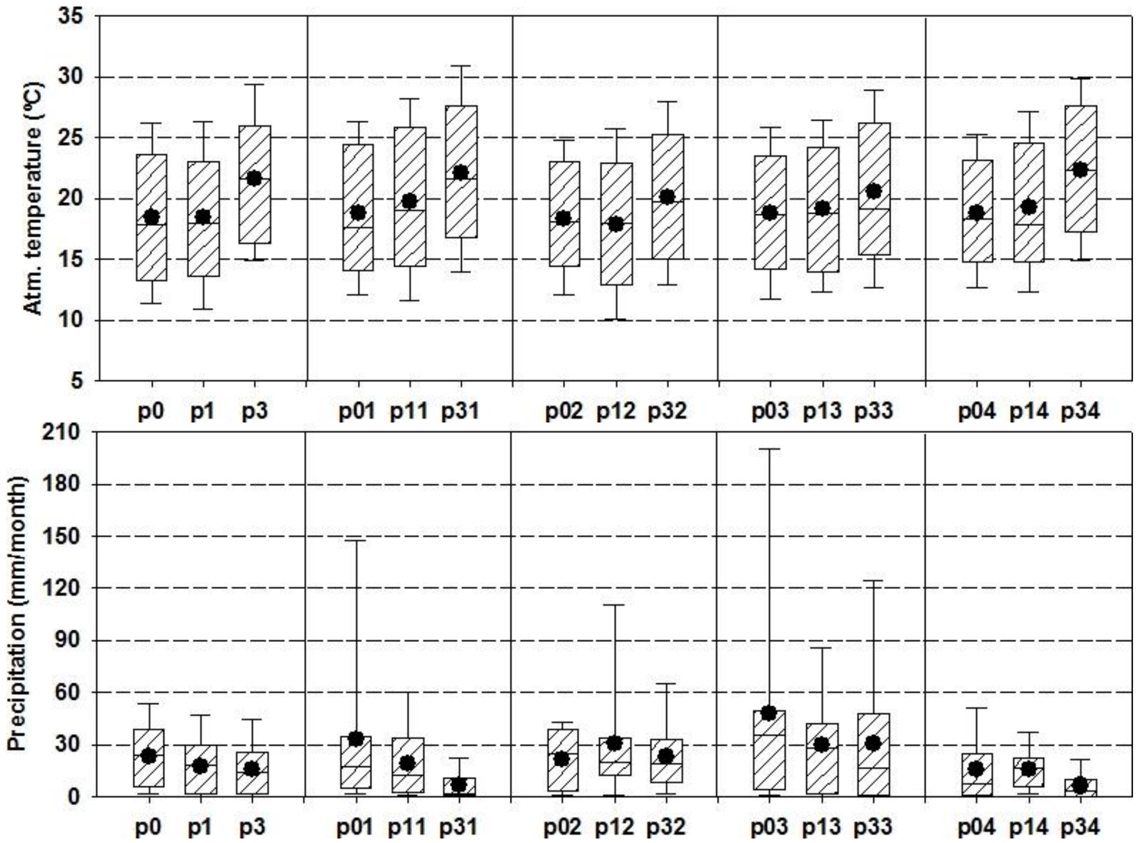


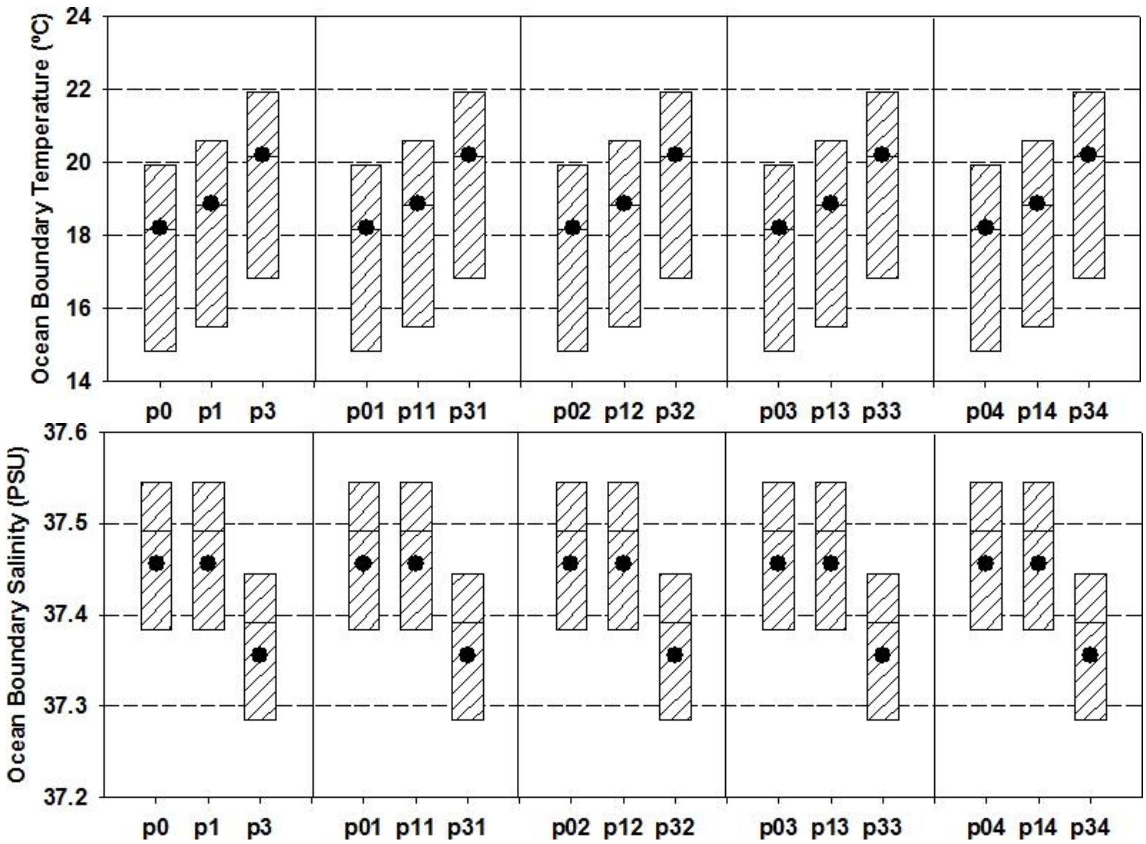
Figure 2.1.1. ENSEMBLES-M10 data for daily atmospheric temperature and monthly precipitation in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

Conditions at the Ocean Boundary in the different selected scenarios were calculated from the annual trends in temperature, salinity and sea level in this particular area of the Mediterranean obtained from various sources, including several reports from the Spanish Oceanographic Institute (IEO) available at www.ieo.es and recent publications on the topic (Marcos & Tsimplis, 2008a,b). These studies confirm an increasing trend for temperature and sea level, but a slight decrease in salinity. Although predictions made for the Mediterranean basin highlight an increase in salinities caused by increased evaporation rates and decreased freshwater inputs, for this particular area, the cited decrease is caused by the increased water exchanges with the Atlantic Ocean (less saline) caused by sea level rise, effects of which are expected to be noted here. Changes in temperature, salinity and sea level were calculated for

the central year in each 30-year period in the future (2025 for p1 and 2085 for p3) and considered the same for each of the five scenarios studied within each period (typical and extreme years). Trends and calculated increases/decreases are presented in Table 2.1.1. Seasonal variations around the yearly average values of temperature and salinity were considered conservative and increases/decreases were applied to the entire sets of data (Figure 2.1.2).

Table 2.1.1. Trends and calculated changes in temperature, salinity and sea level at the Ocean Boundary.

Variable	Trend	2011-2040	2071-2098
Temperature	+ 0.0222 ºC/yr	+ 0.67 ºC	+ 2.00 ºC
Salinity	- 0.0012 PSU/yr	=	- 0.1 PSU
Sea level	+ 0.25 cm/yr	+ 7.5 cm	+ 22.5 cm



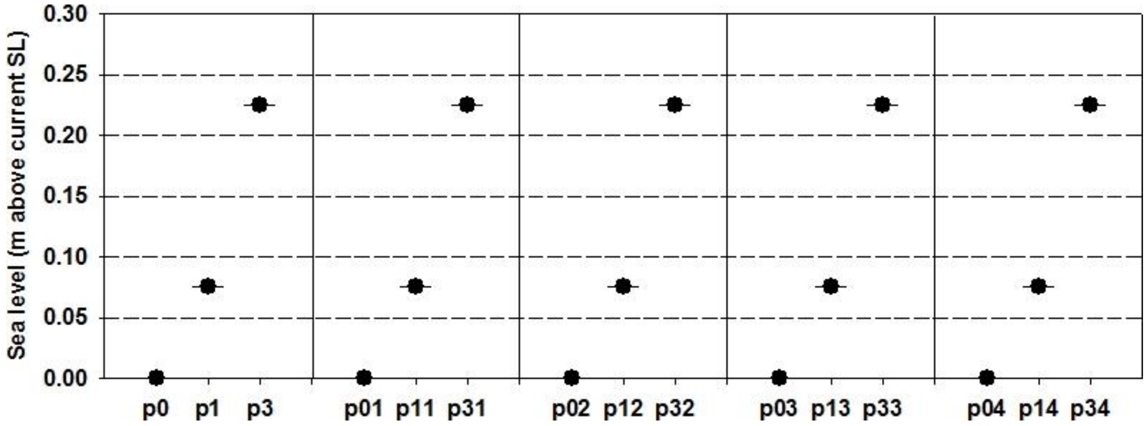


Figure 2.1.2. Calculated values for temperature, salinity and sea level at the Ocean Boundary in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

River discharge data were obtained from SWIM simulations modelled under the same climatic conditions applied for our lagoon model (See LAGOONS-Deliverable 5.1 for details). Variations in river discharges between selected scenarios mostly respond to the observed variation in precipitation data and a general decrease in freshwater inputs entering the lagoon is expected (Figure 2.1.3).

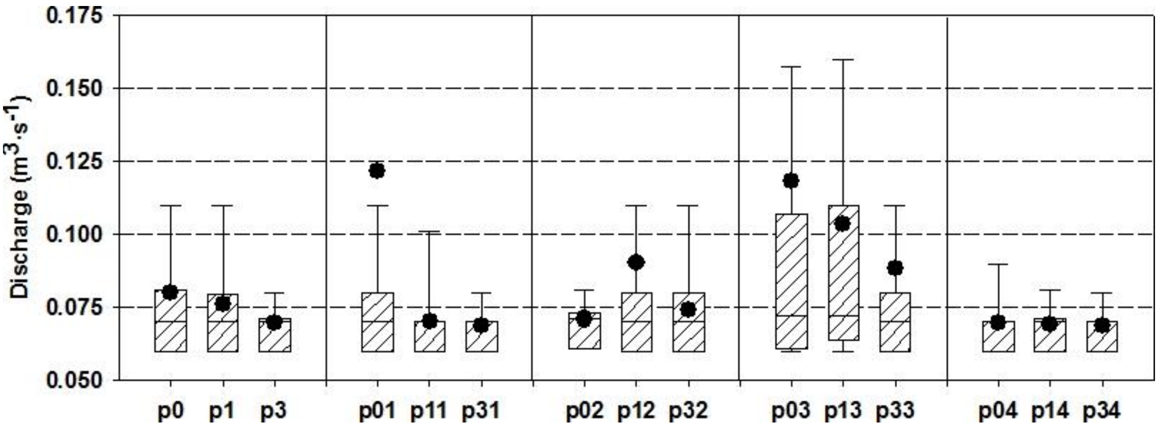


Figure 2.1.3. Variations in daily freshwater discharge values in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

2.2 Loads from catchment

Loads of main inorganic forms of dissolved nutrients (NO_3-N, NH_4-N, PO_4-P) were also obtained from SWIM simulations modelled under the same climatic conditions. Major differences were found for nitrate loads. Nitrate, the major form of inorganic nitrogen entering the lagoon, displays a high interannual variation between the modelled scenarios, variations that are highly dependent on the specific precipitation patterns of the modelled years. In contrast, little variation was found for ammonia and inorganic phosphorus loads, other than a slight decrease in terms of average in the modelled scenarios, as reported in LAGOONS-Deliverable 5.1 (Figure 2.2.1)

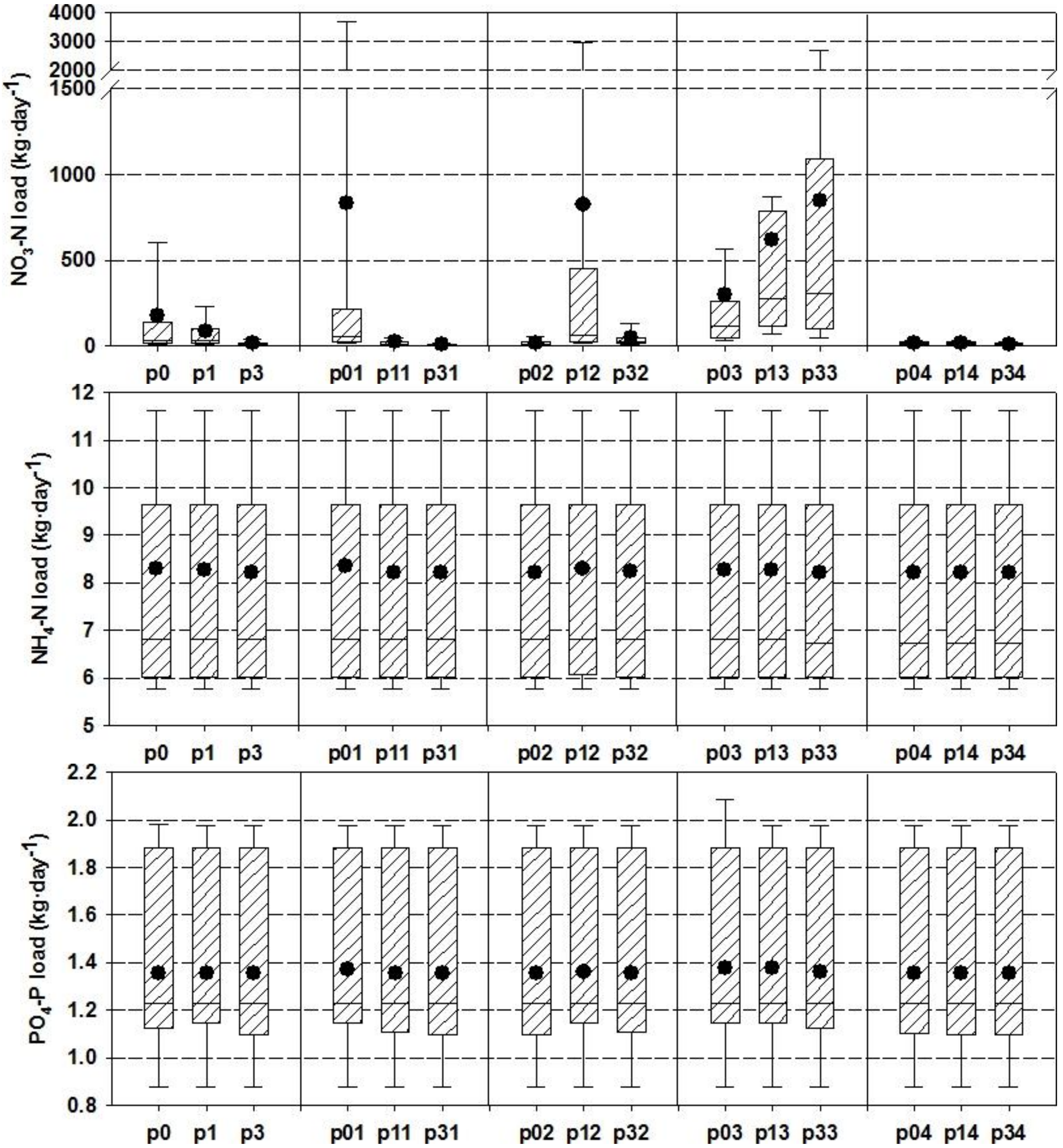


Figure 2.2.1. Variations in daily NO_3,-N, NH_4–N and PO_4-P loads in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

2.3 Lagoon's response and discussion

The impacts of climate change on the Mar Menor lagoon were assessed through the analysis and comparison of modelled time series of main hydrodynamic (temperature, salinity) and water quality (nitrate, inorganic phosphorus, chlorophyll-a, macroalgal biomass) parameters. Due to its particular size and shape, the Mar Menor lagoon was considered as a single big water body and no sub-basins were delineated for the analysis of time series. The analyses were, therefore, carried out upon data integrated for the entire lagoon. However, spatial variability was also assessed by studying the spatial distribution of yearly averaged data for each parameter in order to elucidate possible changes in the main lagoonal environmental gradients.

Temperature

Water temperature in the lagoon ranges from 10 to 30 ºC, displaying a clear seasonal pattern, with minimum temperatures recorded during the winter and maximum during the summer (Figure 2.3.1). Little spatial variability is observed, except for the areas located under the immediate influence of the main inlets, which display a certain effect of the Mediterranean waters entering the lagoon.

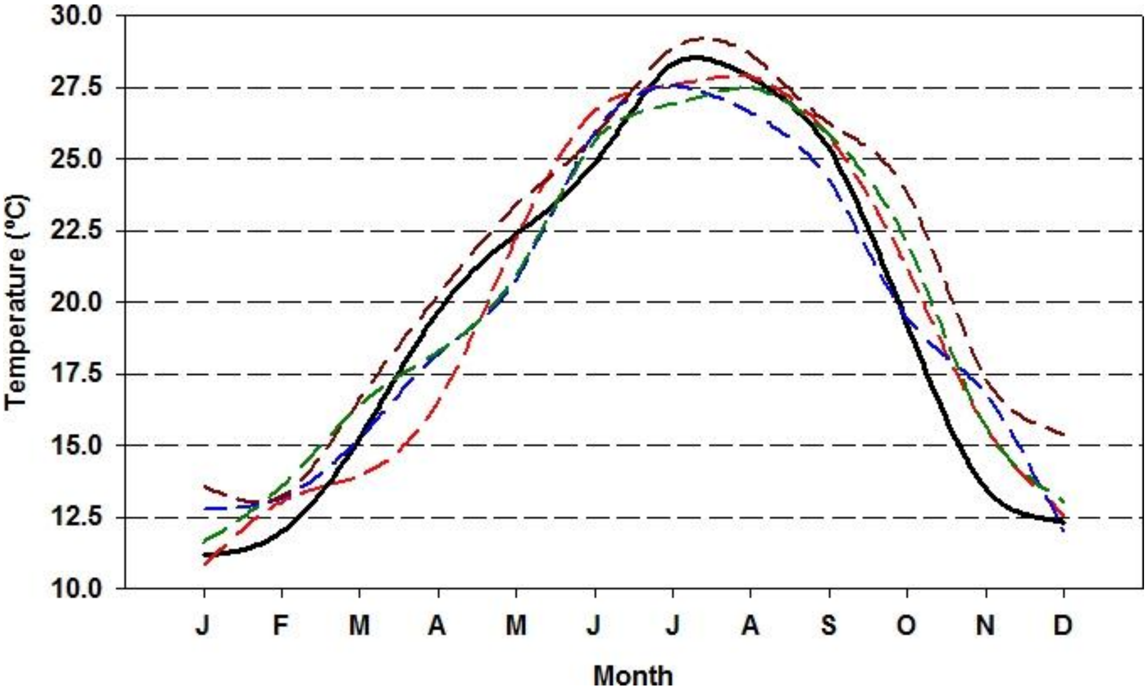


Figure 2.3.1. Computed monthly averaged values for water temperatures in the Mar Menor lagoon in the reference period (p0: solid black line, p01: dashed red line, p02: dashed blue line, p03: dashed brown line, p04: dashed green line).

Temperature in the lagoon is clearly dependent on atmospheric temperatures and, therefore, climate change is expected to cause a significant increase in water temperatures, particularly in those years in which maximum temperatures are recorded (Figure 2.3.2).

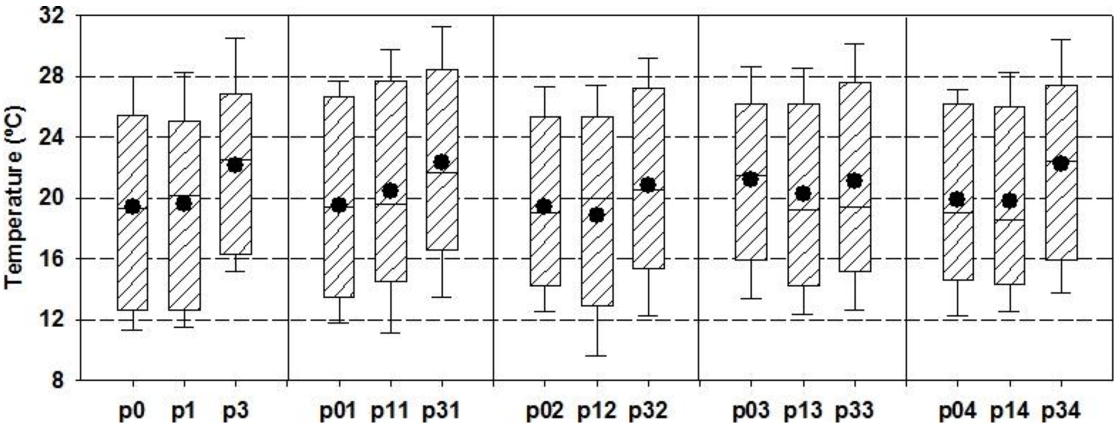


Figure 2.3.2. Variations in daily temperature in the Mar Menor lagoon in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

By the end of the century, the increase in water temperature will be up to 3 ºC in average. This increase in temperature is expected to be noted homogeneously in the entire lagoon (Figure 2.3.3).

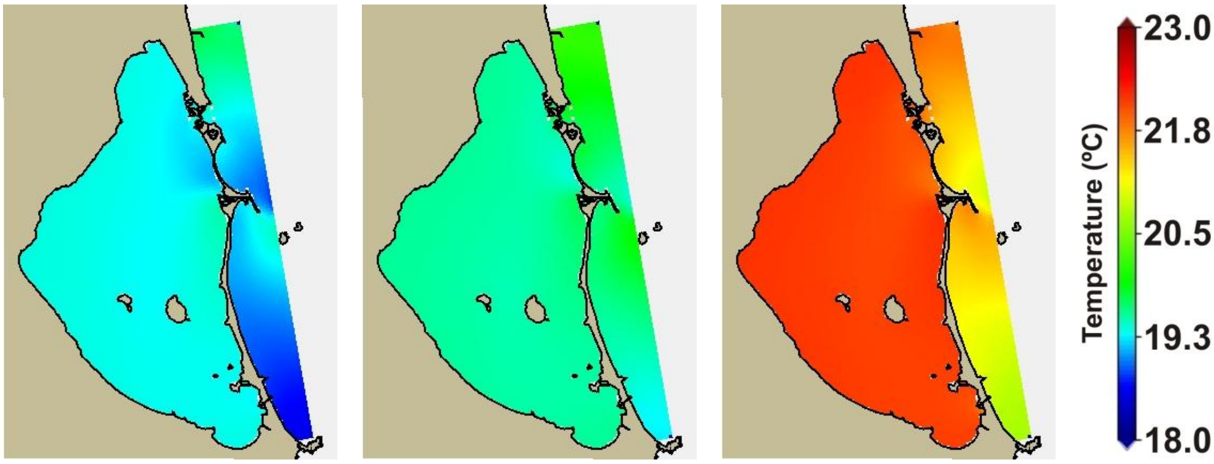
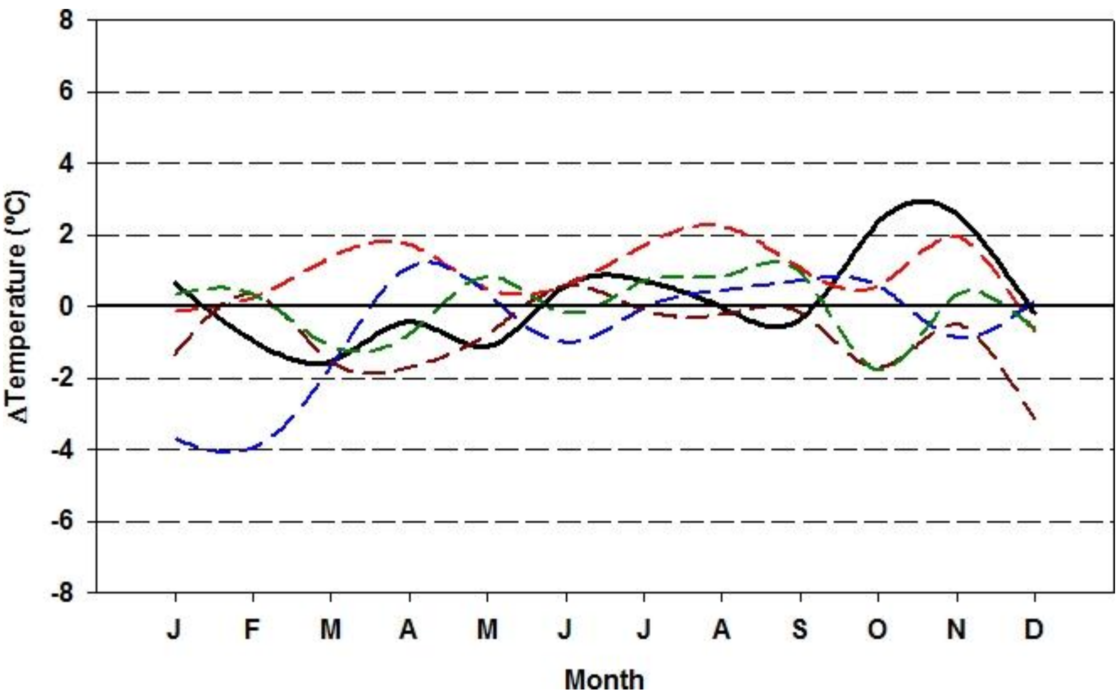


Figure 2.3.3. Spatial distributions of yearly averaged temperature in the lagoon in p0 (left), p1 (centre) and p3 (right) periods.

The increase in temperature will also be evident throughout the year in every season. Temperatures during the winter will become warmer, and summer temperatures will be even more extreme, probably causing a significant increase in evaporation rates during this season. Calculated values for maximum temperatures in the summer during the last years of the century (up to 33-35 ºC) describe a particularly dramatic situation for the overall ecosystem functioning, since these values are considered critical for the survival of benthic macroalgae in the area (Lloret et al., 2008) (Figure 2.3.4).



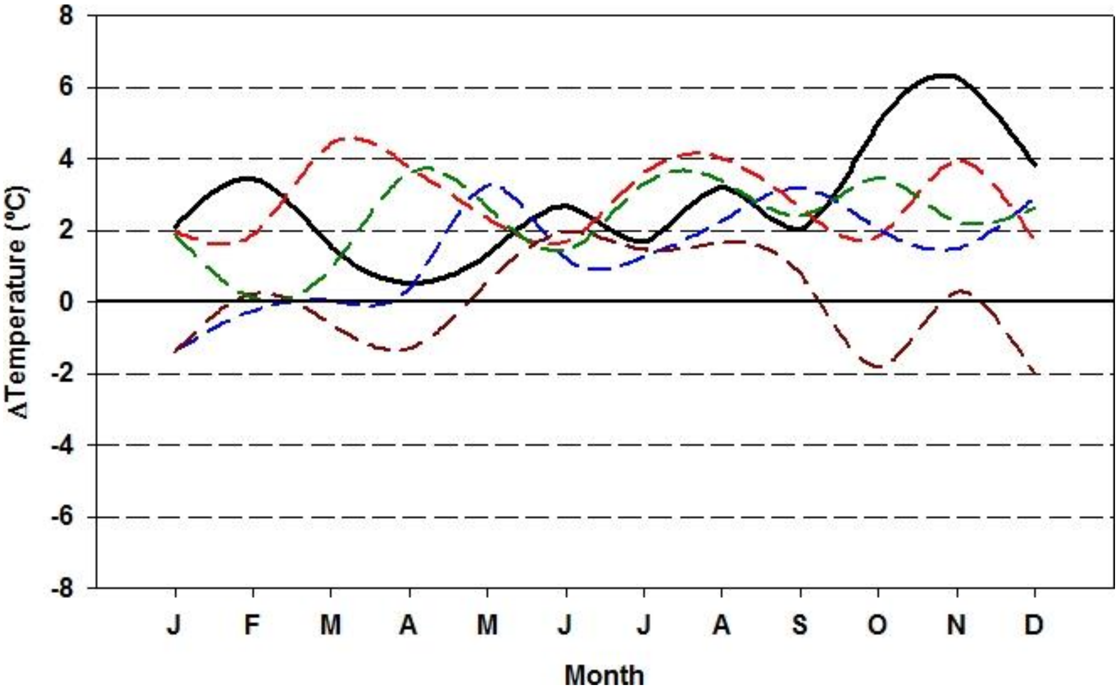


Figure 2.3.4. Differences in monthly averaged water temperatures in the Mar Menor lagoon for the 2011-2040 (top) and 2071-2098 (bottom) scenarios in relation with the equivalent year in the reference period (p0: solid black line, p01: dashed red line, p02: dashed blue line, p03: dashed brown line, p04: dashed green line).

Salinity

Average salinity in the lagoon ranges from 44 to 48 PSU, displaying a clear seasonal pattern, with minimum salinities recorded during the winter and maximum during the end of the summer (Figure 2.3.5). A clear spatial gradient is observed between areas located in the north, under the immediate influence of the main inlets, which display a certain effect of the Mediterranean (less saline) waters entering the lagoon, and southern areas, less influenced by the Mediterranean Sea and with longer residence times.

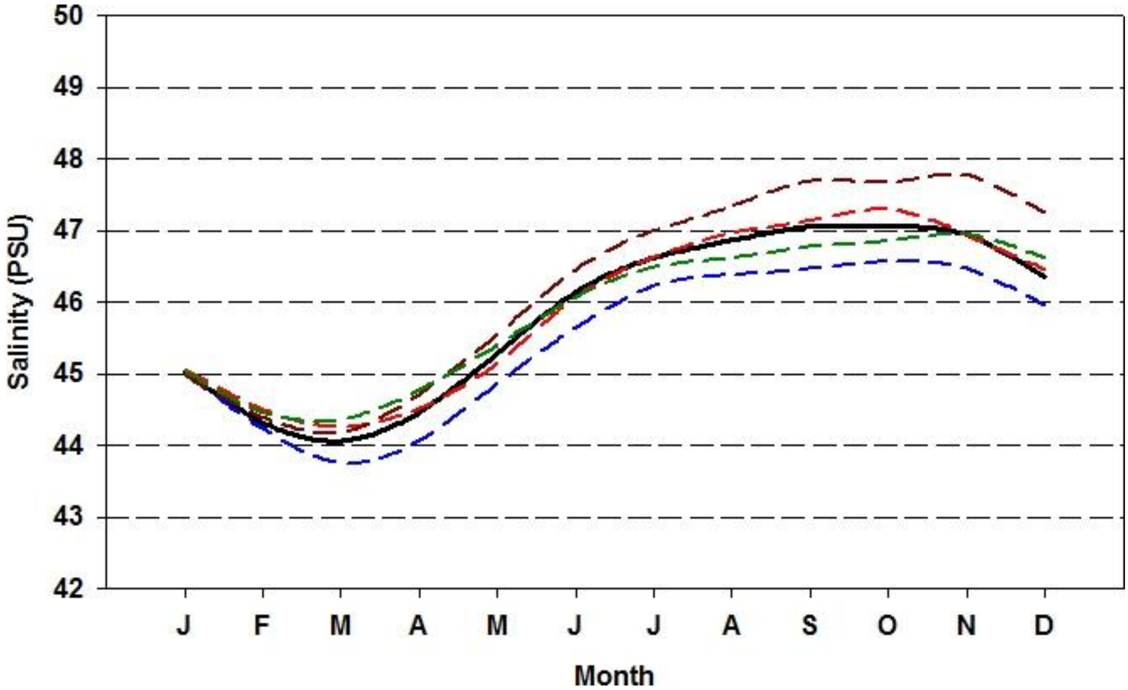


Figure 2.3.5. Computed monthly averaged values for salinity in the Mar Menor lagoon in the reference period (p0: solid black line, p01: dashed red line, p02: dashed blue line, p03: dashed brown line, p04: dashed green line).

Salinity in the lagoon is clearly dependent on atmospheric temperature, which promotes increased evaporation rates, and water exchanges with the Mediterranean. The effect of freshwater inputs is practically null due to the extremely low discharges observed in relation with the total volume of the lagoon. Overall, climate change is expected to cause a decrease in lagoonal salinity, mostly caused by the rise in sea level and the subsequent increase of water exchanges with the Mediterranean Sea. Water residence time is expected to decrease from current 0.79 yr calculated for the reference period, to 0.63 yr for 2011-2040, and 0.51 yr for the 2071-2098 period The expected combined effect of increased temperatures (and evaporation rates) and lower precipitation (and freshwater inputs) is not enough to counteract the effect of decreased water residence time in the lagoon associated with sea level rise (Figure 2.3.6).

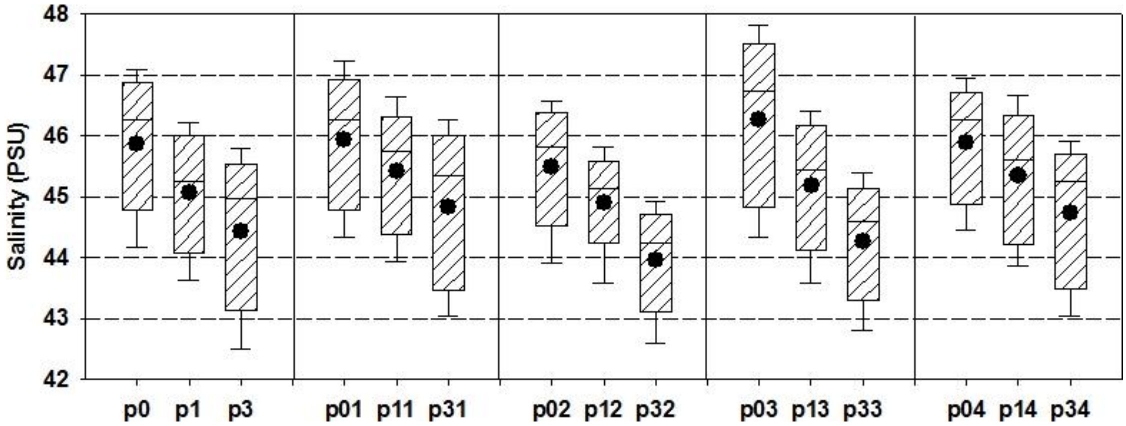


Figure 2.3.6. Variations in daily salinity in the Mar Menor lagoon in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

By the end of the century, the decrease in water salinity will be around 1.5 PSU in average. This decrease in salinity is expected to be noted homogeneously in the entire lagoon (Figure 2.3.7).

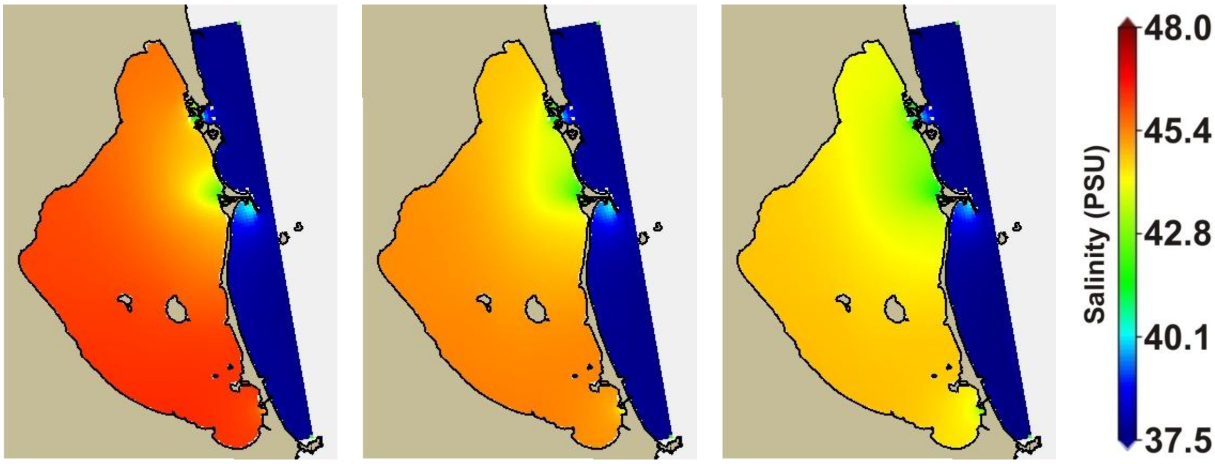
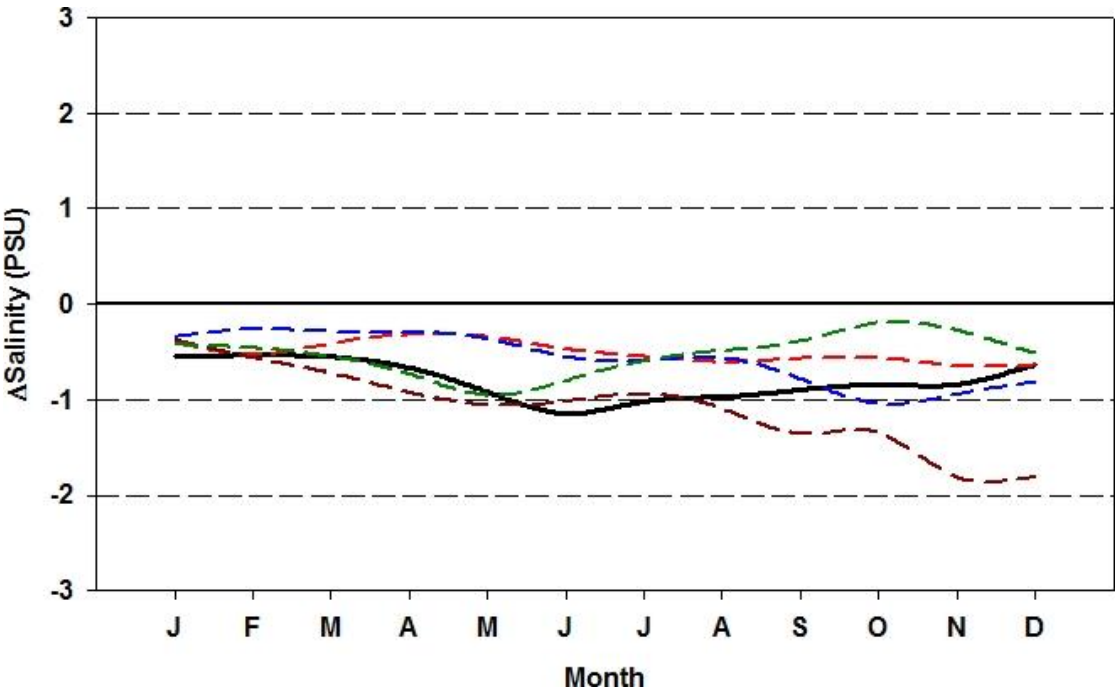


Figure 2.3.7. Spatial distributions of yearly averaged salinity in the lagoon in p0 (left), p1 (centre) and p3 (right) periods.

The decrease in salinity will also be evident throughout the year in every season (Figure 2.3.8). This situation, coupled with the increased water exchanges with the adjacent sea, could promote the colonization of the lagoon by Mediterranean species in a process that can be called 'Mediterraneanisation' of the lagoon. The consequences are difficult to predict, although a similar event occurred during the 70's, when El Estacio inlet was dredged to allow navigation, causing a profound change in lagoonal salinity ranges and allowing the colonization of the lagoon by Mediterranean species, such as the macroalga *Caulerpa prolifera*.



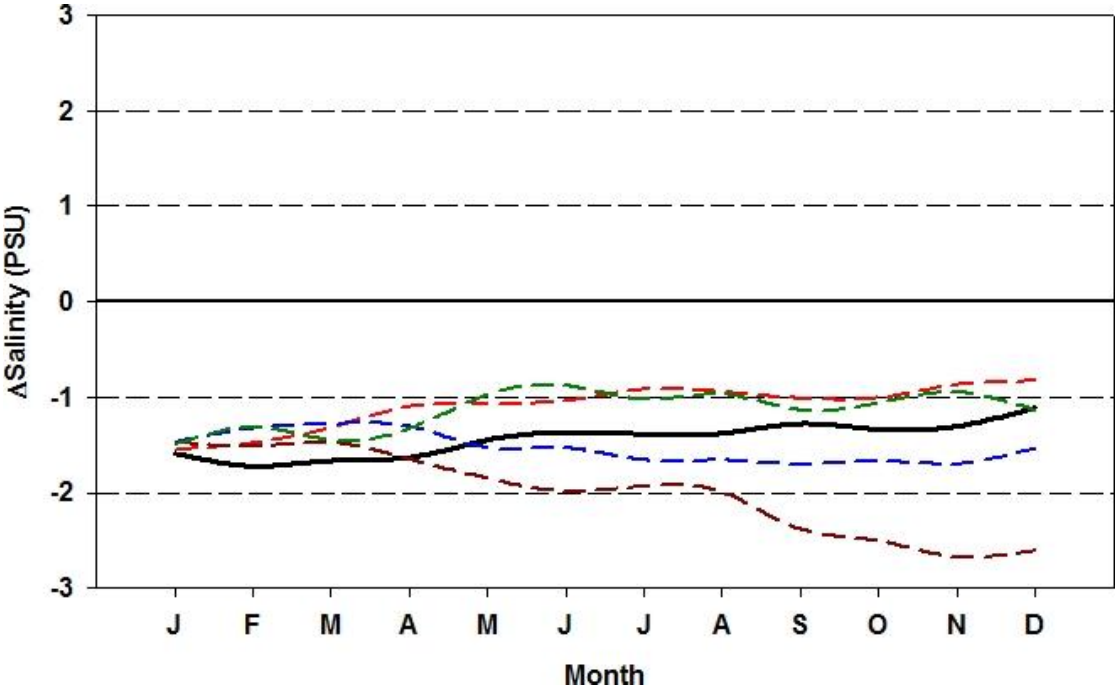


Figure 2.3.8. Differences in monthly averaged salinities in the Mar Menor lagoon for the 2011-2040 (top) and 2071-2098 (bottom) scenarios in relation with the equivalent year in the reference period (p0: solid black line, p01: dashed red line, p02: dashed blue line, p03: dashed brown line, p04: dashed green line).

Nutrient concentrations

NO_3-N concentrations in the lagoon are usually low in average, displaying a clear seasonal pattern with minimum concentrations recorded during the summer and maximum during the rainy season in autumn and winter, when major inputs occur (Figure 2.3.9). A clear spatial gradient is observed between the areas located at the mouth of El Albujon wadi, under the immediate influence of the inputs, and the areas located far from the influence of terrestrial discharges.

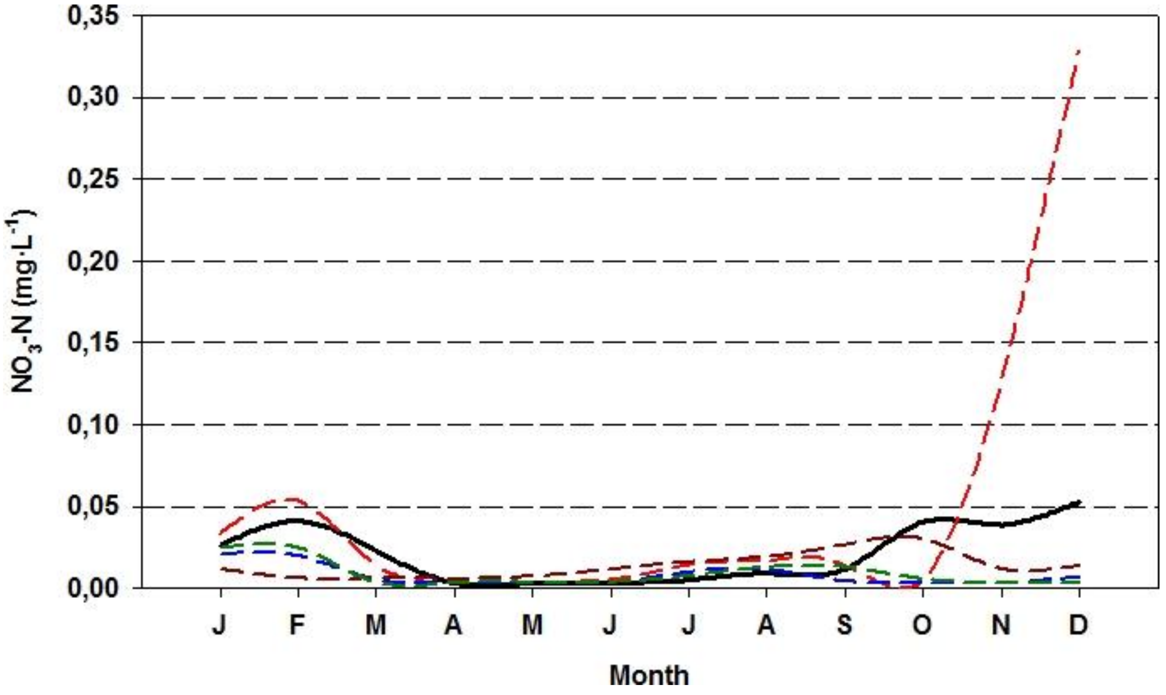


Figure 2.3.9. Computed monthly averaged values for NO_3-N concentrations in the Mar Menor lagoon in the reference period (p0: solid black line, p01: dashed red line, p02: dashed blue line, p03: dashed brown line, p04: dashed green line).

Apart from the clear seasonal pattern, NO_3-N concentrations in the lagoon are highly dependent on inputs, both in terms of total annual inputs as well as the occurrence of extreme precipitation events that originate episodic freshwater runoffs, introducing high amounts of nitrogen compounds and suspended sediments into the lagoon. As a result, NO_3-N interannual variability can be high. Overall, climate change is expected to cause a very slight decrease in lagoonal NO_3-N concentrations for 'typical' years, caused by a parallel decrease in inputs. However, interannual variability may increase, as extreme events become more frequent and/or of higher magnitude as climate change aggravates (Figure 2.3.10).

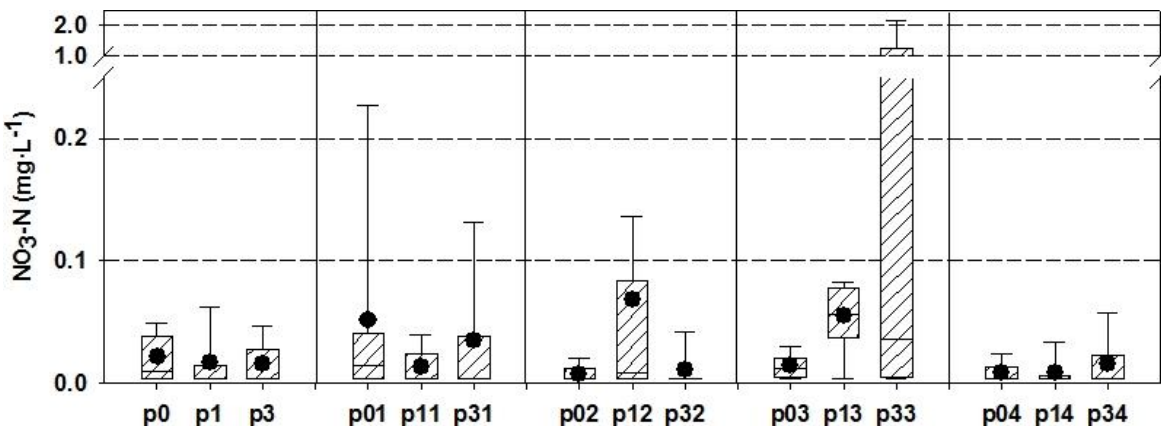


Figure 2.3.10. Variations in daily NO_3-N concentrations in the Mar Menor lagoon in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

By the end of the century, the above-mentioned slight decrease in NO_3-N concentrations for the 'typical' years in each analysed period will be noted as a decrease in the magnitude of the environmental gradients in the lagoon. The effect becomes more evident for the areas located under the influence of the inputs (Figure 2.3.11).

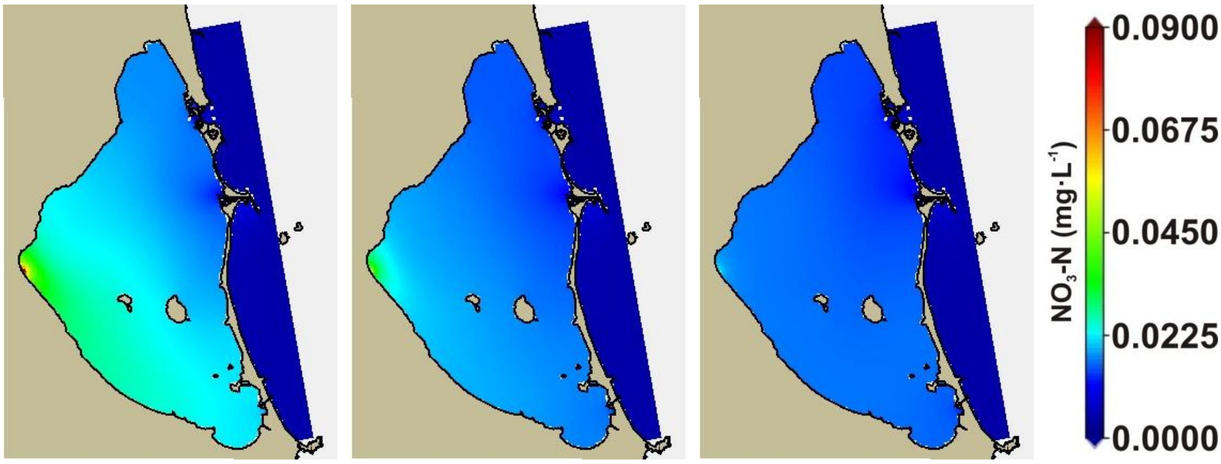
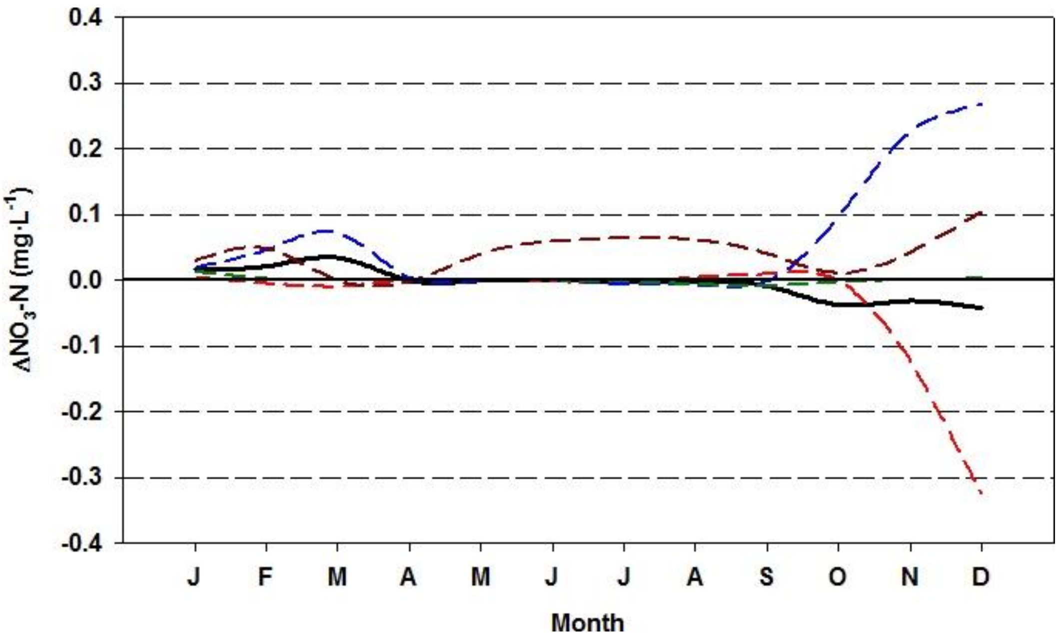


Figure 2.3.11. Spatial distributions of yearly averaged NO_3-N concentrations in the lagoon in p0 (left), p1 (centre) and p3 (right) periods.

Variability in NO_3-N concentrations becomes more evident by the end of the summer and during the autumn season for both climate scenarios analysed. To an extent, this variability could be considered 'natural' and linked to interannual variability in total annual inputs and the magnitude and occurrence of extreme precipitation events (Figure 2.3.12). However the magnitude of these changes is expected to increase by the end of the century, particularly for extremely rainy years (p33). These 'peaking' concentrations in the lagoon may have a cumulative impact in the lagoon if the situation persists, leading to eutrophication and loss of overall water quality.



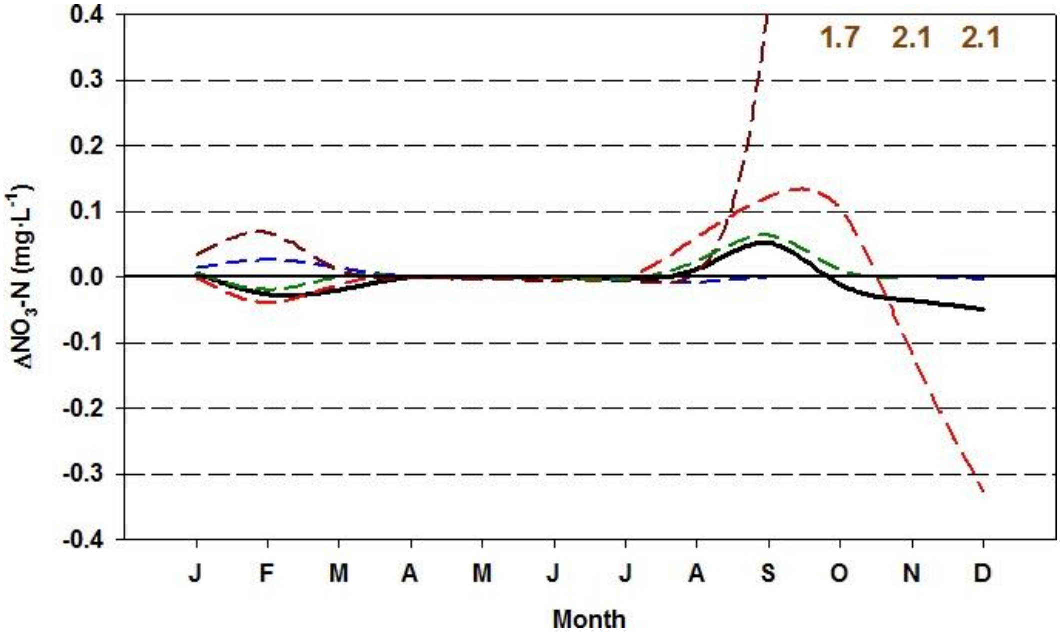


Figure 2.3.12. Differences in monthly averaged NO_3-N concentrations in the Mar Menor lagoon for the 2011-2040 (top) and 2071-2098 (bottom) scenarios in relation with the equivalent year in the reference period (p0: solid black line, p01: dashed red line, p02: dashed blue line, p03: dashed brown line, p04: dashed green line).

PO_4-P concentrations in the lagoon are very low in average, displaying a clear seasonal pattern with minimum concentrations recorded during the summer and maximum during the winter (Figure 2.3.13). A clear spatial gradient is observed between the areas located at the mouth of El Albujon wadi, under the immediate influence of the inputs, and the areas located far from the influence of terrestrial discharges.

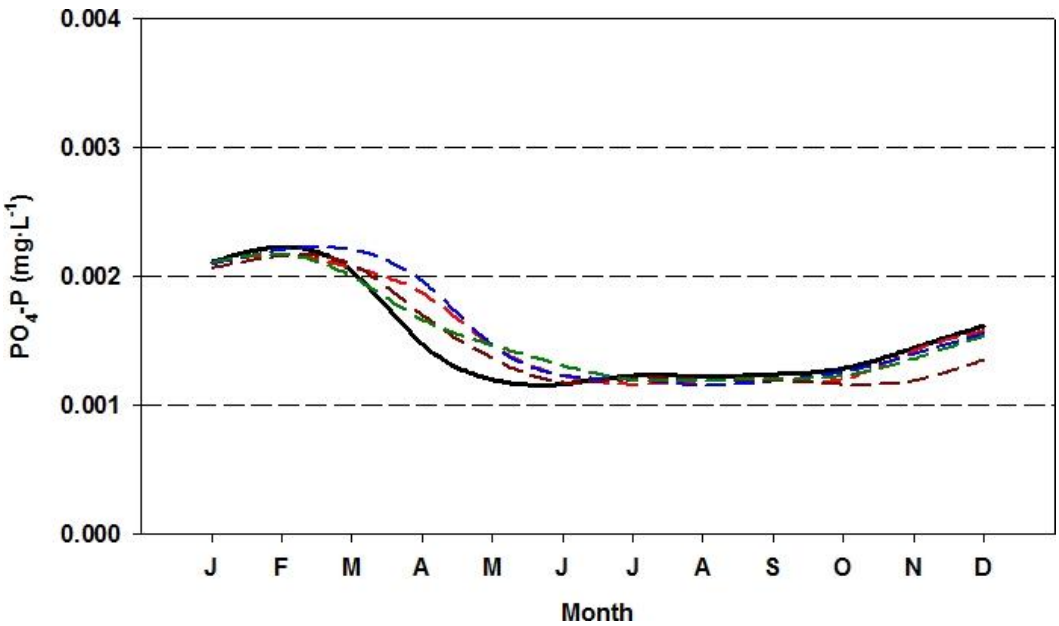


Figure 2.3.13. Computed monthly averaged values for PO_4-P concentrations in the Mar Menor lagoon in the reference period (p0: solid black line, p01: dashed red line, p02: dashed blue line, p03: dashed brown line, p04: dashed green line).

Climate change is expected to cause a very slight decrease in lagoonal PO_4-P concentrations for all analysed years, 'typical' and 'extreme', caused by a parallel decrease in inputs (Figure 2.3.14).

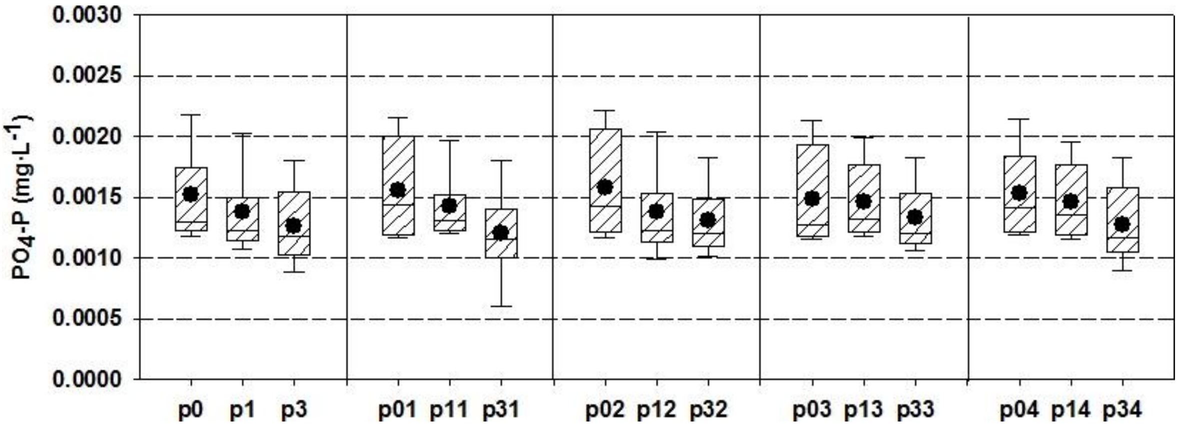


Figure 2.3.14. Variations in daily PO_4-P concentrations in the Mar Menor lagoon in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

The slight decrease in PO_4-P concentrations in average will be probably evident only for the areas located under the direct influence of the inputs, while for the rest of the lagoon concentrations are expected to remain similar to those found during the reference period (Figure 2.3.15).

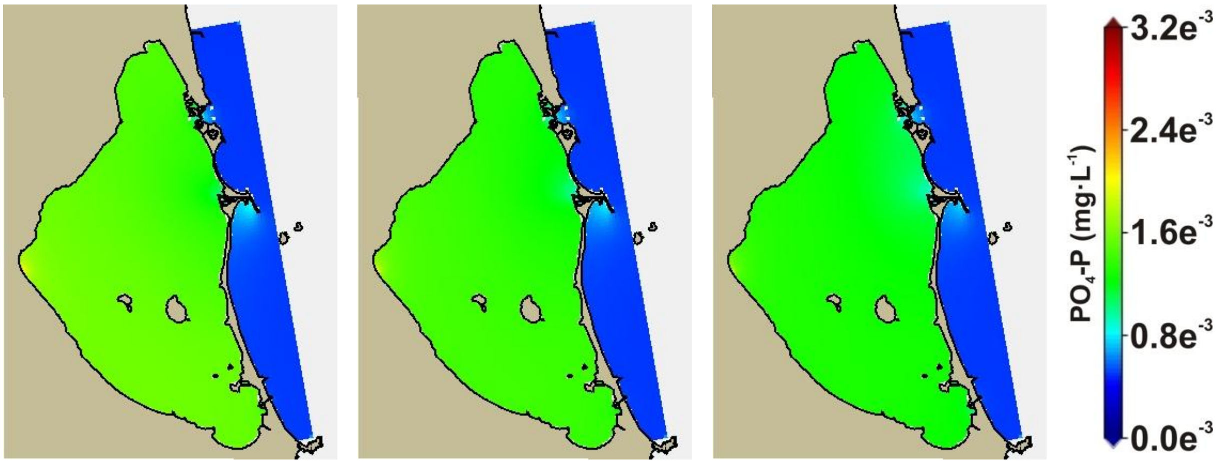


Figure 2.3.15. Spatial distributions of yearly averaged PO_4-P concentrations in the lagoon in p0 (left), p1 (centre) and p3 (right) periods.

Monthly variability in PO_3-P concentrations are mostly observed during the spring for the 2011-2040 analysed scenarios. This variability can be considered 'natural' and linked to differences in the starting of phytoplankton/macroalgae growing seasons and variability in the temperature records for analysed years. However, for the 2071-2098 period, a second period of variability can be also found by the end of summer. This fact can be explained by an increase in phytoplankton densities during these months, which most likely cause PO_4 depletion in the lagoon (Figure 2.3.16).

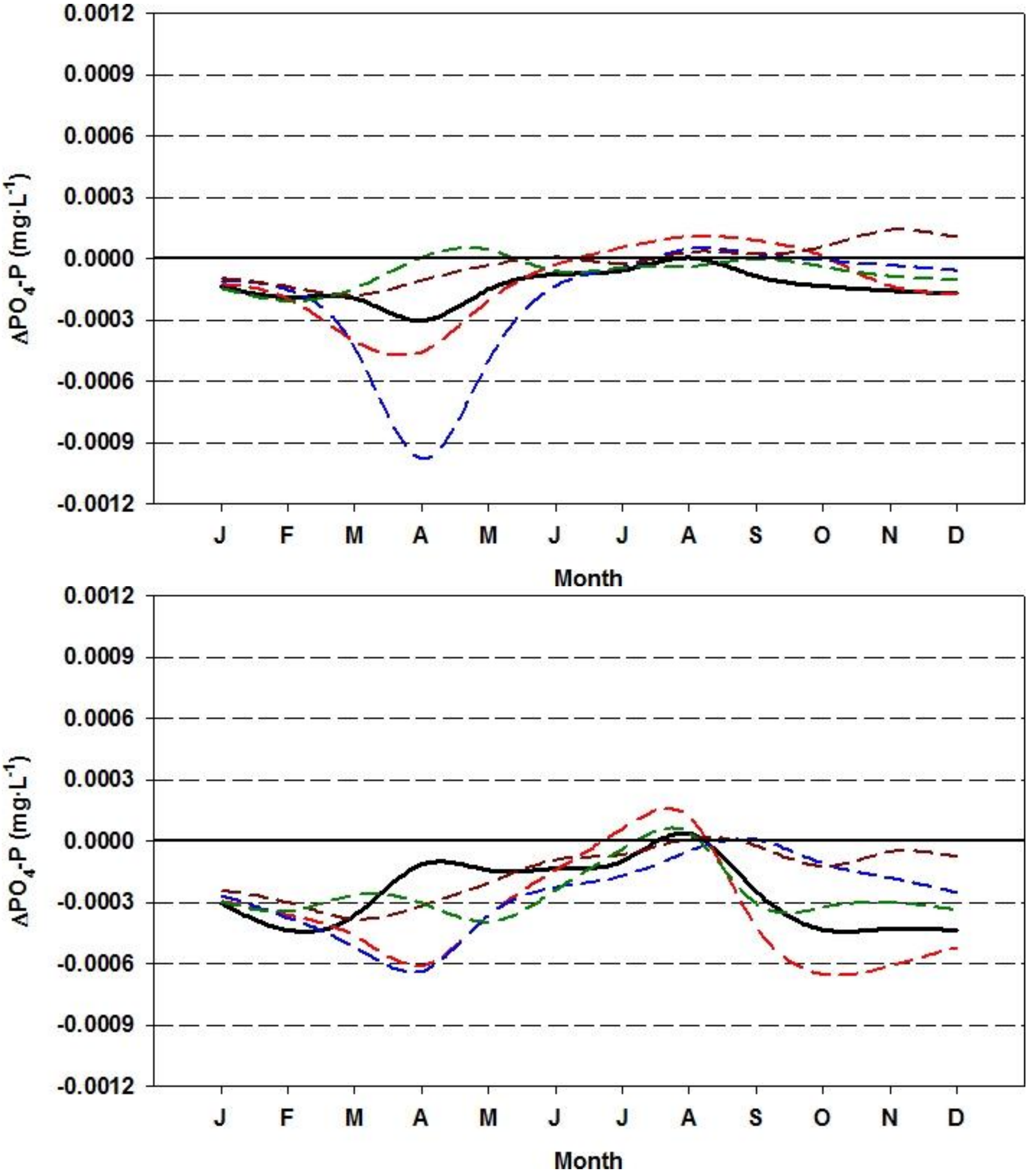


Figure 2.3.16. Differences in monthly averaged PO_4-P concentrations in the Mar Menor lagoon for the 2011-2040 (top) and 2071-2098 (bottom) scenarios in relation with the equivalent year in the reference period (p0: solid black line, p01: dashed red line, p02: dashed blue line, p03: dashed brown line, p04: dashed green line).

Chlorophyll-a concentrations

Chl-*a* concentrations in the lagoon are usually low in average, displaying a clear seasonal pattern, with minimum concentrations recorded during the winter and maximum during the spring and summer seasons (Figure 2.3.17). A clear spatial gradient is observed between the areas located at the mouth of El Albujon wadi, under the immediate influence of nutrient inputs, and the areas located far from the influence of terrestrial discharges.

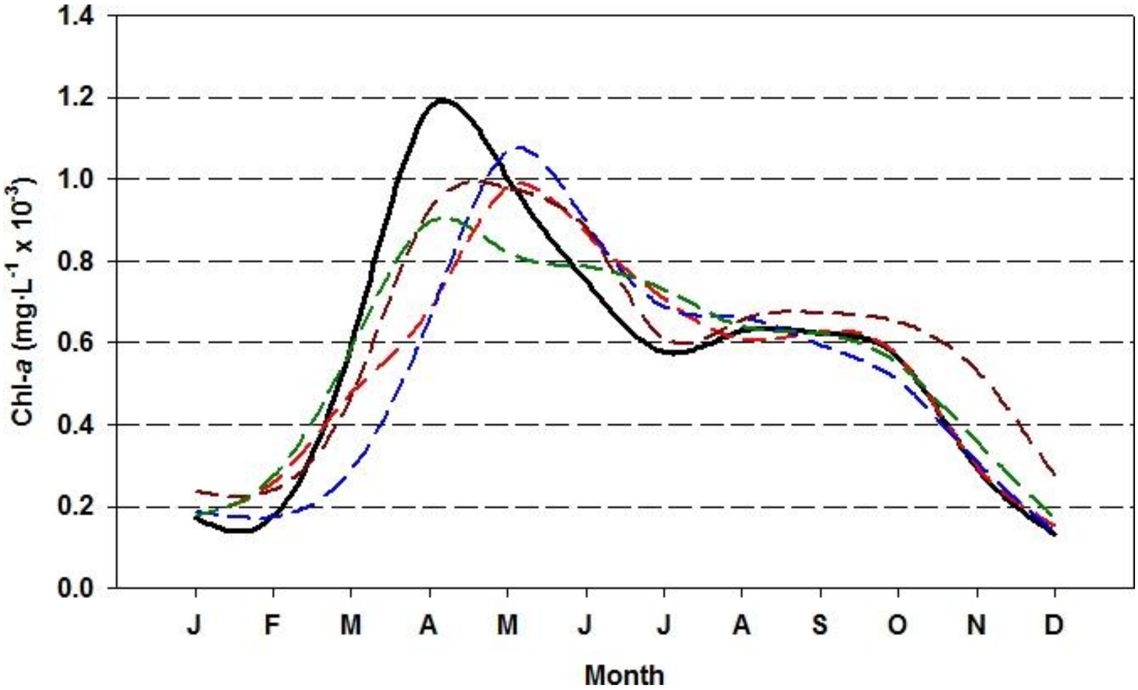


Figure 2.3.17. Computed monthly averaged values for Chl-*a* concentrations in the Mar Menor lagoon in the reference period (p0: solid black line, p01: dashed red line, p02: dashed blue line, p03: dashed brown line, p04: dashed green line).

Apart from the clear seasonal pattern, Chl-*a* concentrations in the lagoon are highly dependent on nutrient inputs, mostly phosphorus, and the beginning of the productive season defined by temperature regimes in the lagoon. As a result, interannual variability during the spring can be high. Overall, climate change is expected to cause a very slight decrease in lagoonal Chl-*a* concentrations, caused by a parallel decrease in nutrient inputs (Figure 2.3.18).

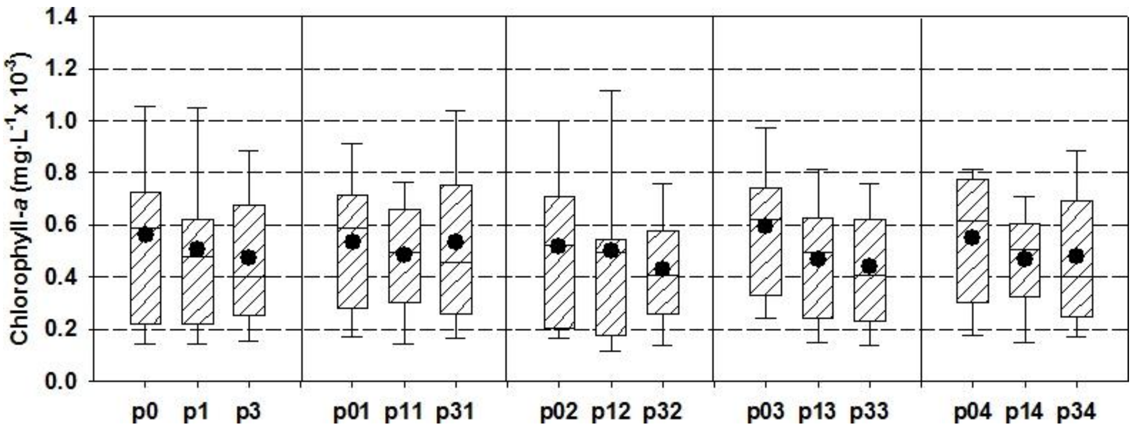


Figure 2.3.18. Variations in daily Chl-*a* concentrations in the Mar Menor lagoon in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

By the end of the century, the cited slight decrease in Chl-*a* concentrations for the 'typical' years in each analysed period will be noted as a decrease in the magnitude of the

environmental gradients in the lagoon. The effect becomes more evident for the areas located under the influence of the inputs (Figure 2.3.19).

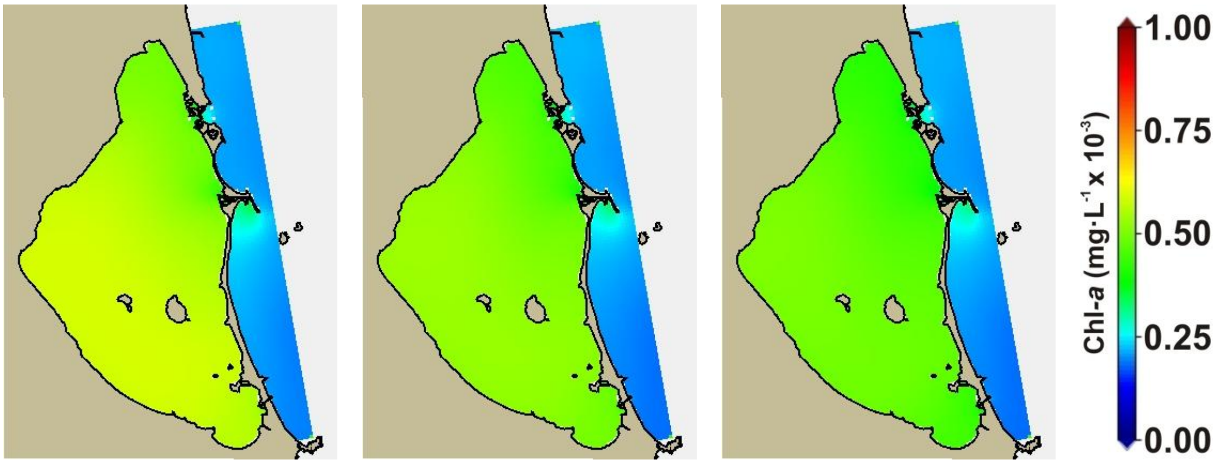
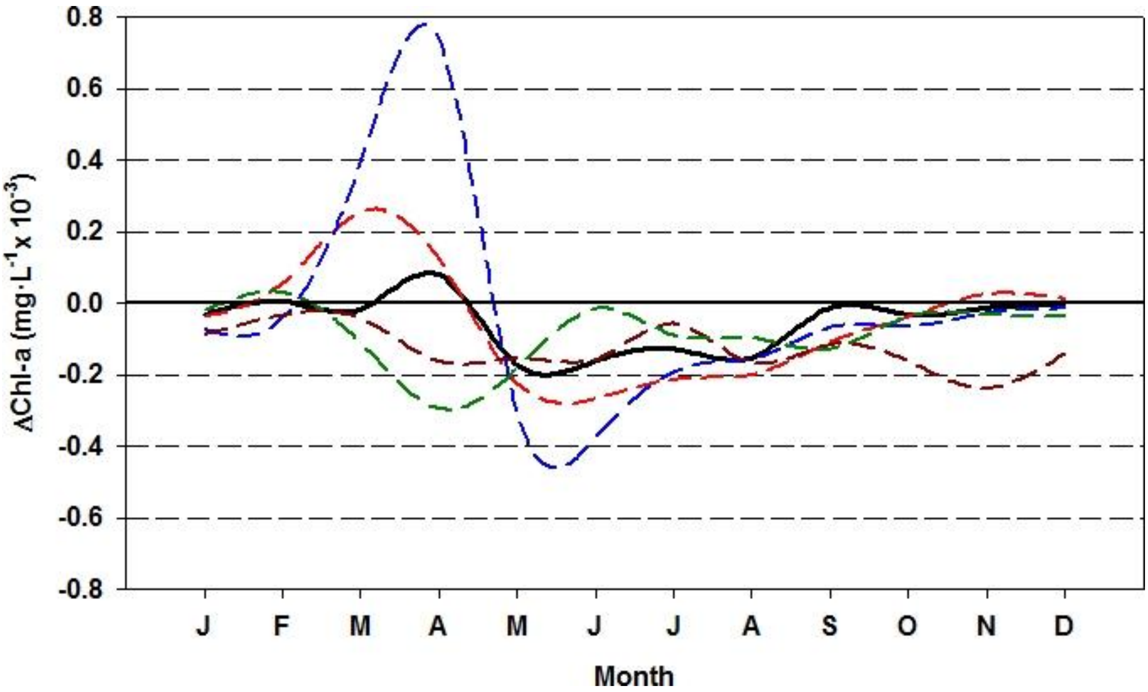


Figure 2.3.19. Spatial distributions of yearly averaged Chl-*a* concentrations in the lagoon in p0 (left), p1 (center) and p3 (right) periods.

Apart from the general slight decrease in Chl-*a* concentrations, certain monthly variability is also expected. During the 2011-2040 period, the largest variability is found during the spring, corresponding to the beginning of the productive cycle. However, for the 2071-2098 period, variability is mostly recorded by the end of summer, associated to the variability observed also for NO_3-N and PO_4-P (Figure 2.3.20).



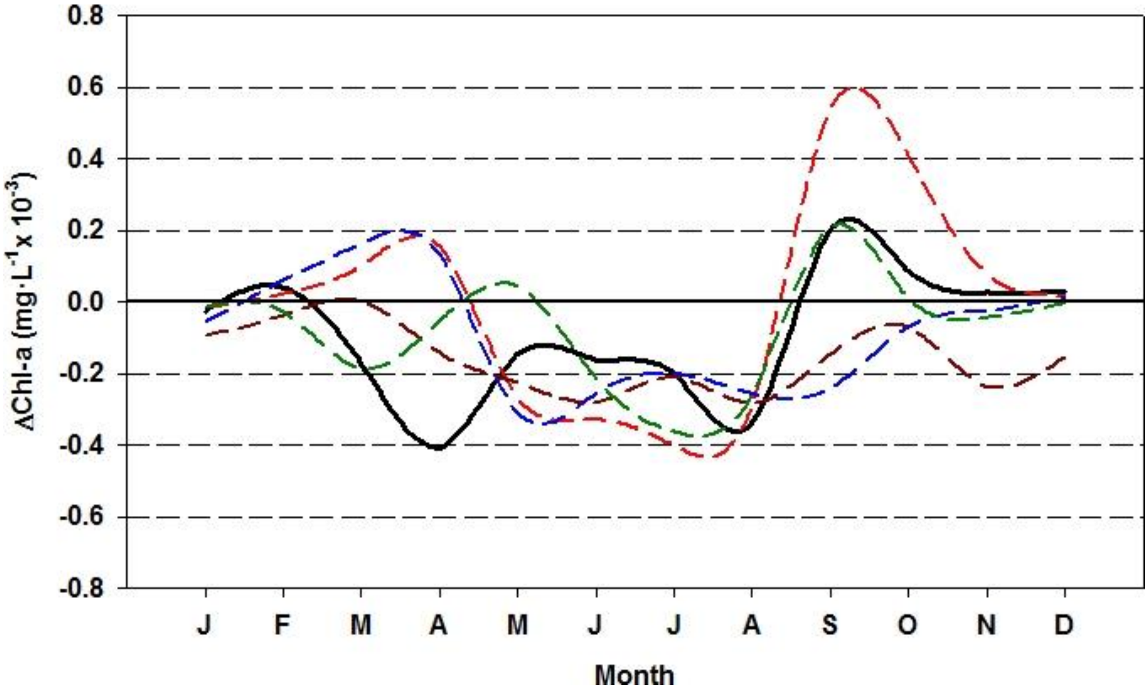


Figure 2.3.20. Differences in monthly averaged Chl-*a* concentrations in the Mar Menor lagoon for the 2011-2040 (top) and 2071-2098 (bottom) scenarios in relation with the equivalent year in the reference period (p0: solid black line, p01: dashed red line, p02: dashed blue line, p03: dashed brown line, p04: dashed green line).

Macroalgal biomass

Caulerpa prolifera biomass in the lagoon is very high, around 8,000 TonC, displaying a seasonal pattern, with maximum biomass recorded during the spring and minimum during the end of the winter season (Figure 2.3.21). A clear spatial gradient is observed between the areas located at the centre of the lagoon, with higher biomasses, and very shallow areas, where *C. prolifera* is almost absent.

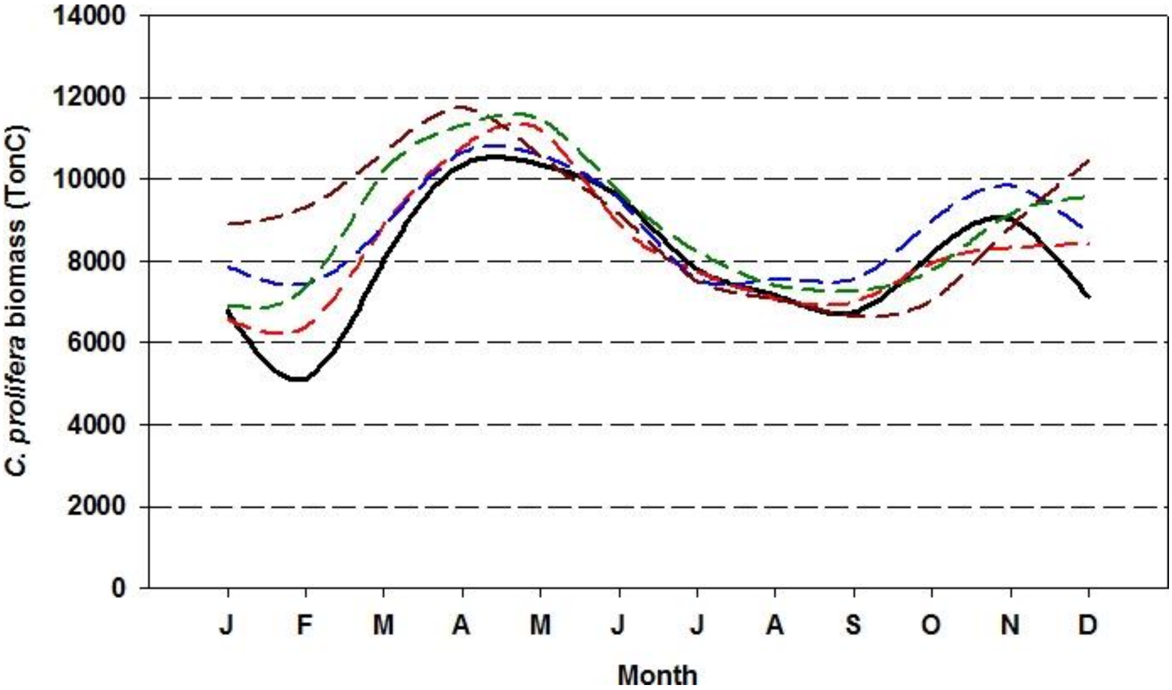


Figure 2.3.21. Computed monthly averaged values for macroalgal biomass in the Mar Menor lagoon in the reference period (p0: solid black line, p01: dashed red line, p02: dashed blue line, p03: dashed brown line, p04: dashed green line).

C. prolifera biomass is sensitive to nutrient availability, and to variations in the amount of light reaching the bottoms and the occurrence of extreme summer temperatures (Lloret et al. 2005, Lloret et al. 2008). As a result of the combined effect of impacts on these three variables, climate change is expected to cause a significant decrease in lagoonal macroalgal biomass, in all climate scenarios, and particularly marked (around 20% decrease in average) by the end of the century (Figure 2.3.22).

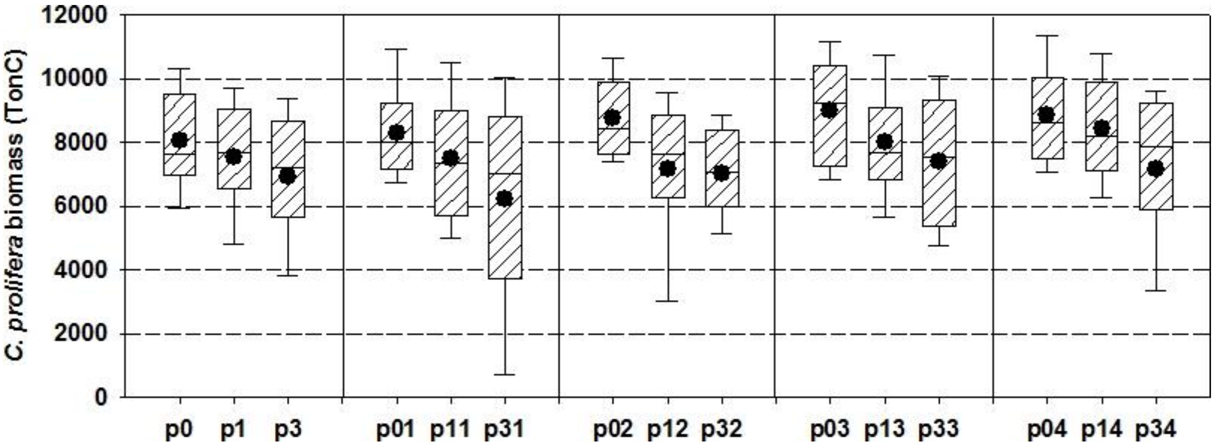


Figure 2.3.22. Variations in daily macroalgal biomass in the Mar Menor lagoon in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

The above-mentioned decrease becomes more evident in the deepest areas of the lagoon, where higher biomasses are found (Figure 2.3.23). These areas are more sensitive to changes

in lagoonal light conditions, and the combined effect of sea level rise and increased light attenuation may have a profound impact on *C. prolifera* biomass. The increase of temperatures associated to climate change, particularly during the summer (when temperatures above 30 ºC are expected to be more frequent) will aggravate the situation, due to the impact on the balance between macroalgal photosynthesis and respiration. Furthermore, the computed decrease in macroalgal biomass is expected to have a significant effect on nutrient concentrations in the lagoon, as nutrient uptake by *C. prolifera* beds is diminished, resulting in a deleterious impact for the entire ecosystem and overall ecological status of the lagoon.

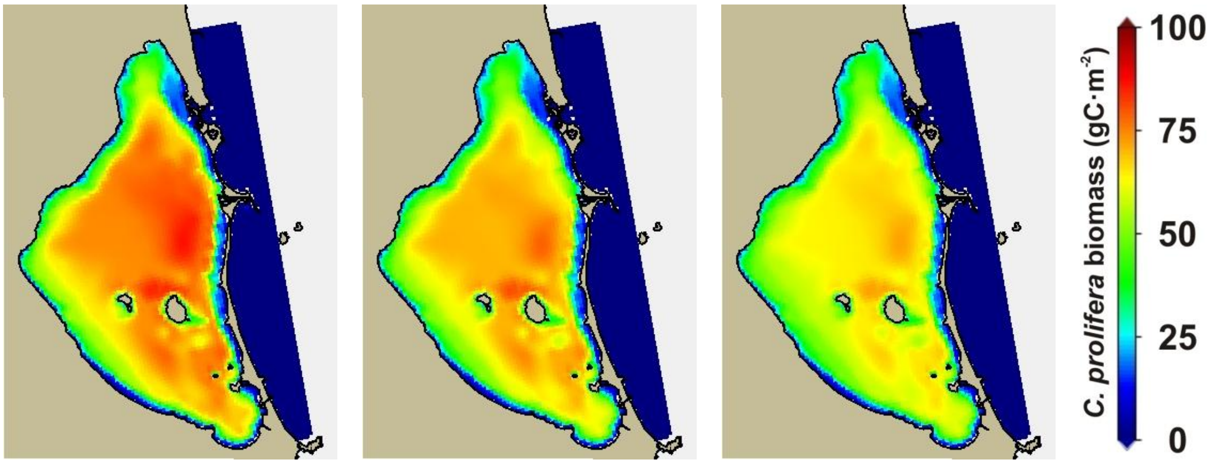


Figure 2.3.23. Spatial distributions of yearly averaged macroalgal biomass in the lagoon in p0 (left), p1 (centre) and p3 (right) periods.

Apart from the general average decrease in lagoonal macroalgal biomass, the situation becomes more dramatic when analysing monthly differences between the different climatic periods considered (Figure 2.3.24). For the first 2011-2040 period, major differences were found by the end of winter and the beginning of the growing season in spring. In this case, reduced light conditions and lowered nutrient concentrations are having a synergistic impact on macroalgal growth. More nutrients become available for phytoplankton, explaining the peaking concentrations of Chl-*a* found in these months during the same period. The model predicts a recovery phase during the summer and autumn. For the second period 2071-2098, most of the monthly variability is found at the end of the summer. Extreme summer temperatures will have a profound impact on macroalgal biomass, to virtually disappear from lagoonal bottoms in some cases (90% loss in p31 scenario during August and September). Both, NO_3-N and Chl-*a* concentrations, peak during the same months in this period due to the impact on macroalgal nutrient uptake. The model again predicts a recovery phase during the autumn and winter, but that situation is very unlikely to happen, since other opportunistic species may occupy the empty niche left by *C. prolifera* as it disappears from the bottoms, a situation that was not included in our model definition.

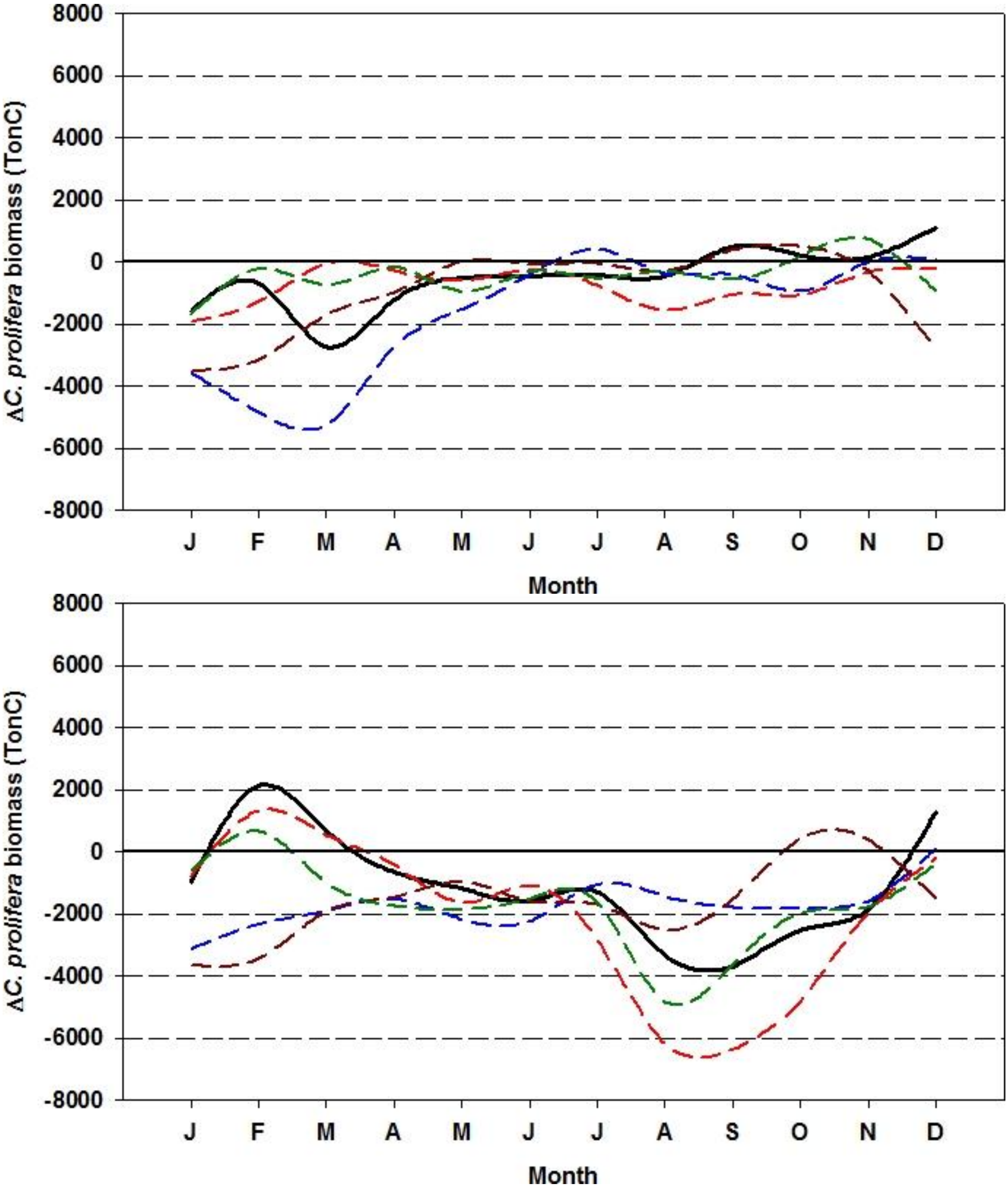


Figure 2.3.24. Differences in monthly averaged macroalgal biomass in the Mar Menor lagoon for the 2011-2040 (top) and 2071-2098 (bottom) scenarios in relation with the equivalent year in the reference period (p0: solid black line, p01: dashed red line, p02: dashed blue line, p03: dashed brown line, p04: dashed green line).

Summary

Differences for the whole-basin yearly averaged data for all the parameters analysed between the two climate change scenarios and their corresponding years in the reference period are presented in the following table:

Table 2.3.1. Differences between analysed climate change scenarios and the reference period.

Dif.	Temperature (ºC)	Salinity (PSU)	NO_3-N ($mg \cdot L^{-1}$)	PO_4-P ($mg \cdot L^{-1}$ $x10^{-3}$)	Chl-*a* ($mg \cdot L^{-1}$ $x10^{-3}$)	*C. prolifera* (TonC)
p1-p0	0.20	-0.80	-0.004	-0.137	-0.053	-509
p11-p01	0.94	-0.50	-0.038	-0.121	-0.051	-784
p12-p02	-0.63	-0.57	0.060	-0.198	-0.015	-1612
p13-p03	-0.87	-1.09	0.042	-0.017	-0.127	-980
p14-p04	-0.01	-0.53	0.000	-0.068	-0.085	-461
p3-p0	2.80	-1.43	-0.006	-0.257	-0.090	-1103
p31-p01	2.83	-1.09	-0.017	-0.354	0.000	-2058
p32-p02	1.38	-1.53	0.003	-0.261	-0.088	-1737
p33-p03	-0.03	-2.01	0.539	-0.155	-0.157	-1613
p34-p04	2.36	-1.14	0.007	-0.259	-0.076	-1703

3. Combined socio-economic and climate change impact on the lagoon

3.1 Climate forcing

Climate forcing for all four combined socio-economic and climate change scenarios correspond to those applied for the 'typical' year in the 2011-2040 period (see chapter 2.1 for details). The atmospheric forcing and the conditions at the ocean boundary were considered the same as in p1 in all four cases. The only differences regard freshwater discharges (Figure 3.1.1) due to the effect of differences in water resource management between the four selected scenarios (see LAGOONS Deliverable 4.2 for details).

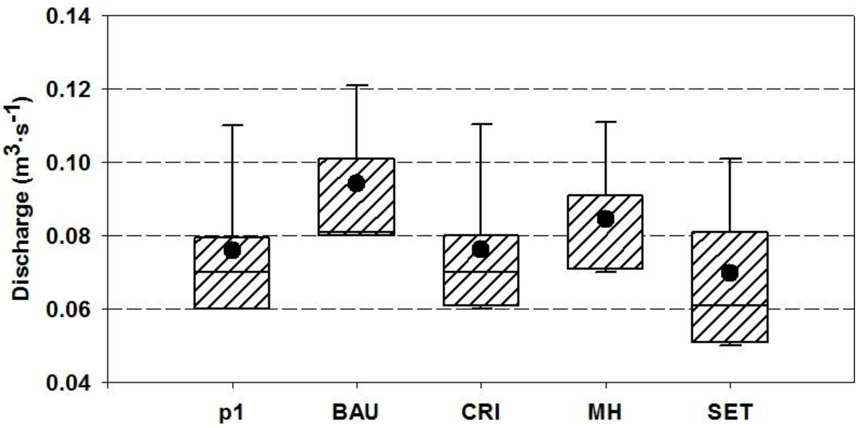


Figure 3.1.1. Variations in daily freshwater discharge values in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

Two scenarios, BAU and MH, assume an increase in freshwater discharges, while SET scenario predicts a slight decrease. No major changes are expected for CRI scenario. For most of the year, except during torrential rain events, freshwater discharges into the lagoon are a result of the surplus of water used for irrigation in the agricultural crops located in the watershed. In this sense, differences found in freshwater discharges among the selected scenarios mostly respond to changes in the use of water for irrigation.

3.2 Loads from catchment

Loads of main inorganic forms of dissolved nutrients (NO_3-N, NH_4-N, PO_4-P) were obtained from SWIM simulations modelled under the same climatic and socio-economic conditions. Differences were found for all dissolved nutrient loads. Nitrate, the major form of inorganic nitrogen entering the lagoon, was found higher in BAU and MH scenarios, little differences occurred for SET scenario and was slightly lower for CRI scenario. NH_4-N was again higher in BAU and MH scenarios, but in this case, lower inputs where found for SET scenario while remaining the same in CRI scenario. The same pattern is again observed for PO_4-P loads (Figure 3.2.1)

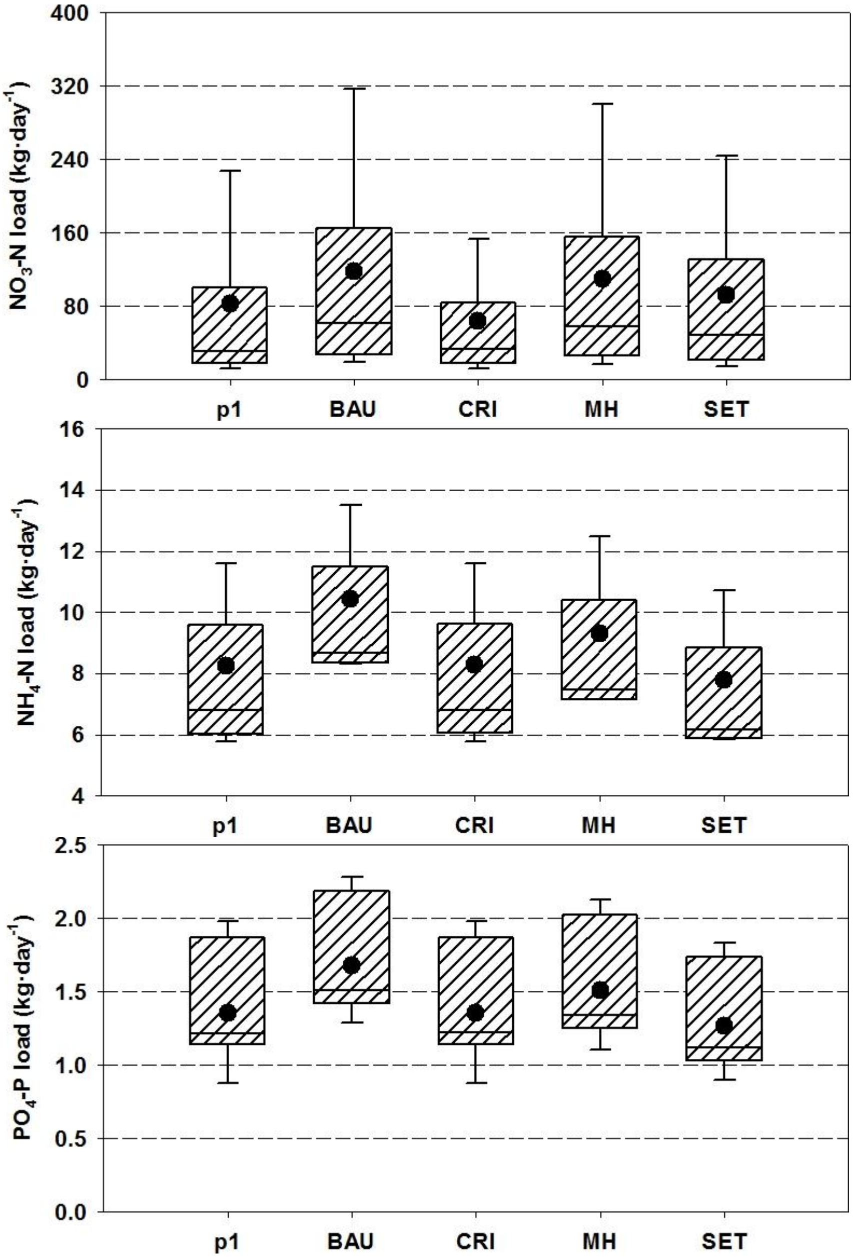


Figure 3.2.1. Variations in daily NO_3,-N, NH_4–N and PO_4-P loads in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

3.3 Lagoon's response and discussion

The impacts of combined socio-economic and climate changes on the Mar Menor lagoon were assessed through the analysis and comparison of modelled time series of main hydrodynamic (temperature, salinity) and water quality (nitrate, inorganic phosphorus, chlorophyll-a, macroalgal biomass) parameters. Due to its particular size and shape, the Mar Menor lagoon was considered as a single big water body and no sub-basins were delineated for the analysis of time series. The analyses were, therefore, carried out upon data integrated for the entire lagoon.

Temperature and salinity

Temperature and salinity in the Mar Menor lagoon are defined by the observed yearly patterns in atmospheric temperature, evaporation rates, and water exchanges with the adjacent Mediterranean Sea. Variability in freshwater discharges has no effect on water temperatures and salinities, except for the areas located immediately under the influence of discharges at the very mouth of the watercourses. As a consequence, and since the only difference between p1 ('typical' year for 2011-2040 period) and our four socio-economic scenarios regard moderate changes in freshwater discharges, and no changes are observed for water temperature and salinity as a consequence of the combined impact of socio-economic and climate change, apart from those already reported for p1 (Figure 3.3.1).

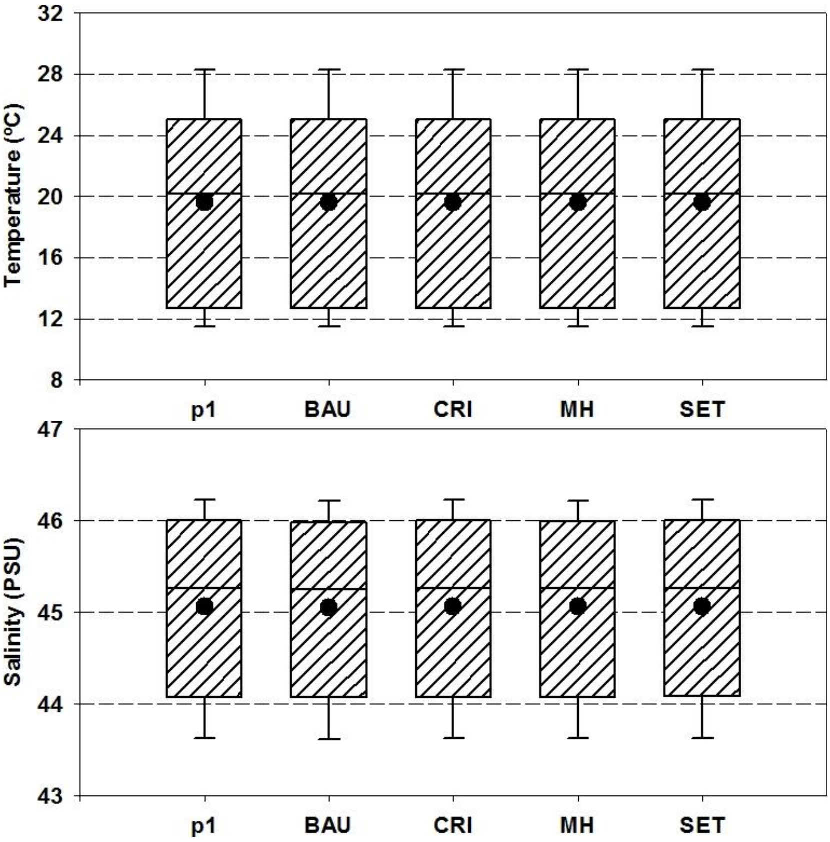


Figure 3.3.1. Variations in daily water temperature (top) and salinity (bottom) in the Mar Menor lagoon in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

Nutrient concentrations

NO_3-N concentrations in the lagoon display an almost parallel response to the increases/decreases of inputs in each of the analysed scenarios. In this sense, very slight increases are expected for BAU and MH scenarios, while CRI and SET scenarios show little variation or slight decreases (Figure 3.3.2). Due to the large volume of the lagoon in comparison to inputs, the enormous biomass of macroalgae, the huge organic matter content in the sediments and the long water residence time, most of the nitrogen is being constantly recycled and the system does not show an immediate response to slight changes in nutrient inputs. In the mid to long term, however, these changes may have a cumulative effect since,

despite the high denitrification rates that usually characterise this ecosystem, nitrogen tends to accumulate for long periods within the lagoon.

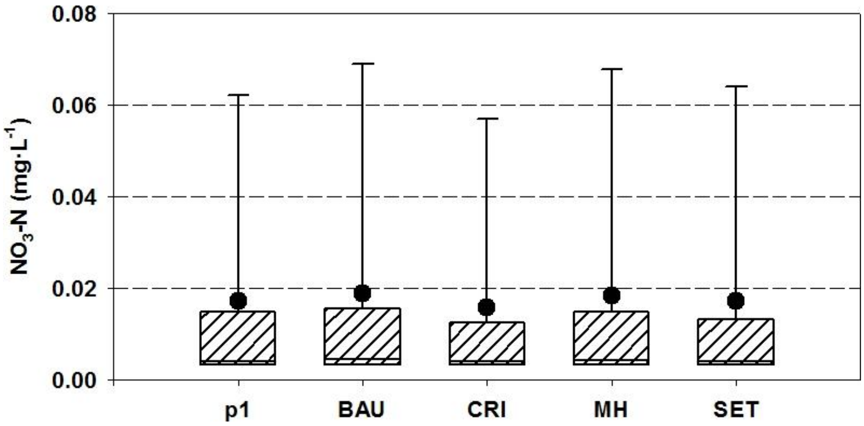


Figure 3.3.2. Variations in daily NO_3-N concentrations in the Mar Menor lagoon in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

Most of the variability found in NO_3-N concentrations among the selected scenarios corresponded to changes occurring in areas located under the immediate influence of El Albujon wadi, while the rest of the lagoon remained the same as observed in p1. No major monthly or seasonal differences were found, and the observed increases/decreases are homogeneously distributed during the year.

PO_4-P concentrations in the lagoon display an almost parallel response to the increases/decreases of inputs in each of the analysed scenarios. In this sense, very slight increases are expected for BAU and MH scenarios, while CRI scenario shows little variation and SET scenario displays a slight decrease (Figure 3.3.3). Due to the extremely low concentrations of PO_4-P found in the lagoon in relation to nitrogen, phosphorus can be considered limiting for phytoplankton productivity, so any changes in PO_4-P inputs may potentially have negative effects on phytoplankton densities and overall ecosystem ecological status.

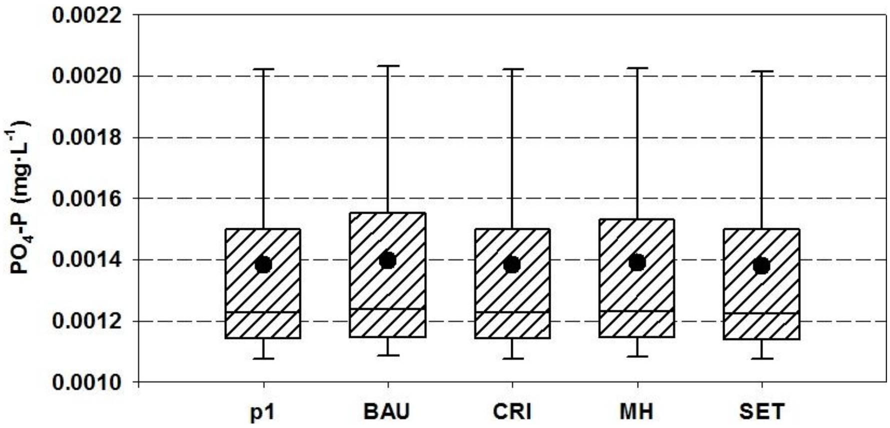


Figure 3.3.3. Variations in daily PO_4-P concentrations in the Mar Menor lagoon in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

Most of the variability found in PO_4-P concentrations among the selected scenarios corresponded to changes occurring in the areas located under the immediate influence of El Albujon wadi, while the rest of the lagoon remained the same as observed in p1. No major monthly or seasonal differences were found, and the observed increases/decreases are homogeneously distributed during the year.
Considering the low magnitude of changes in both NO_3-N and PO_4-P concentrations among the different socio-economic scenarios, we can conclude that no major differences in the ecological status of the lagoon are to be expected, apart from those described in Chapter 2 due to the impact of climate change only during this period.

Chlorophyll-a concentrations
Chl-*a* concentrations in the lagoon display a parallel response to the increases/decreases of PO_4-P inputs in each of the analysed scenarios. In this sense, very slight increases are expected for BAU and MH scenarios, while CRI scenario shows little variation, and SET scenario predicts slight decreases (Figure 3.3.4). As it was mentioned before, phosphorus seems to be limiting for phytoplankton productivity. Therefore, changes in PO_4-P inputs seem to have an immediate effect on Chl-*a* concentrations in the lagoon.

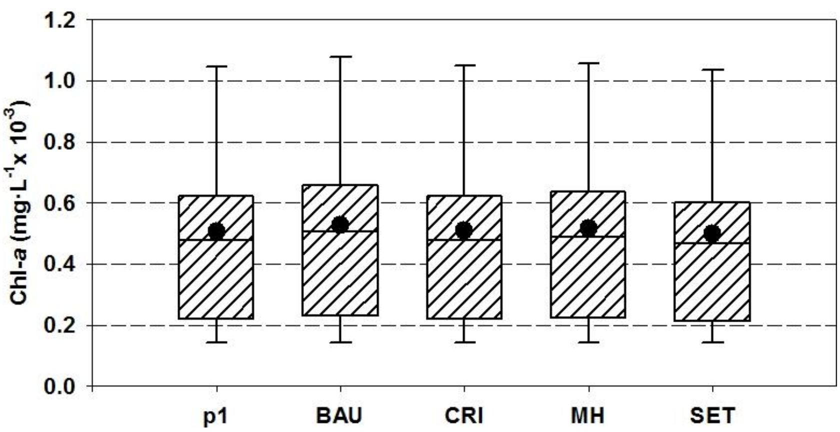


Figure 3.3.4. Variations in daily Chl-*a* concentrations in the Mar Menor lagoon in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

Most of the variability found in NO_3-N concentrations among the selected scenarios corresponded to changes occurring in the areas located under the immediate influence of El Albujon wadi, while the rest of the lagoon remained the same as observed in p1. No major changes were found in seasonal Chl-*a* concentrations, and the observed increases/decreases are homogeneously distributed during the year.
Considering the low magnitude of changes in Chl-*a* concentrations among the different socio-economic scenarios, we can conclude that no major differences in the ecological status of the lagoon are to be expected, apart from those described in Chapter 2 due to the impact of climate change only during this period.

Macroalgal biomass
Macroalgal biomass does not seem to display a response to the slight changes in nutrient inputs between the different scenarios. Very slight decreases were found for BAU, practically

no changes occurred for CRI and MH scenarios, and a very slight increase was found for SET scenario (Figure 3.3.5). *C. prolifera* biomass dynamics seems to be determined mostly by the temperature regimes in the lagoon, a parameter that does not display any changes between the scenarios. Even though *C. prolifera* is able to intercept nutrients entering the system, as revealed by differences in the isotopic signature (Lloret and Marin 2009), most of the macroalgal requirements are satisfied by nutrients recycled within the ecosystem. Despite the fact that minimum changes were observed, the cumulative effect of reduced macroalgal biomass throughout the years might have a deleterious effect on the overall ecosystem functioning and the role of the macroalgal beds to process excess nutrients from the watershed, therefore increasing ecosystem's vulnerability to eutrophication.

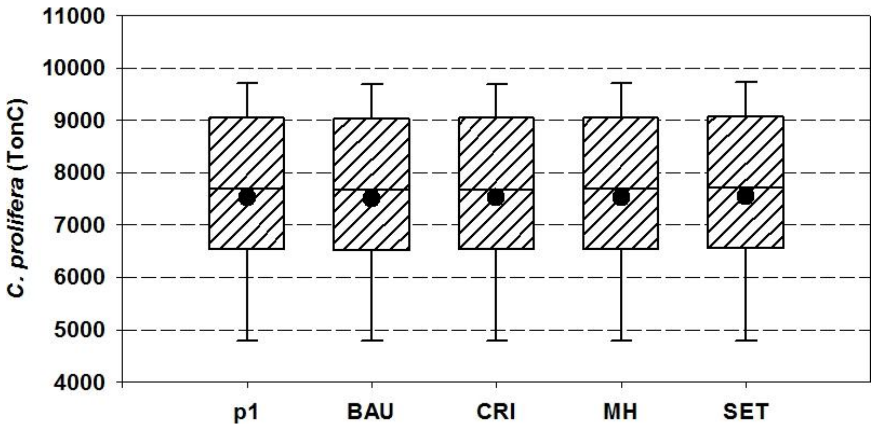


Figure 3.3.5. Variations in daily macroalgal biomass in the Mar Menor lagoon in the selected scenarios. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario.

No major changes were found in seasonal macroalgal biomass, and the observed slight increases/decreases are homogeneously distributed during the year.

Summary

Differences for the whole-basin yearly averaged data for all the parameters analysed between the four combined socio-economic and the climate change scenarios for the period p1 are presented in the following table:

Table 3.3.1. Differences between analysed combined socio-economic and climate change scenarios and the typical year in 2011-2040 period (p1).

Dif.	Temperature (ºC)	Salinity (PSU)	NO_3-N ($mg \cdot L^{-1}$)	PO_4-P ($mg \cdot L^{-1}$ x10^{-3})	Chl-*a* ($mg \cdot L^{-1}$ x10^{-3})	*C. prolifera* (TonC)
BAU-p1	0.00	-0.01	0.002	0.014	0.021	-19
CRI-p1	0.00	0.00	-0.001	0.000	0.001	-6
MH-p1	0.00	-0.01	0.001	0.007	0.009	-5
SET-p1	0.00	0.00	0.000	-0.004	-0.009	12

4. Conclusions and recommendations

The analysis of the Mar Menor lagoon's response to climate change impacts revealed a pretty dramatic situation if climate change predictions become true. The combination of expected future changes in the physico-chemical and biological (main primary producers) characteristics in the lagoon clearly point to a situation where current ecosystem functioning will be profoundly altered, probably resulting in major changes in the ecological status of the lagoon and the maintenance of current biodiversity and the ecosystem services it supports.

On one hand, the analysis of 'typical' years in future climate change scenarios revealed a certain decrease in both nitrogen and phosphorus in the lagoon caused by a parallel decrease in inputs and an increase in the amount of nutrients being flushed out of the system as a consequence of the rise in sea level, which in turn can be translated into lower phytoplankton densities and an improvement of water quality. However, nutrient dynamics in the lagoon is not entirely determined by input variations, but clearly associated to primary producers' productive cycles, mostly governed by annual temperatures and the amount of light reaching the bottoms. In this sense, water temperatures are expected to increase dramatically, particularly during the summer. These extreme temperatures may progressively lead to the disappearance of important masses of *C. prolifera*, causing a decrease in nutrient uptake by the macroalga, and therefore, nutrient concentrations in the lagoon may increase, particularly during extreme rainfall events that will become more frequent and of higher magnitude in the future. Despite the expected general decrease in precipitation and freshwater and nutrient inputs, most of the nutrients in the lagoon are temporarily retained in macroalgal biomass and in the sediments. The disappearance of macroalgal beds in the lagoon will make these nutrients available for other primary producers, such as floating macroalgae and phytoplankton, leading to more severe eutrophication.

On the other hand, the expected rise in sea level and its effect on water residence time and salinity in the lagoon could aggravate the situation, since other Mediterranean species could occupy the empty niche left by *C. prolifera*, transforming current ecosystem functioning in a direction that is difficult to predict.

A possible solution for this problem will require large and continued efforts at reducing nutrient inputs entering the lagoon. More controls on fertilizer use in the agricultural area surrounding the lagoon will help reduce the amount of nitrogen that is being introduced into the system, and more effective water treatment plants, particularly during the peak tourist season, and torrential water collectors, could help reduce the amount of phosphorus, a nutrient to which phytoplankton seems to be very sensitive in the Mar Menor.

In this sense, the analysis of combined socio-economic and climate change scenarios let us conclude that BAU, CRI and MH scenarios are not very desirable for the future of the region. Both BAU and MH scenarios predict a certain economic growth in the area, accompanied by certain increases in inputs. CRI scenario, a very undesirable scenario from a socio-economic perspective, is not effective either at reducing nutrient concentrations in the lagoon, and other side-effects derived from the loss of investments in environmental protection measures could also result in environmental degradation and impacts on the ecological status of the lagoon not included in our model. SET scenario seems to be the most appropriate scenario for the lagoon. This scenario predicts a certain reduction of inputs and, even though its effect on lagoonal concentrations is not immediate, the cumulative effect throughout the years could prevent the appearance of severe eutrophication in the future.

Due to the Mar Menor's peculiar physical (big size, high surface/volume ratio, extremely long water residence time, minimum freshwater inputs, hypersaline, extreme temperatures) and biological (huge macroalgal biomass and coverage) characteristics, nutrient dynamics does not seem to respond to increases or decreases in inputs in the short term. The cumulative effects of these increases or decreases throughout several years/decades should be further addressed in order to obtain better conclusions about lagoonal response to climate and socio-economic changes in the area. Due to limitations in computational time and space, our models were unable to produce results for decades of continued changes in inputs, although the analysis of 'typical' and 'extreme' years allowed us to infer the direction of future changes in the lagoon and assess about their possible ecological consequences. The continued use of ecological models in the near future, together with the development of a monitoring program in the Mar Menor, could help improve our knowledge about the possible consequences of climate and socio-economic changes, and assess the adequacy of the environmental management strategies to be applied in the area.

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Chapter 4

The Tyligulskyi Liman Lagoon - Results of combined climate and ecosystem processes: Report describing results of combined climate and ecosystem processes

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1. Scenarios

1.1 Climate change scenarios

In order to detect and conduct analysis of climate characteristics under the impact of global warming in the basin of the Tyligulskyi Liman, characteristic (typical) years for the four periods of 1971-2000, 2011-2040, 2041-2070 and 2071-2090 were selected by means of analyzing three meteorological characteristics – air temperature, total precipitation and wind speed. On the basis of the obtained results, the period of 1971-2000 is to be represented by the year1982, 2011-2040 – by 2014, 2041-2070 – by 2062, and 2071-2090 – by 2085.
An analysis of changes in climate characteristics in the selected years revealed a trend towards a growth in average annual values of air temperature in the Tyligulskyi Liman basin (Figure 1). Compared to 1982, the increase in temperature in 2014 will equal 2.2°C (22%), in 2062 - 3ºC (29%), and in 2085 - 4.1°C (40%). The estimated average annual air temperature of 2098 is to be 14.3°C, that is, in one hundred years the temperature is expected to grow by 4ºC.
Fig. 1b shows a change in the average annual precipitation. A reduction in precipitation of 413 mm per year (14% as compared to 1982) is expected in 2014 in the basin of the Tyligulskyi Liman, in the period of 2041-2070 – an increase in the amount of precipitation, followed by its consecutive reduction in the late 21st century. The corresponding analysis of changes in relative humidity, cloud cover and wind speed showed no significant differences in these characteristics throughout the studied years.
The water regime in the Tyligulskyi Liman lagoon is determined by the amount of water inflow from the catchment basin of the lagoon, the ratio of precipitation that falls on the water surface of the lagoon, the amount of evaporation from the latter, and the availability of water exchange with the sea through the artificial connecting channel.
The total annual volume of surface water inflow into the Tyligulskyi Liman in the present period is estimated at $24{\cdot}10^6$ m^3. The total water surface area of the lagoon is 128.85 km^2, the evaporation from its water surface is equal to 722 mm per year (at the water salinity of 20 PSU) or $93{\cdot}10^6$ m^3.

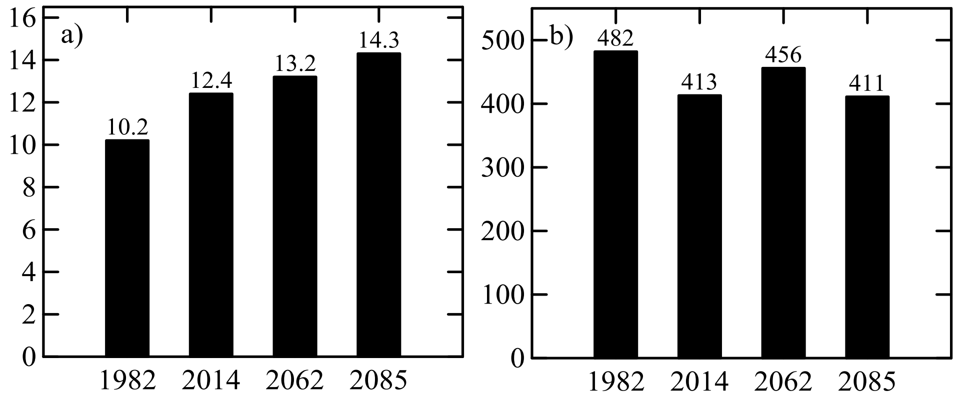


Figure 1. Change in the average annual values of air temperature (a) and precipitation (b) for typical years of scenarios p0-p4 in the Tyligulskyi Liman basin.

The input component conditioned by the atmospheric precipitation totals $58 \cdot 10^6$ m^3. Therefore, even in a year of average climatic parameters, a significant shortage of water balance (about $11 \cdot 10^6$ m^3) is formed. To prevent a reduction in water level of the lagoon the deficiency is compensated by a refill with sea water through the channel. In the years with low precipitation and intensive evaporation, the water balance deficit increases significantly.
Presently, the connection of the Tyligulskyi Liman with the sea through the artificial connecting channel is maintained for an average of 3 months a year: from clearing of sand and channel dredging in April to its natural closure resulting from the sea-side sanding. Under such a mode of water exchange with the sea, the lagoon is actually a standing-water water body, as the water from the external sources (comprising the river of Tyligul and other watercourses located in the drainage basin of the lagoon, as well as the sea - through the connecting channel) only flows into the lagoon, carrying the contained nutrients and salts, while the outflow takes place in negligible amounts under the influence of wind-driven phenomena. The loss of water amount in the lagoon is controlled by intensive evaporation in summer. The period of total external water replacement in the lagoon is about 8 years, which leads to accumulation of salts and nutrients over many years and an increase in their concentrations.
A significant decrease in salinity in the lagoon occurs in the years with heavy spring floods and high water. For example, in March 2003, when the water level in the estuary rose to 0.3 m BS, the surface layer, even in the southern part of the estuary, desalinated by up to 6 PSU.
Given the above, to compare the results of ecological modelling, selected extreme years were compared to each other (Table 1):

Table 1. Climate change scenarios description.

Scenario ID	**Climate periods**	**Selected year**	**Description of scenario**	**Atmospheric forcing/river input**	**Ocean boundary**
p0	1971 - 2000	1982	Typical reference year	M10/SWIM	OSENU (2011)
p01	1971 - 2000	1977	Extreme event (high water year)	M10/SWIM	OSENU (2011)
p02	1971 - 2000	1998	Extreme event (low water year)	M10/SWIM	OSENU (2011)
p1	2011 - 2040	2014	Typical year for near future	M10/SWIM	OSENU (2011)
p11	2011 - 2040	2030	Extreme event (high water year)	M10/SWIM	OSENU (2011)
p2	2041 - 2070	2062	Typical year for middle future	M10/SWIM	OSENU (2011)
p3	2071 - 2098	2085	Typical year for far future	M10/SWIM	OSENU (2011)
p32	2071 - 2098	2086	Extreme event (low water year)	M10/SWIM	OSENU (2011)

(1) Extreme high water (wet) years of 1977 and 2030, with the highest values of the annual amount of the precipitation and river runoff in the reference period of 1971- 2000 (p01) and the near future period of 2011-2040 (p11). The purpose of the analysis is to assess decreases in salinity and a the change of the environmental characteristics of the lagoon, with a maximum of fresh water inflow in the period p1, which is characterized by a minimum average perennial freshwater runoff into the lagoon as compared to the reference period of p0, and with the forecast periods of p2 and p3.
(2) The extremely water-short (dry) years are 1998 (p02) and 2086 (p32), with high average annual air temperature, and the minimum amount of annual precipitation and river runoff. Selection of the extreme year from the period p3 is substantiated by the maximum temperatures of air and water forecast in this period, high evaporation rate, and, consequently, the minimum input of fresh water from the drainage basin into the lagoon, and the maximum inflow of sea water through the canal to compensate the shortage of freshwater balance.
Comparative analysis of salinity and environmental characteristics of the waters in the lagoon in the extreme years of the selected forecast periods and the reference periods gives an idea of the range of variability of these characteristics under anomalous values of hydrometeorological factors caused by the climate change.
Conditions at the maritime boundary were based on the results of the research project "Investigation of the Effect of Climate Change on the Hydrological and Hydrochemical Conditions of Waters in the North-western Part of the Black Sea", which was carried out at Odessa State Environmental University in 2009-2011 (grant from the Ministry of Education and Science of Ukraine) (OSENU, 2011). Within the scope of the project, based on a stochastic 'climate-runoff' model developed at OSENU (Loboda, 2010, 2011), changes in the river runoff of the Danube, the Dnieper, the Dniester and the Southern Bug Rivers into the north-western part of the Black Sea (NWBS) in the 21st century (Loboda, 2010; Loboda and Tuchkovenko 2010) were evaluated for transient climate scenario GFLD (the climate model of the Geophysical Fluid Dynamics Laboratory, USA). On the basis of these estimates, spatio-temporal variability of hydrological and hydrochemical characteristics in the NWBS waters during the annual cycles for various periods of the 21st century was calculated with the use of a 3-D hydroecological model of OSENU-MECCA-EUTRO (Ivanov and Tuchkovenko, 2008), developed on the basis of MESSA (Model for Estuarine and Coastal Circulation Assessment) hydrothermodynamic model (Hess, 2000).
Changes in the level of the Black Sea near the Tyligulskyi Liman under the climate change were estimated with the use of an empirical relationship between the monthly averages of sea level and the runoff of the largest rivers of Dnieper and Danube (Fig. 2).

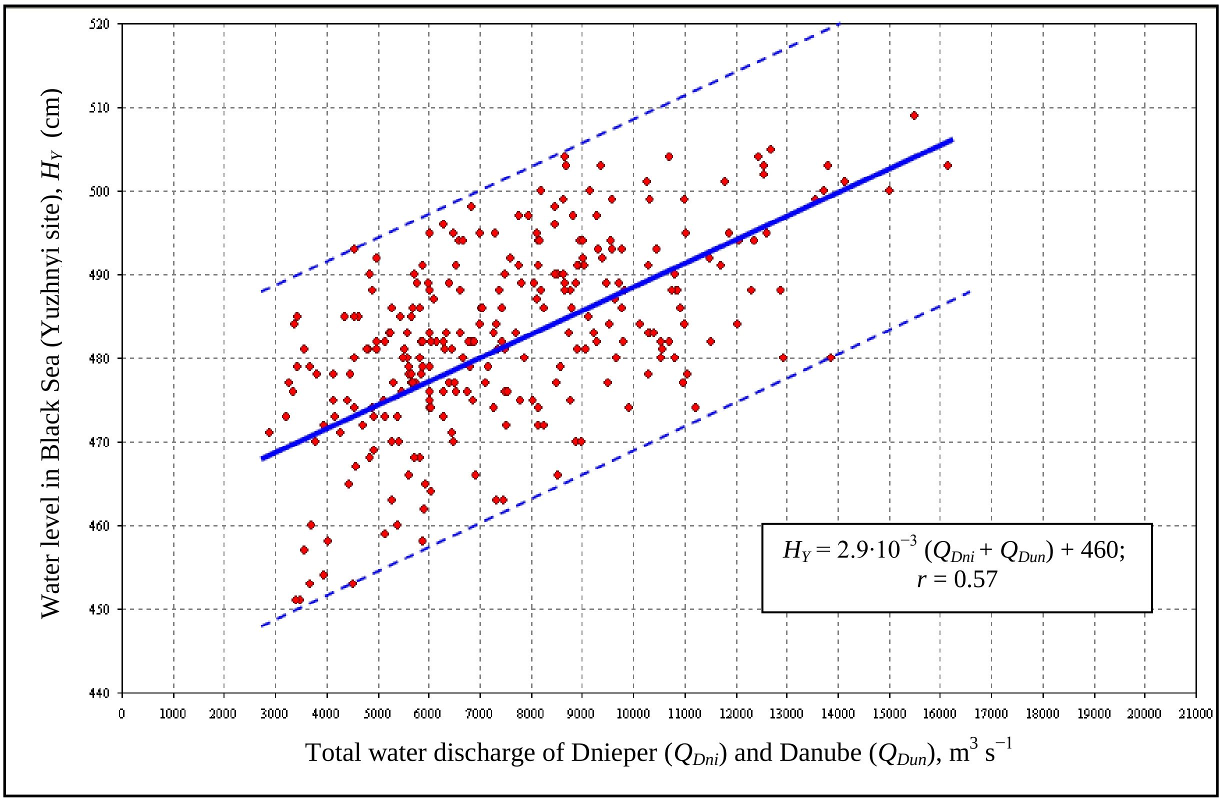


Figure 2. Relation of average monthly values of water level in the area of Tyligulskyi Lagoon, H_Y, and the total water discharge on the rivers of Dnieper and Danube, for the period of January 1982 through December 2004.

1.2 Socio-economic and environmental scenarios

The following scenario storylines are based on the focus group and citizen jury outputs and statistical data available on the Tyligulskyi Liman lagoon area. There are four scenarios per CSA which consist of: Business As Usual (BAU), Managed Horizons (MH), Set Aside (SET), and Crisis (CRI) (Baggett and Gooch, 2014).

Business As Usual

It was assumed that Ukraine recently had joined the EU. There has been an overall population decrease in the region with a 4% decrease in the Odessa region and 12% within the Mykolaiv region, along with a slight decrease in employment in the region as a whole. The intensification of agriculture through the use of more industrial farming methods, including the quantity of chemical fertilizers used, intensive livestock management, and the upsurge in deforestation has led to an increase in rural areas. These agricultural changes, coupled with an unregulated development with no new household waste or wastewater treatment facilities, unlawful and damaging use of the landscape park and some industrial pollution, have all significantly contributed to the deterioration and decline of both water quality and ecological conditions, leading to eutrophication. Recent weather changes have also been observed.

Ecosystem services are declining, which is also influenced by poaching. For example, the quantity and number of species for hunting and fishing are decreasing, with periodic fish kills not unknown, as well as changes in the type of fish species seen. It is evident that natural resources are declining; however, there is very little activity in estimating and providing an

inventory of species to estimate the rate of decline. Despite the increasing need for more environmental protection, the number of staff employed by the environmental authorities has not changed since 2010, and the staff is overstretched. The number of tourists to the area keeps increasing. In the lower part of the lagoon which is close to the Black Sea, there is significant recreation (attracting around 300,000 people annually), but this is mainly concentrated during the summer months.
There is a lack of policy, planning and environmental management and enforcement levels, mainly due to low investment and insufficient legislation for implementing the management of the region as a whole. Coastal erosion and lack of control of illegal sand mining further contribute to the area's ecological and environmental decline, and there are still a number of competing views regarding the use and zoning of the landscape park and the channel. A single control unit – in the form of a National Natural Park within the Odessa and Mykolaiv regions - with clearly demarcated areas for different uses, including recreation and tourism, is still viewed as desirable. The management and physical infrastructure required to achieve that, however, is still not in place. Alternative forms of energy production are also not very evident. Expenditure on the protection of the environment is low.

Set Aside

There has been an overall population decrease of 10% in the whole region, with a 15-20% decrease in employment in the region. The uptake of sustainable agricultural and livestock management is prominent, although the total area available for agriculture is less. A number of land and water based designated protected areas have either restricted or no-access status, which benefits the area by providing essential recuperation of natural resources that, in turn, generate indirect income through the ecosystem services provided to the region. Zoned hunting and fishing areas in the lagoon are also well managed, monitored and controlled, with designated no-access areas retained for conservation purposes.
All building and development works within the area are well regulated under an agreed sustainability code for the area, along with provision of household waste/recycling and wastewater treatment facilities for all households and businesses. High and recreational and ecotourism activities are prominent, although overall tourist numbers have not increased significantly. These activities have been developed following strict planning and control procedures that are sustainable and provide a sound economy and stable employment in a number of sectors for the area, which is becoming well established and gaining a good all round reputation. Environmental management and enforcement throughout the area is backed up by clear and transparent policies, which also contribute to the maintenance of the areas as a coastal ecological corridor. Regular meetings are held for stakeholders to discuss and resolve any issues regarding, for example, the landscape park or channel/water exchange.

Managed Horizons

An overall population and employment levels remain unchanged in the whole region. While the area of land for agriculture also remains unchanged, there are positive changes seen in the landscape and environmental status of the area due to revised practices in relation to agriculture, livestock management and levels of forestation, which are reviewed and appropriate recommendations and actions are taken. These agricultural changes, coupled with a well regulated and updated sustainability code, ensure that: buildings and any form of development adhere to the code; household waste or wastewater treatment facilities are always adequate; ecologically sound use and status of the landscape park is retained; the likelihood of pollution events due to industry in the area is low. These actions contribute to the continued safeguarding of both water quality and ecological conditions, minimising the chances of eutrophication.

Ecosystem services are steadily improving, enhanced by regular monitoring and reporting of any changes or possible impacts. For example, the quantity and number of species for hunting and fishing are increasing, and there is a full examination of the causes when periodic fish kills or any other unusual events occur to establish a cause. The recent weather changes which have been observed are closely monitored in case action is required.

Policy, planning and environmental management and enforcement levels are improving due to higher investment levels. Competing views on uses of the landscape park and the configuration of the channel exist; however, current action plans are regularly reviewed jointly by stakeholders and authorities. Coastal erosion due to weather events or climatic changes is closely monitored, and remedial action is taken as required, while illegal sand mining is strictly prohibited.

Crisis

There has been an overall population decrease by 30-40%, and employment levels have dropped by nearly 20% in the whole region. Intensification of agriculture and livestock management has rapidly increased, along with severe and continuous deforestation which has led to very high levels of rural runoff. High levels of unregulated development, with no household waste or wastewater treatment facilities, unmonitored, uncontrolled and unlawful use of the landscape park, and high levels of industrial pollution also contribute significantly to the severe decline and worsening of both water quality and ecological conditions, leading to eutrophication.

Ecosystem services have declined rapidly due to ecological and environmental deterioration, which are further impacted by heavy poaching of fish and game animals. For example, the quantity and number of species for hunting and fishing are very low, with frequent fish kills as well as changes in the type of fish species seen. Recent weather changes have also been observed. A complete lack of policy, planning and environmental management and enforcement levels is predominantly due to low investment. There are also competing and intractable views on uses of the landscape park and the configuration of the channel, with no management of the situation to try to resolve them. Coastal erosion and illegal sand mining has also significantly contributed to the area’s ecological and environmental decline.

Table 2 shows a short description of the above scenarios.

Table 2. Socio-economic and environmental scenarios description.

Scenario ID	Climate periods	Selected year	Description of scenario	Atmospheric forcing/river input	Ocean boundary
p1	2011 - 2040	2014	Typical reference year	M10/SWIM	OSENU (2011)
BAU	2011 - 2040	2014	BAU combined with climate change	M10/SWIM	OSENU (2011)
CRI	2011 - 2040	2014	CRISIS combined with climate change	M10/SWIM	OSENU (2011)
MH	2011 - 2040	2014	MANAGED HORIZONS combined with climate change	M10/SWIM	OSENU (2011)
SET	2011 - 2040	2014	SET ASIDE combined with climate change	M10/SWIM	OSENU (2011)

2. Climate change impact on the lagoon

2.1 Climate forcing

The ENSEMBLES project (van der Linden and Mitchell, 2009) provided a set of climate scenario data in Europe. The future European climate has been projected by running an ensemble of regional climate models. In the ENSEMBLES climate data set, there are 15 climate scenarios, with the 25-km horizontal resolution and the time length up to the end of 21st century. These climate scenarios fit better to the scale of the Tyligulskyi Liman catchment areas, and the aim is to simulate changes in runoff and water quality until the end of the 21st century. Also, the model results of MPI-REMO (M10) were selected as a 'best fitting' scenario for the Tyligulskyi Liman lagoon (Hesse et al., 2013).

Climate change signals were calculated as differences in long-term (30 years) average temperature and precipitation between three future periods 2011-2040 (near future), 2041-2070 (middle future) and 2071-2098 (far future), and the reference period 1971-2000 (present). Table 3 summarizes the results.

Table 3. Annual climate change signals for the 'best fitting' scenario in the Tyligulskyi Liman for temperature and precipitation (adopted from Hesse et al., 2013).

	Periods		
	near future – present	**middle future – present**	**far future – present**
Temperature (°C)	+1.1	+2.0	+3.4
Precipitation (%)	−8.7	+2.0	−3.2

After calibration and validation of the SWIM model for river discharge and water quality in the Tyligulskyi Liman catchment, assessment of climate change impacts was performed. Figures 3-6 show the daily discharges simulated by the SWIM model under the M10 scenario, as well as temperature and precipitation for the four climate scenarios p0-p3.

The most prominent feature of the water discharge to the Tyligulskyi Liman are their very low values, with an exception of a few days during the spring high water period. On the contrary, summer or autumn heavy rainfalls do not usually provoke any maximums in the water discharge.

It can be also noted that the typical year for the scenario p1 is characterized by the extremely low water discharge during the spring high water time– the maximal values are about 6 m^3 s^{-1} in comparison to 30-40 m^3 s^{-1} for the other scenarios.

The typical year for the scenario p3 is characterized by very high daily temperatures in the August, which exceed 30°C. Moreover, the summer for the scenario p3 is very dry – a few days only will be with precipitation. Due to the hot and dry weather, the water discharge will be about zero starting from the May.

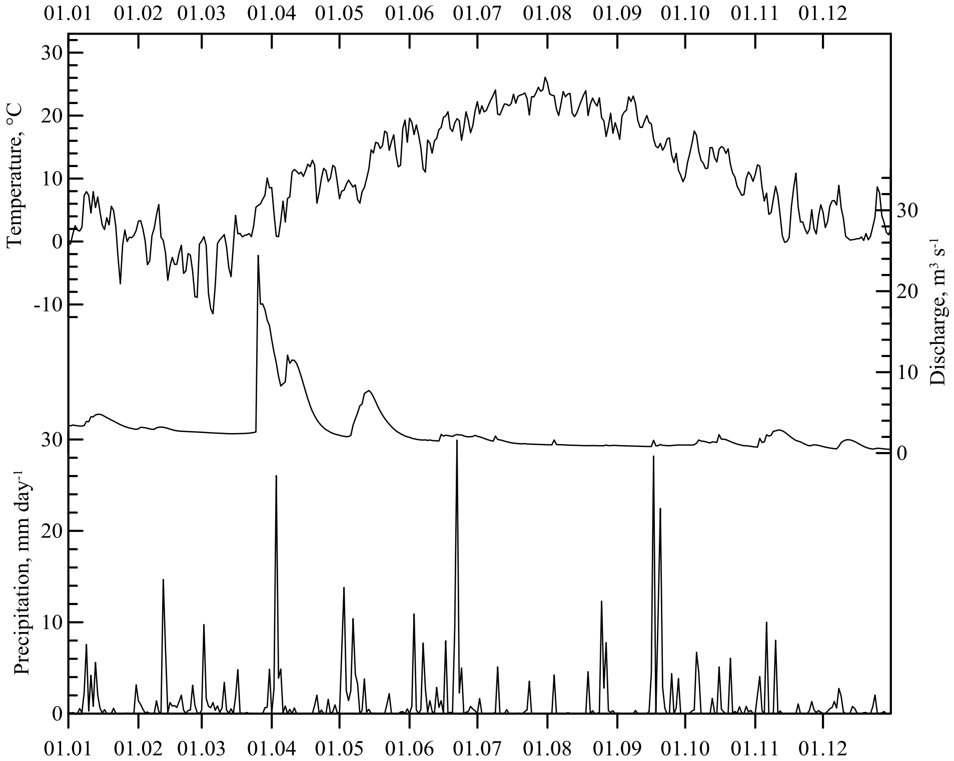


Figure 3. Simulated daily temperature, water discharge and precipitation for the scenario p0.

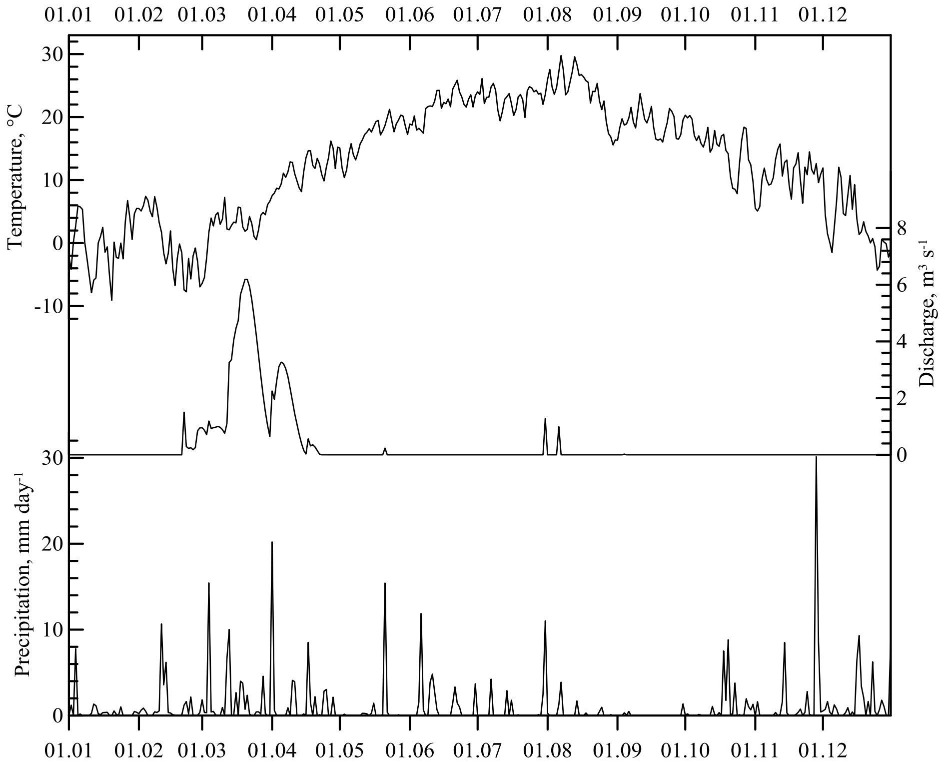


Figure 4. Simulated daily temperature, water discharge and precipitation for the scenario p1.

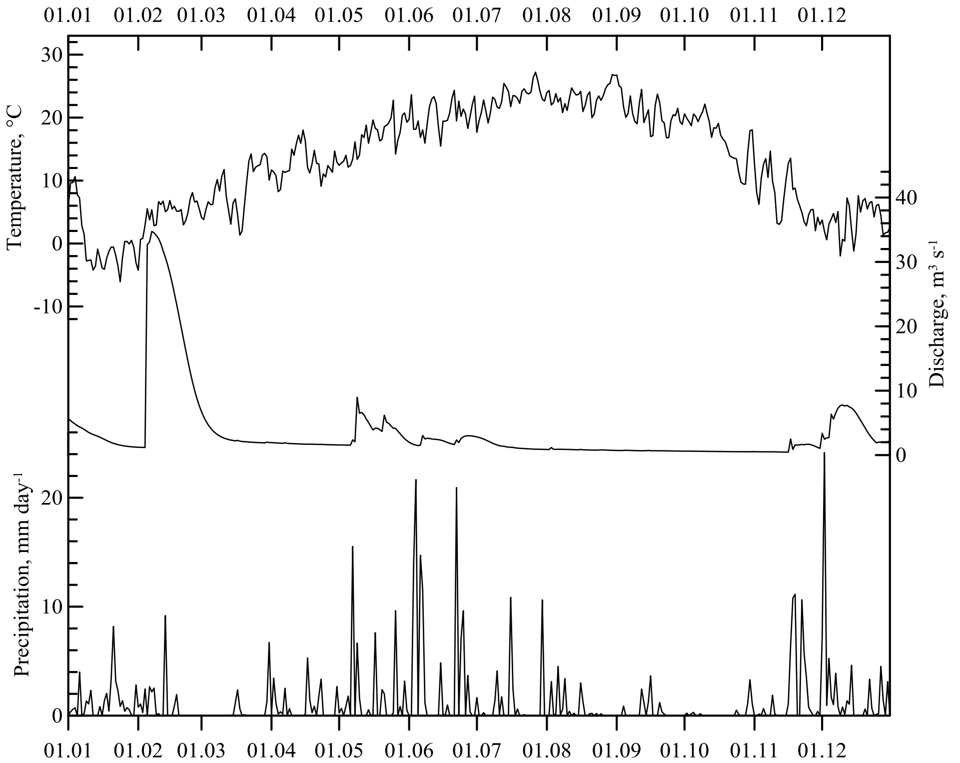


Figure 5. Simulated daily temperature, water discharge and precipitation for the scenario p2.

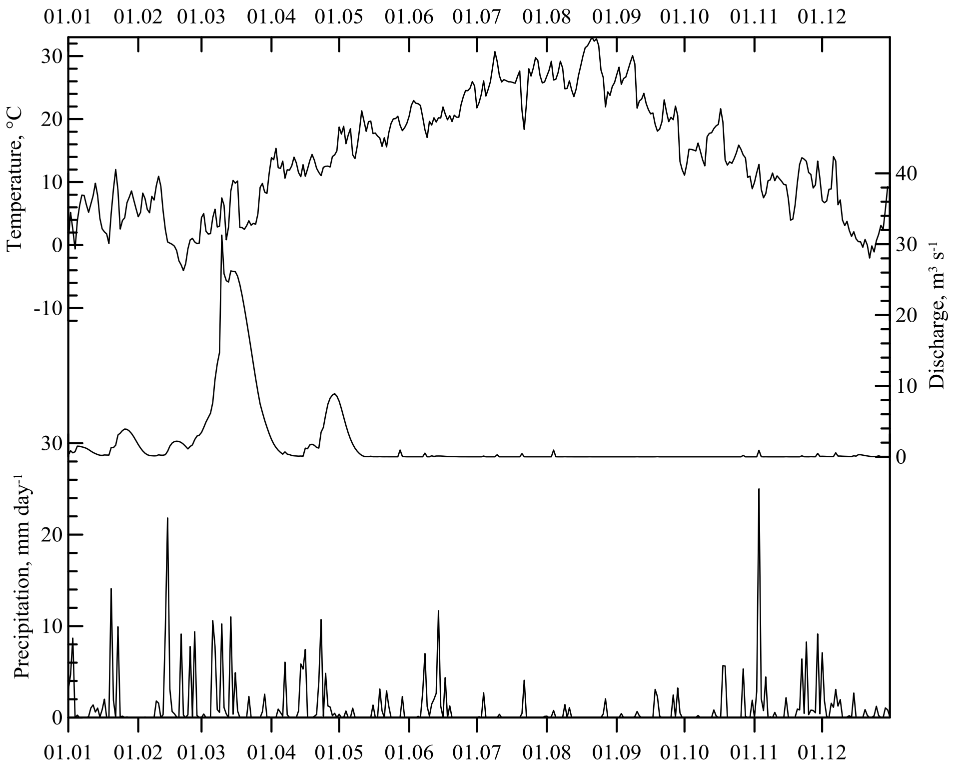


Figure 6. Simulated daily temperature, water discharge and precipitation for the scenario p3.

2.2 Loads from catchment

Climate impacts on the nutrient loads introduced to the Tyligulskyi Liman are similar to the impacts on water discharge. Figures 7-10 show daily changes of nitrate nitrogen, ammonium nitrogen and phosphate phosphorous loads coming to the Tyligulskyi Liman for all four future periods – p0, p1, p2, p3. Maximal values can be detected during the spring high water period, which are in good agreement with the daily discharges (see Figs. 3-6). Also, some peaks can be noticed during the heavy rainfalls (in summer or in autumn). However, the loads are very low, especially for the scenarios p1 and p3, when their values are almost zero during the summer and autumn months. Usually, the load of nitrate nitrogen has the larger values than the loads of ammonium nitrogen and phosphate phosphorous.

In general, the nutrient loads behave similarly to the water discharges. This is partly the result of the influence of ponds implemented in the model. These are defined not only to take the inflowing water, but also the nutrient loads coming with them. Therefore, nutrients can only reach the lagoon with the rest water coming to the river outlet (Hesse et al., 2013).

The maximal values of nitrate nitrogen, ammonium nitrogen and phosphate phosphorous will be loading into the Tyligulskyi Liman during the early February in the scenario p2. It is noteworthy that this scenario is also characterized by very early snow melt, and the water discharge will be maximal in the first decade of February. However, the loads will sharply decrease to the March.

The minimal values of loads will be observed for the scenario p1. These values will differ from zero only during two months – in March and April. This fact is attributed to the very low water discharge during the typical year of the period p1.

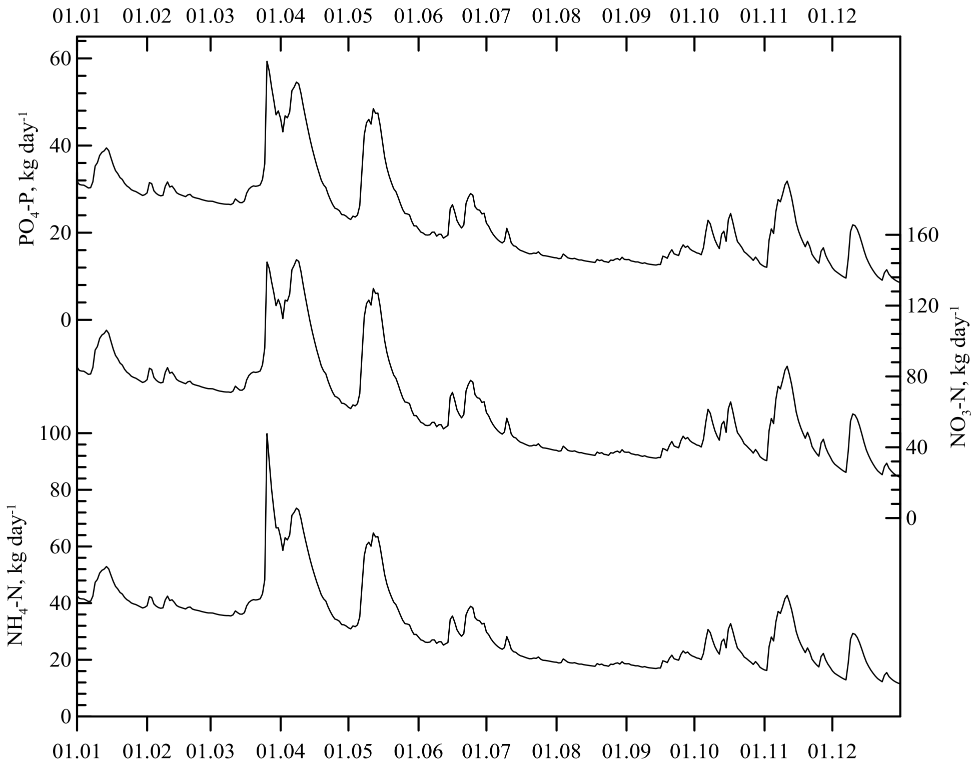


Figure 7. Simulated daily loads of NO_3-N, NH_4-N and PO_4-P for the scenario p0.

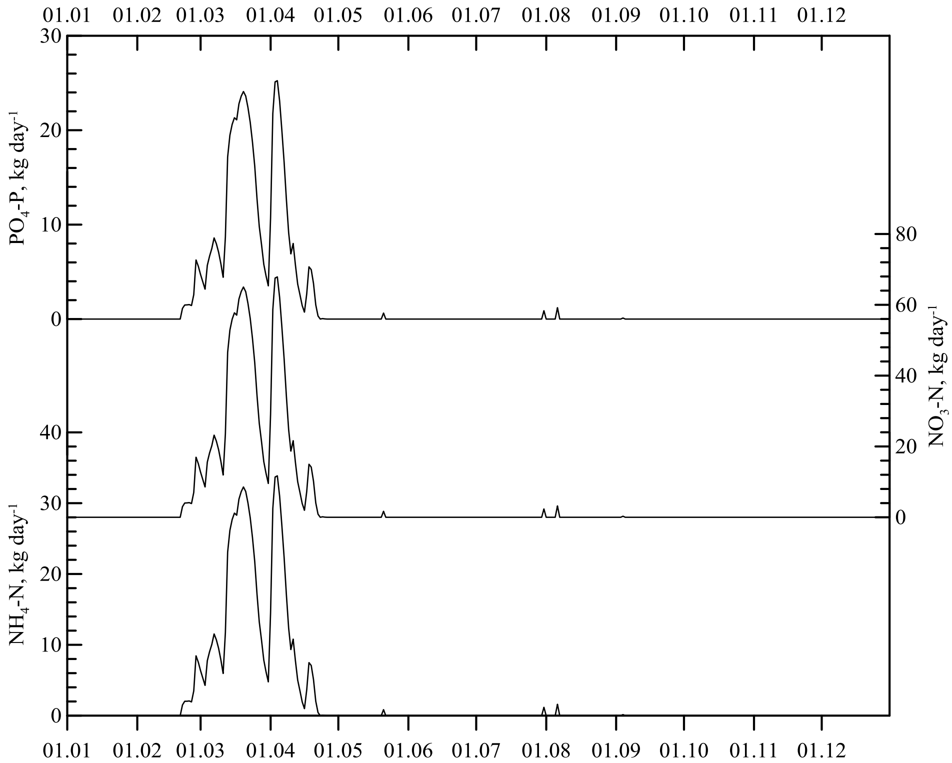


Figure 8. Simulated daily loads of NO_3-N, NH_4-N and PO_4-P for the scenario p1.

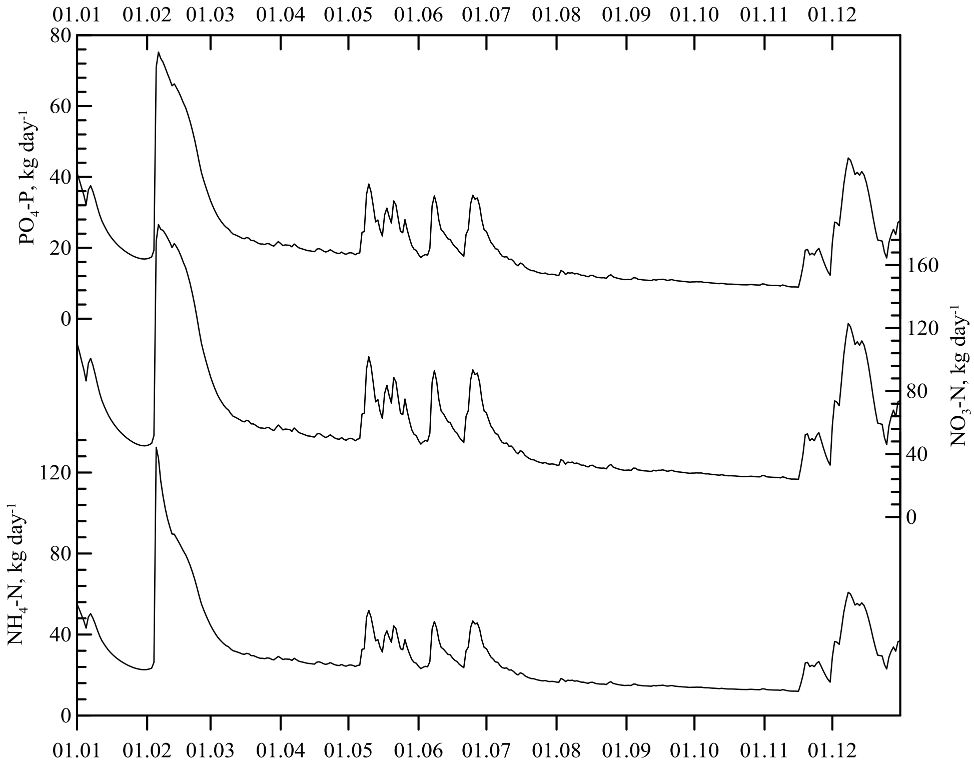


Figure 9. Simulated daily loads of NO_3-N, NH_4-N and PO_4-P for the scenario p2.

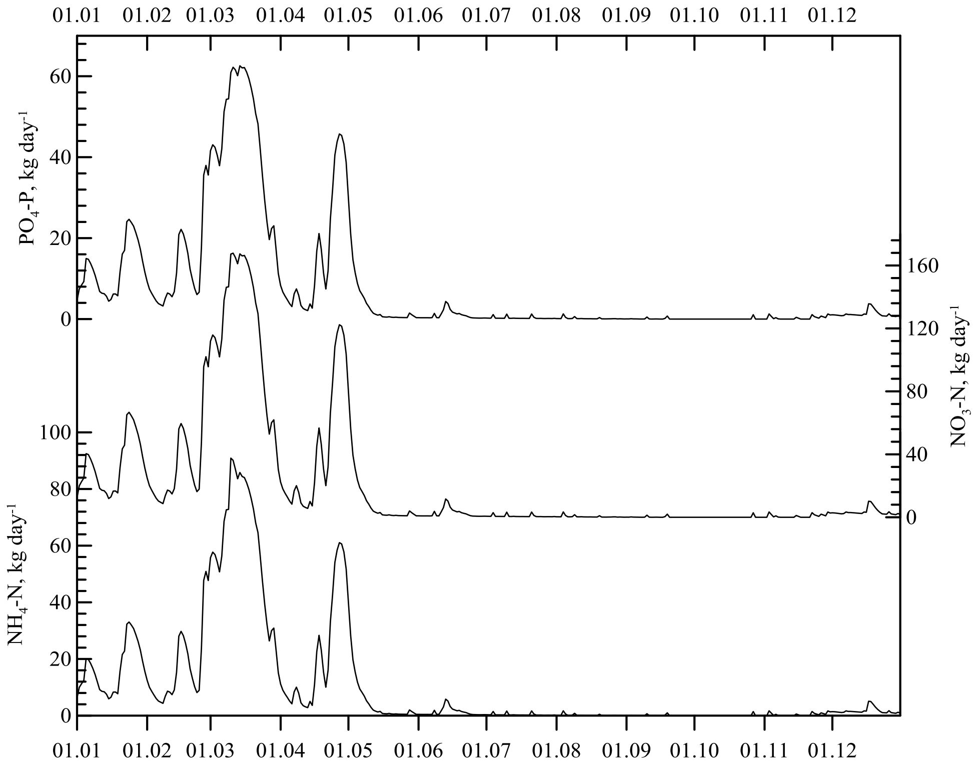


Figure 10. Simulated daily loads of NO_3-N, NH_4-N and PO_4-P for the scenario p3.

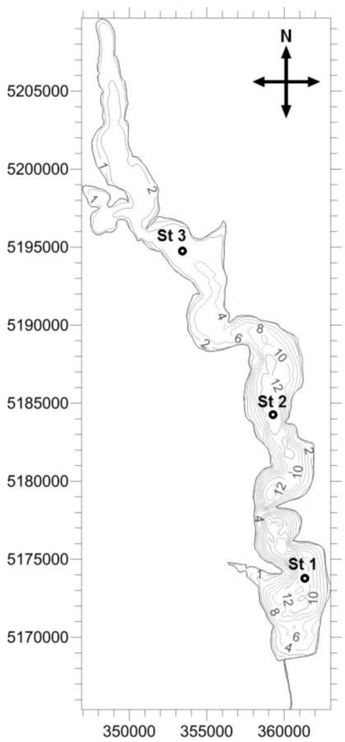


Figure 11. The depth map and the location of three observation points used for the analysis of modeling results for the Tyligulskyi Liman. On the coordinate axes, marks of grids of the Universal Transverse Mercator system are indicated with a grid of 5000 m, area 36N.

Therefore, the river discharge and nutrient loads are expected to decline in the nearer future (p1), and to increase in the two last periods (p2 and p3), with a bit higher increase in p2 than in p3; however, the period with the significant discharge and loads will be longer in the period p3. The loads show a similar behaviour to the river discharge; this is partly due to the impacts of the pond's water and nutrient storage potential (Hesse et al., 2013). As the modelled discharge is highly influenced by water management measures in the drainage area, the ecosystem responses due to the climate change only become hardly detectable.

2.3 Lagoon's response and discussion

Estimation of influence of the climate change on the Tyligulskyi Liman is performed on the basis of model calculations for typical years, which were selected with the use of a technique presented in

Section 1.1. The extremes were additionally considered by the volumes of fresh water flow in a year of a particular climate period. Results of the calculations were analyzed for three points of the lagoon, which are located in the deep southern and central parts (St 1, 2), as well as in the shallow northern part St 3 (Fig. 11). The southern part is influenced by the water exchange with the sea through an artificial connecting channel in the period of its functioning (April-June), and the northern part is influenced by the fresh water flow (more than 90 %), mostly from the Tyligul River.

Figure 12 shows the general information on the variability of main forcing factors – the annual runoff and lagoon water temperature. The annual runoff is presented instead of discharge, because the non-zero (and relatively high) river water discharge into the Tyligulskyi Liman for the scenarios p1, p02, p32 is predicted only during a few months.

Features of intra-annual variability in the simulated environmental variables in different parts of the lagoon in characteristic years of various forecast periods are shown in Figs. 13 and 14. The phytoplankton biomass (mgC) is presented instead of chlorophyll-*a*, as the model was calibrated based on the observations data of the raw biomass of phytoplankton. The observations suggest that the ratio of mg Chl-*a*/mgC varies considerably during the year. The approximate ratio of mg Chl-*a*/mg C = 0.021 can be used.

Algae biomass reaches its maximum value in August and early September. In the periods of p0 and p1, in the southern and the central parts of the lagoon, against the background of the principal peak of the biomass, the peaks are subdivided into two local ones – in early August and early September. The peak of the algal biomass in September dominates in the shallow northern part of the lagoon. It is here that the biomass reaches its maximum value for the entire lagoon.

Typical years **Moist year** **Dry year**

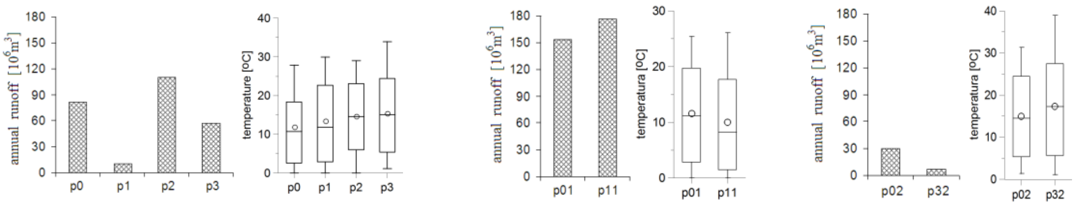


Figure 12. The variability of annual runoff and lagoon water temperature in Tyligulskyi Liman for typical and extreme years.

In the period p2, a powerful peak of biomass with a maximum value in late August formed in all parts of the lagoon. In the northern part, the biomass of algae reached its historical maximum.

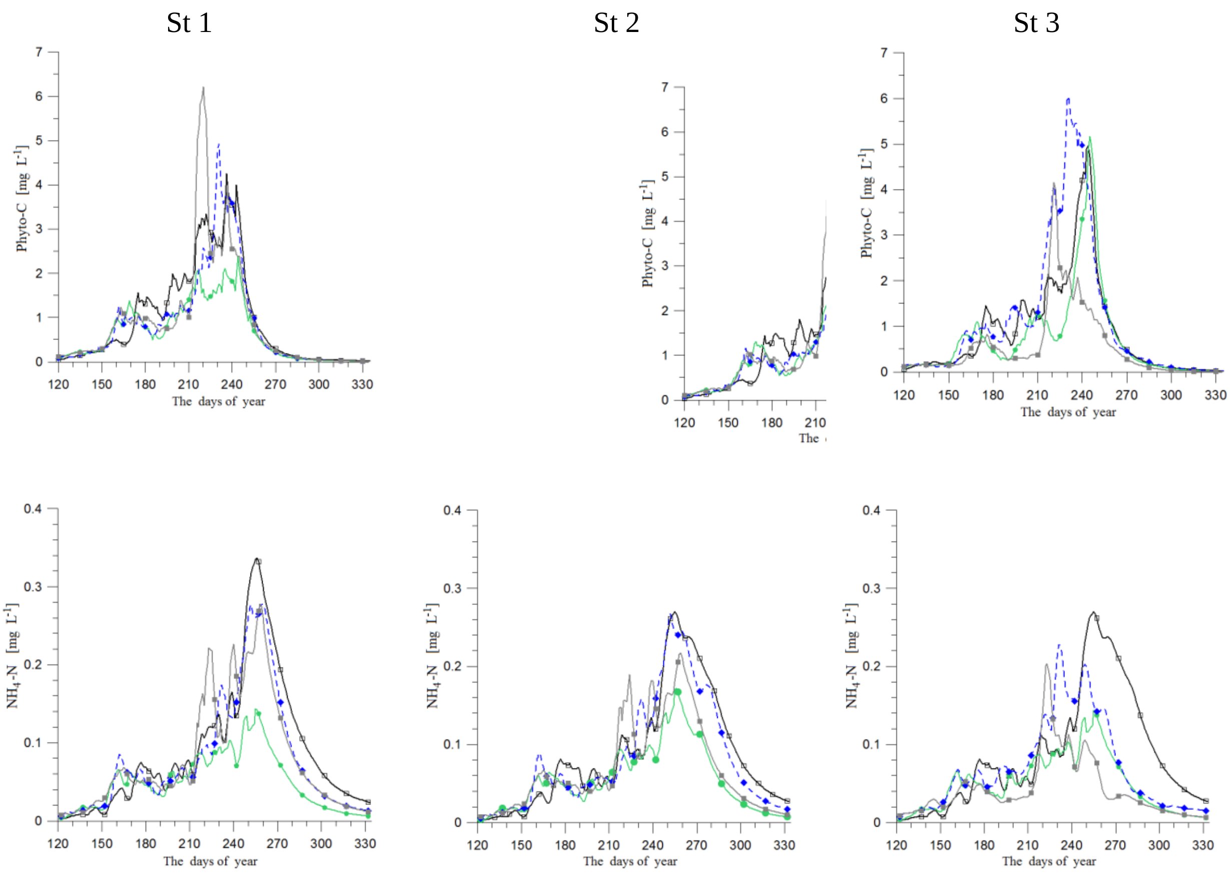
In the period p3, a peak of phytoplankton biomass dominated in all parts of the lagoon in early August. In contrast to previous periods, the maximum values of biomass coincide with the ones for the southern part of the lagoon. This is a consequence of an increase in the inflow of sea water into the lagoon through the connecting canal, which supplies the lagoon with additional mineral nitrogen that limits production of algae.

The minimum concentration of phosphates in all the periods of the simulation corresponds to phases of intensive growth (production) of phytoplankton biomass. In the northern part of the lagoon, phosphate concentration in autumn and winter can decrease by several times as compared to the ones in spring. Phosphate reserves in this part of the reservoir are for the most part replenished by the inflow of river water from the drainage basin in late winter and spring, and mineralization of deposits of organic matter in sediments.

Maximum annual variability in concentrations of ammonium nitrogen is shifted by one month relative to the maximum algal biomass, and is observed in September and early October. It is formed as a result of organic matter mineralization of the dead algae. The maximum concentrations of nitrate nitrogen occur in late October - early November as a result of nitrification of ammonium nitrogen.

Intra-annual variability of salinity in the lagoon predicted by the model in various periods is shown in Figs. 15 and 16. It is formed under the influence of an occasional inflow of river runoff from the catchment area in the northern part of the lagoon (mainly in spring), the input of sea water through the connecting channel (April through June) in the amounts necessary to compensate the shortage of freshwater balance of the lagoon, which is formed prior to the moment the canal is opened, and intensive evaporation in the warm season. Under the absence of significant freshwater runoff from the drainage basin in the second half of the year, the shallow northern part of the lagoon turns a source of water of high salinity for the whole of the lagoon (periods p1 and p3) as a result of intense evaporation. Intense flow of sea water through the canal in the years with a significant shortage of freshwater balance (p1, p3) facilitates reduction in salinity in the southern part of the lagoon. In the years when runoff from the catchment is significant, its pronounced effect manifests itself in a decrease in salinity not only in the northern, but also in the southern part of the lagoon (p0, p2).

Generalized information on spatio-temporal variability of basic hydroecological features of the lagoon, such as salinity, phytoplankton biomass, NO_3-N, NH_4-N, PO_4-P, and O_2 is presented in Figs. 17 and 18. Also, Table 4 summarizes the lagoon-averaged values of modelled variables in the typical and extreme years in comparison with the period p0.



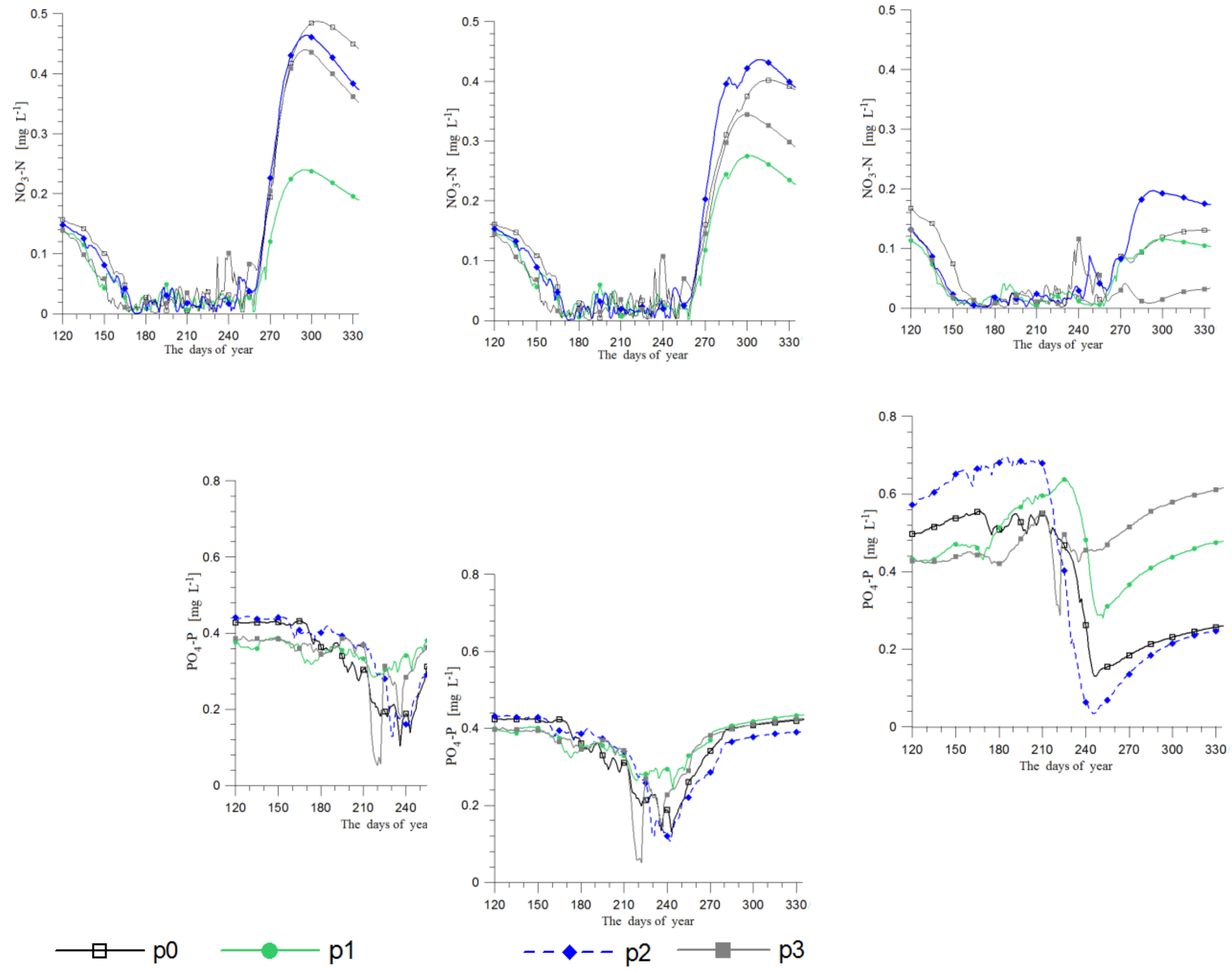
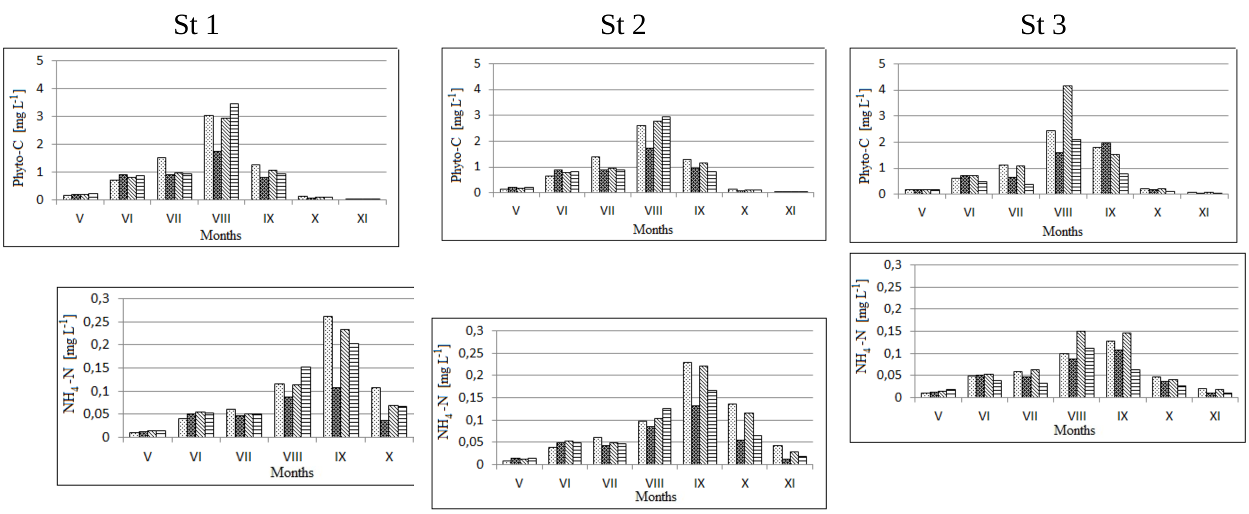


Figure 13. Variability of daily environmental variables for Tyligulskyi Liman in May through November for scenarios p0, p1, p2, p3 at different points St1, St2, St3.



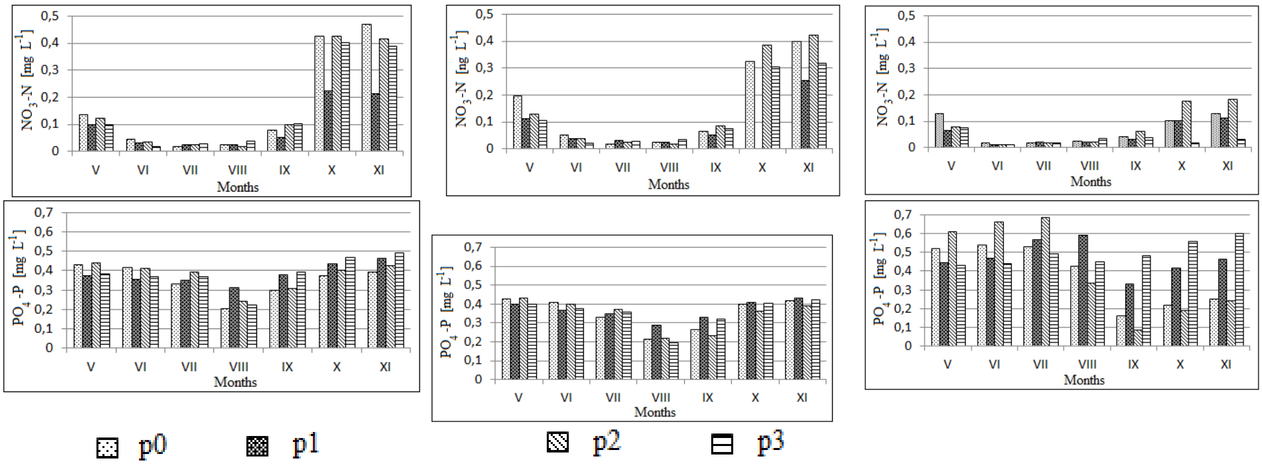


Figure 14. Variability of monthly environmental variables for Tyligulskyi Liman in May through November for scenarios p0, p1, p2, p3 at different points St1, St2, St3.

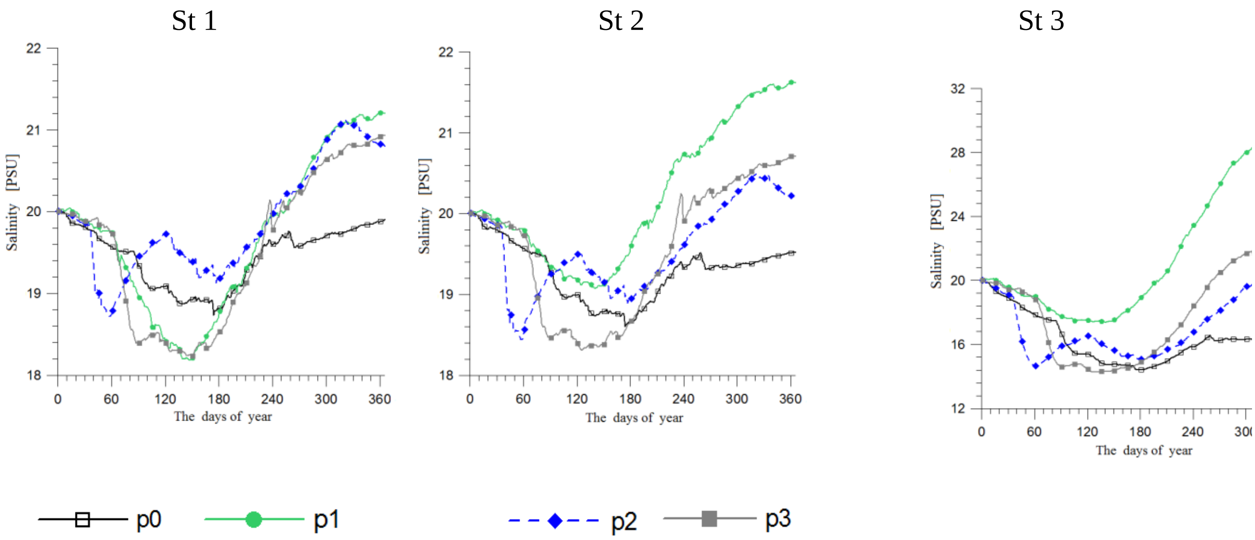


Figure 15. Annual variability of salinity in Tyligulskyi Liman for scenarios p0, p1, p2, p3 at different points St1, St2, St3.

The results of the model calculations testify that the present-day period (p1) is characterized by minimal average long-term volumes of lateral fresh flow into the lagoon, which results in an increase in water salinity, diminishing concentrations of NH_4-N, the deficit of which leads to limited primary water-weed production in summer months, and an overall biomass reduction and a raise in concentrations of PO_4-P.

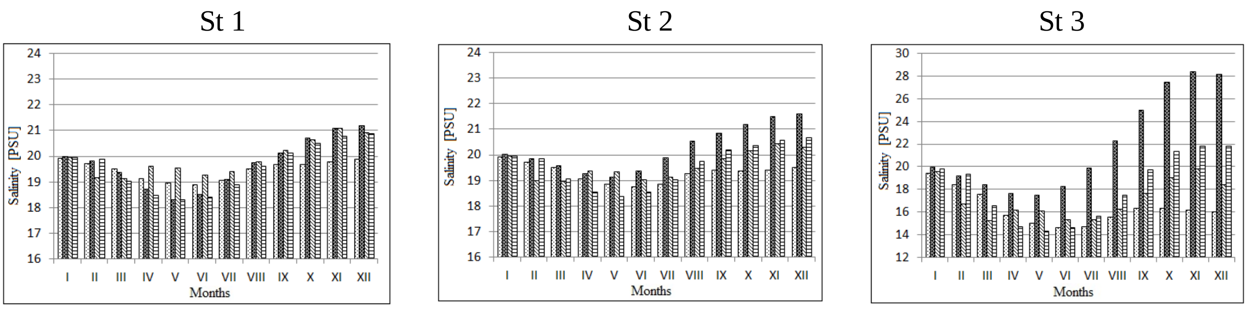


Figure 16. Variability of monthly salinity in Tyligulskyi Liman for scenarios p0, p1, p2, p3 at different points St1, St2, St3.

The deep southern and central parts of lagoon, the volume of water in which amounts to 80% of the total volume of water in the lagoon, pose a considerable damping effect as regards the influence of the river flow (1.5 % of the total volume of water in the lagoon). However, even in these parts, an increase in salinity of water by a few PSU units is observed in the course of an annual cycle, which in a few decades will result in an increase in salinity of water in the lagoon by some tens of PSU. The most intensive increase in salinity takes place in the shallow northern part of the lagoon. In view of a lack of fresh water flow and intensive evaporation in summer months, the salinity here could reach 27 PSU by the end of the year. These salty waters get to the central and the southern parts of the lagoon, thus contributing to their salinization. The obtained results of hydrodynamic modelling are substantiated by independent calculations with the use of a model of water-salt balance in the lagoon, according to which an average salinity of water in the lagoon will rise, to reach 30-35 PSU by the end of the period p1.

In the forecast period p2, a considerable increase of lateral fresh water flow into the lagoon is expected. The inflow of mineral compounds of nitrogen will increase together with the flow, which will entail an increase in water-plant biomass in the lagoon, as well as intensification of their «blooming» (at the maximum values of the biomass). In spite of an increase of utilization of PO_4-P by the water plants, median and maximal values of the PO_4-P concentration will increase due to an additional inflow with river runoff during the spring high water (Fig. 17). Considerable incidental diminishing in the concentration of PO_4-P is however possible in periods of «flashes» of the biomass, especially in the shallow northern part of the lagoon. For the scenario p2, the lagoon-mean values of phytoplankton biomass and NH_4-N concentration are similar to those which are recorded for the scenario p0 (Table 4).

Table 4. Relative changes (in %) in concentrations of Chl-*a*, NO_3-N, NH_4-N, PO_4-P, O_2 and salinity for typical and extreme years.

Scenario		Chl-*a*	NO_3-N	NH_4-N	PO_4-P	O_2	Salinity
Typical 1	p1/p0	-26,93	5,84	-32,51	9,86	-9,28	10,10
Typical 2	p2/p0	-1,04	30,58	-1,1	3,44	-11,19	3,86
Typical 3	p3/p0	-10,59	27,98	-12,05	6,04	-13,38	3,39
Moist year	p11/p01	34	25,63	46,18	-15,38	5,37	-9,29
	p01/p0	-22,55	-22,82	-32,53	11,35	4,2	-5,93
	p11/p1	36,52	-8,39	46,14	-14,23	21,04	-22,5
Dry year	p32/p02	6,38	50,17	24,69	-15,96	-21,85	5,38
	p02/p0	-23,46	-0,24	-30,32	21,34	-5,4	11,17
	p32/p3	-8,93	17,06	-1,21	-3,83	-14,64	13,31

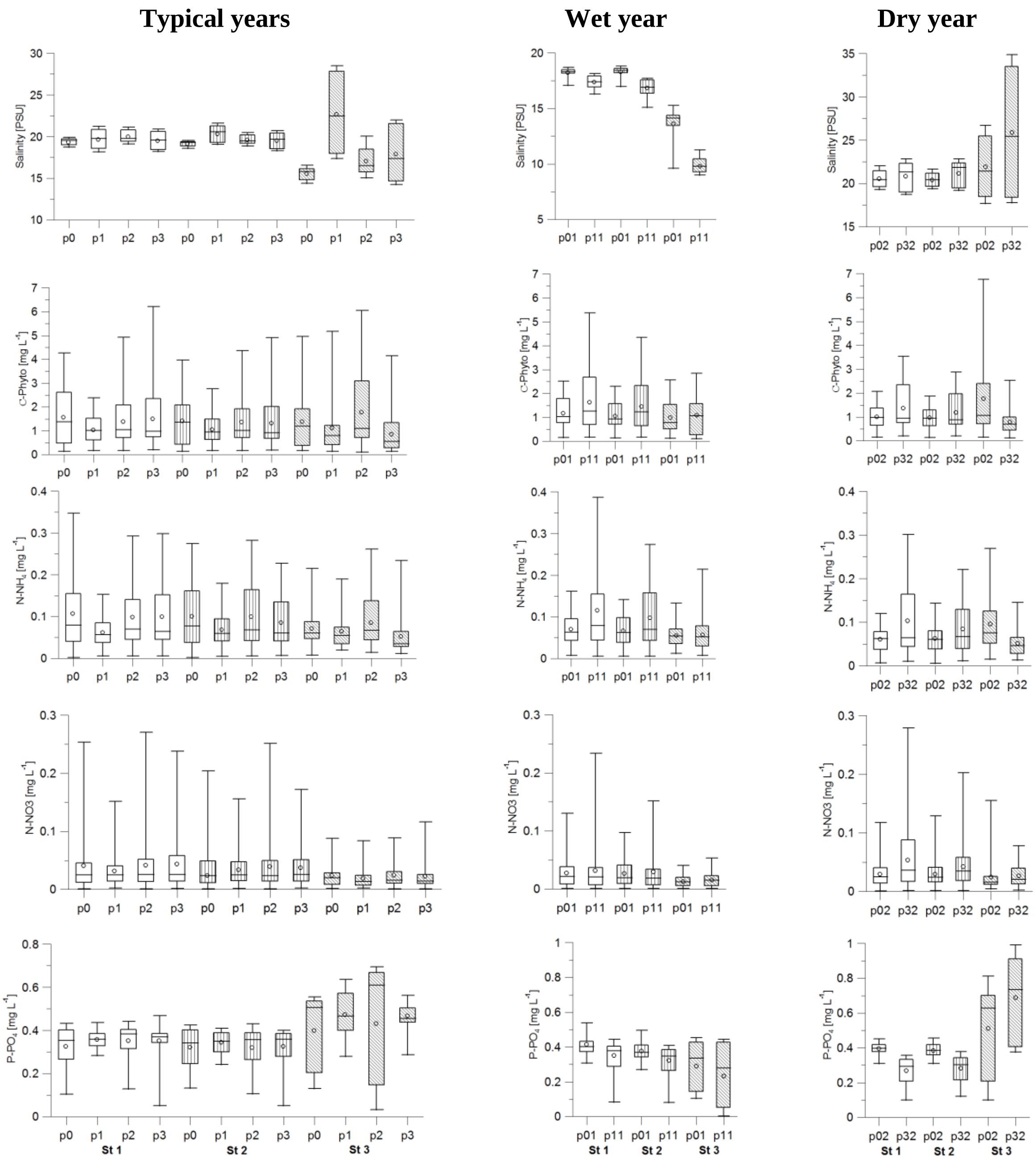


Figure 17. Model results for stations St 1, St 2, St 3 in Tyligulskyi Liman. The box plots visualize min/max, 25/75-percentile, median and average (dots) of the calculated variables per scenario (p1, p2, p3, p11, p32) compared to the reference period (p0 - typical and p01, p02 - extreme).

If one compares the scenario p2 with the scenario p1, the mean values of water salinity, PO_4-P and O_2 will decrease, and the mean values of NO_3-N will significantly increase.
The period p3 is characterized by a lower river flow as compared to p2 and p0, which is, however, higher than in the period p1. In the same period, the temperature of water and air and, consequently, evaporation rates from the water surface in the lagoon will attain the maximum values. To set off the deficit of fresh water balance, the inflow of salt waters into

the southern part of the lagoon through the channel will increase. Spatial distribution of phytoplankton biomass in this period will be characterized by the maximum values in the southern part of the lagoon, and minimum ones in the northern part, where development of the water plants will be restrained by the lack of NH_4-N (Fig. 17). The lagoon-mean values of phytoplankton biomass and NH_4-N will be smaller, and those for NO_3-N and PO_4-P will be larger than for the scenario p0. As compared with other periods of the 21st century, the period p3 will be characterized by the minimal concentrations of O_2, by the maximal valued of NO_3-N, and by the intermediate (between the periods p1 and p2) concentrations of NH_4-N, PO_4-P, and phytoplankton biomass.

Parallel to a general tendency of increasing water temperature and phytoplankton biomass in the deep southern and central parts of the lagoon in the 21st century, the oxygen regime will also become worse (Table 4), and the minima of oxygen in the benthic layer, especially in the central part of the lagoon, will turn deeper (Figure18).

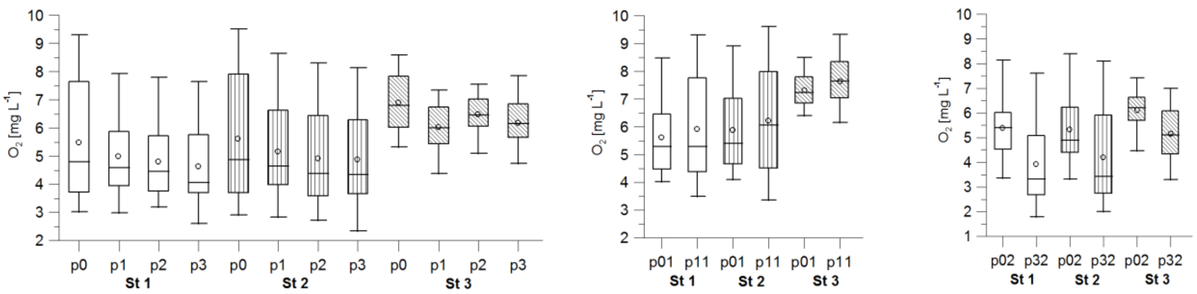


Figure 18. Model results of dissolved oxygen content in Tyligulskyi Liman at stations St 1, St 2, St 3.

Comparison of the calculation results for the extreme years in various forecast periods provides an insight into their influence on spatial hydroecological descriptions (Fig. 17). In the years with the maximum flow (p11) in the period p1, the concentrations of NH_4-N, NO_3-N and phytoplankton biomass in the lagoon will be higher, and the concentration of PO_4-P and the salinity will be lower than in an extreme year (p01) in the period p0 (Fig. 17, Table 4). In an extreme year with a minimum flow p32, the concentration of NH_4-N and phytoplankton biomass will be higher, and the concentration of PO_4-P will be lower than in the case of p02, in the deep southern and central parts of the lagoon. In the case of the northern part, it is quite the contrary. The concentrations of NO_3-N in the all three parts of the lagoon will increase. In the extreme dry year p32, as compared with p02, the lagoon-mean values of the salinity, phytoplankton biomass and mineral nitrogen NH_4-N, NO_3-N will increase, and the lagoon-values of PO_4-P and O_2 will decrease (Table 4).

It is very interesting to consider the relative changes of mean concentrations in extreme years as compared with those for the typical years of the same periods (Table 4). For the scenarios p01 and p2, the mean concentrations of mineral nitrogen NH_4-N, NO_3-N as well as the phytoplankton biomass will decrease, and the mean concentration of PO_4-P will increase as compared with the typical year in p0. For the scenarios p11 and p32, the concentrations of NH_4-N and phytoplankton biomass will increase, and PO_4-P will decrease during the high-water year (p11), and vice versa during the low-water year. For all the modelled periods, the mean values of O_2 will decrease during the dry years, and will increase during the high-water years.

3. Combined socio-economic and climate change impact on the lagoon

3.1 Climate forcing

In order to analyze the climate change impact on the Tyligulskyi Liman, we use the scenario p0 that was described in Section 2.1. Let us to note again that the typical year for the scenario p1 is characterized by the extremely low water discharge during the spring high water period – the maximal value is about 6 $m^3 s^{-1}$.

3.2 Loads from catchment

As it was already mentioned in Section 2.2, both the water discharge and nitrate nitrogen, ammonium nitrogen and phosphate phosphorous loads coming to the Tyligulskyi Liman are very small, and are observed only during the spring high water period. All scenarios consider a decrease of river runoff into the lagoon: BAU and CRI – due to a decrease in population and, as a consequence, the reduced water use, MH and SET – due to the 50% and 75% decrease in artificial reservoirs on the lagoon's drainage area. The loads of nitrate nitrogen, ammonium nitrogen and phosphate phosphorous are changed respectively to the discharges.

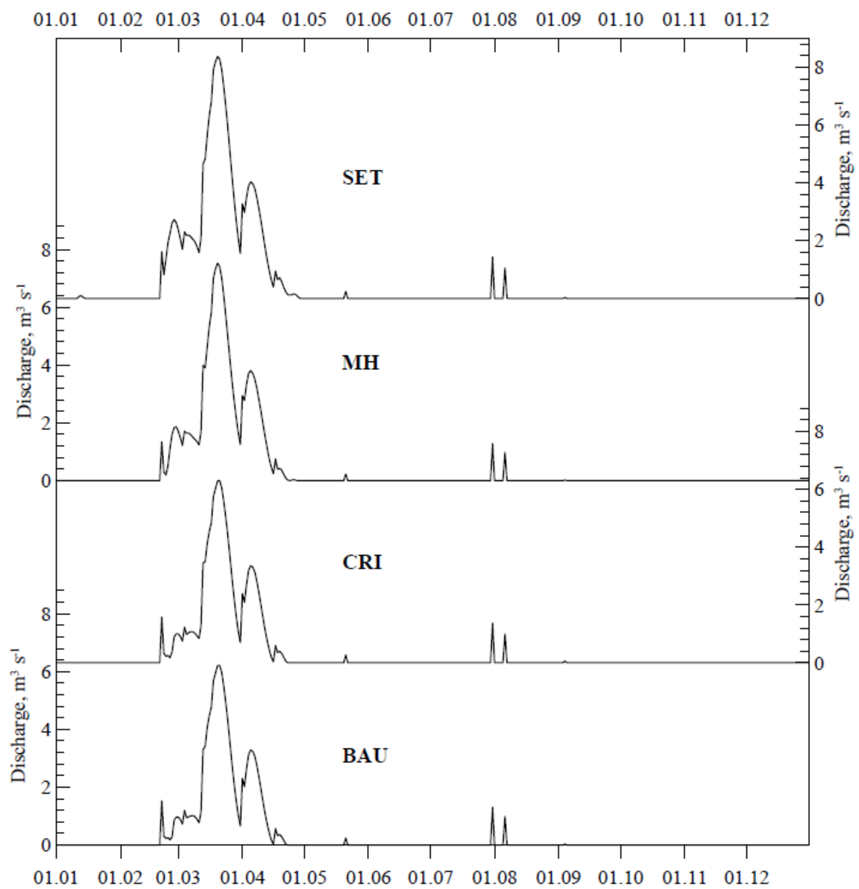


Figure 19. Simulated daily water discharges for scenarios BAU, CRI, MH, and SET.

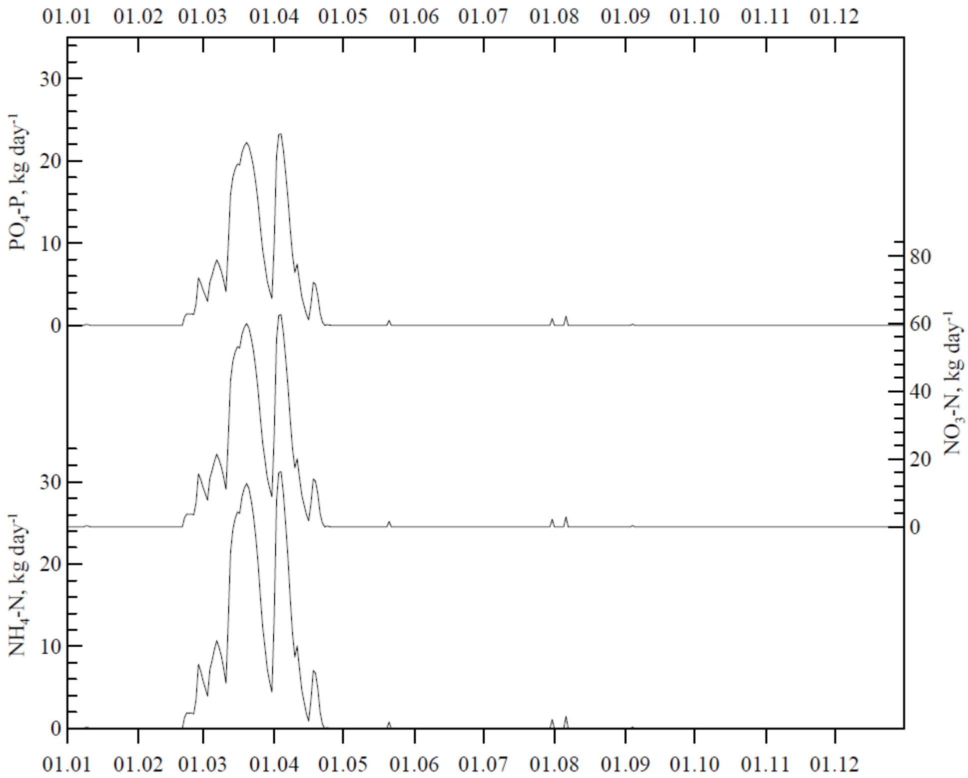


Figure 20. Simulated daily loads of NO_3-N, NH_4-N and PO_4-P for the scenario BAU.

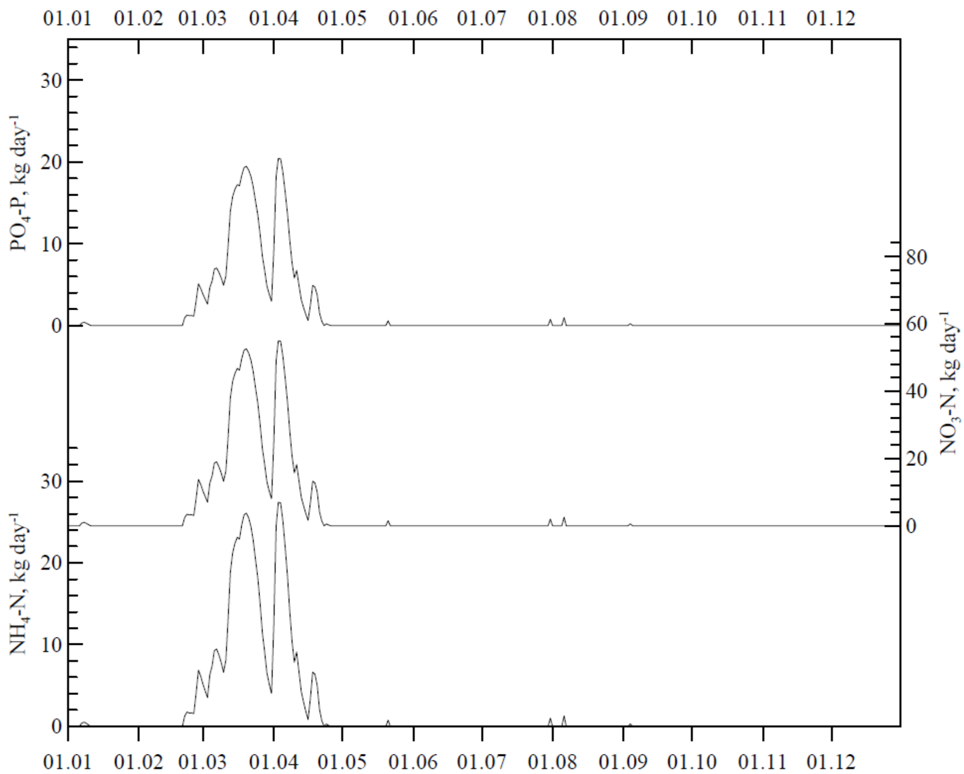


Figure 21. Simulated daily loads of NO_3-N, NH_4-N and PO_4-P for the scenario CRI.

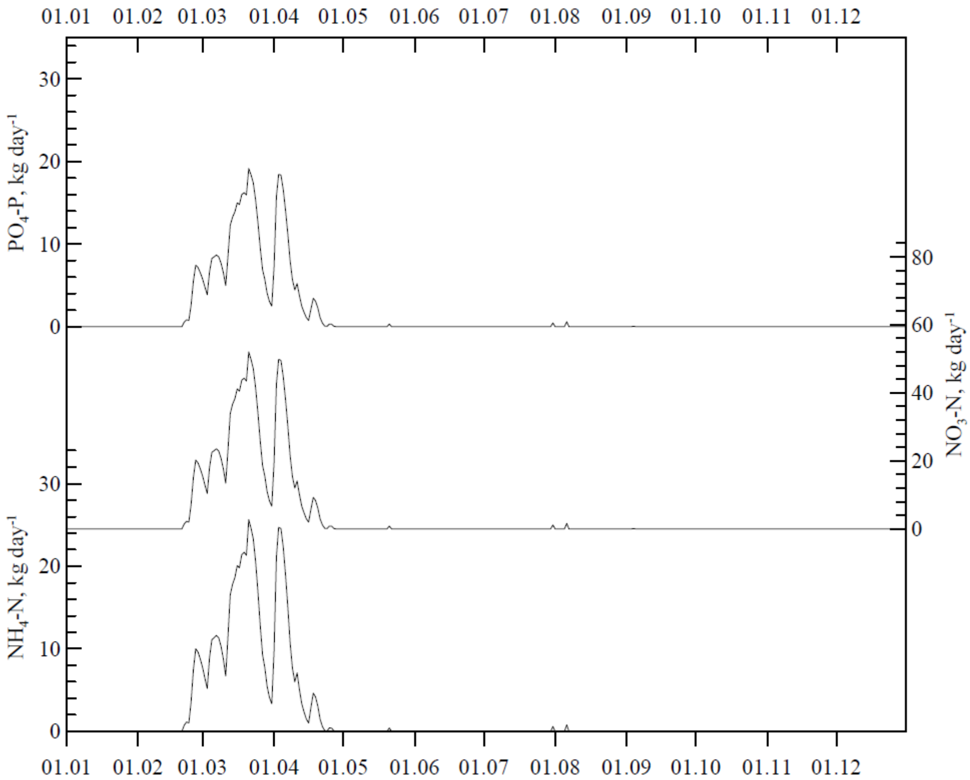


Figure 22. Simulated daily loads of NO_3-N, NH_4-N and PO_4-P for the scenario MH.

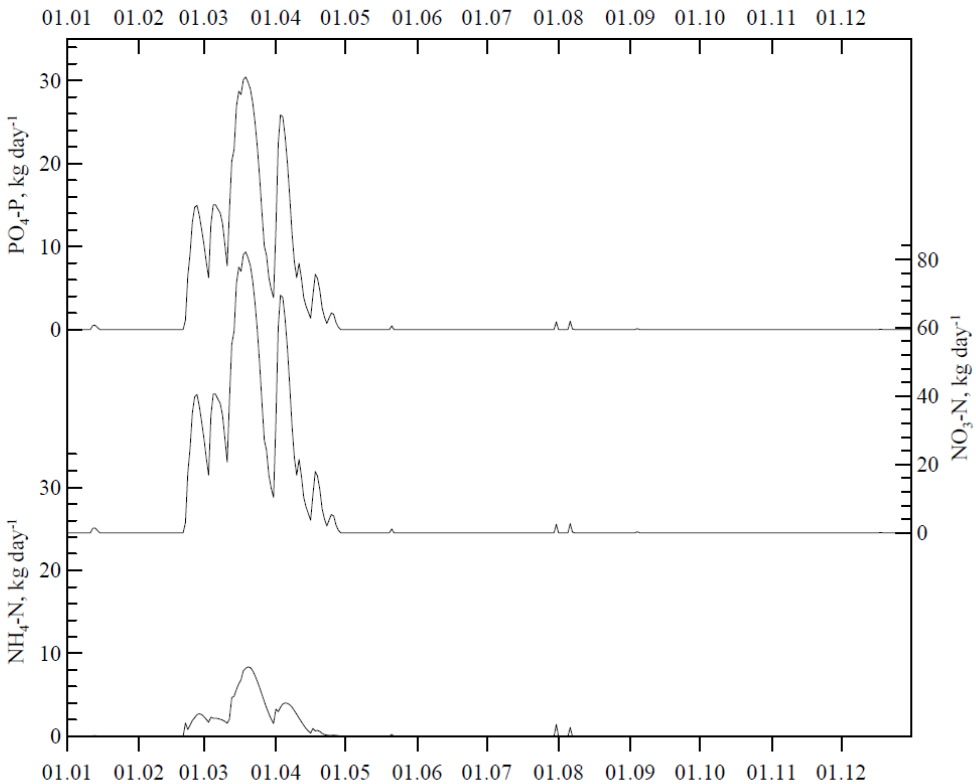


Figure 23. Simulated daily loads of NO_3-N, NH_4-N and PO_4-P for the scenario SET.

3.3 Lagoon's response

The ecological status of the Tyligulskyi Liman can be influenced by socio-economic conditions in its drainage area as well as a regime of water exchange between the lagoon and the sea through the artificial channel. The socio-economic factors, such as the land use and water management, define the values of freshwater and biogenic matter inflow. During the last decade, the water exchange with the sea has been carried out mainly to compensate the deficit of freshwater balance in the lagoon and, as a result, to stabilize its water level and to prevent its shoaling. Under the climate change, the use of the channel for the fishing purpose was secondary. Therefore, the runoff of water and biogenic matter from the lagoon's drainage area and the regime of water exchange with the sea are two factors which make it possible to control the ecological status of the Tyligulskyi Liman to some extent.

In this chapter the joint impact of climate change in the nearest future (the typical year for the period p1; 2011–40) together with four possible scenarios of land and water use, as well as different conditions of water exchange with the sea, are considered. The hydrometeorological conditions in the lagoon's drainage area and on the sea border of the channel were assumed the same in all scenarios. The changes in the runoff of water and biogenic matter due to the different land and water use conditions in the lagoon's drainage area were varied in all scenarios. Figure 24 and Table 5 show the main model results.

As it was noticed in Chapter 2.2, the period p1 is characterized by the minimal long-term values of lateral freshwater runoff (just 1.5% of the lagoon's water volume). This feature predetermines the model results. In spite of drastic measures, the impact of socio-economic scenarios in the lagoon's drainage area becomes apparent only in its shallow northern part, which is the main (more 90%) recipient of the Tyligul River runoff.

All scenarios consider a decrease of river runoff into the lagoon: BAU and CRI – due to a decrease of population and, as a consequence, the reduced water use, MH and SET – due to the 50% and 75% decrease of artificial reservoirs in the lagoon's drainage area. The rate of water salinity increase will slow down if the latter two scenarios will be realized.

The primary production of organic matter in the Tyligulskyi Liman is limited by the mineral nitrogen. For the scenarios CRI and MH, the inflow of mineral nitrogen from the drainage area will decrease. These changes will result in the insignificant decrease in the mean concentrations of NH_4-N, NO_3-N, and algae biomass, as well as in the increase in PO_4-P concentration in the lagoon, especially in its northern part. A negligible decrease in the maximal concentrations of mineral nitrogen and algae biomass can be observed in the central (scenario CRI) and southern (scenario MH) parts of the lagoon.

For the scenario SET, the inflow of the mineral nitrogen into the lagoon will increase up to the values that are representative for the typical year of the period p1. In the northern part of the lagoon, most of the model values of the ecological characteristics will return to those which are representative for the typical year of the period p1. The water salinity in the northern part of the lagoon will nevertheless decrease. However, for whole lagoon, the tendencies in the changes of these ecological characteristics are similar to those which were described earlier for other scenarios.

As it was mentioned above, the water exchange between the lagoon and the sea through the connecting channel can also regulate the ecological conditions in the Tyligulskyi Liman. The channel is mainly used to refill the lagoon by sea water; as a result of high evaporation rate the salt is accumulated in the lagoon. The intra-annual variability of the lagoon's water balance was preliminary analyzed to determine an acceptable operating regime of the channel.

The analysis showed that the channel must be operated during a whole year to ensure the salt water outflow from the lagoon to the sea. This scenario is referred to as p1S.

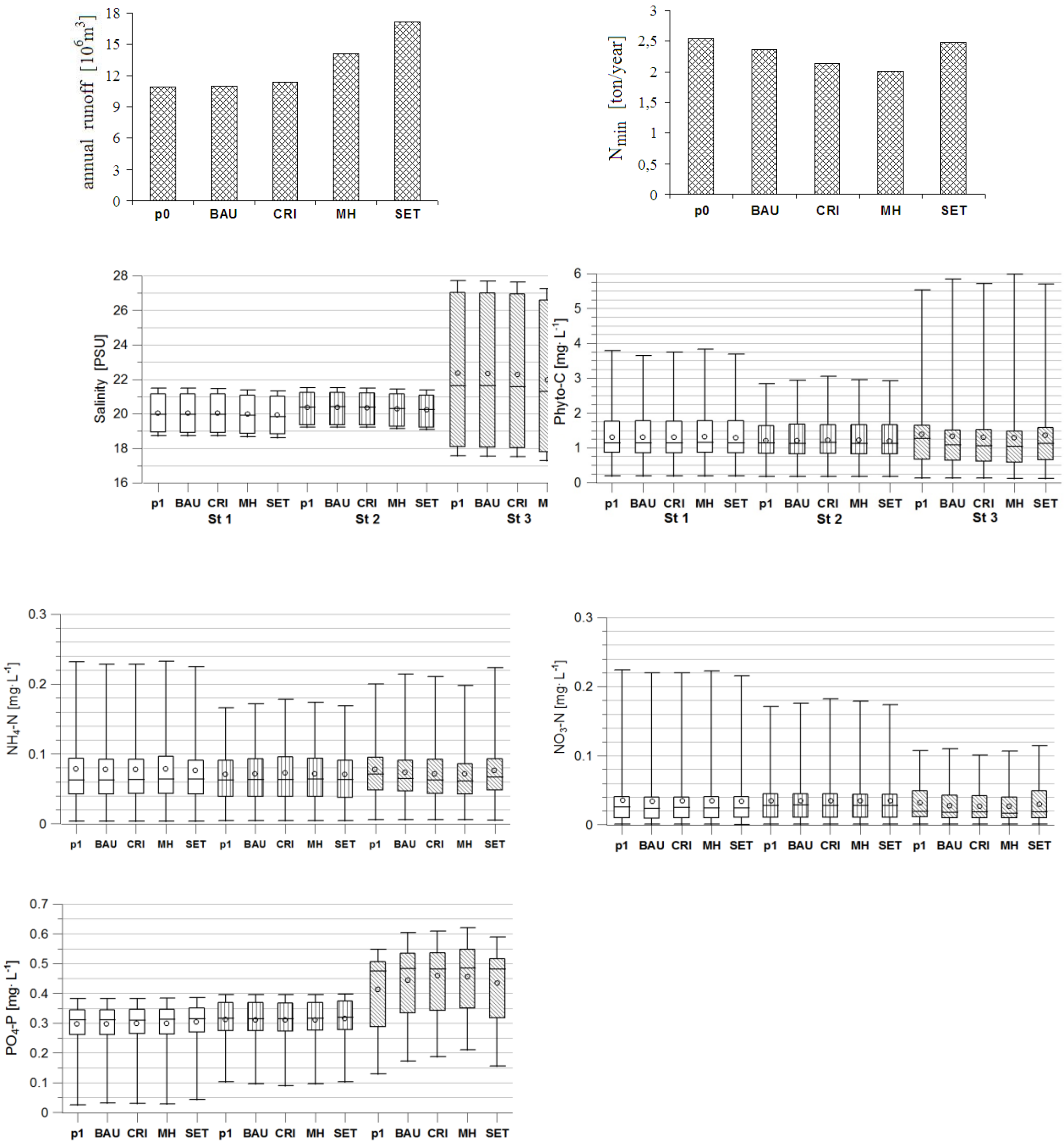


Figure 24. Boundary conditions applied in scenarios at rivers (annual runoff and mineral nitrogen load) and modelling results in Tyligulskyi Liman at three locations St 1, St 2, St 3. The box plots visualize min/max, 25/75-percentile, median and average (dots) values of the calculated variables per scenario (BAU, CRI, MH, SET) compared to the reference period p1.

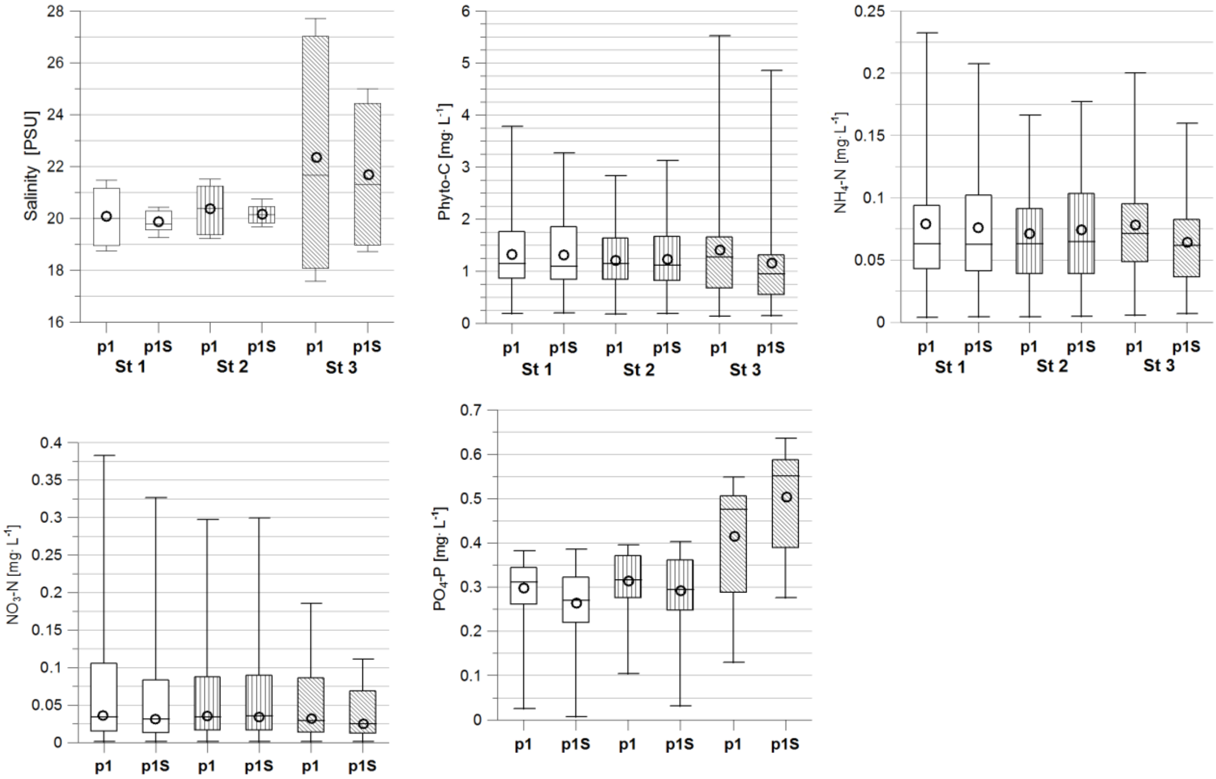


Figure 25. Model results of salinity and ecological characteristics in Tyligulskyi Liman at three stations St 1, St 2, St 3. The box plots visualize min/max, 25/75-percentile, median and average (dots) values of the calculated variables for scenario p1S compared to the reference period p1.

Figure 25 shows that the rate of the salt accumulation can be decelerated under the scenario p1S, just like in the SET scenario. Also, the amplitude of salinity variations will decrease in all parts of the lagoon, which results positively in the lagoon's ecological status. Nevertheless, the year-round water exchange with the sea will influence the ecological characteristics of the lagoon in different ways. The concentrations of NH_4-N will decrease in the southern and northern parts of the lagoon, and will increase in the central one. The concentrations of PO_4-P will decrease in the southern and central parts of the lagoon, and will increase in the northern one. The mean and most probable concentrations of algae biomass will significantly decrease in the northern part of the lagoon, and will not practically change in the southern and central ones. Results in Table 5 confirm that the most preferable scenario is that in which the channel provides the year-round water exchange between the lagoon and the sea, as this provides the greatest decrease in water salinity and other hydrochemical parameters.

Table 5. Relative changes (in %) of water discharge, concentrations of Chl-*a*, NO_3-N, NH_4-N, PO_4-P and salinity in each of the scenarios compared to the period p1 (2011–2040).

Scenario	Discharge	Chl-*a*	NO_3-N	NH_4-N	PO_4-P	Salinity
BAU	0,90	-0,56	-3,62	-0,56	1,51	-0,02
CRI	4,05	-0,22	-3,18	-0,28	2,13	-0,11
MH	28,61	-0,58	-3,19	-0,58	2,15	-0,60
SET	56,65	-1,14	-2,70	-1,04	2,36	-1,18
p1S	0,00	-2,32	-9,19	-2,12	-2,29	-2,78

4. Conclusions and recommendations

For the Tyligulskyi Liman lagoon, its biodiversity and fish productivity during the period p1 will be endangered by the gradual increase in the water salinity up to the mean values of 30-40 PSU. The increase will arise from the reduction in the freshwater inflow into the lagoon. Nevertheless, the mineral nitrogen will limit the production of organic matter by algae. During the period p2, the increasing freshwater inflow will diminish the problem of water salinity. However, the additional input of mineral nitrogen will increase the primary production of organic matter; as a result, the eutrophication with all its negative effects, e.g. hypoxia and anoxia, will develop. The high evaporation rate will be observed during the period p3. This will result in the inflow of sea water, together with the mineral nitrogen, that can deteriorate ecological conditions in the southern part of the lagoon.

In the case of the Tyligulskyi Liman, the shallowest northern part of the lagoon is most influenced by the climate changes. The ecological indicators in the southern part of the lagoon are influenced by the volume of water inflow through the connecting channel. The volume is highly impacted by the evaporation rate and intra-annual variability of freshwater inflow.

Owing to the low lateral freshwater runoff into the Tyligulskyi Liman during the period p1, the impact of the scenarios with different land and water uses (even if the measures will be drastic) will be only apparent in the shallow northern part of the lagoon. In case the MH and SET scenarios are to happen, the practical realization of these scenarios requires both considerable expenses and a solution of numerous socio-economic problems.

As a rough approximation, the scenario p1S, which provides the year-round water exchange between the lagoon and the sea, is most preferable due to its relative simplicity and cheapness. However, it has to be additionally investigated as observations on the variability of ecological characteristics in the sea water near the inlet of the channel are missing. The presented analysis used the data relevant to the vast space of Dnieper-Bug region in the north-western part of the Black Sea.

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