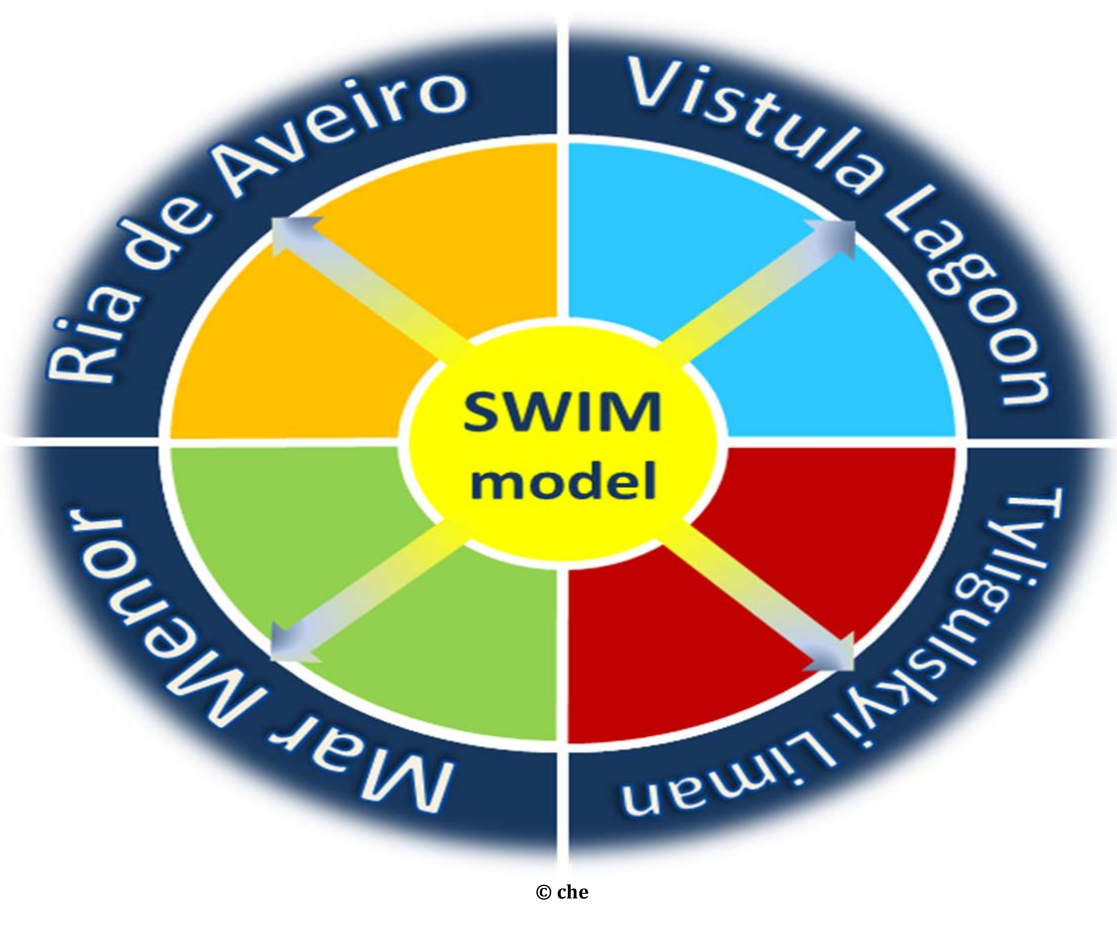
DELIVERABLE D5.2

Combined climate and land use change impact assessment

Results for four lagoon catchments



Title Combined climate and land use change impact assessment – Results for four lagoon catchments
Author(s) Anastassi Stefanova, Cornelia Hesse and Valentina Krysanova Potsdam-Institute for Climate Impact Research
Report No. LAGOONS Report No. D5.2
This report should be cited as: LAGOONS 2014. Combined climate and land use change impact assessment – Results for four lagoon catchments. LAGOONS Report D5.2, 102 pp.
Organisation name of lead contractor for this deliverable Potsdam-Institute for Climate Impact Research
No. of pages 102
Due date of deliverable: 30.09.2014
Actual date of deliverable: 09.10.2014
Dissemination level[1] PU
Key words Climate scenarios, socio-economic scenarios, quantitative scenarios, river discharge, nutrient input

Title of project: *Integrated water resources and coastal zone management in European lagoons in the context of climate change*
Instrument:
Contract number: 283157
Start date of project: October 2011 Duration: 36 months

Disclaimer

The information provided and the opinions given in this publication are not necessarily those of the authors or the EC. The authors and publisher assume no liability for any loss resulting from the use of this report.

[1] PU Public
PP Restricted to other programme participants (including the Commission Services)
RE Restricted to a group specified by the consortium (including the Commission Services)
CO Confidential, only for members of the consortium (including the Commission Services)

CONTENTS

LIST of FIGURES

LIST of TABLES

SEVENTH FRAMEWORK PROGRAMME

ACKNOWLEDGEMENTS

The study was performed in the framework of the project LAGOONS funded by the European Commission 7th Framework Programme for Research under grant agreement N° 283157 whose support is gratefully acknowledged.

The ENSEMBLES data were funded by the EU FP6 Integrated Project ENSEMBLES (Contract number 505539) whose support is gratefully acknowledged, too.

The authors would like to thank Vanessa Wörner for her support in SWIM modelling and post-processing of model results as well as Stein Turtumøygard, Lisa Sousa and João Soares for their help in developing case study area and scenario specific land use maps for SWIM.

The authors also gratefully acknowledge the LAGOONS partners from the University of Dundee for their work in developing the framework and methodologies that were used to create the qualitative socio-economic scenarios as well as the LAGOONS case study partners for organizing and running the stakeholder workshops and for providing the information used to develop the qualitative scenarios for each case study area.

1 INTRODUCTION

This deliverable presents material, methods and results of a combined climate and land use change impact assessment on water quantity and quality performed for the catchments of four European lagoons investigated as Case Study Areas (CSAs) in the European LAGOONS project (see Figure 1.1.1):

- Ria de Aveiro, Atlantic Ocean // Portugal,
- Mar Menor, Mediterranean Sea // Spain,
- Tyligulskyi Liman, Black Sea // Ukraine
- Vistula Lagoon, Baltic Sea // Poland and Russia

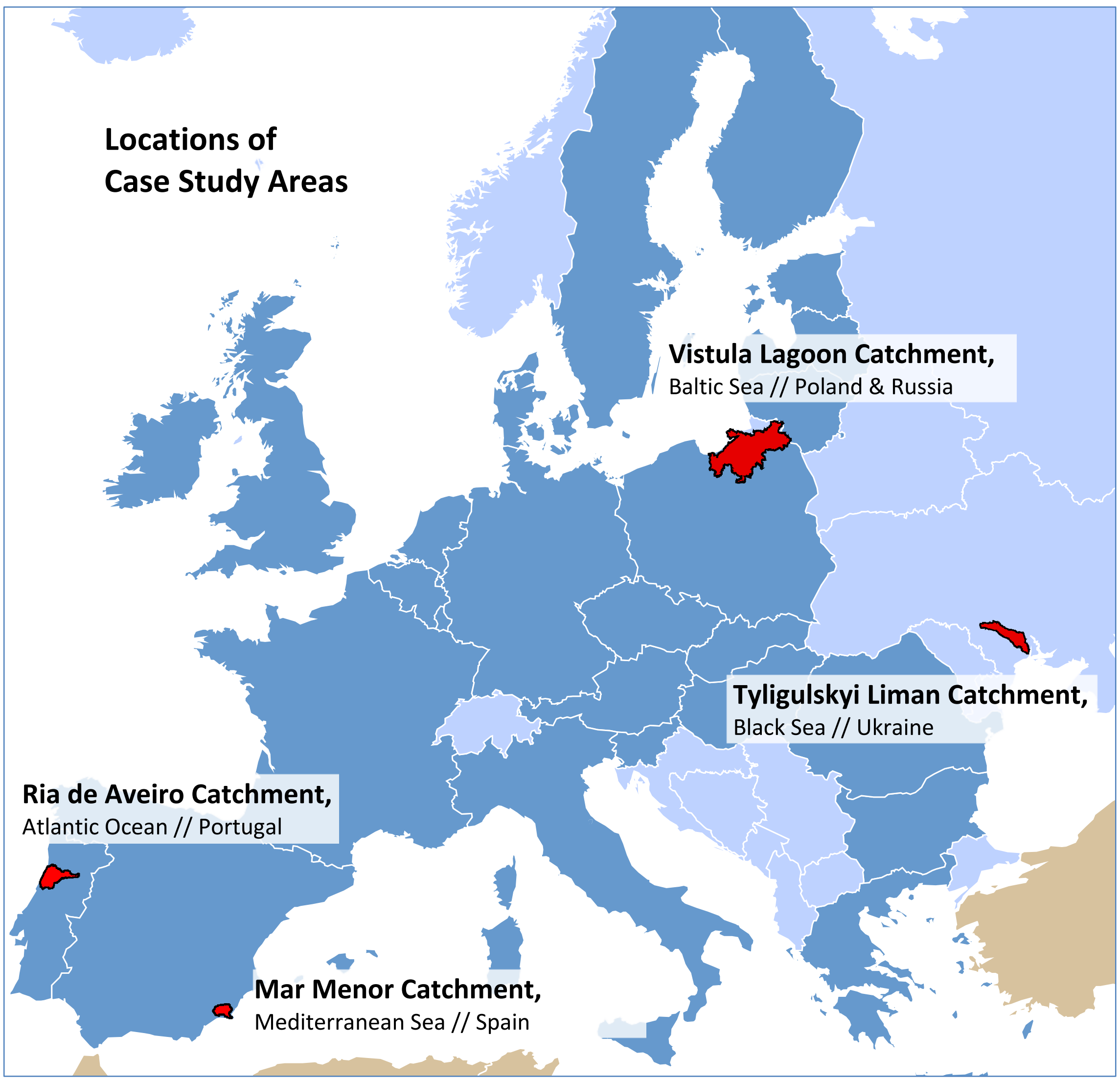


Figure 1.1: Locations of the four Case Study Areas investigated in the European LAGOONS project

The specific characteristics of the drainage basin areas (or catchments) of the four lagoons are presented in Deliverable D5.1 (LAGOONS, 2013), as well as in more detail in the Deliverables D2.1a, D2.1.b, D2.1c and D2.1d (LAGOONS, 2012a, 2012b, 2012c and 2012d), which give an overview of the current knowledge base and gab analysis for each of the four case study areas.

The project report in hand was prepared by Work Package (WP) 5 of the LAGOONS project whose task is the quantitative drainage basin scenario modelling in the context of climate and land use change. More specifically, it aims to translate the qualitative socio-economic scenarios developed in WP 4 into quantitative scenarios and uses these scenarios together with selected climate scenarios to evaluate the potential changes in water inflow and nutrient (N, P) loads from the drainage basin areas. The model outputs produced per scenario and case study are provided to WP 6 for quantitative lagoons modelling and to WP 7 for inclusion in the DPSIR framework. Moreover, the analysis of the combined impacts for a specific lagoon catchment can also support the design of future development and management strategies in the region. The results of quantitative lagoon modelling, as well as recommendations for each of the four case study areas can be found in Deliverable D6.2 (LAGOONS, 2014b).

WP 5 also aims to estimate the uncertainty of results related to climate and land use change scenarios. Deliverable D5.1 (LAGOONS, 2013), in which solely the impacts of potential climate change for the four CSAs were presented, quantified and discussed the uncertainties related to climate scenarios. In this report the uncertainty related to land use change scenarios is discussed in addition to that.

In the following land use change scenarios will be referred to more generally as socio-economic scenarios, as these include changes in land use patterns as well as changes in population, tourism, agricultural practices and water management. Alterations in any of these characteristics influence water resources in the drainage basin area and consequently in the lagoons themselves. Variations in water inflow and nutrient loads from the catchment can cause changes in the lagoon and disturb its ecosystems. Therefore, it is important to assess the impacts of socio-economic changes in addition to potential climate change. Moreover, as climate change may intensify or reverse certain trends in river discharge and nutrient loads the assessment of socio-economic scenarios should be performed in combination with it.

Therefore, this report presents potential socio-economic scenarios and their impacts on water quantity and quality as well as the combined impacts of socio-economic scenarios and climate change scenarios. Chapter 2 describes the material, methods and scenarios used. The analysis of results for the four lagoon catchments is presented in Chapter 3.

2 METHODS and MATERIALS

This chapter gives an overview of the tools and data used to assess climate and socio-economic impacts on water quantity and quality in the four lagoon catchments. It includes a brief description of the applied eco-hydrological model (section 2.1) as well as of the climate scenarios used for the assessment (section 2.2). The socio-economic scenarios for each CSA are presented in detail in the following section (section 2.3). The method used for evaluation of results is described in the last section 2.4.

2.1 Eco-hydrological Modelling with SWIM

The impacts of climate and socio-economic changes on water resources in the drainage areas of four CSAs were investigated using the eco-hydrological model SWIM (Soil and Water Integrated Model, Krysanova et al. 1998, 2000). SWIM is a semi-distributed process based model integrating hydrological processes, vegetation growth and nutrient cycles at the river basin scale. It has been successfully applied to various catchments of different sizes in Europe (Buckener Au, Weiße Elster, Nuthe, Elbe, Rhin, Danube), Africa (Blue Nile, Niger, Ubangi, Limpopo), Asia (Yellow, Jinghe, Tailan, Aksu, Ganges) and South America (Sao Francisco) (Krysanova et al., 1998: Hatterman et al., 2005; Hesse et al., 2008; Liersch et al., 2012; Vetter et al., 2013: Aich et al., 2014; Krysanova et al., 2014).

More information on case study specific model adaptation, model history and structure as well as detailed information on specific processes can be found in Deliverable D5.1 (LAGOONS, 2013) or in the SWIM manual (Krysanova et al., 2000). The nitrogen cycle, and especially the processes related to ammonium nitrogen in soils are described in more detail in Hesse et al. (2012).

SWIM model set-up requires a set of different input data. This includes i) spatial data, such as DEM, land use and soil maps, ii) time series, such as climate data on daily temperatures, precipitation, solar radiation and air humidity and iii) management data, such as dates and amounts of fertilizer applications or water abstractions. The data is unique for each CSA and can be partly changed (e.g. land use map) for impact assessment once the model has been calibrated and validated. A full description of the model set-up, as well as results of model calibration and validation towards observed discharge and nutrient concentrations for each CSA, is provided in Deliverable D5.1 (LAGOONS, 2013). The modified SWIM input data used for combined climate and socio-economic impact assessment are presented in the following sections (2.2 and 2.3). Section 2.2 deals with the climate scenario data applied in this study and section 2.3 describes the different land use maps and management settings used for the assessment.

2.2 Climate Scenarios

The climate scenarios used to drive SWIM for the impact assessment are taken from the outputs of the ENSEMBLES project (van der Linden and Mitchel, 2009). A full description of the data set is given in Deliverable D5.1 (LAGOONS, 2013). The assumed emission scenario for all applied models within the ENSEMBLES project is A1B, which can be referred to as an intermediate scenario. In this scenario global population is assumed to increase up to 8.7 billion people by 2050 with a balanced use of fossil and non-fossil energy resources (Bates et al., 2008). The

projections of global warming for the A1B scenario range between 1.8 and 4.4°C, and simulate a 2.8°C average rise in temperature until the end of the century (Meehl et al., 2007).

For the assessment of climate change impacts SWIM was driven by a set 15 climate scenarios (s1-s15). The time series were split into four periods of 30 years each; a reference period (p0: 1971-2000) and three future periods (p1: 2011-2040, p2: 2041-2070, and p3: 2071-2098). The results of climate impact assessment are presented in Deliverable D5.1 (LAGOONS, 2013).

For the combined climate and socio-economic impact assessment the model was run for the reference (p0) and first future (p1) period using the "best-fitting" climate scenario in each CSA only. The periods p2 and p3 were not considered, as the socio-economic scenarios were developed for the timeframe of 2030. The "best-fitting" climate scenario for each catchment was selected based on a preceding evaluation of the scenario data, using the criteria of minimal "distance" to the mean monthly observed temperature and precipitation, and taking into consideration some specific preferences of the case study partners. For the evaluation, station data from the historical period was compared to climate scenario data from the nearest grid cell in the region under study. The climate scenarios selected for each CSA are described in section 2.2.1. Section 2.2.2 presents the average annual and monthly climate trends of the selected scenarios for the first future period p1.

2.2.1 Choice of climate scenarios

In order to evaluate the reliability of all 15 climate scenarios, the scenario data was compared to the observed temperature (T) and precipitation (P) in the historical period. The stations and time periods with available records for P and T in each catchment are listed in Deliverable D5.1 (LAGOONS, 2013), Table 2.5.2 and ff. The methodology and overall results of the scenario evaluation are also described in the previous report (LAGOONS, 2013).

Table 2.2.1 gives an overview of the selected scenarios for each CSA, responsible Institutes, and applied RCMs and GCMs. Figures 2.2.1 – 2.2.4 show the seasonal averages of the modulus of mean monthly differences between climate scenario data and observed station data for precipitation (in %) and temperature (in °C) per scenario as well as the average seasonal dynamics of 15 climate scenarios (including the chosen "best fitting" scenario) and the observed data at each station.

Table 2.2.1: Overview of applied "best-fitting" climate scenarios per CSA

Catchment	Scenario	Institute	RCM	GCM
Ria de Aveiro	s7	The Royal Netherlands Meteorological Institute (KMNI)	RACMO	ECHAM5-r3
Mar Menor, Tyligulskyi Liman & Vistula Lagoon	s10	Max Planck Institute for Meteorology (MPI)	REMO	ECHAM5-r3

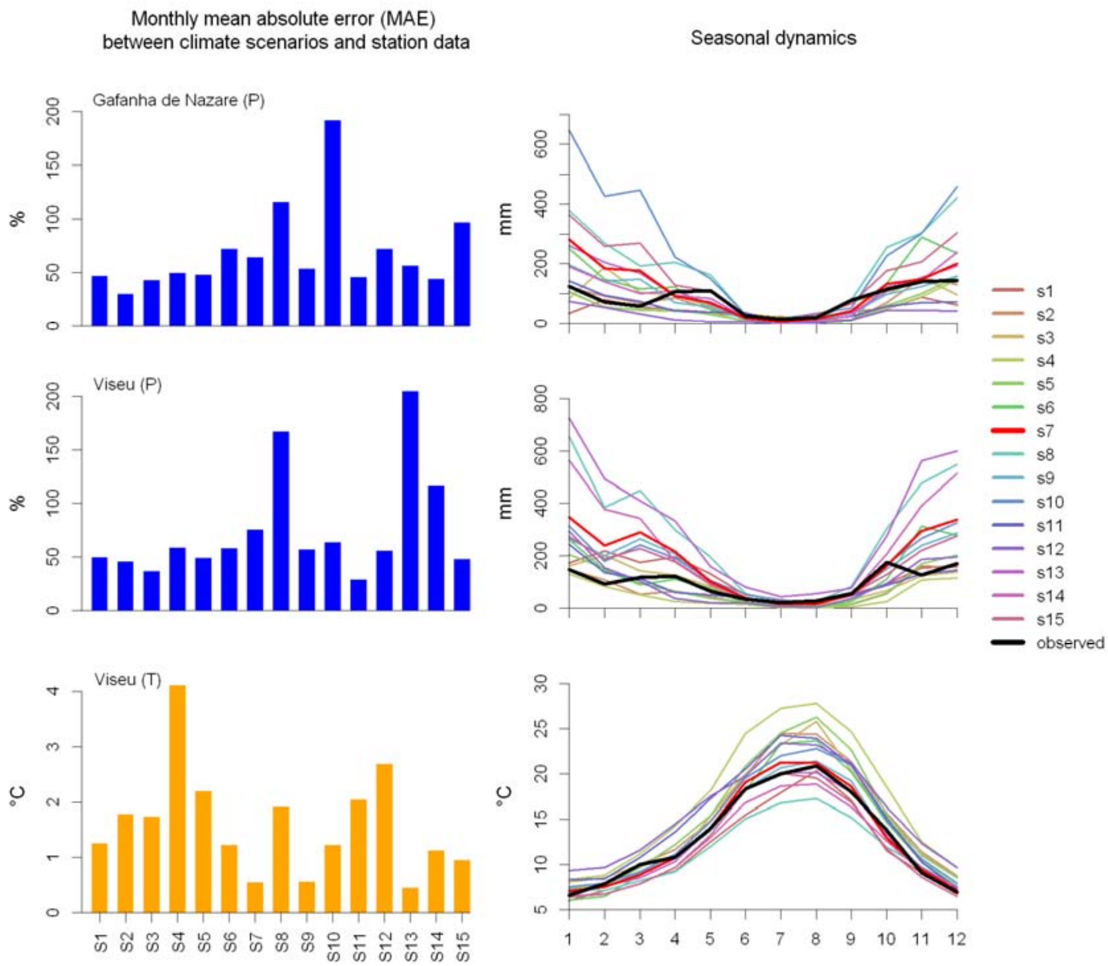


Figure 2.2.1: Climate scenario evaluation for the Ria de Aveiro catchment

The combined impact assessment for the Ria de Aveiro catchment was performed using the s7 scenario. This scenario was chosen by the case study partners based on findings from several studies dealing with the evaluation of RCMs for that region. According to the scenario evaluation (see Figure 2.2.1) the s7 reproduces the observed temperature in the catchment well, but it is less reliable regarding precipitation. Therefore, a different scenario, the s3 was identified as "best-fitting" for the Ria de Aveiro in LAGOONS (2013). The s7 scenario is produced by the The Royal Netherlands Meteorological Institute using the RACMO RCM and boundary conditions from the ECHAM5-r3 GCM.

In the case of the Vistula Lagoon, the Tyligulskyi Liman and the Mar Menor the s10 scenario was chosen as the "best fitting" to drive SWIM for the combined impact assessment. The s10 has been generated by the Max Planck Institute for Meteorology (MPI) using the REMO Regional Climate Model (RCM) and boundary conditions from the ECHAM5-r3 General Circulation Model (GCM). In Deliverable 5.1 a different scenario, the s9 was identified as "best-fitting" for the Mar Menor catchment. However, the case study partners and especially the lagoon modellers from this region decided to give more importance to a correct temperature representation and thus selected the s10 scenario.

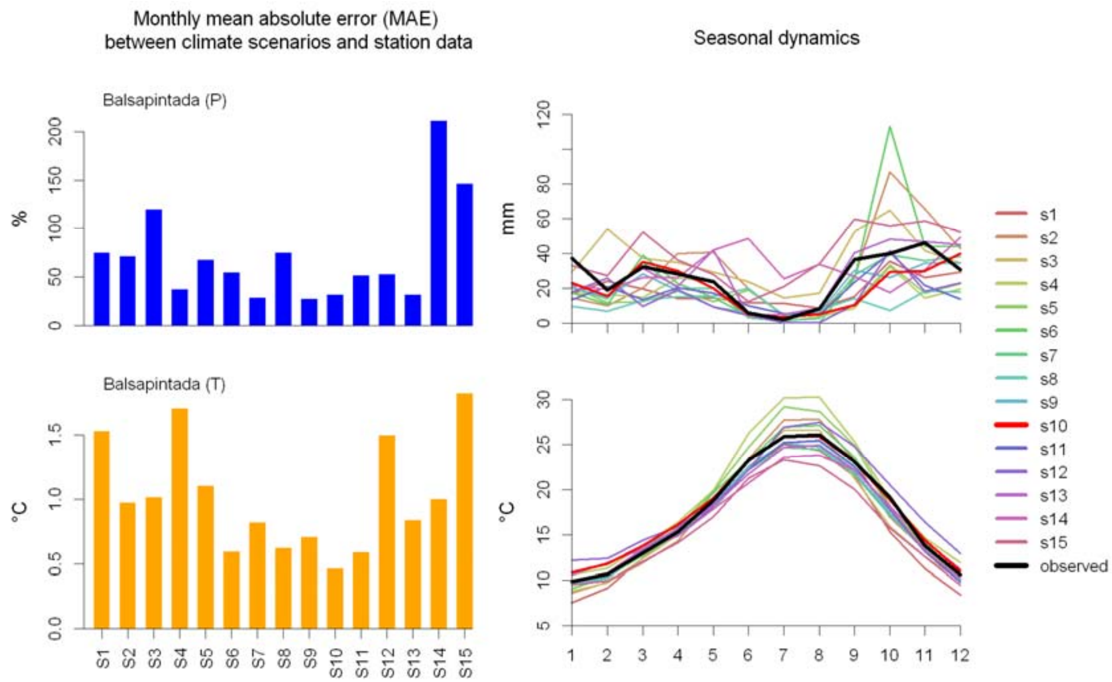


Figure 2.2.2: Climate scenario evaluation for the Mar Menor catchment

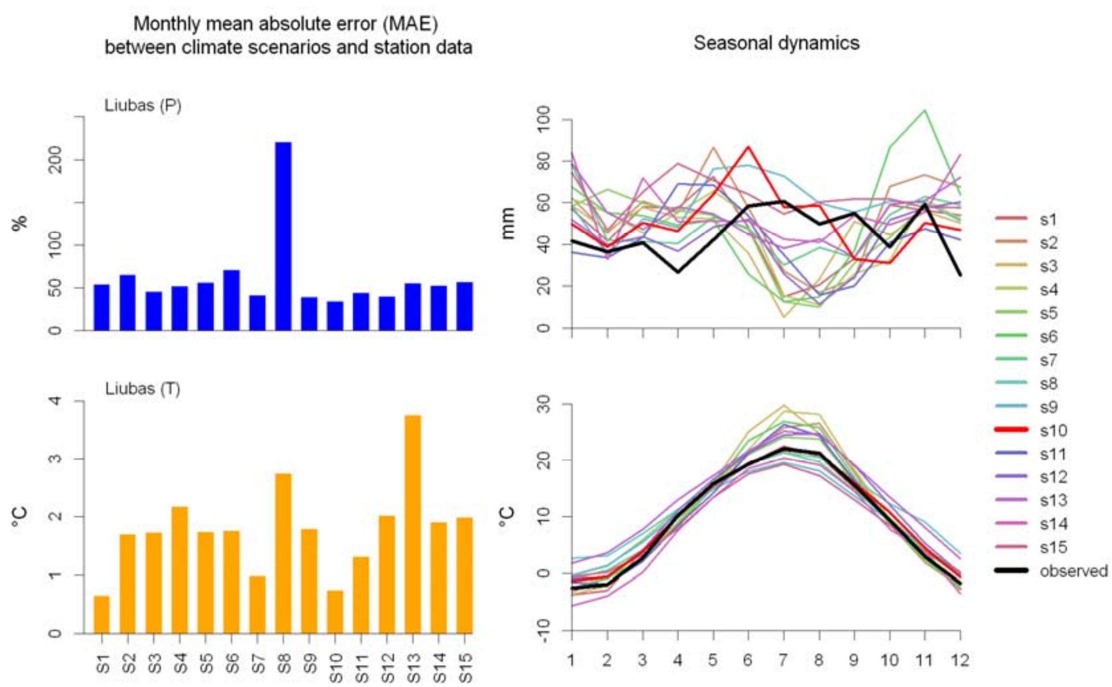


Figure 2.2.3: Climate scenario evaluation for the Tyligulskyi Liman catchment (excluding s8 seasonal dynamics for precipitation)

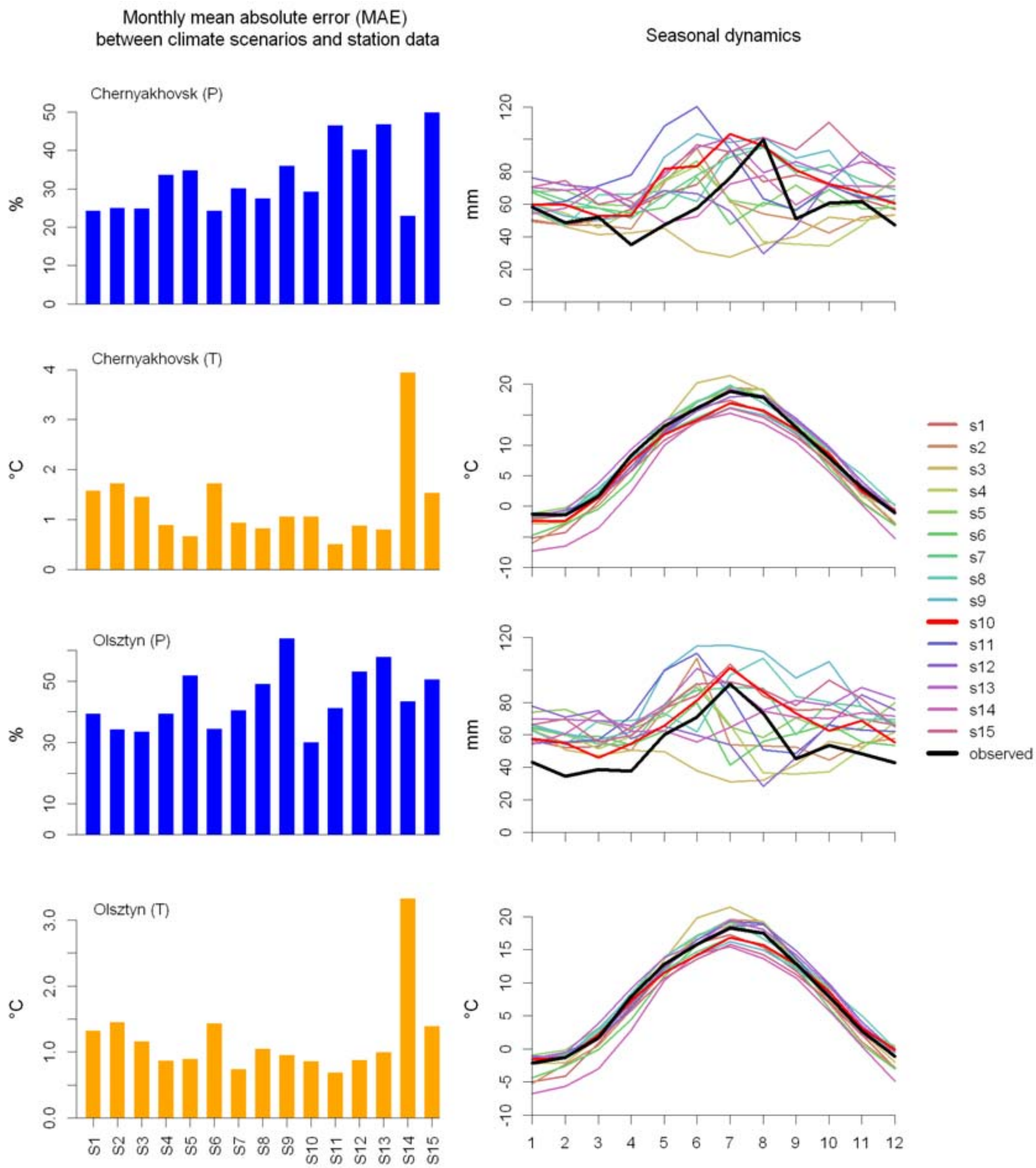


Figure 2.2.4: Climate scenario evaluation for the Vistula Lagoon catchment

2.2.2 Climate change signals

Climate change signals were calculated for all 15 scenarios. Figure 2.2.5 shows the long-term average monthly changes in temperature (°C) and precipitation (%) for the future scenario period p1 (2011-2040) compared to the reference period p0 (1971-2000). On average temperature is projected to rise in all four CSAs. For the Ria de Aveiro catchment the average annual increase is about 0.78°C for the applied "best-fitting" climate scenario. It is 0.56°C for the Mar Menor catchment, 1.11°C for the catchment of the Tyligulskyi Liman and 0.8°C for the Vistula Lagoon catchment.

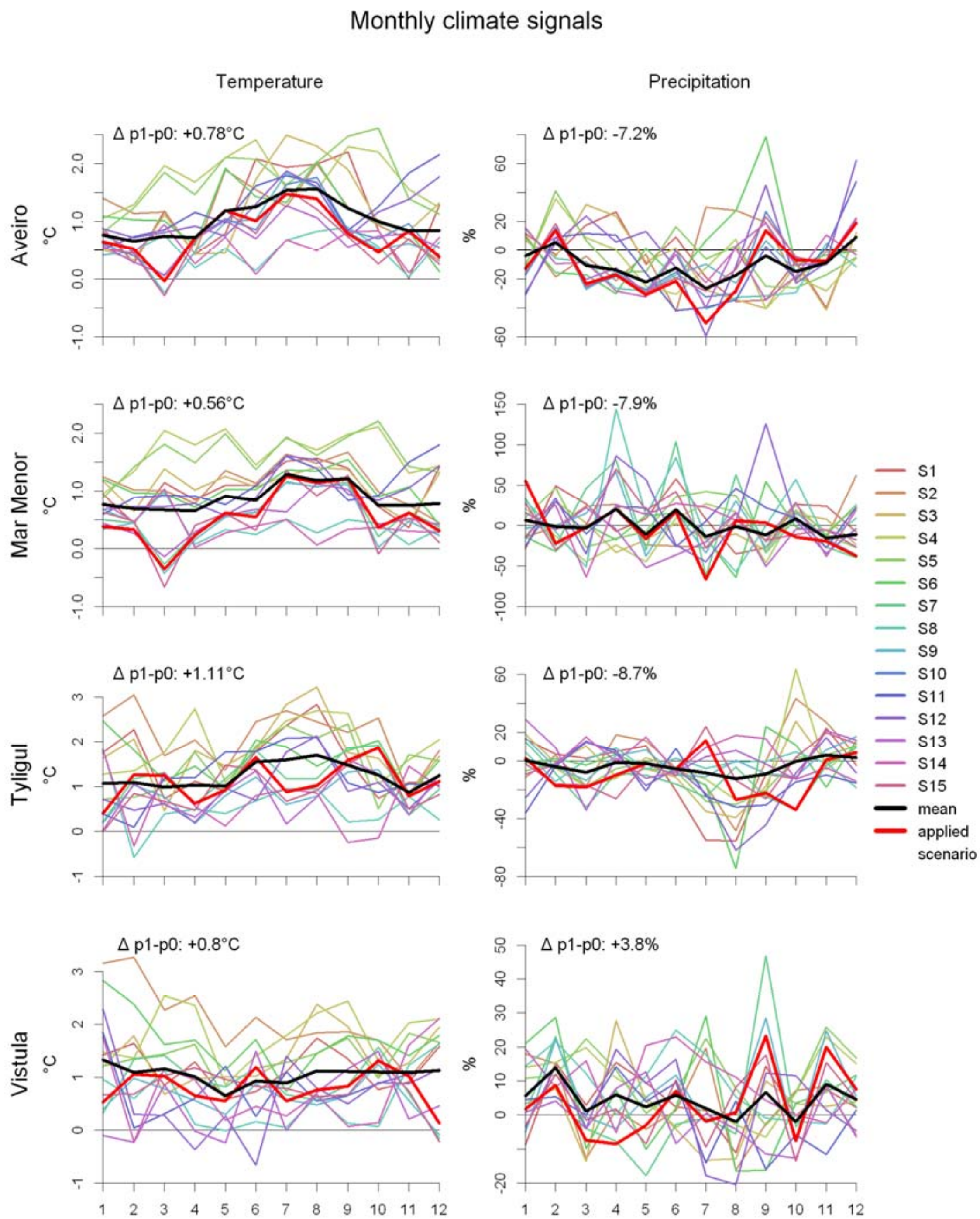


Figure 2.2.5: Seasonal climate change signals for p1 (2011-2040) compared to p0 (1971-2000) and long-term average annual changes for the “best-fitting” climate scenario per CSA. Left: temperature [°C]; Right: precipitation [%]

In the catchments of Ria de Aveiro, the Mar Menor and partly the Tyligulskyi Liman the projected temperature increase during summer is noticeably higher than during the rest of the year. In the Vistula Lagoon catchment the mean (average of 15 scenarios) temperature increase is nearly homogeneous throughout the year.

The projected changes in precipitation do not show a common trend among case study areas for the future period 2011-2040. An average annual decrease of 7-8% is projected by the case study area specific "best-fitting" climate scenarios for the Ria de Aveiro, Mar Menor and Tyligulskyi Liman catchments. In the catchment of the Vistula Lagoon an average annual increase of precipitation by about 4% is projected by the s10 scenario.

2.3 Socio-Economic Scenarios

This section describes how the qualitative scenarios and storylines developed in WP 4 were translated into quantitative scenarios and how they were applied scenarios in each CSA.

Figure 2.3.1 visualizes the basic concept of the socio-economic scenarios used in this project. There are four scenarios: the Business As Usual (BAU), the Managed Horizons (MH), the Crisis (CRI) and the Set-Aside (SET) scenario. Each of them represents a certain combination of the economic situation (growing or shrinking economy) and the consideration of environmental issues during development (towards degradation or environmental-friendly development) of the region. A detailed description of the four scenarios can be found in Deliverable 4.2 (LAGOONS, 2014a).

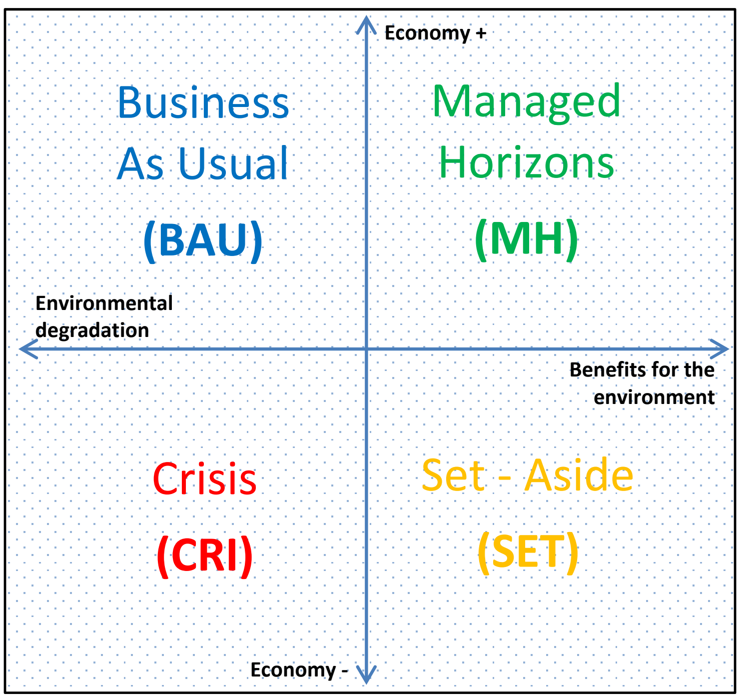


Figure 2.3.1: Matrix of socio-economic scenarios used in this study

In order to apply the socio-economic scenarios to SWIM the development of four scenario specific land use maps for each CSA as well as the definition of scenario specific changes of relevant management parameters used for SWIM was needed.

As a first step, percental changes in major land use classes (agriculture, fallow, grassland and forest) were assumed following the storylines presented in Deliverable D4.2 (LAGOONS, 2014a) and based on the EUROSTAT statistics and expert knowledge from the Dundee team and the

case study partners. Next, these percental changes were applied to the existing basic land use maps, which resulted in four (one per scenario) new additional land use maps for each catchment. The new maps were created using a GIS tool. To create them, the reference land use map of each lagoon drainage basin area was processed considering several factors. The most relevant criteria for changing land use patterns were: soil quality (in terms of water holding capacity), distances to the lagoon and urban areas, morphology of the basin, extent of existing irrigation systems (for Mar Menor only) and rainfall distribution. The exact realization of the pre-defined land use changes in the new land use maps for each the lagoon catchments is described in the following sections separately for each CSA.

The other changes concerning future population sizes, tourism development, degree of sewage treatment, share of organic farming, number of livestock and others were also transformed into SWIM input parameters. This concerns water management (e.g. abstractions, discharges, irrigation, ponds etc.), diffuse pollution from agricultural land (through applied fertilizers) and point source pollution (e.g. from Urban Wastewater Treatment Plants, UWTPs). The agricultural practices (crop type, cover crop, seeding and harvesting day and others) remained unchanged for all scenarios and all CSA. Solely the amounts of applied mineral and organic fertilizers were changed.

2.3.1 Ria de Aveiro Catchment

In the following the four socio-economic scenarios applied to the Ria de Aveiro catchment are described. Figure 2.3.2 shows the reference and scenario land use maps for the catchment as well as the shares of land use classes for the reference conditions and the four scenarios as a small table. In this case the changes affected cropland (=agricultural land), grassland, fallow and forests.

In the **BAU scenario** agricultural land was reduced by 10% and converted primarily to fallow and to some extent also to grassland. The changes in the land use pattern were made mainly in areas close to the mouth of the main river (Vouga) and around the streams of the major tributaries Aguéda and Cértima. By that, the share of fallow in the catchment increased three times and that of grassland almost twice.

In the **CRI scenario** 15% of the agricultural land was converted to fallow and grassland. The conversion was made in similar areas as in the BAU scenario. Furthermore 20% of the forested areas, mainly such located in the central part of the catchment were converted to fallow and grassland.

In the **MH scenario** afforestation was subject to land use change. All fallow and grassland areas in the land use map were converted to forest, corresponding to an increase of forested area by 2.5%. Most of the converted area is located near or in the Bocage area (mouth of Vouga) and partly in the mountainous regions close to the borders of the catchment.

In the **SET scenario** large areas (30%) of agricultural land and of grassland (10%) were abandoned. The selected areas were converted to fallow and to some extend also to forest. The changes were performed in similar areas as the abandonment of agricultural land under the BAU scenario and the conversion of grassland under the MH scenario.

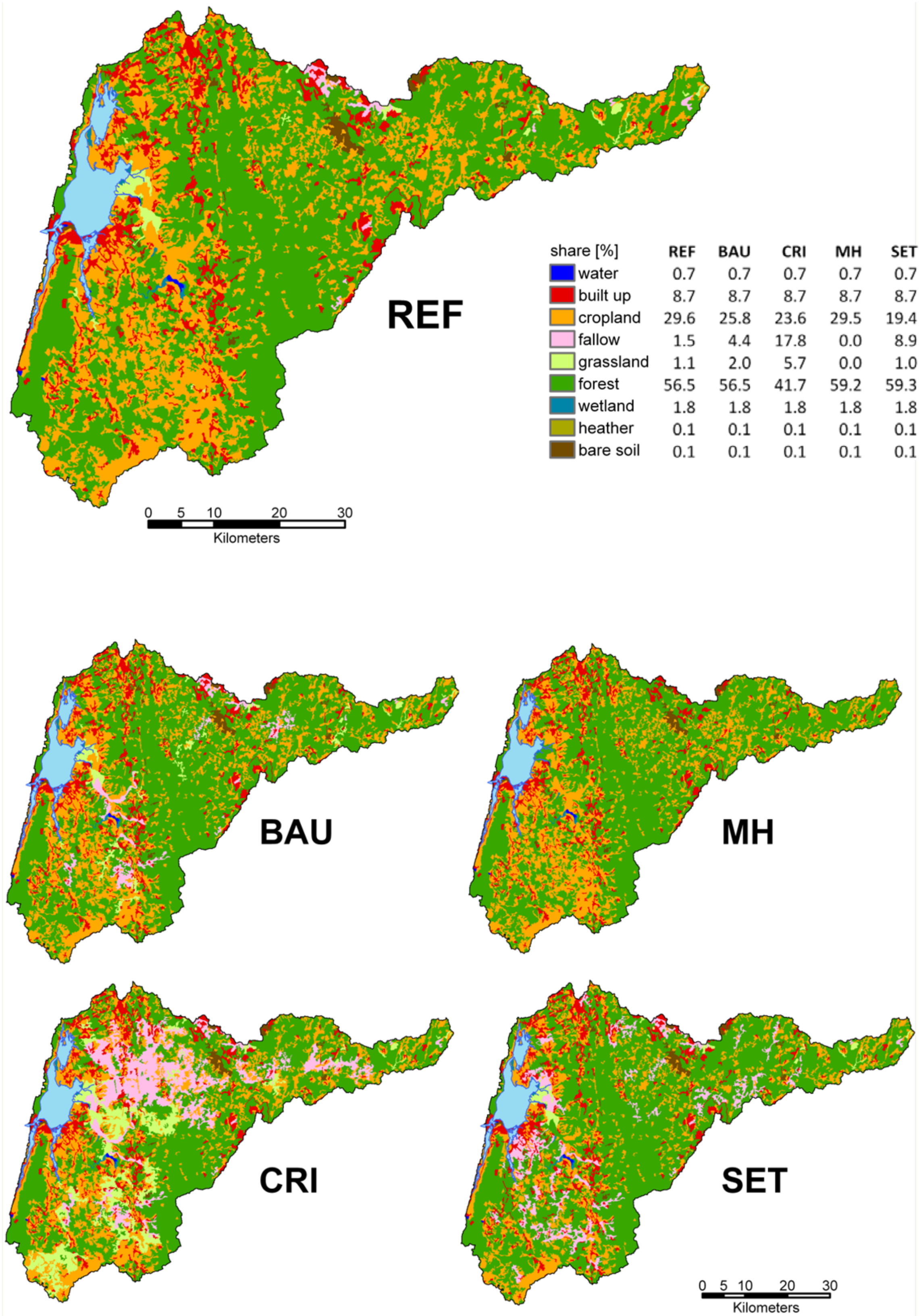


Figure 2.3.2: Reference (REF) and scenario (BAU, CRI, MH, SET) land use maps for the Ria de Aveiro catchment and shares of land use classes for the reference conditions and the four socio-economic scenarios

The modifications of SWIM input parameters were implemented as annual relative changes. They are summarized in Table 2.2. The reference settings for these parameters can be found in LAGOONS (2013), Figure 3.1.4 (point sources), Figure 3.1.5 (water management) and Table 3.1.1 (fertilizers).

Table 2.3.1: Scenario specific changes of SWIM input parameters for the Ria de Aveiro catchment

Changes [%]	BAU	CRI	MH	SET
Point sources	-2	+7	-8	-18
Fertilizers -mineral-	+5	-20	-15	-20
Fertilizers -organic-	+10	-20	+15	+20
Discharge / Abstraction	+6	-30	+12	-15

2.3.2 Mar Menor Catchment

In this section the four socio-economic scenarios applied to the Mar Manor catchment are described. Figure 2.3.3 shows the reference and scenario land use maps for the catchment as well as the shares of land use classes for the reference conditions and the four scenarios as a small table. The changes made affected cropland, grassland, fallow and forests.

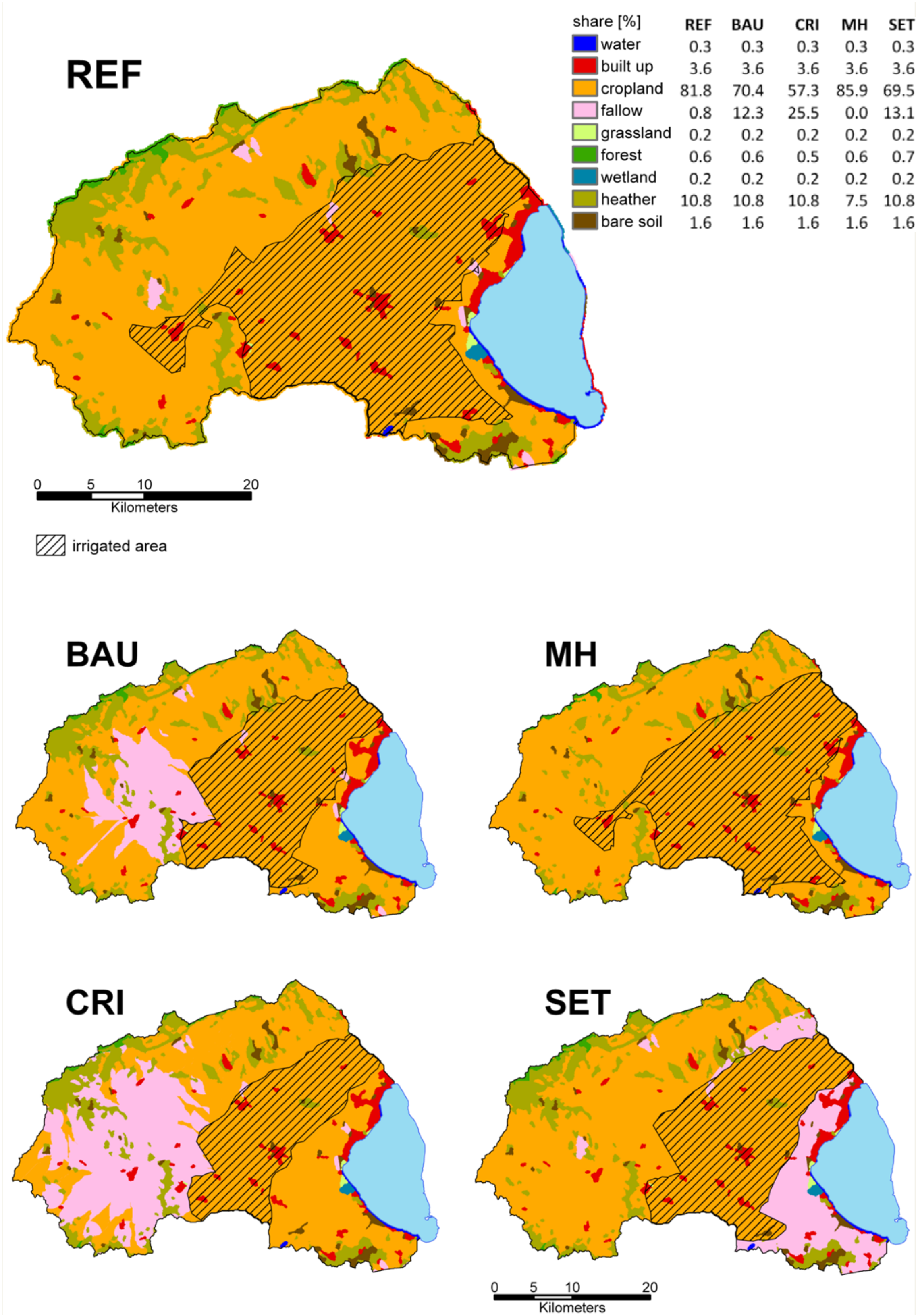
The extent of the irrigated area was also varied between scenarios (see Table 2.3). In the BAU, CRI and SET scenarios a decrease of irrigation area was assumed. It was implemented by excluding unit furthermost from the main water supply channel. Following the same principle for the MH scenario, additional units were added nearest to the main water supply channel. The amount of water applied to one m^2 of agricultural land remained unchanged.

In the **BAU scenario** agricultural land was reduced by 14% and converted to fallow. For that it was assumed that the least suitable land for cultivation will be abandoned. The changes were made outside the irrigation zone on areas with low precipitation rates and on soils with low water holding capacity. A map of precipitation distribution in the catchment can be found in Deliverable 5.1, Figure 4.2.3. The soil map is presented in Deliverable 5.1, Figure 4.1.3.

In the **CRI scenario** 30% of the agricultural land and 20% of the forested land were converted to fallow. For the conversion of agricultural land the same assumptions as in the BAU scenario were used. Deforestation was implemented close to urban areas (=built up), preferably on soils with low water holding capacity.

In the **MH scenario** all abandoned land (fallow) and 5% of the land cover heather were converted to agricultural land. The conversion was made mainly within the irrigated area inside the Albujon catchment (Deliverable D5.1, Figure 4.1.1) but also on areas outside the irrigation zone, preferably on soils with high water capacity.

In the **SET scenario** 15% of the agricultural land was converted to fallow. By definition the SET scenario is characterized by environmental orientation and shrinking economy. Therefore the abandoned land was allocated as close as possible to the lagoon, which created a kind of buffer strip along the water body. In addition to that, areas outside the irrigation zone with soils having low water holding capacity were converted. Some little cropland areas at high elevations were also converted to forest, which increased the share of forest within the catchment by 10%.



share [%]	REF	BAU	CRI	MH	SET
water	0.3	0.3	0.3	0.3	0.3
built up	3.6	3.6	3.6	3.6	3.6
cropland	81.8	70.4	57.3	85.9	69.5
fallow	0.8	12.3	25.5	0.0	13.1
grassland	0.2	0.2	0.2	0.2	0.2
forest	0.6	0.6	0.5	0.6	0.7
wetland	0.2	0.2	0.2	0.2	0.2
heather	10.8	10.8	10.8	7.5	10.8
bare soil	1.6	1.6	1.6	1.6	1.6

Figure 2.3.3: Reference (REF) and scenario (BAU, CRI, MH, SET) land use maps for the Mar Menor catchment and shares of land use classes for the reference conditions and the four socio-economic scenarios

The modifications of SWIM input parameters were implemented as annual relative changes. They are summarized in Table 2.3. The reference settings for these parameters can be found in Deliverable D5.1, Figure 4.1.4 (point sources), Figure 4.1.5 (water management) and Table 4.1.1 (fertilizers).

Table 2.3.2: Scenario specific changes of SWIM input parameters for the Mar Menor catchment

Changes [%]	BAU	CRI	MH	SET
Point sources	+24	-7	+34	-6
Fertilizers -mineral-	-	-20	-15	-20
Fertilizers -organic-	-	-20	+15	+20
Discharge / Abstraction	+28	-20	+10	-10
Irrigation area	-22	-45	+5	-25

2.3.3 Tyligulskyi Liman Catchment

In this section the four socio-economic scenarios applied to the Tyliguskyi Liman catchment are described. Figure 2.3.4 shows the reference and scenario land use maps for the catchment as well as the shares of land use classes for the reference conditions and the four scenarios as a table. The changes made affected cropland, grassland, fallow and forests.

In the **BAU scenario** the land use pattern remained unchanged, but a population decrease was assumed leading to reduced point source emissions and water abstraction for human use.

In the **CRI scenario** deforestation of a half of the forested area was assumed. Therefore forested areas close to urban areas (= built up) were converted to fallow.

In the **MH scenario** an "ecological" corridor along the major river (Tyligul) in the catchment was created. In fact, this corridor already exists and agricultural cultivation within its boundaries is prohibited by regulation act. However, at the present time the regulation is ignored by most of the population. Assuming an increasing awareness towards environmental friendly development for the near future, the agricultural land within this corridor was converted to grassland. In the northern part of the corridor some agricultural land was also converted to forest, which increased the latter one by 10%.

In the **SET scenario** the agricultural land within the "ecological" corridor was converted to fallow. Furthermore some of the northernmost agricultural areas in the catchment, preferably those with soils having low water holding capacities were converted to forest.

The modifications of SWIM input parameters were implemented as annual relative changes. They are summarized in Table 2.2. The reference settings for these parameters can be seen in Deliverable D5.1 (LAGOONS, 2013), Figure 5.1.4 (point sources), Figure 5.1.6 and Table 5.1.2 (water management) and Table 5.1.1 (fertilizers).

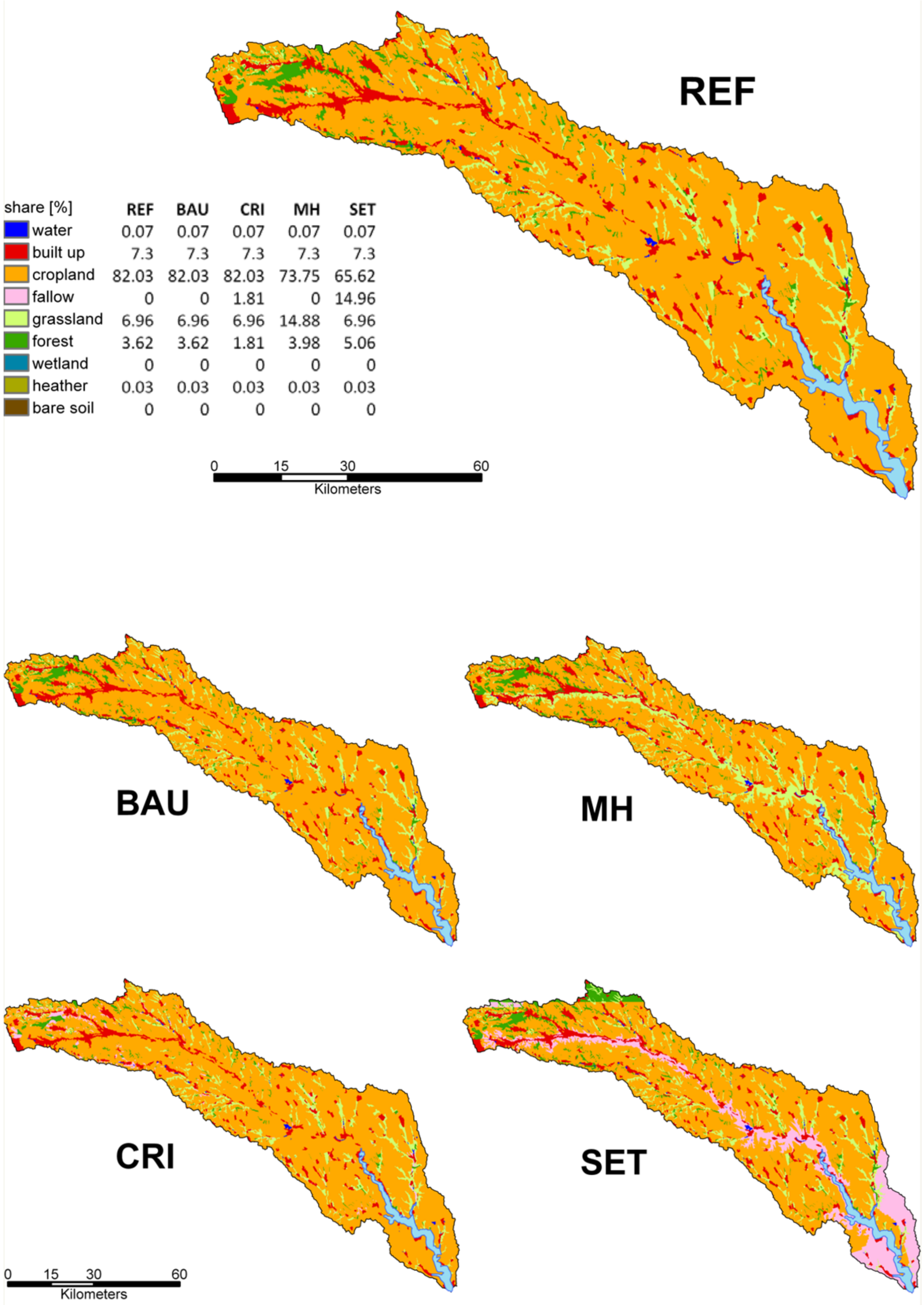


Figure 2.3.4: Reference (REF) and scenario (BAU, CRI, MH, SET) land use maps for the Tyligulskyi Liman catchment and shares of land use classes for the reference conditions and the four socio-economic scenarios.

The changes in water management apply to the abstraction of groundwater (left map in Figure 5.1.6: "Irretrievable use of water ") as well as the effective volume of existing ponds in the catchment (right map in Figure 5.1.6: "Ponds effective volume"). They were applied equally to all management zones. Changes in water abstraction were assumed with declining population, a reduced volume of ponds was expected for the two more ecologic scenarios.

Table 2.3.3: Scenario specific changes of SWIM input parameters for the Tyligulskyi Liman catchment

Changes [%]	BAU	CRI	MH	SET
Point sources	-8	-20	-50	-35
Fertilizers -mineral-	-	-50	+5	+2
Fertilizers -organic-	-	+10	+10	-10
Abstraction	-8	-30	-	-15
Ponds	-	-	-50	-75

2.3.4 Vistula Lagoon Catchment

In this section the four socio-economic scenarios applied to the Vistula Lagoon Catchment are described. Figure 2.3.5 shows the reference and scenario land use maps for the catchment as well as the shares of land use classes for the reference conditions and the four scenarios as a table. The changes made affected cropland, grassland, fallow and forests.

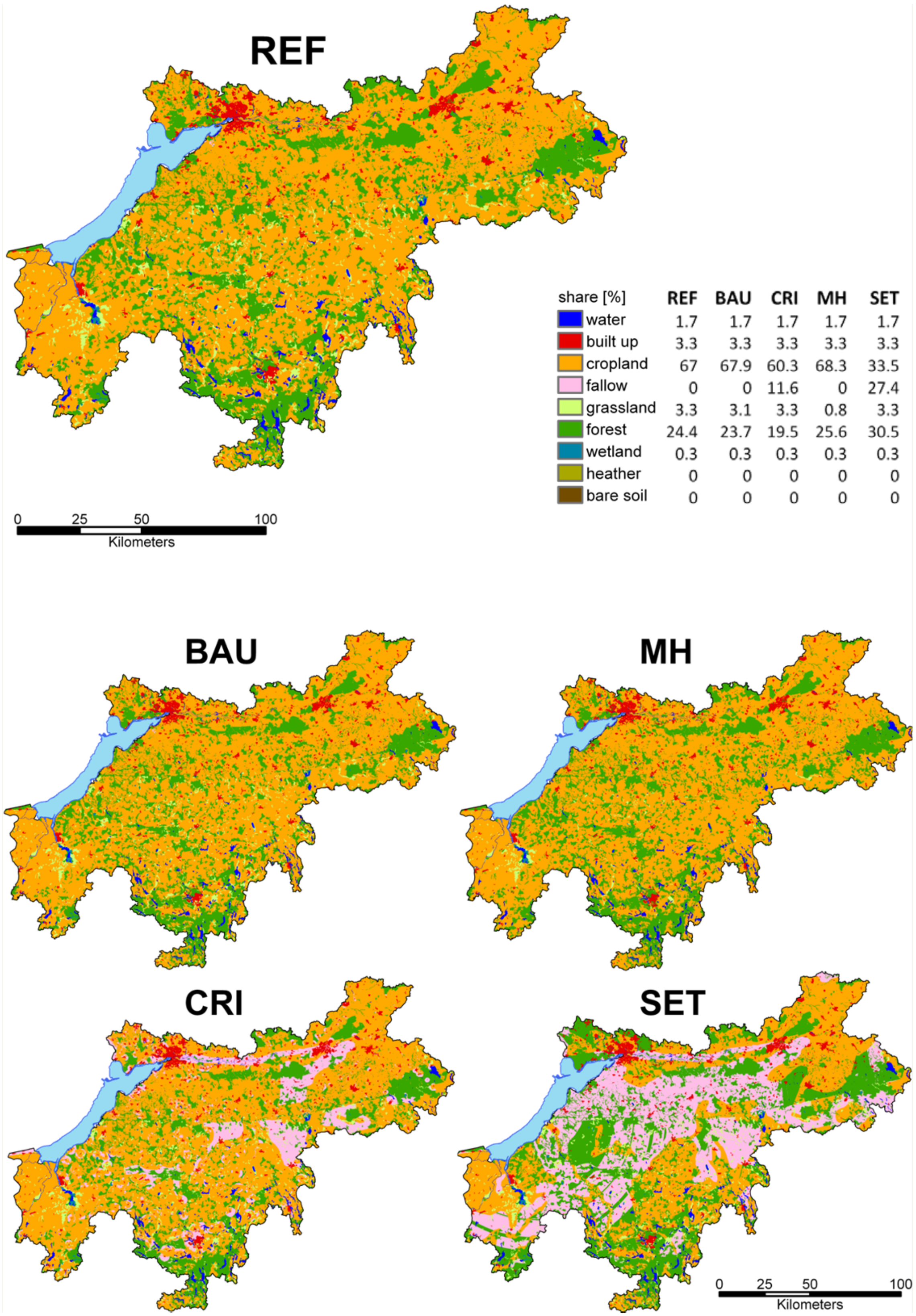
In the **BAU scenario** some small areas with soils having high water holding capacity and covered by grassland or forest were converted to agricultural land, which increased the latter one by 1.4%.

In the **CRI scenario** agricultural land and forested areas were reduced by 10 and 20% respectively. Both land use classes were converted to fallow. Abandonment of cropland was implemented in areas located furthermost from settlements and urban areas (=built up) with soils having low water holding capacity. Deforestation was implemented in areas close to settlements, regardless of the soil quality.

In the **MH scenario** about 2/3 of the grassland area were converted to agricultural land and forest. Arable land was created on soils with high water holding capacity and increased by 2%. The afforestation was implemented on soils with low water holding capacity and forest was increased by 5%.

In the **SET scenario** the agricultural area was reduced by 50%. Therefore the areas with least suitable soils for crop cultivation (soils with low water holding capacity) were selected. From these areas, some small parts with favourable conditions for natural forest development (areas with soils having relatively high water holding capacity compared to other soils within this area) were converted to forest. The remaining area (the bigger share) was converted to fallow.

The modifications of SWIM input parameters were implemented as annual relative changes. They are summarized in Table 2.5.



share [%]	REF	BAU	CRI	MH	SET
water	1.7	1.7	1.7	1.7	1.7
built up	3.3	3.3	3.3	3.3	3.3
cropland	67	67.9	60.3	68.3	33.5
fallow	0	0	11.6	0	27.4
grassland	3.3	3.1	3.3	0.8	3.3
forest	24.4	23.7	19.5	25.6	30.5
wetland	0.3	0.3	0.3	0.3	0.3
heather	0	0	0	0	0
bare soil	0	0	0	0	0

Figure 2.3.5: Reference (REF) and scenario (BAU, CRI, MH, SET) land use maps for the Vistula Lagoon catchment and shares of land use classes for the reference conditions and the four socio-economic scenarios

The reference settings for these parameters can be seen in Deliverable D5.1 (LAGOONS, 2013), Figure 6.1.4 (point sources) and Table 6.1.1 (fertilizers). Changes in water management were not considered for any of the scenarios (common decision with the case study partners).

Table 2.3.4: Scenario specific changes of SWIM input parameters for the Vistula Lagoon catchment

Changes [%]	BAU	CRI	MH	SET
Point sources	-10	-30	-40	-35
Fertilizers -mineral-	-	-10	+100	+10
Fertilizers -organic-	-	-10	+300	-

2.4 Model Runs and Evaluation of Model Results

For the combined climate and land use change impact assessment the calibrated and validated SWIM model of each CSA (see LAGOONS, 2013) was run several times. First the reference conditions were simulated. For that, the model was driven by the reference climate (p0: 1971-2000) using the reference land use map and the reference settings of SWIM input parameters. Next the model was driven by climate data for the first future period (p1: 2011-2040) using i) the reference set-up of land use pattern and management data and ii) the model input of each of the four socio-economic scenarios (four different land use maps in combination with four different parameter settings). In total this makes six different runs per CSA: p0(reference), p1(reference), p1(BAU),p1(CRI), p1(SET) and p1(MH).

Using the results of these model runs different analyses could be performed. Climate change impacts only could be detected by comparing the model runs with land use and management reference parameter settings for the reference period p0 and the future period p1. These impacts are analyzed in detail per CSA in Deliverable D5.1 (LAGOONS, 2013).

In order to assess the combined climate and socio-economic impacts we evaluated the changes between each of the four scenario runs and the reference run for the reference time period (p0).

- **a)** ***combined impacts:***
  "p1(scenarios)" – "p0(reference)"

The socio-economic impacts only were evaluated using the scenario runs and the reference run for the first future period (p1).

- **b)** ***socio-economic impacts only:***
  "p1(scenarios)" – "p1(reference)"

For both cases ("a" and "b") we calculated long–term average annual and monthly changes of various model outputs. More specifically we analysed the total water inflow (Q) and nutrient input (NO_3-N, NH_4-N and PO_4-P) to each of the four lagoons as well as the runoff (RUN), groundwater recharge (GWR) and actual evapotranspiration (ET_a) for each catchment.

Furthermore we created maps showing the spatial changes of RUN, GWR and ET_a as well as graphs including information about the mean annual changes of Q, NO_3-N, NH_4-N and PO_4-P for separately each river flowing into the lagoon.

3 RESULTS

The results of the impact assessment for the four lagoon catchments are presented separately for each CSA in sections 3.1 - 3.4. The evaluations include the combined climate and socio-economic impacts as well as the impacts of socio-economic changes only. First, the annual and monthly changes in total inflow to the lagoon (Q), groundwater recharge (GWR) and actual evapotranspiration (ET_a) in the catchment as well as the annual changes in nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N) and phosphate phosphorus (PO_4-P) loads are shown and discussed. Next, spatial changes in runoff (RUN), GWR and ET_a as well as average annual changes in Q, NO_3-N, NH_4-N and PO_4-P for the individual lagoon tributaries are presented. At the end of each section a summary of the obtained results is given.

3.1 Ria de Aveiro Catchment

3.1.1 Water quantity – annual and monthly changes

Total inflow to the lagoon

The total inflow to the Ria de Aveiro is hardly influenced by the socio-economic changes simulated for the catchment but it is indeed affected by climate change.

The left graph in Figure 3.1.1 shows the sum of average daily discharges (Q) from all rivers flowing into the Lagoon for six different cases (six bars). Under the reference conditions (REF) and the reference climate (1971-2000) the average daily Q is 118 m^3/s (first bar in the figure). Under the climate of the future scenario period (2011-2040) it is reduced to 110 m^3/s. The values for each of the four socio-economic scenarios simulated for the same period are practically the same. The differences are visible in the first position after the decimal point only. Therefore, the evaluation of potential socio-economic changes in the catchment (upper right graph) shows very little impacts on the total inflow (0.08%, 0.39%, 0.01% and -0.03%) for these four scenarios. In contrast to that, the combined impact analysis, when climate change is included (lower right graph) shows a decrease in total inflow of about 6% on average. A detailed discussion on the impacts of climate change on total inflow to the Ria de Aveiro until the end of the 21st century (15 RCM/GCM combinations), and under a set of 15 different climate scenarios can be found in Stefanova et al. (2015).

The only scenario, which is a little bit different, is the crisis (CRI) scenario. In this scenario a strong process of deforestation is assumed and 20% of the forested areas in the catchment are converted to fallow. This drastic change in land cover leads to a noticeable decrease in actual evapotranspiration. Forests have the highest transpiration rates, mainly due to their high leaf area indices (LAI) mainly. If less water is transpired by the current vegetation in the catchment more water remains in the system and is available for runoff or groundwater recharge, which in consequence increases the total inflow to the lagoon. The assumed changes in water management (e.g. 30% less water discharged into rivers) counteract this process but the effect is negligible. The water management does not have a noticeable hydrological relevance for the area under the reference conditions, neither do the assumed changes.

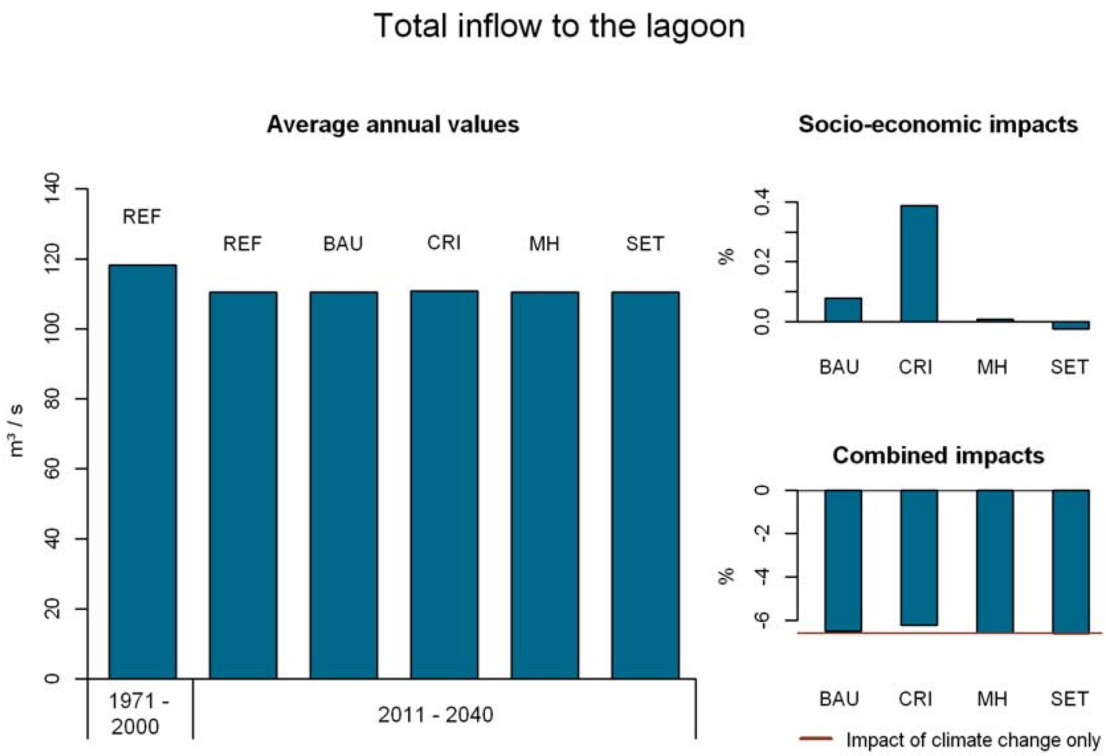


Figure 3.1.1: Impacts on total inflow (Q) to the Ria de Aveiro Lagoon. Left: long-term mean annual discharges [m^3/s] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on Q for each scenario.

Groundwater recharge

The overall impacts on groundwater recharge are comparable to those of total inflow to the lagoon. The average groundwater recharge in the catchment is hardly influenced by the simulated socio-economic changes but it is noticeably affected by climate change.

The left graph in Figure 3.1.2 shows the long-term average annual rates of groundwater recharge (GWR) in the catchment for six different cases (six bars). Under the reference conditions (REF) and the reference climate (1971-2000) the average annual GWR is 767 mm (first bar in the figure), whereas it is reduced to about 700mm in the future scenario period (2011-2040). The differences between the scenarios and the reference conditions in p1 are minor (upper right graph) and range between -0.33% and 0.072%. The combined impacts (lower right graph) of both climate change and socio-economic changes show a clear decrease in GWR of about 9% in the four scenarios. The decrease is strongest for the set-aside scenario (SET), in which the largest proportions of agricultural land and grassland among all scenarios are abandoned (30% and 10%) and converted to fallow. This is because agricultural land, compared to other vegetation covers, has the highest GWR rate followed by grassland, woodland and scrubland (Kim and Jackson, 2012).

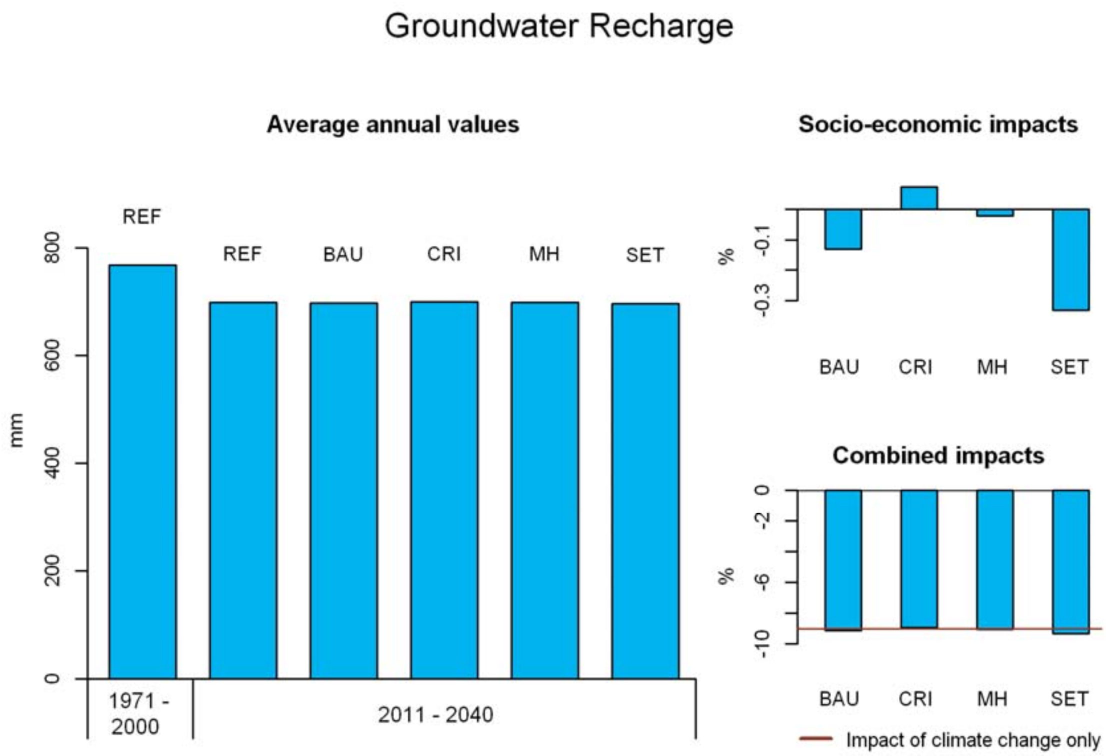


Figure 3.1.2: Impacts on groundwater recharge (GWR) in the Ria de Aveiro Lagoon Catchment. Left: long-term mean annual recharge rates [mm] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on GWR for each scenario.

Actual evapotranspiration

The potential impacts on actual evapotranspiration (ET_a) are presented in Figure 3.1.3. The same as for water inflow and groundwater recharge, the average annual ET_a is influenced much stronger by climate change than by socio-economic changes.

The left graph in Figure 3.1.3 shows the long-term average annual ET_a for six different cases (six bars). The reference evapotranspiration rate (REF, 1971-2000) is about 384 mm and it is only few millimetres lower in the future scenario period (2011-2040). Differences between the reference conditions and the four scenarios in p1 are hardly visible.

Considering the socio-economic impacts only (upper right graph) , we can conclude that ET_a is projected to increase slightly by 0.35%, 0.2% and 1.3% for the BAU, MH and SET scenarios, and to decrease by 0.7% for the CRI scenario. These observations can be tracked back to changes in the land use patterns of the catchment. In the SET and MH scenarios forested areas are increased by 4% and 2.5%, leading to an increased plant transpiration and interception by vegetation and thus the increased total ET_a in the catchment.

The effects of land use change in the CRI scenario are a bit more complex. While on the one hand, deforestation leads to a decrease in ET_a, the abandonment of agricultural land (which is converted to grassland in the model) causes an increase. Averaged over the catchment these two processes lead to a small decrease in total actual evapotranspiration.

The effects of land use change in combination with climate change (lower right graph) show the same direction of change for all four socio-economic scenarios. Namely, in the combined scenario analysis, actual evapotranspiration is projected to decrease between 1.5% and 3.5%.

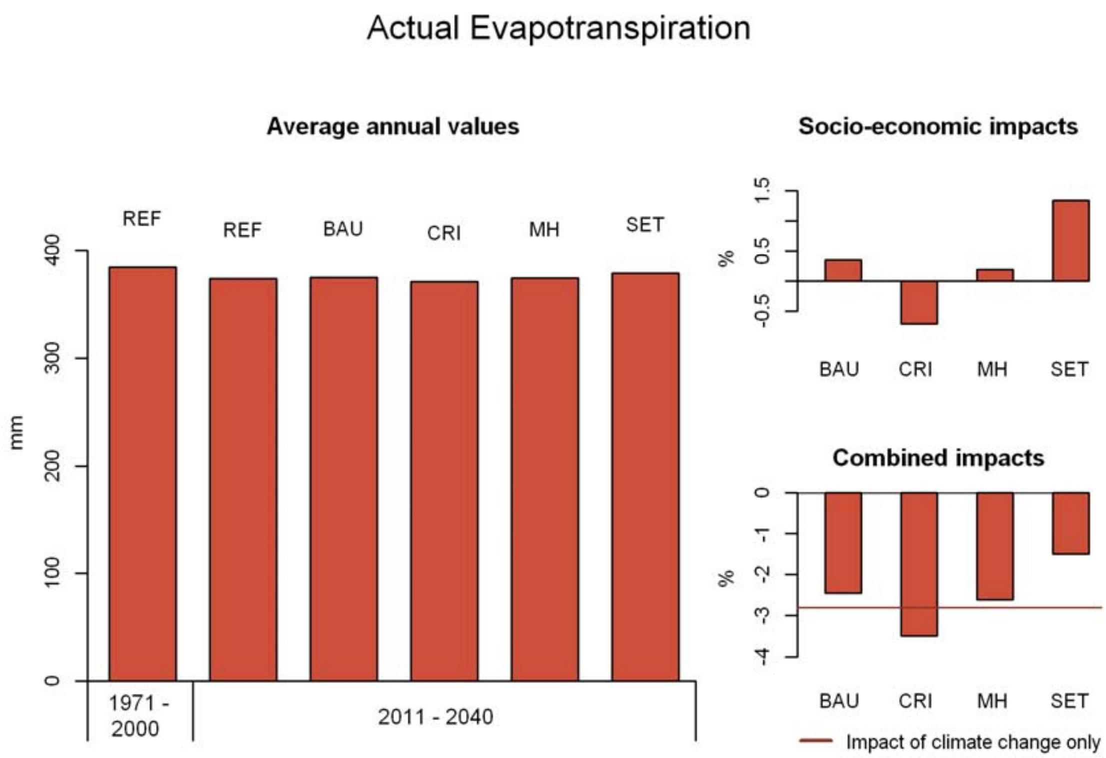


Figure 3.1.3: Impacts on actual evapotranspiration (ET_a) in the Ria de Aveiro Lagoon Catchment. Left: long-term mean annual evapotranspiration rates [mm] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on ET_a for each scenario.

Average monthly changes in discharge, groundwater recharge and evapotranspiration

Figure 3.1.4 shows the seasonal dynamics of the long-term average changes in water quantity components. While the total annual inflow to the lagoon under the combined scenarios (solid lines) is projected to decrease by about 6% on average (Figure 3.1.1), the monthly changes of Q show a variation between +6% and – 18% (upper left graph in Figure 3.1.4). The strongest decrease in average monthly Q can be observed in April and May. For February and December a little increase of 3% and 6%, correspondingly, is simulated. The differences between the scenarios are hardly distinguishable. The impacts of socio-economic changes only (dashed lines) are negligible: the lines concentrate along the zero line for all months and all scenarios.

Groundwater recharge (GWR) in the catchment is projected to decreases under combined scenarios as well (see upper right graph in Figure 3.1.4, solid lines). The strongest decrease can be observed during summer (100% in July), which is the period when the actual GWR is extremely low and close to 0. In February and December the projected GWR shows increases by 11% and 16% is simulated. The socio-economic impacts on GWR are much weaker than the combined ones and only visible between April and October (dashed lines). In the CRI scenario

GWR increases up to 20% in June and decreases by 6% in September, due to changes in land use and management only.

The seasonal impacts on actual evapotranspiration in the catchment (ET_a) show a more diverse picture (lower left graph). An increase is simulated under combined scenarios for most months during winter, spring and autumn, while a decrease is projected in June, July, August and September. In contrary to the other two variables (Q and GWR) there are some differences between the individual scenarios. Still the sign of change is the same throughout the year and for all four scenarios. In summer, the CRI scenario shows the least decrease in ET_a. This is because the socio-economic changes assumed in this scenario have an opposite effect on ET_a and cause even an increase during these months when driven by socio-economic scenario only (green dashed line).

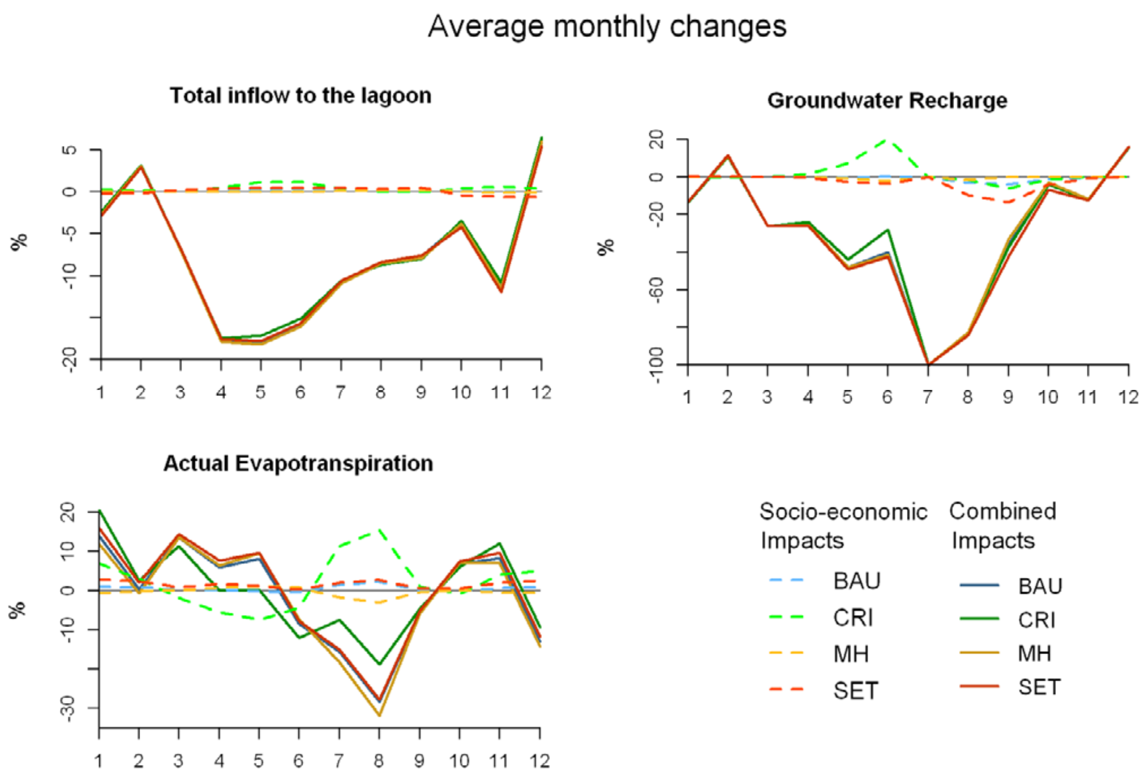


Figure 3.1.4: Long-term mean monthly relative changes [%] of Q, GWR and ET_a in the Ria de Aveiro Lagoon Catchment showing the socio-economic impacts (dashed lines) and the combined impacts (solid lines) for each scenario.

3.1.2 Water quality – annual changes

Nitrate nitrogen loads

The left graph in Figure 3.1.5 shows the total sum of nitrate nitrogen (NO_3-N) loads brought to the lagoon all inflowing rivers in the scenario runs. Under the reference conditions (REF) and the reference climate (1971-2000) the average daily NO_3-N load to the Ria de Aveiro is 10.5 tonnes. Under the climate of the future scenario period (2011-2040) it is reduced to 9.6

tonnes. This is because NO_3-N is generated mainly by diffuse pollution from agricultural land, which is reduced when precipitation and thus surface runoff are decreased. Unlike the water quantity components Q, GWR and ET_a described above, the total average annual NO_3-N load to the lagoon is strongly influenced by changes in land use and management.

All four socio-economic scenarios cause a decrease in NO_3-N loads (upper right graph). The reduction of NO_3-N is smallest for the BAU scenario. In this scenario agricultural land is reduced by 10% but at the same time the amounts of applied mineral and organic fertilizers are increased by 5% and 10%, correspondingly. The combination of these changes eventually leads to a small decrease (1.7%) of NO_3-N loads only. In the MH scenario the share of agricultural land remains unchanged. However, the amounts of applied mineral fertilizers are reduced by 15%. The organic fertilization is increased by the same value (15%) but since its share in the total applied nitrogen fertilizers is very little (15%), the effect of its reduction is little too. On average, in this scenario NO_3-N loads are reduced by 5.5%.

In the CRI and SET scenarios agricultural land is reduced by 15% and 30%, correspondingly. In addition to that mineral fertilization is reduced by 20% and 15% and organic fertilization is increased by 20% in the SET scenario. As a result, all applied changes in these two scenarios lead to a decrease of NO_3-N loads by 12% and 14%, correspondingly. In combination with climate change (lower right graph) the trend in NO_3-N reduction is even more pronounced, and the depletion reaches about 20% for two scenarios: CRI and SET.

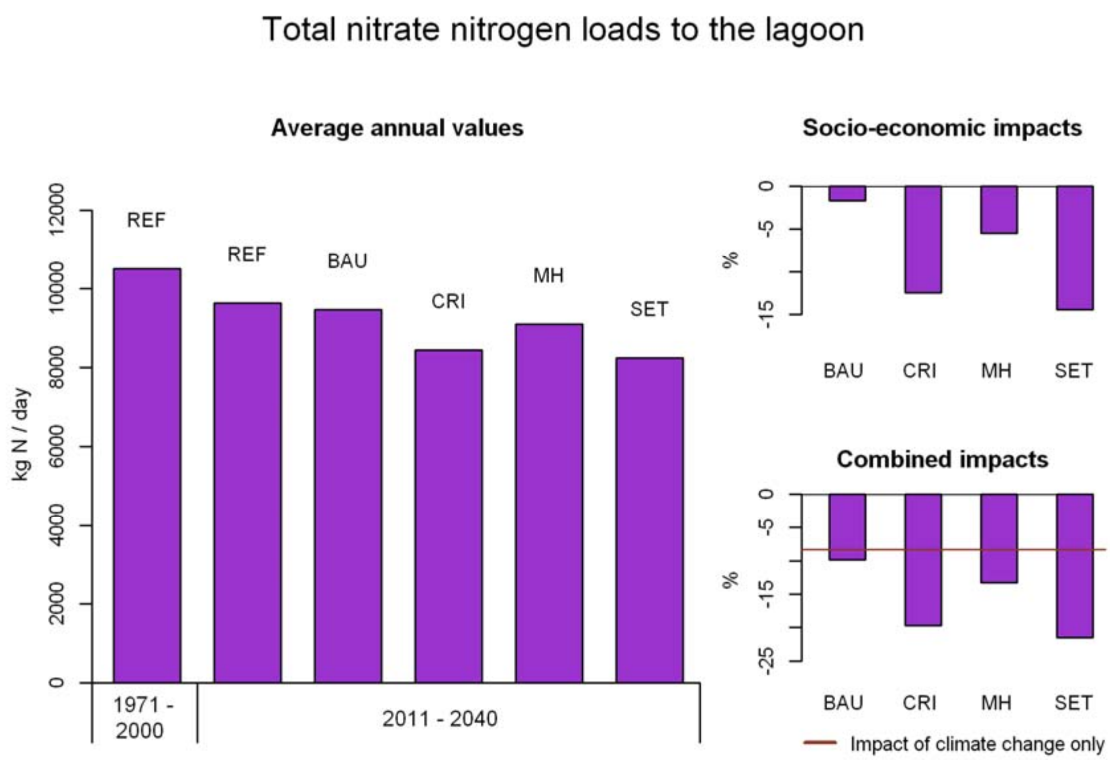


Figure 3.1.5: Impacts on total nitrate nitrogen (NO_3-N) input to the Ria de Aveiro Lagoon. Left: long-term mean annual loads [kg N/day] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on NO_3-N for each scenario.

Ammonium nitrogen loads

The left graph in Figure 3.1.6 shows the total sum of ammonium nitrogen (NH_4-N) loads brought to the lagoon by the inflowing rivers in the studied scenarios. Ammonium nitrogen loads in surface waters strongly depend on the mineralization of organic matter and the leaching processes from the soil profile. The organic nitrogen available for mineralization (formation of ammonium) can be of natural origin (e.g. plant residues) or added to the system through fertilization. In general, the mineralization process is enhanced with higher soil temperatures and soil water contents. However, at the same time the transformation of ammonium to nitrate (nitrification) is also enhanced. At soil saturation, nitrification reaches a maximum and then declines again, as oxygen concentrations become insufficient, while mineralization continues.

In future, ammonium loads can be expected to decrease, as warmer climate favours nitrification, and decreasing precipitation and runoff slow down mineralization and reduce the ammonium leaching from the soils. Indeed, a decrease in NH_4-N loads was observed in most of the simulations driven by 15 climate scenarios during the climate impact assessment performed earlier (LAGOONS, 2013). On average ammonium nitrogen was projected to decrease by about 15% for the first scenario period (compare with LAGOONS, 2013, page 39, Figure 3.6).

However for the chosen climate scenario the simulated NH_4-N loads show an increase of about 8.5%. Under the reference conditions (REF) and the reference climate (1971-2000) the average daily NH_4-N load to the Ria de Aveiro is about 2.2 tonnes.

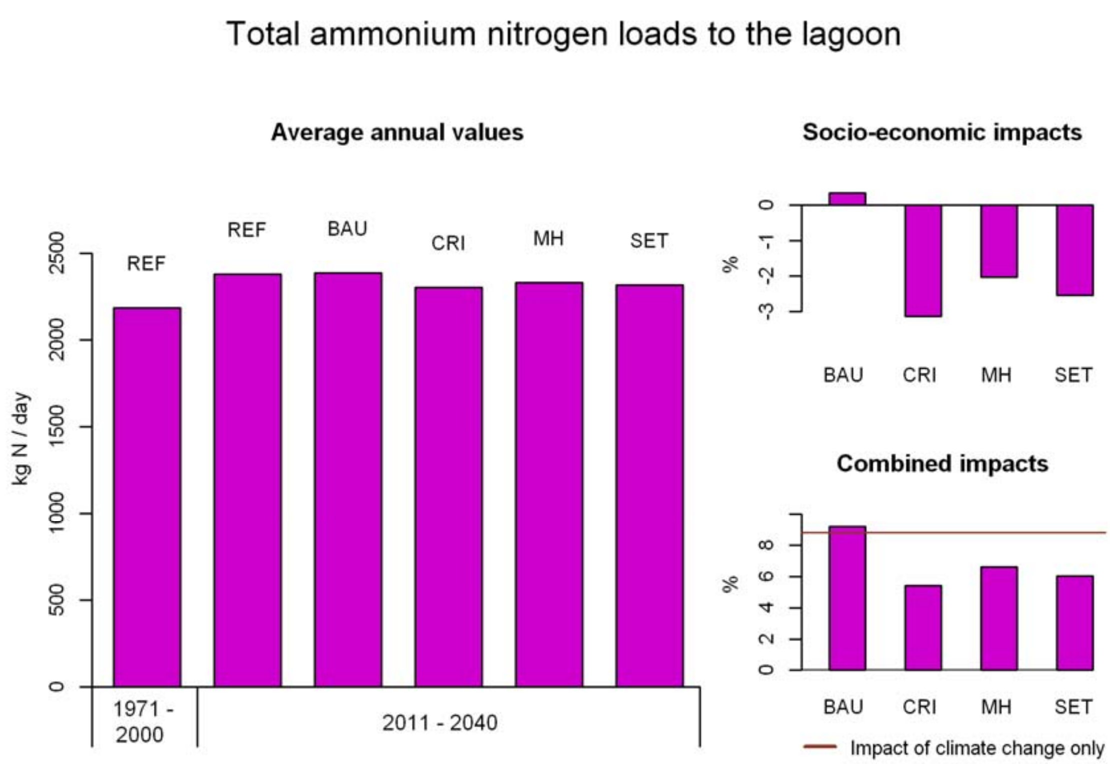


Figure 3.1.6: Impacts on total ammonium nitrogen (NH_4-N) input to the Ria de Aveiro Lagoon. Left: long-term mean annual loads [kg N/day] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on NH_4-N for each scenario.

It is increased to 2.4 tonnes under the climate of the future scenario period (2011-2040). In order to understand this trend other factors (e.g. runoff, soil moisture and temperature, fertilizer application dates) rather than the long-term average annual changes in climate must be considered.

When, for example, an extreme precipitation event occurs shortly after fertilization with organic nitrogen, the availability of ammonium in the soil increases rapidly (enhanced mineralization and reduced nitrification, due to soil saturation) and NH_4-N subsequently becomes subject to increased leaching into the surface waters. This can cause high annual peaks for some years of the simulation and even lead to an average increase in loads for the whole 30 years period.

During the whole simulation period in the catchment of Ria de Aveiro, such a coincidence occurred three times. The amount of the leached ammonium in these years was incomparably high and reached maximum values of up to 30 000 kg N/day. On the long-term, these three peaks caused an average increase for the whole catchment by about 8.5% in NH_4-N load. In most of the other years the simulated loads were lower compared to the reference period and average annual maximum values hardly exceeded 10 000 kg N/day.

In addition to climate change, socio-economic changes have an impact on NH_4-N loads as well, although this is less pronounced. Similar as for NO_3-N loads, a decrease of the agricultural land can reduce the diffuse pollution with NH_4-H, while an increase of the applied amount of fertilizers per hectare would have the opposite effect. Except for the BAU scenario, in which both mineral and organic fertilizers are increased, NH_4-N loads are reduced between 2% and 3% for all scenarios, due to socio-economic changes only (upper right graph).

Phosphate phosphorus loads

The left graph in Figure 3.1.7 shows the total sum of phosphate phosphorus (PO_4-P) loads brought to the lagoon by the inflowing rivers in the scenario runs. Under the reference conditions (REF) and the reference climate (1971-2000) the average daily PO_4-P load to the Ria de Aveiro is about 335kg. Under the climate of the future scenario period (2011-2040) it is reduced to 319kg. Similar as NO_3-N, PO_4-P loads in the catchment originate mainly from diffuse pollution and only to a minor extent from point sources. Therefore, the total annual input to the lagoon depends mostly on the share of agricultural land in the catchment and its management (fertilization).

PO_4-P is projected to decrease in all four socio-economic scenarios (upper right graph). The reduction is the least for the BAU scenario (-3%), in which agricultural land is reduced and fertilizer rates are increased. The decrease of PO_4-P is the strongest for the SET scenario (-14%), in which both agricultural land and mineral fertilization are reduced substantially (-30% and -20%). In general, PO_4-P trends in scenario runs show a very similar behaviour as NO_3-N. The effect of climate change enhances the observed trends (lower right graph) and causes a decrease of 8% for the BAU, 12% for the CRI, 9% for the MH and 18% for the SET scenario.

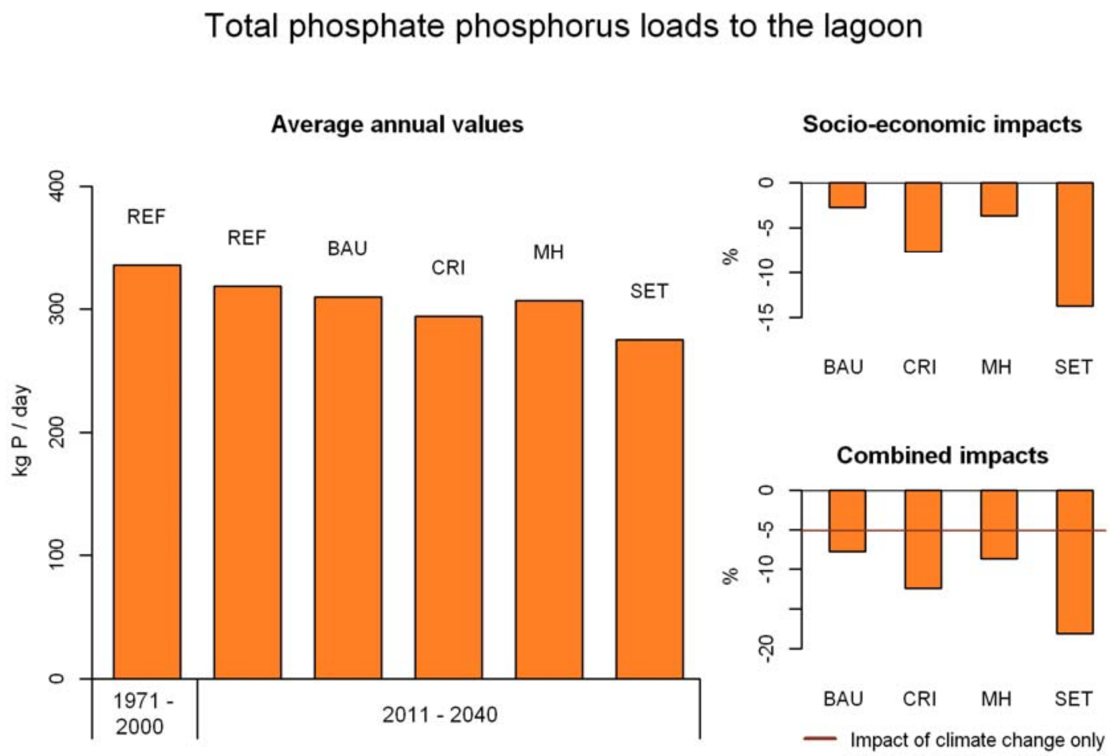


Figure 3.1.7: Impacts on total phosphate phosphorus (PO_4-P) input to the Ria de Aveiro Lagoon. Left: long-term mean annual loads [kg P/day] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on PO_4-P for each scenario.

3.1.3 Spatial changes

This section includes maps of the Ria de Aveiro catchment showing the long-term average annual changes in runoff (RUN), groundwater recharge (GWR) and actual evapotranspiration (ET_a) for each of the four socio-economic scenarios (Figures 3.1.8 – 3.1.10). It further provides the long-term average annual changes in discharge (Q) and nutrient (NO_3-N, NH_4-N and PO_4-P) inputs for the individual rivers flowing into the lagoon (Figure 3.1.11). In both cases the socio-economic impacts as well as the combined climate change and socio-economic impacts are presented. The resolution of the maps is on the level of hydrotopes (see Deliverable D5.2, page 11). RUN is defined as the sum of surface and subsurface flows in the catchment.

Runoff

The socio-economic impacts on runoff in the Ria de Aveiro catchment (left column of maps in Figure 3.1.8) can be easily related to the patterns of land use changes assumed for each of the four scenarios (compare with Figure 2.3.2). However, the direction of change and magnitude of changes also depend on the soil, and to some extent, on terrain characteristics of the area.

In the BAU scenario runoff is projected to decrease by 50 mm to 300 mm on former agricultural land that was converted to fallow or grassland. In general, runoff from agricultural land is higher than runoff generated on fallow or grassland. One of the main reasons is an increased soil

compaction, which is usually caused by the heavy agricultural machinery. The use of these machines can lower soil permeability and reduce water infiltration, which favors overland flow and impairs groundwater recharge.

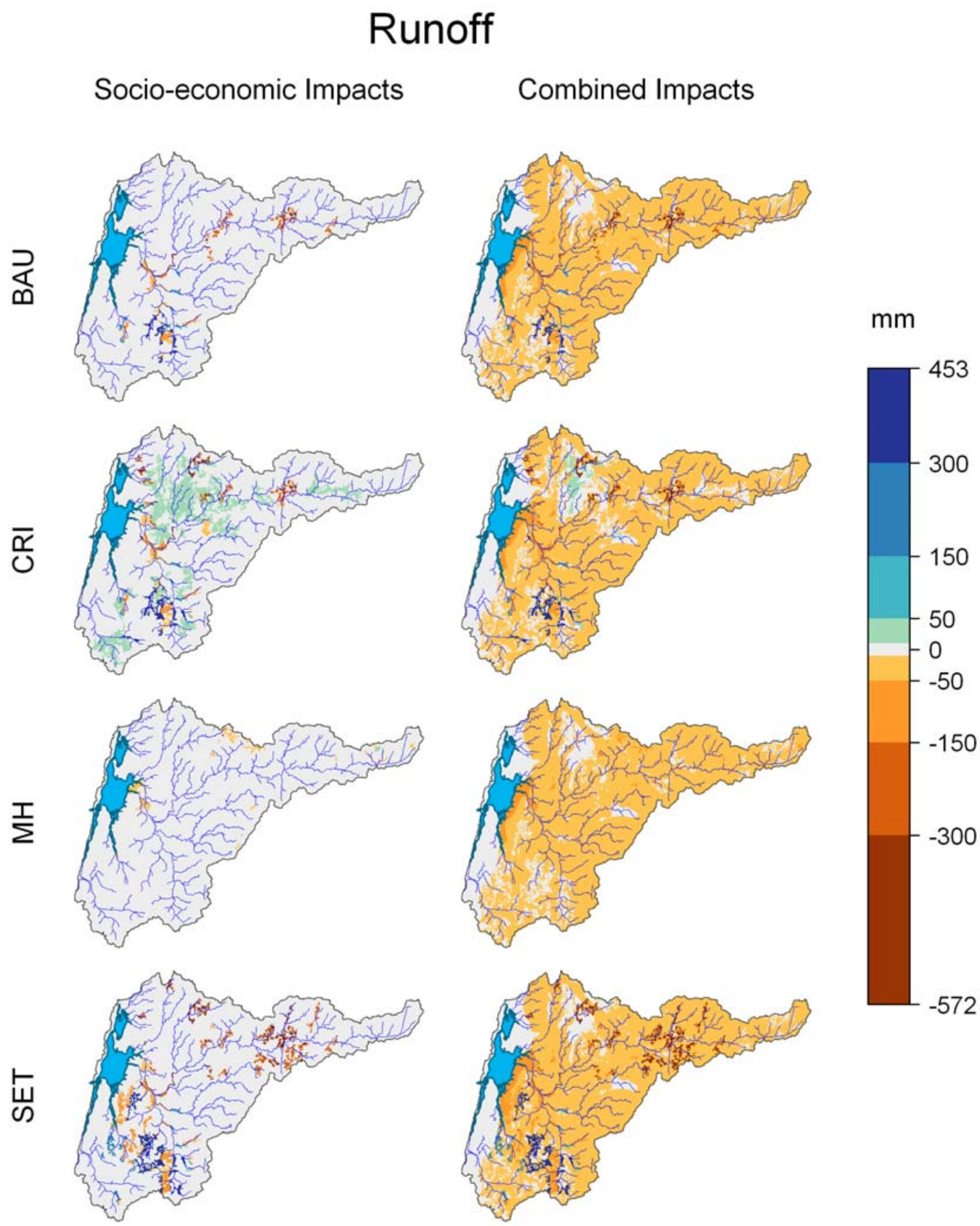


Figure 3.1.8: Maps showing long-term average annual spatial changes in runoff (RUN) for the Ria de Aveiro catchment. Left: socio-economic impacts; Right: combined impacts.

Furthermore, the absence of a complete and permanent vegetative soil cover on agricultural land use allows more water to reach the soil surface and ultimately to contribute to runoff. The permanent vegetation cover on fallow areas causes higher evapotranspiration rates and leaves less water for runoff generation.

Nevertheless, in some areas, the implemented land use changes also lead to an increase in runoff. At the same time groundwater recharge (GWR) in these areas decreases (see Figure 3.1.9). This interaction between RUN and GWR occurs typically on soils with very low permeability. Under the reference land use (agriculture), these soils were loosen by the roots of the planted crop (in this case maize), which "artificially" increased their infiltration rate and enabled soil water movement towards the aquifer. The root penetration of the new vegetation cover (grass) is weaker. The plant roots are less effective in increasing soil porosity and therefore a decrease in GWR and an increase in RUN can be observed from these soils.

In the CRI scenario 15% of the agricultural land (10% in BAU) is converted to fallow and grassland and thus the projected changes in RUN are comparable to those observed in the BAU scenario. In addition to this, about 20% of the forested areas are transformed into fallow or grassland too, which leads to the opposite effect: a higher runoff in these areas. The main reason for this is a decrease in actual evapotranspiration (compare Figure 3.1.9) in those areas, which is due to a lower leaf area index (LAI) of fallow or grassland compared to forest. As less water is transpired by the vegetation, more water remains available for the runoff generation in those areas and hence runoff increases.

In the MH scenario, only some changes in the Bocage area (around the mouth of the main river Vouga) and partly at some mountainous areas close to the catchment borders can be observed. Runoff decreases in those areas by 50-100 mm on average. This decline is caused by afforestation. Forests have higher evapotranspiration rates (compare Figure 3.1.9) due to the higher LAI of vegetation, which leads to less available water and reduces the generated runoff in those areas.

In the SET scenario the implemented land use changes and projected runoff changes are very similar to the ones in the BAU scenario. The spatial extent of these changes is slightly different, as larger areas of agricultural land (30%) were assumed abandoned and converted to fallow and grassland in this scenario.

Looking at the combined climate and socio-economic impacts (right column of maps in Figure 3.1.8) on runoff in the Ria de Aveiro catchment, we can observe a nearly homogenous picture among scenarios. On average, RUN is projected to decrease by about 50-150 mm. The decrease is stronger in areas where land use changes already caused a decline in runoff, and it is less strong in areas where land use changes caused an increase in runoff. In some areas the combined impacts show increasing trends, however this is noticeably weaker than the increasing trend due to land use changes only. In total, the mapped outputs are in agreement with the results presented in section 3.1.1 above.

Groundwater Recharge

Similar as for runoff, the socio-economic impacts on groundwater recharge (GWR) in the Ria de Aveiro catchment (left column of maps in Figure 3.1.9) can be related to the patterns of land use changes assumed for each of the four scenarios (compare with Figure 2.3.2) and also to some extent to the soil and terrain characteristics of the area.

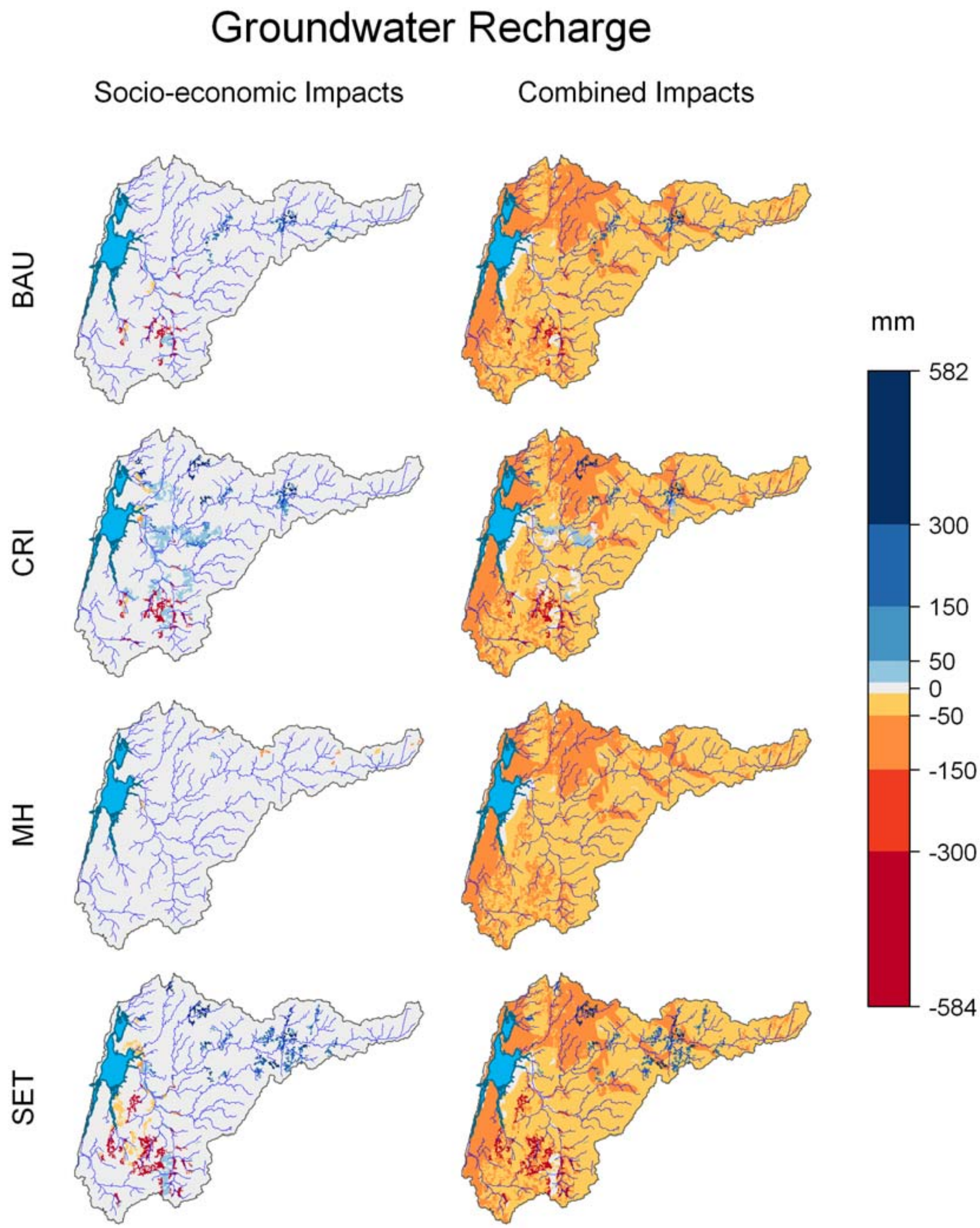


Figure 3.1.9: Maps showing long-term average annual spatial changes in groundwater recharge (GWR) for the Ria de Aveiro catchment. Left: socio-economic impacts; Right: combined impacts.

Groundwater recharge is strongly interrelated with surface and subsurface runoff. In most cases a decrease in runoff due to land use change means an increase in groundwater recharge and vice versa.

However, there are also areas that are more vulnerable towards changes in groundwater recharge rather than changes in runoff, and vice versa. Some areas may show an increase in GWR, although runoff there did not seem to be affected at all (e.g. in CRI: light blue colored area along tributary of the Vouga close to the mouth). Also there might be areas, in which runoff is projected to increase, but groundwater recharge does not show a noticeable decrease (e.g. in CRI: forested areas that are converted to fallow). This can happen when the increase in RUN is mainly due a decrease in actual evapotranspiration (ET_a). In most areas affected by land use change, GWR changes by the same magnitude as RUN, with the opposite sign.

Considering climate change in addition, we can see that the decrease in groundwater recharge in some areas is considerably stronger compared to that of runoff. This is especially the case for those areas that already have very high recharge rates under the reference climate and generate only very little runoff (compare with LAGOONS, 2013, page 30, Figure 3.2.2). Hence we can hardly observe a decrease in RUN there, but in GWR.

Actual evapotranspiration

Similar as for RUN and GWR, the socio-economic impacts on actual evapotranspiration (ET_a) in the Ria de Aveiro catchment (left column of maps in Figure 3.1.10) reflect the patterns of land use changes assumed for each of the four scenarios (compare Figure 2.3.2).

ET_a increases by up to 100 mm on areas where cropland is converted to fallow or grassland, because the vegetation cover there is permanent and more water can be transpired by the plants.

In the CRI scenario, we can observe a decrease (up 75 mm) in actual evapotranspiration on deforested areas. The combined impacts intensify this trend. The effect of climate change on areas with increasing ET_a due to land use change is almost negligible.

Impacts for individual rivers

The spatial changes were evaluated also for the long-term average annual changes in discharge (Q) and nutrient inputs (NO_3-N, NH_4-N and PO_4-P) for the individual rivers flowing into the lagoon (compare with LAGOONS, 2013, page 24, Figure 3.1.1,). The combined impacts are shown as bars, and the socio-economic impacts only – as circles in Figure 3.1.11.

The combined impacts on long-term average annual discharges (Q) of all rivers flowing into the Ria de Aveiro lagoon are between -6% and -10%. There are almost no differences between scenarios, except for the rivers Antua and Caster. In the catchments of these two rivers large waste water treatments plants (WWTPs) discharge their treated effluents into the streams (compare with LAGOONS, 2013, page 26, Figure 3.1.5). This makes the share of natural flow in the rivers considerably smaller compared to other catchments. Therefore, the socio-economic changes, such as changes in the size of population, or the level of effluent treatment have visible effects on water discharge in these two rivers.

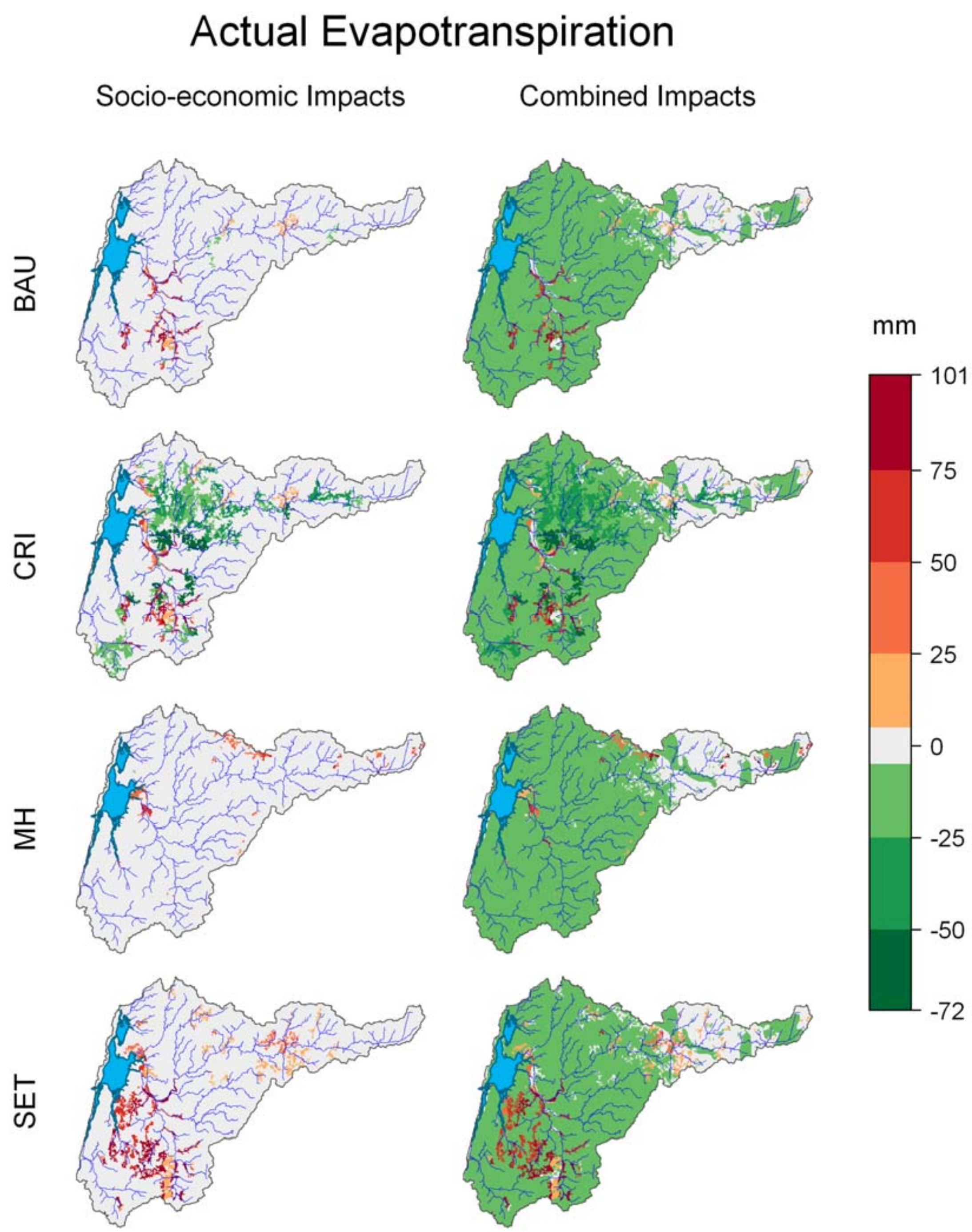


Figure 3.1.10: Maps showing long-term average annual spatial changes in actual evapotranspiration (ET_a) for the Ria de Aveiro catchment. Left: socio-economic impacts; Right: combined impacts.

In the catchment of the Ilhavo channel, neither abstraction points (for drinking water supply) nor discharge points (from WWTPs) (compare with LAGOONS, 2013, page 26, Figure 3.1.5) exist. Still, some minor differences between scenarios can be observed. Variations in RUN, GWR and ET_a, due to land use change (see Figures 3.1.8 – 3.1.10) lead to small, yet visible changes in

Q in this case. Nevertheless, in total, the socio-economic impacts on river discharge (circles in the graph) in the Ilhavo channel and in most of the other inflowing rivers are much lower compared to the combined impacts (bars).

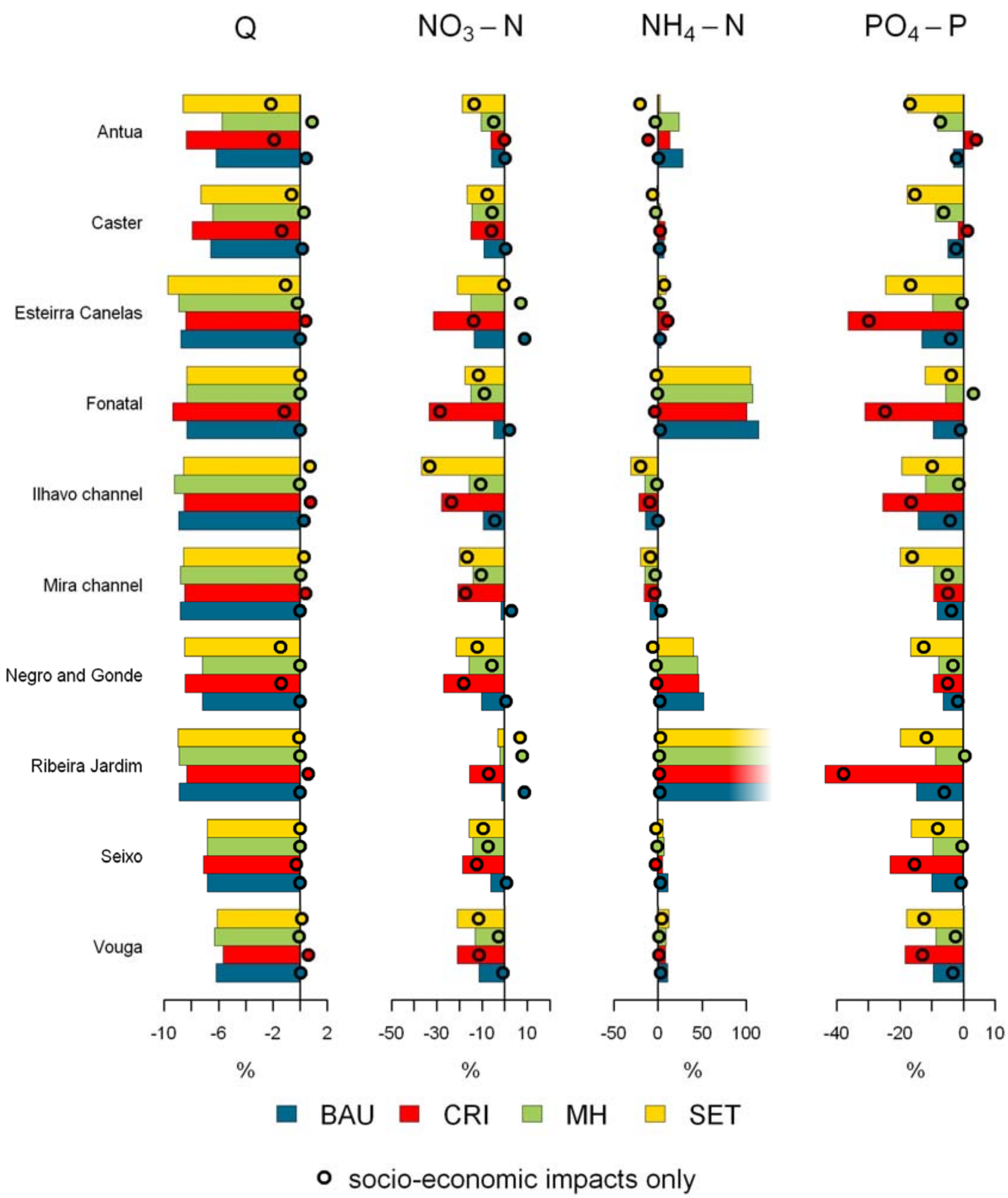


Figure 3.1.11: Relative changes [%] in long-term mean annual discharge (Q) and nutrient loads (NO_3-N, NH_4-N and PO_4-P) showing the combined (bars) and socio-economic (circles) impacts for individual tributaries of the Ria de Aveiro.

However, this observation does not apply to the impacts on nutrient loads. In many cases the socio-economic impacts (circles) are as strong as the combined impacts (bars) regarding nitrate nitrogen, ammonium nitrogen and phosphate phosphorus in the rivers. The nutrient loads strongly depend on the total amount of applied fertilizers in each subcatchment, which in turn is affected by a combination of factors: i) fertilization rate per hectare, ii) the share of mineral and organic fertilizers and iii) the size of the agricultural area. Furthermore nutrient loads also depend on the pollution from point sources, such as effluent discharges from WWTPs and/or vineries. Therefore the effects of changes in any of these parameters are quite significant.

In Esteirra Canelas for example, the socio-economic impacts show an opposite effect on nitrate nitrogen (NO_3-N) loads for the MH and BAU scenarios than the combined impacts do. In both scenarios point sources were reduced by 8% and 2%. The mineral fertilization was reduced by 15% and organic fertilization was increased by 15% in the MH scenario, while in the BAU scenario both were increased by 5% and 10%. Besides, large agricultural areas within the catchment of Esteirra Canelas were converted to fallow or grassland in both the MH and the BAU scenario. In the end, the combination of these changes caused an increase in NO_3-N loads in the catchment of Esteirra Canelas. However, when climate change is added to the socio-economic impacts, the NO_3-N loads show a decrease decrease in all four scenarios. This is due to a strong decrease in runoff, which is caused by lower precipitation rates and increasing temperatures projected by the s7 climate scenario. As less runoff is generated in the catchment of Esteirra Canelas, less nutrients can be washed away from the agricultural fields and transported to the rivers.

This also applies to the phosphate phosphorus loads in most rivers but not to the ammonium nitrogen loads. In the case of NH_4-N a decrease in runoff can still lead to an increase in loads, when other climate parameters, such as daily temperatures change accordingly (see detailed explanation on that in section 3.1.2). The combined impacts on ammonium nitrogen lead to an increase in loads in seven out of ten rivers. The percental changes are sometimes high (e.g. Fonatal, Ribeira Jardim), if the basic values are low. But the changes in absolute values are comparable between different rivers. For example, in the Ribeira Jardim the increase is even 500%, which for clarity reasons is not shown in Figure 3.1.11. It should be considered though, that such changes do not always imply an environmental disaster. The NH_4-N loads in the Ribeira Jardim increase from 0.001 kg N/day to 0.5 kg N/day, which is still far below any threshold regarding water quality issues.

3.1.4 Summary

In summary, it can be stated that the socio-economic changes (land use and management) hardly influence water inflow (Q) to the Ria de Aveiro, except for the CRI scenario. In this scenario evapotranspiration is strongly reduced by deforestation, which in turn leads to an increase in runoff from the catchment and consequently to a small, yet negligible increase by 0.4% in total inflow to the lagoon (see Figure 3.1.12). The groundwater recharge and evapotranspiration are impacted only very little by the socio-economic scenarios, too and show no significant changes, expect some increase in ET_a in the SET scenario.

Regarding water quality, land use changes and altered management show a visible impact on total nutrient loads flowing to the Ria de Aveiro. A decrease in nitrate nitrogen (NO_3-N),

ammonium nitrogen (NH_4-N) and phosphate phosphorus (PO_4-p) loads is simulated for all four socio-economic scenarios, while NO_3-N and PO_4-P show the strongest reduction (up to 14% for the SET scenario). These two components originate from diffuse pollution (agricultural land) mainly, and a decrease of their loads occurs when agricultural land and applied fertilizers are reduced. On the contrary, NH_4-N loads in the Ria de Aveiro catchment originate primarily from point source pollution (e.g. WWTPs) and only to a minor extent from diffuse pollution. Therefore, as the assumed changes in point sources for the four scenarios are rather small, the depletion of NH_4-N is much weaker compared to that of NO_3-N and PO_4-P.

The combined climate and socio-economic impacts show a decrease for all scenarios in five out of six analyzed variables (Q, GWR, ET_a, NO_3-N and PO_4-P), mainly as a result of decreasing precipitation rates projected by the s10 climate scenario for the future (2011-2040). The ammonium nitrogen load to the Ria de Aveiro is the only component which is projected to increase in future for all four scenarios. This increase is due to changes in other factors, such as soil moisture, temperature and runoff (as explained earlier), and cannot be related to changes in precipitation directly.

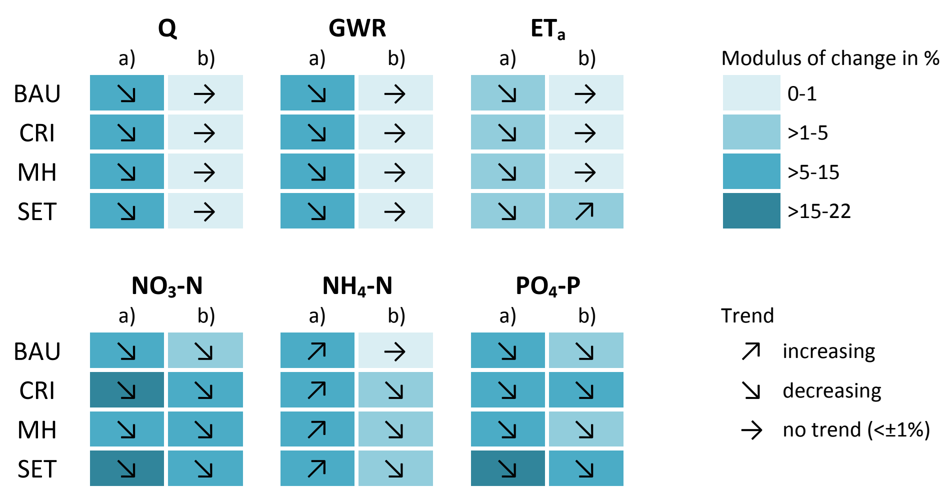


Figure 3.1.12: Summary of trends for analysed parameters (discharge - Q, groundwater recharge - GWR, actual evapotranspiration - ET_a, nitrate nitrogen - NO_3-N, ammonium nitrogen - NH_4-N, phosphate phosphorus - PO_4-P) in the Ria de Aveiro catchment caused by potential future changes: (a) – combined impacts, (b) – socio-economic impacts.

3.2 Mar Menor Catchment

3.2.1 Water quantity – annual and monthly changes

Total inflow to the lagoon

The catchment of the Mar Menor is highly managed and therefore socio-economic changes assumed in the four scenarios may have a significant impact on water resources in the region. Besides, as the area is very dry and river discharge is extremely low, climate change as well may notably affect water flows.

The left graph in Figure 3.2.1 shows the sums of average daily discharges (Q) from all streams flowing into the lagoon for six scenarios (six bars). Under the reference conditions (REF) and the reference climate (1971-2000) the average daily discharge is about 0.13 m^3/s only (first bar in the figure) and it is even lower (0.12 m^3/s) under the climate of the future scenario period (2011-2040). The long-term average daily discharges simulated for each of the four socio-economic scenarios (BAU, CRI, MH and SET) are all below the reference discharge. Nevertheless the differences between the scenarios are clearly visible.

In the BAU and MH scenarios discharge is projected to increase by 12% and 6.5%, correspondingly, whereas it decreases by 4% and 13% in the CRI and SET scenarios, due to socio-economic changes only (see with upper right graph in Figure 3.2.1). These impacts can be attributed to changes in water management mainly, and only to some extent to changes in the land use patterns. For example, water supply for the population in the Mar Menor catchment is provided by water transfer from another catchment, while the sewage water (after treatment) is discharged into the Albujon wadi, which adds additional water to the Mar Menor catchment from outside. Therefore, an increase in population and tourism comes along with an increase in external water transfer and effluent released from the waste water treatment plant (WWTP) and subsequently leads to an increase of total inflow to the lagoon. Consequently, decreasing population and tourism, as assumed for the SET and CRI scenarios lead to a decrease in Q.

However, water discharge is also influenced by changes in the land use patterns. In the SET scenario, for example, the effluent is reduced less than in the CRI scenario (-10% and -20%), and also the irrigated area is reduced by 25%, while it is almost halved (45%) in the CRI scenario. Still the decrease in discharge in the SET scenario is higher compared to the CRI scenario. The reason therefore is the difference in assumed land use changes, and their impacts on the major water fluxes: runoff, groundwater recharge and evapotranspiration. A reduction of 30% of agricultural land, especially on areas close to the lagoon (as it was assumed for the SET scenario), causes a stronger decrease in the groundwater recharge and hence in groundwater contribution to the total inflow, than a reduction of 15% of arable land performed entirely in the western part of the catchment, as it was assumed for the CRI scenario.

The combined scenarios were simulated by adding climate change to the socio-economic changes. Under the combined scenarios the total inflow to the lagoon decreases for all four scenarios, as climate becomes warmer and dryer (lower right graph in Figure 3.2.1). The combined impacts on discharge are strongest for the SET scenario, in which inflow decreases by about 24%, and smallest for the BAU scenario, in which it decreases by 3% only. In the CRI and MH scenarios the inflow to the Mar Menor decreases by 17% and 8%, respectively.

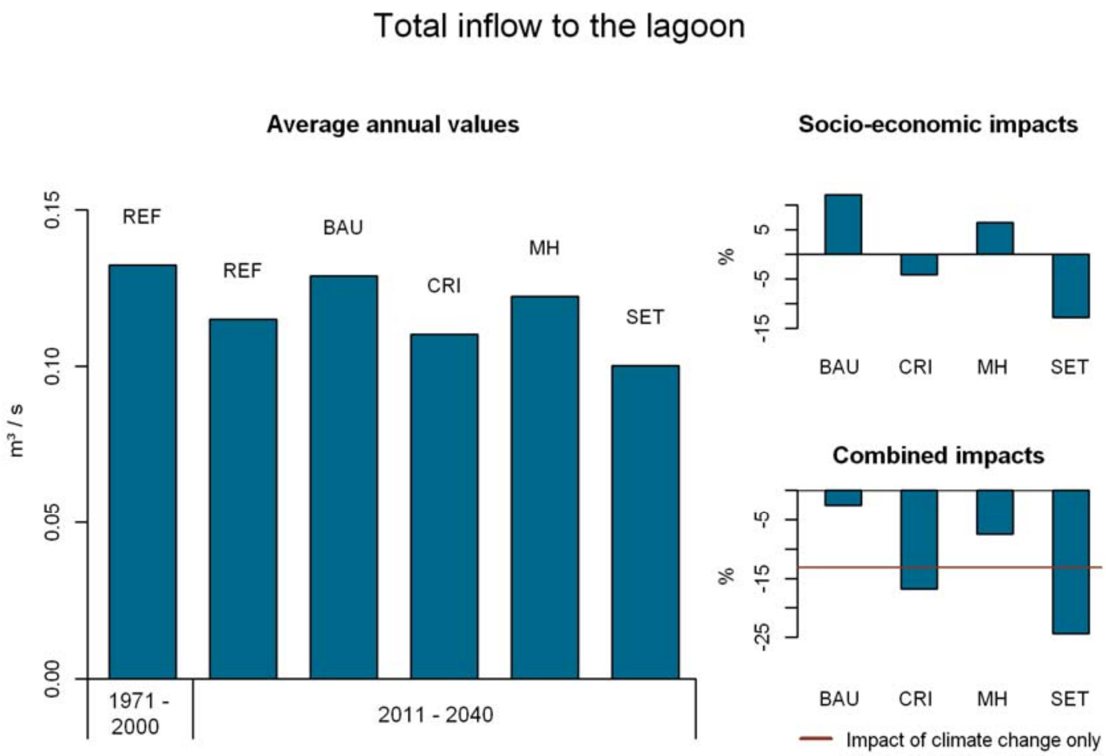


Figure 3.2.1: Impacts on total inflow (Q) to the Mar Menor. Left: long-term mean annual discharges [m^3/s] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on Q for each scenario.

Groundwater recharge

Similarly as water inflow to the lagoon, the groundwater recharge (GWR) in the Mar Menor catchment is influenced by both socio-economic changes and climate change, with the impact of climate change being twice as much.

The left graph in Figure 3.2.2 shows the long-term average annual groundwater recharge (GWR) in the catchment for six scenarios (six bars). Under the reference conditions (REF) and the reference climate (1971-2000) the average GWR is 32mm per year (first bar in the figure), and it is projected to decrease to 22 mm in the future scenario period (2011-2040) under climate change impact only. The groundwater recharge rates for the four socio-economic scenarios (BAU, CRI, MH and SET) are between 19 mm and 23 mm.

For three of them (BAU, CRI and SET) groundwater recharge is projected to decrease, due to socio-economic changes only (see upper right graph in Figure 3.2.2), and only for the MH scenario an average increase of about 1% is simulated. These trends can be related to land use changes, and especially to the conversion of agricultural land to other land uses with permanent vegetation. Besides, groundwater recharge in the catchment is also affected by changes in the irrigated area.

The strongest decrease in GWR can be observed for the SET scenario (-15%), in which 15% of the agricultural land are converted to fallow and the irrigated area is reduced by 25%. In the

CRI scenario, 30% of the agricultural land are transformed into fallow and the irrigated area is reduced more drastically (-45%), however the decrease in groundwater recharge is lower (-13%). In general, groundwater recharge under agricultural land is higher compared to GWR under fallow or grassland (for explanations see section 3.1.3 on spatial changes in the Ria de Aveiro catchment), and therefore groundwater recharge decreases in these scenarios. However, GWR is even higher under irrigated agricultural land, as additional water can infiltrate through the soil. In the SET scenario, large parts of the converted agricultural land used to be irrigated under the reference conditions, and therefore GWR there was higher than in other non-irrigated areas. The agricultural land converted to fallow in the CRI scenario was only to some extent within the boundaries of the irrigation zone, and thus the overall decrease in GWR for this scenario was lower.

The smallest reduction in GWR (-7%) is simulated for the BAU scenario, in which 14% of the agricultural land (mostly areas located outside the reference irrigation zone), were converted to fallow. In the MH scenario, an increase in agricultural land (5%) and irrigated area (5%) causes an overall small increase in groundwater recharge of about 1%.

In combination with climate change, the groundwater recharge in the catchment decreases for all four scenarios by 29% to 40%. The impact of climate change on groundwater recharge is about twice the impacts of socio-economic changes only.

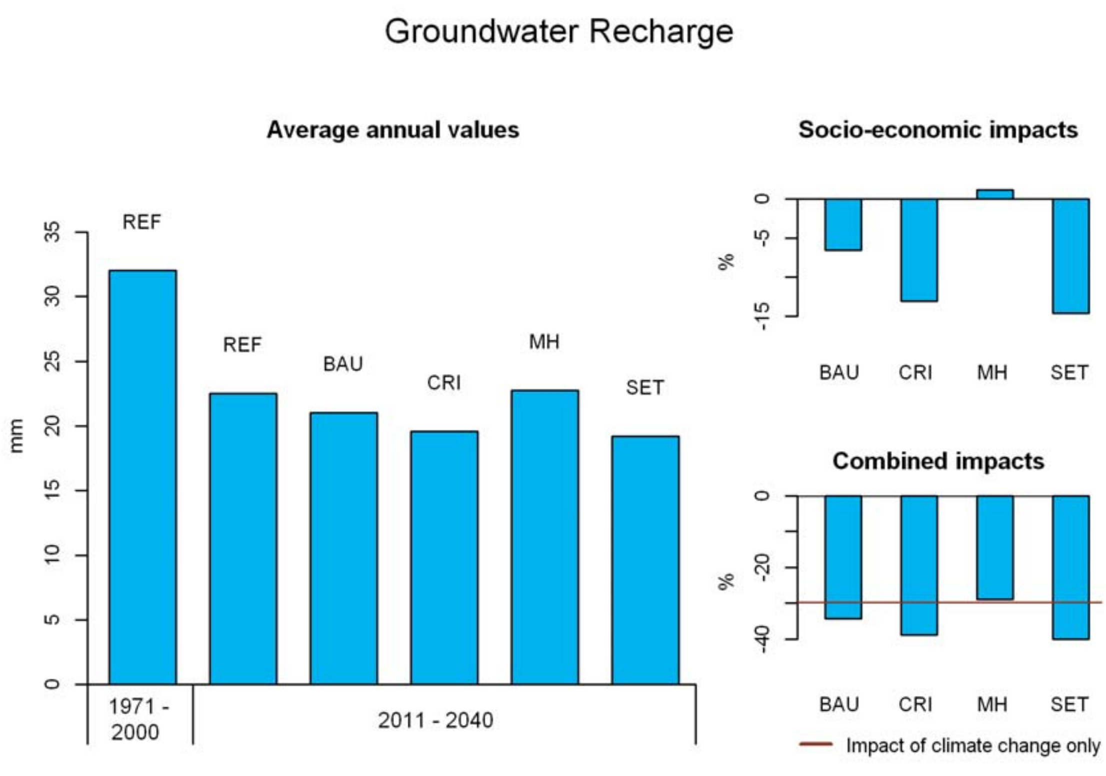


Figure 3.2.2: Impacts on groundwater recharge (GWR) in the Mar Menor catchment. Left: long-term mean annual recharge rates [mm] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on GWR for each scenario.

Actual evapotranspiration

The actual evapotranspiration (ET_a) in the Mar Menor catchment shows a very similar behavior as groundwater recharge for the four socio-economic scenarios.

The left graph in Figure 3.2.3 shows the long-term average annual evapotranspiration rates in the catchment for six different cases (six bars). Under the reference conditions (REF) and the reference climate (1971-2000) the average ET_a is about 520 mm per year (first bar in the figure), which is notably higher than the amount of the average annual precipitation for the applied climate scenario (350 mm). For the future period (2011-2040), ET_a is projected to decrease to 500mm, as temperature would rise and precipitation would decrease. The simulated evapotranspiration rates for the four socio-economic scenarios (BAU, CRI, MH and SET) are between 480 mm and 510 mm.

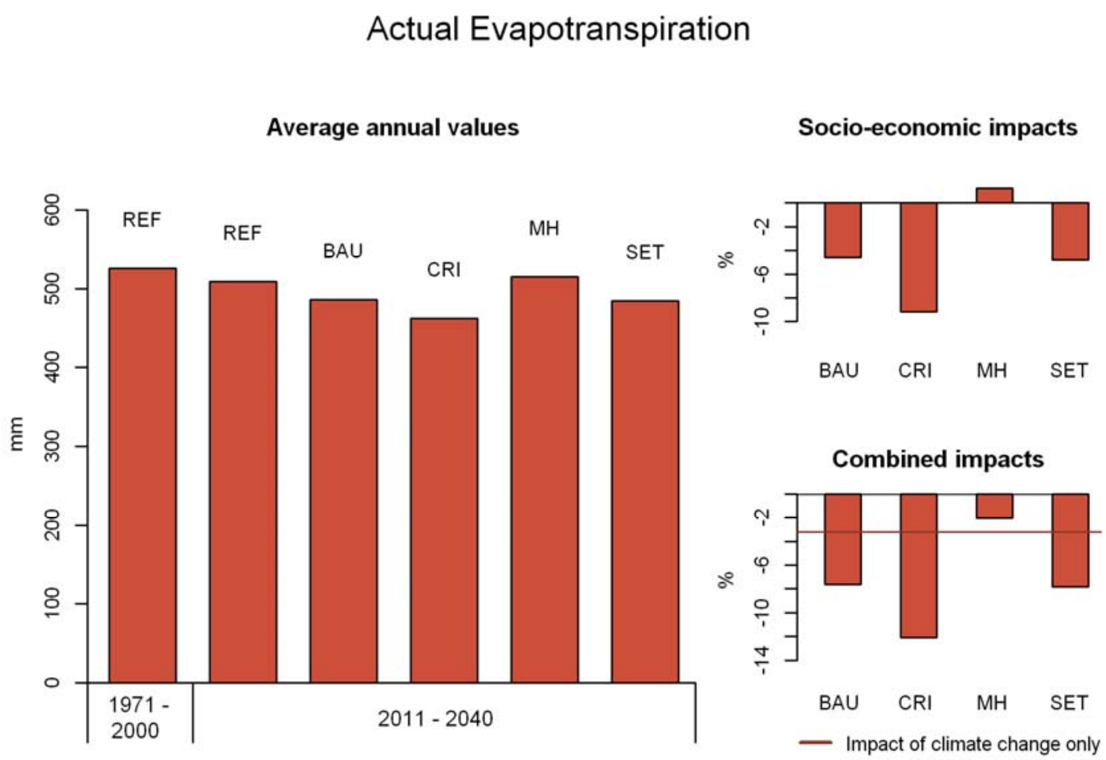


Figure 3.2.3: Impacts on actual evapotranspiration (ET_a) in the Mar Menor catchment. Left: long-term mean annual evapotranspiration rates [mm] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on ET_a for each scenario.

The impacts of the socio-economic changes only (upper right graph in Figure 3.2.3) show a decrease between 4.5% and 9% for three of the four scenarios (BAU, CRI and SET), and an increase of about 1.5% for the MH scenario. Similar as for groundwater recharge, these changes can be attributed to the assumed in scenarios changes in agricultural land and size of the irrigated area. The actual evapotranspiration shows the strongest decrease (about 9%) for the CRI scenario, in which the most significant land use changes were assumed. The decreases for

the BAU and the SET scenarios, are quite similar (4.5% and 5%), and so are the assumed changes in land use (14% and 15% of agricultural land transformed to other land uses).

Only in the MH scenario, the ET_a is projected to increase slightly due to socio-economic changes, as this is the only case in which both an increase of the agricultural land and an increase of the irrigated area are assumed. While the second measure adds more water to the system, which is then available for evapotranspiration, the first one increases the transpiration rate of the vegetation.

In combination with climate change, the ET_a in the Mar Menor catchment decreases for all four scenarios. The decrease ranges between 2% for the MH scenario and 12% for the CRI scenario. Unlike the GWR case, the impact of climate change only on evapotranspiration in the catchment is smaller in percent (3%). The socio-economic changes and especially changes in the agricultural land clearly have a stronger impact on evapotranspiration than climate change.

Average monthly changes in discharge, groundwater recharge and evapotranspiration

Figure 3.2.4 shows the long-term average seasonal changes in water flow components in the catchment of the Mar Menor.

The impacts of the combined scenarios on the total inflow to the Mar Menor show a variation between -60% and 50% in different months (solid lines in upper left graph in Figure 3.2.4), while the impacts of the socio-economic scenarios (dashed lines) show a variation between -20% and 38% only.

Climate change influences discharge (Q) almost equally strong in all four combined scenarios during the colder months (from October until February), and therefore only little differences between the scenarios are visible for this period. In the dry summer months, the average monthly impacts of the combined scenarios on discharge are more distinguishable, and changes in one month can vary from -10% to 10% (e.g. SET and BAU in August). Compared to the combined impacts, the monthly socio-economic impacts on Q are relatively homogenous during the whole year.

The changes in the seasonal dynamics of groundwater recharge in the Mat Menor lagoon catchment are shown in the absolute values (upper right graph). It makes more sense to analyze these dynamics, because the monthly groundwater recharge is very low, and the relative changes in percent may reach very high values, though the absolute changes are very small. The pattern of seasonal changes in GWR is very similar to that of runoff. The differences between scenarios are smaller compared to runoff. The impacts of the combined scenarios are clearly stronger and show higher seasonality than the socio-economic impacts only. The changes in groundwater recharge under the combined scenarios range between -8.5mm and 2.2mm, whereas they are between -0.7 mm and 0.2 mm for the socio-economic scenarios only.

The seasonal impacts on actual evapotranspiration in the Mar Menor catchment (lower left graph) show a decrease for almost all scenarios and all months. The MH scenario is the only outlier for both the combined and the socio-economic impacts. In general, ET_a decreases between -20% and –2% during the year, while the decrease is strongest for July, August and September, which are the months with the lowest evapotranspiration rates under the reference conditions already now. The decrease for these months is the weakest in the MH scenario, as in

this scenario additional water is added to the system through irrigation, which compensates to some extent the effect of the decreasing precipitation. Under the socio-economic scenario of MH this change in land use and water management even leads to a slight increase in ET_a of 1% to 3%, as more water is available for evapotranspiration (dashed yellowish line).

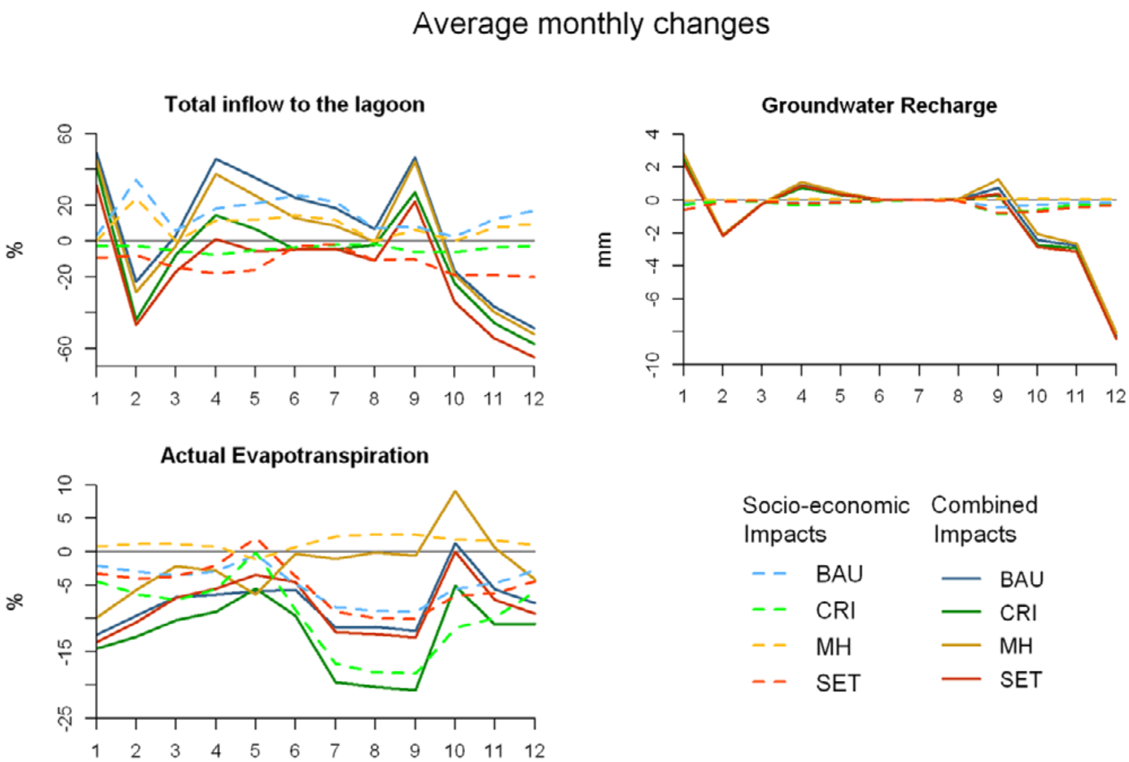


Figure 3.2.4: Long-term mean monthly relative changes [%] of Q and ET_a, and long-term mean monthly absolute changes for GWR in the Mar Menor catchment showing the socio-economic impacts (dashed lines) and the combined impacts (solid lines) for each scenario.

3.2.2 Water quality – annual changes

The nutrient loads in the Mar Menor catchment can be subdivided into two groups: nutrient loads from diffuse sources mainly, and nutrient loads from point sources mainly. Nitrate nitrogen (NO_3-N) originates mainly from diffuse pollution (arable land), while ammonium nitrogen (NH_4-N) and phosphate phosphorus (PO_4-P) are introduced to the environment mainly by point sources (effluent from WWTP). Therefore, climate change impacts on the NO_3-N loads are considerably higher compared to the socio-economic impacts only, while the climate change impacts on the NH_4-N and PO_4-P loads are almost negligible. On the other hand, the socio-economic changes can have high impacts on both types of pollution (diffuse and point source), and hence on all three nutrient components (NO_3-N, NH_4-N and PO_4-P). This is clearly visible from the scenario results described below.

Nitrate nitrogen loads

The impacts on the total nitrate nitrogen loads to the Mar Menor are shown in Figure 3.2.5. Under the reference conditions (REF) and the reference climate (1971-2000) the average daily NO_3-N load to the Mar Menor lagoon is about 980 kg N, and it is reduced to about 780 kg N per day in the future scenario period (2011-2040), as precipitation and consequently runoff are reduced in the catchment. In addition to climate change, the NO_3-N loads are also strongly influenced by socio-economic changes, and the long-term average annual loads for the four future scenarios vary between 500 and 770 kg N per day. It means that all four socio-economic scenarios cause a decrease in the NO_3-N loads to the lagoon.

The strongest decrease, due to socio-economic changes only can be observed for the SET scenario (-75%) (upper right graph). In this scenario, neither the strongest decrease in agricultural land (15% only), nor the strongest decrease in irrigated area (-25% only) or in applied fertilizers (-15% for mineral and +15% for organic) were assumed and still the location of the applied changes (conversion to fallow in close proximity to the lagoon) led to a very strong depletion in average NO_3-N loads to the lagoon.

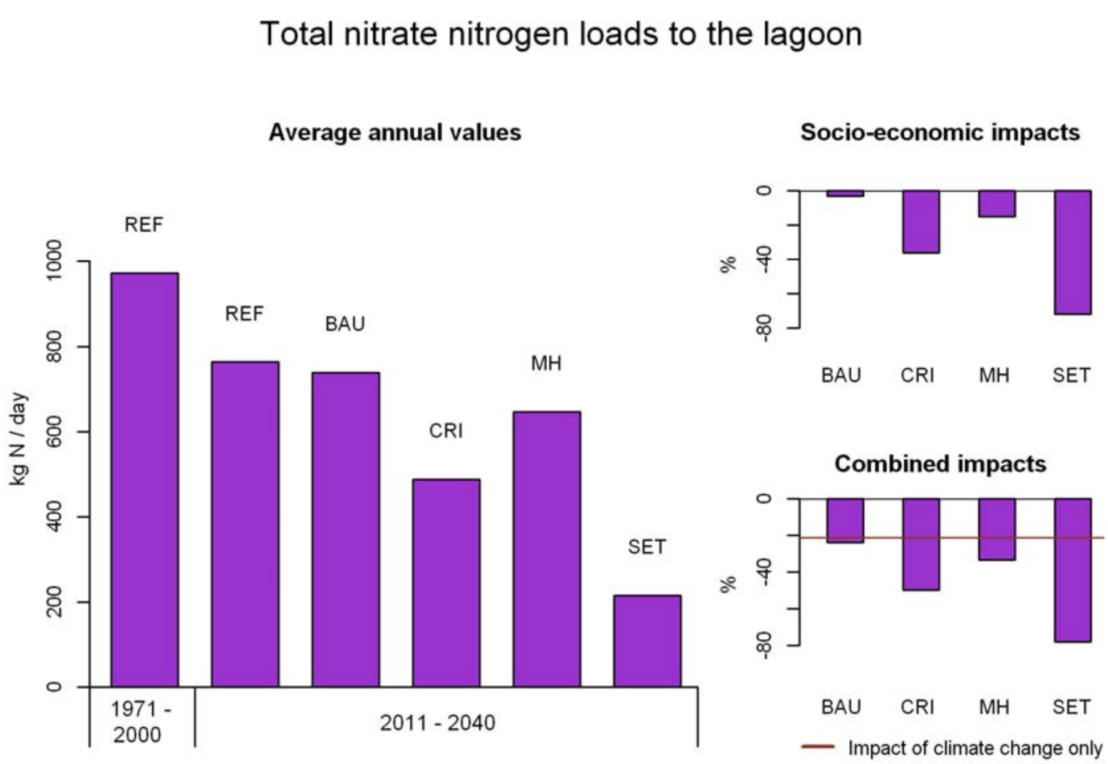


Figure 3.2.5: Impacts on total nitrate nitrogen (NO_3-N) input to the Mar Menor. Left: long-term mean annual loads [kg N/day] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on NO_3-N for each scenario.

In contrary to that, in the CRI scenario, the strongest decrease of agricultural land (-30%) as well as of irrigated area (-45%) and applied fertilizers (-20% for mineral and organic) were

assumed, but only the second strongest decrease in NO_3-N loads was projected. This is because the land use changes were performed far away from the lagoon in the western part of the catchment and had therefore less influence on the overall load generation from diffuse sources. It is also worth mentioning, that in the MH scenario, in which increases of agricultural land and irrigated area by 5% each were assumed, the NO_3-N load to the lagoon were still projected to decrease by about 20%, mainly as a result of the reduced mineral fertilization (-20%).

The climate change adds further reduction to these trends and the NO_3-N loads decrease by 20-80% under the combined scenarios (lower right graph), as precipitation and runoff decrease.

Ammonium nitrogen loads

In Figure 3.2.6 the impacts on the total ammonium nitrogen loads to the Mar Menor are presented. The average daily NH_4-N load to the lagoon for the reference climate and the reference conditions (REF, 1971-2000) is about 8 kg N only and almost no change is visible under the future scenario period (REF, 2011-2040), as the NH_4-N load is hardly influenced by changes in precipitation and runoff. However, the average daily load shows visible differences between the four socio-economic scenarios in future. The amounts of daily NH_4-N loads vary from 7.8 - 10.5 kg N depending on the assumed changes.

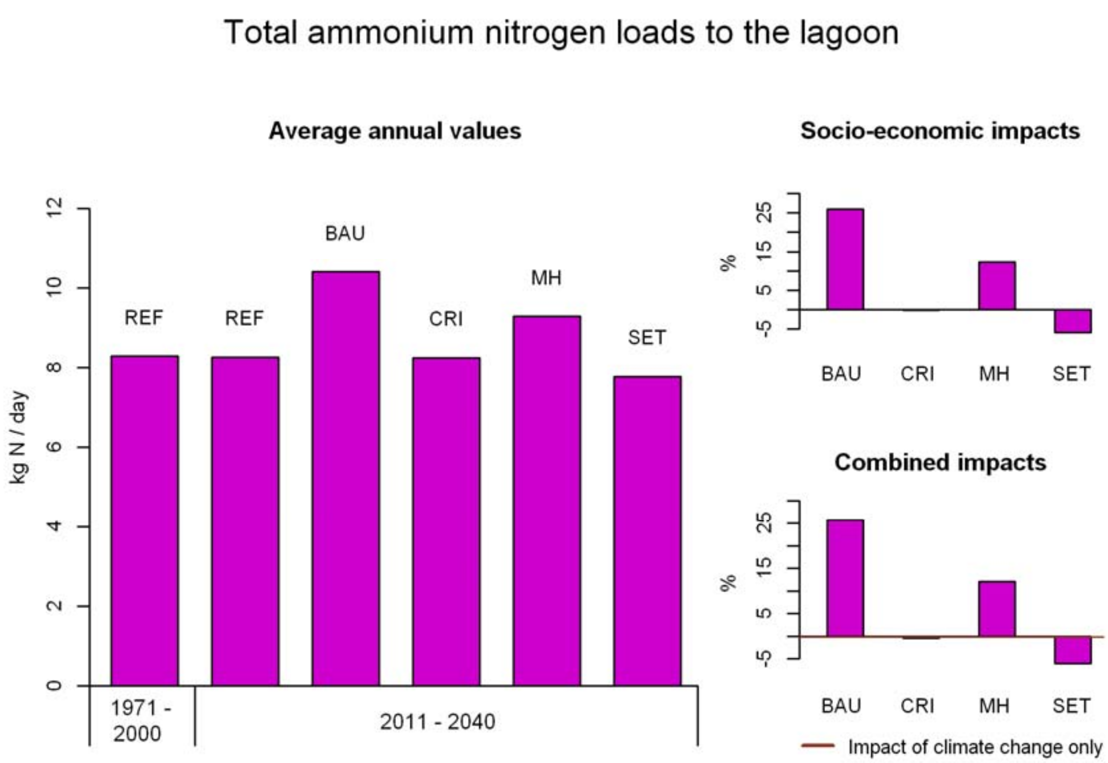


Figure 3.2.6: Impacts on total ammonium nitrogen (NH_4-N) input to the Mar Menor. Left: long-term mean annual loads [kg N/day] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on NH_4-N for each scenario.

Looking at the socio-economic impacts on the ammonium nitrogen load to the lagoon (upper right graph), we can see that the strongest increase (25%) is projected for the BAU scenario, in which point sources are increased by 24%. In the MH scenario, the assumed increase in point sources is higher (34%). However, in this scenario in addition to changes in point sources the mineral fertilization is reduced by 15%, so the total decrease in NH_4-N loads is about 13% only. For the remaining two scenarios (CRI and SET) the NH_4-N loads are projected to decrease, as both point sources and fertilization are reduced. The decrease under the SET scenario is visibly stronger, which again can be attributed to the performed land use changes in close proximity to the lagoon embankments. The reduction of agricultural land in exactly this area, which functions like a buffer strip for the water body, has a very strong effect on the nutrients transport to the lagoon.

The effect of climate change on the ammonium nitrogen load in this catchment is almost negligible, for the reason that this nutrient component originates mainly from point sources.

Phosphate phosphorus loads

The phosphate phosphorus loads in the Mar Menor catchment show nearly the same behavior as the NH_4-N loads. Figure 3.2.7 shows the impacts on total PO_4-P loads for the scenarios under study.

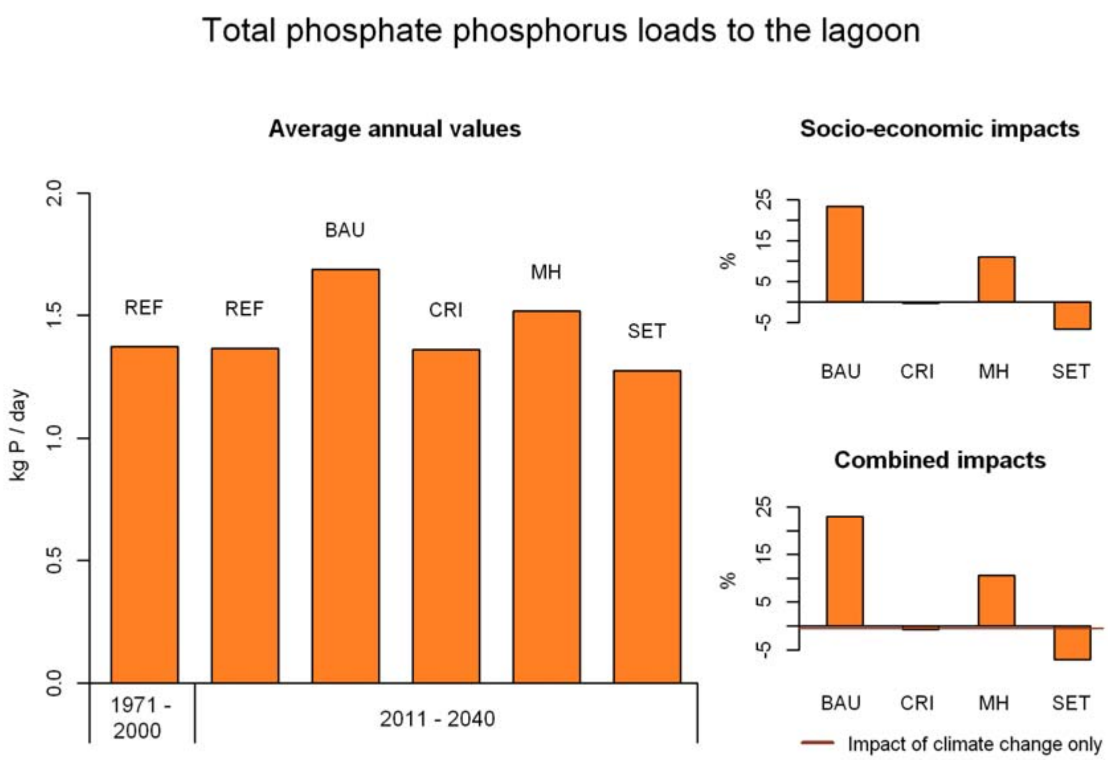


Figure 3.2.7: Impacts on total phosphate phosphorus (PO_4-P) input to the Mar Menor. Left: long-term mean annual loads [kg P/day] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on PO_4-P for each scenario.

The long-term average daily load to the Mar Menor under the reference climate and management conditions (REF, 1971-2000) is about 1.4 kg P and it is practically the same for the future scenario period (REF, 2011-2040).

Regarding the socio-economic impacts only, the phosphate phosphorus load increases for the two scenarios assuming an increase in point sources (BAU and MH), and decreases for the other two scenarios assuming a decrease in point sources (CRI and SET) (upper right graph). The amounts of the long-term average relative changes in PO_4-P loads are nearly the same as already observed for the NH_4-N loads (compare with upper right graph in Figure 3.2.6). The effect of climate change is also negligible.

3.2.3 Spatial changes

In this section maps of the Mar Menor catchment showing the long-term average annual changes in runoff (RUN), groundwater recharge (GWR) and actual evapotranspiration (ET_a) for each of the four socio-economic scenarios are presented (Figures 3.2.8 – 3.2.10). In addition, this section provides the long-term average annual changes in discharge (Q) and nutrient (NO_3-N, NH_4-N and PO_4-P) inputs for the individual streams flowing into the Mar Menor (Figure 3.2.11). For both, the maps and the river specific changes, the socio-economic impacts as well as the combined impacts are given. The resolution of the maps is at the hydrotope level (see LAGOOSN 2013, page 11). The runoff is defined as the sum of surface and subsurface flows in the catchment.

Runoff

The socio-economic impacts on runoff in the catchment of the Mar Menor (left column of maps in Figure 3.2.8) can be easily related to the applied land use changes for each of the four socio-economic scenarios (compare with Figure 3.3.2), and especially to the changes in irrigated area. The projected changes further depend on the soil type, and to some extent, on the terrain characteristics of the catchment.

For the BAU, CRI and SET scenarios the average annual runoff is projected to decrease by up to 30mm on areas of the former partly irrigated agricultural land that was converted to fallow or grassland in the scenarios. One of the main reasons is that the input of additional water to the system is reduced under the three socio-economic scenarios, and thus the generated runoff decreases. Furthermore, the absence of a complete and permanent vegetative soil cover on agricultural land allows more water to contribute to runoff, whereas the all year vegetation cover on fallow or grassland, with their higher annual evapotranspiration rates, leaves less water for runoff generation.

In the MH scenario, both the agricultural land and the irrigated area are increased by 5% each, leading to an increase in average annual runoff of up to 28 mm in the converted areas.

When climate change is added to these impacts the runoff decreases for all four scenarios (right column of maps in Figure 3.2.8) in most parts of the catchment, but equally strong over the whole area. In areas with extremely low to no runoff under the reference conditions (western part of the catchment) no changes visible. Furthermore, in the MH scenario, climate change

clearly compensates the increase in runoff in the middle part and leads to zero change in a narrow stripe surrounded by an area with the projected decreasing runoff.

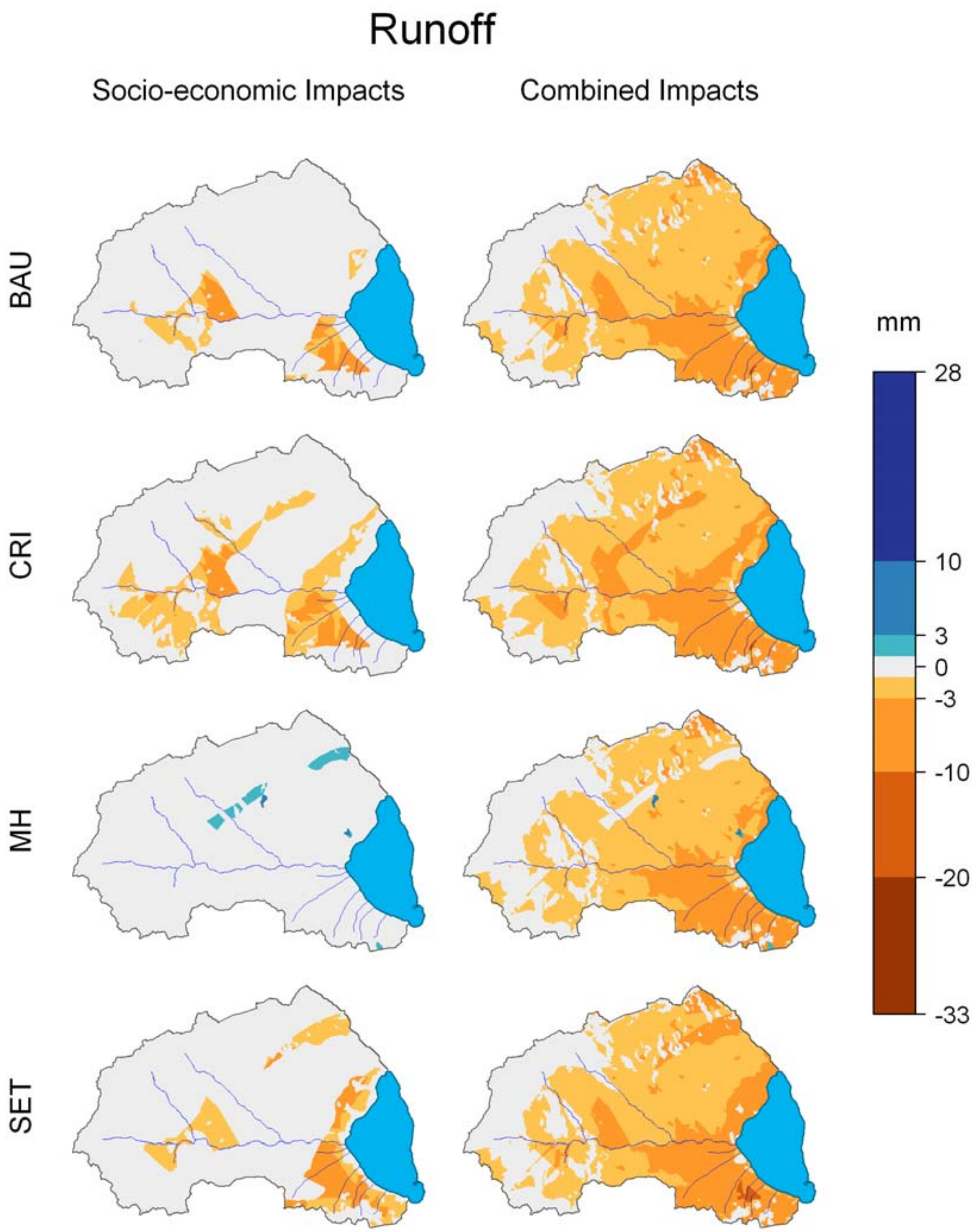


Figure 3.2.8: Maps showing long-term average annual spatial changes [mm] in runoff (RUN) for the Mar Menor catchment. Left: socio-economic impacts; Right: combined impacts.

Groundwater recharge

The projected changes in groundwater recharge in the catchment of the Mar Manor show a very similar behaviour as runoff. Similarly as for runoff, the impacts on groundwater recharge (left column of maps in Figure 3.2.9) can be related to the applied land use changes for each of the four scenarios (compare with Figure 3.3.2) and also to some extent to the soil types and terrain characteristics of the catchment.

In most cases the relative decrease in groundwater recharge is stronger than the decrease in runoff. The long-term average annual groundwater recharge rate decreases by up to 50 mm for the BAU, CRI and SET scenarios (left column of maps in Figure 3.2.9). Unlike the changes in the Ria de Aveiro catchment, groundwater recharge decreases also in areas where runoff decreases. This is because in both cases the reduction of irrigated area leads to a reduction of infiltrating water and thus to a reduction of water, which can become subsurface or groundwater flow.

In the MH scenario, groundwater recharge increases by up to 90 mm per year, due to the implanted land use changes.

The changes in climate visibly enhance the trends simulated for the BAU, CRI and SET scenarios in the Mar Menor lagoon catchment (right column of maps in Figure 3.2.9). In these three scenarios, groundwater recharge is projected to decrease by up to 123 mm, whereas the average annual decrease due to the socio-economic changes only was maximum 90 mm per year. The trends simulated for the MH scenario are weakened by climate change, and the projected changes reach an average increase in annual GWR of 20 mm only. Still, in contrary to the impacts on runoff, the impacts on groundwater recharge in the MH scenario are not fully compensated by climate change.

Actual evapotranspiration

The changes in actual evapotranspiration in the Mar Manor catchment are strongly interrelated with the changes in runoff and groundwater recharge. Therefore, the projected socio-economic impacts on actual evapotranspiration (left column of maps in Figure 3.2.10) can also be fully related to the assumed changes in land use (compare with Figure 2.3.3) and to some extent to the soil and terrain characteristics of the catchment.

Looking at the long-term average annual socio-economic impacts on actual evapotranspiration, we can observe that evapotranspiration is projected to decrease by up to 250-391 mm per year in areas that used to be irrigated under the reference conditions but do no longer receive additional water under the BAU, CRI and SET scenarios. In addition to that, in the SET scenario, the conversion of agricultural land into fallow outside the irrigation zone causes an increase in ET_a of about 50 mm. When averaged over the year, fallow has a higher transpiration rate compared to agricultural land, due to its permanent vegetation cover.

In the MH scenario, an increase in average annual evapotranspiration by about 360 mm can be observed on areas that were included to the irrigation zone, and on which under the scenario conditions additional water is added through irrigation.

Compared to the socio-economic impacts, the effect of climate change on actual evapotranspiration is rather small (right column of maps in Figure 3.2.10). A decrease in

average annual evapotranspiration of about 50mm per year is simulated for most areas in the catchment, those which are affected by land uses changes too.

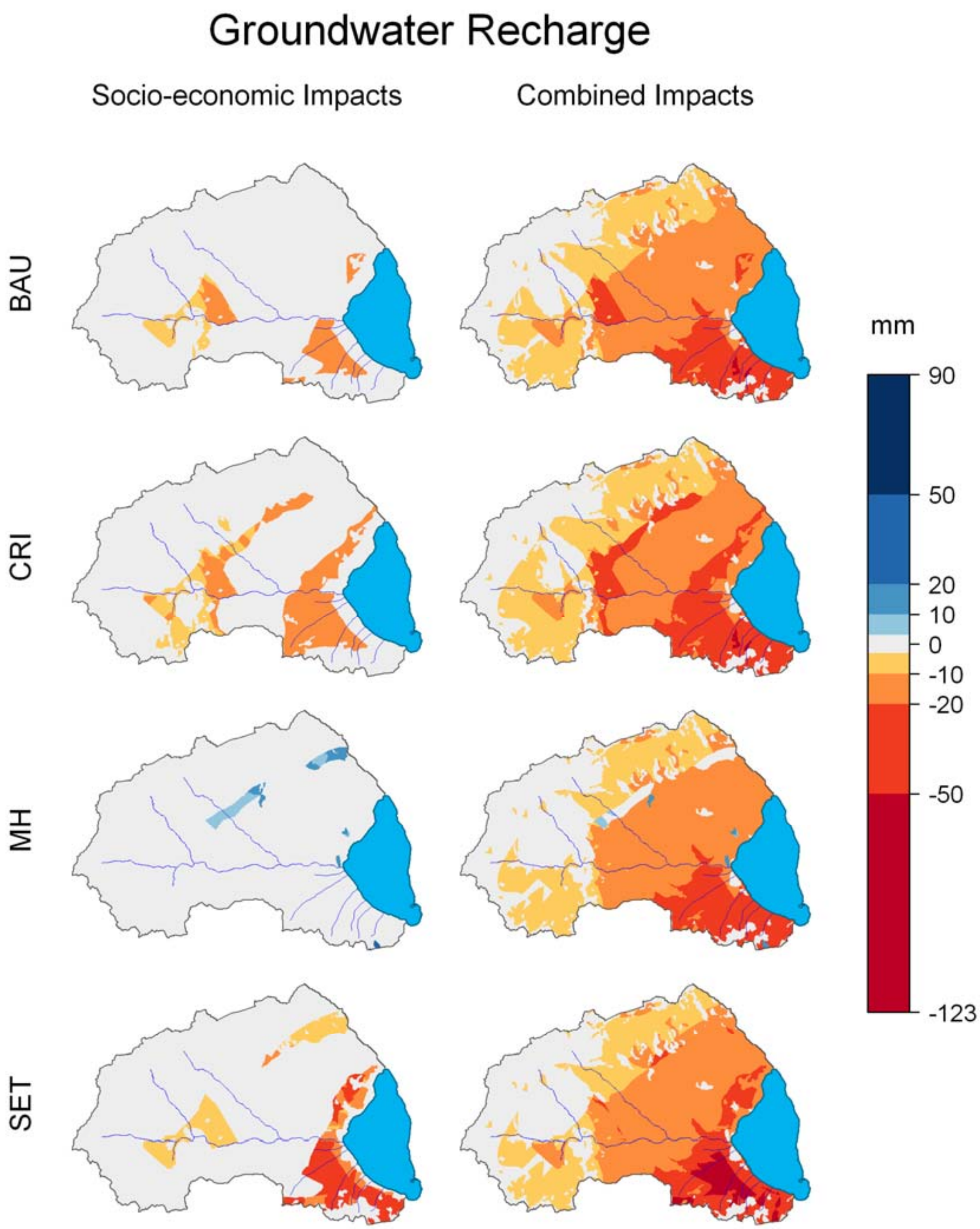


Figure 3.2.9: Maps showing long-term average annual spatial changes [mm] in groundwater recharge (GWR) for the Mar Menor catchment. Left: socio-economic impacts; Right: combined impacts.

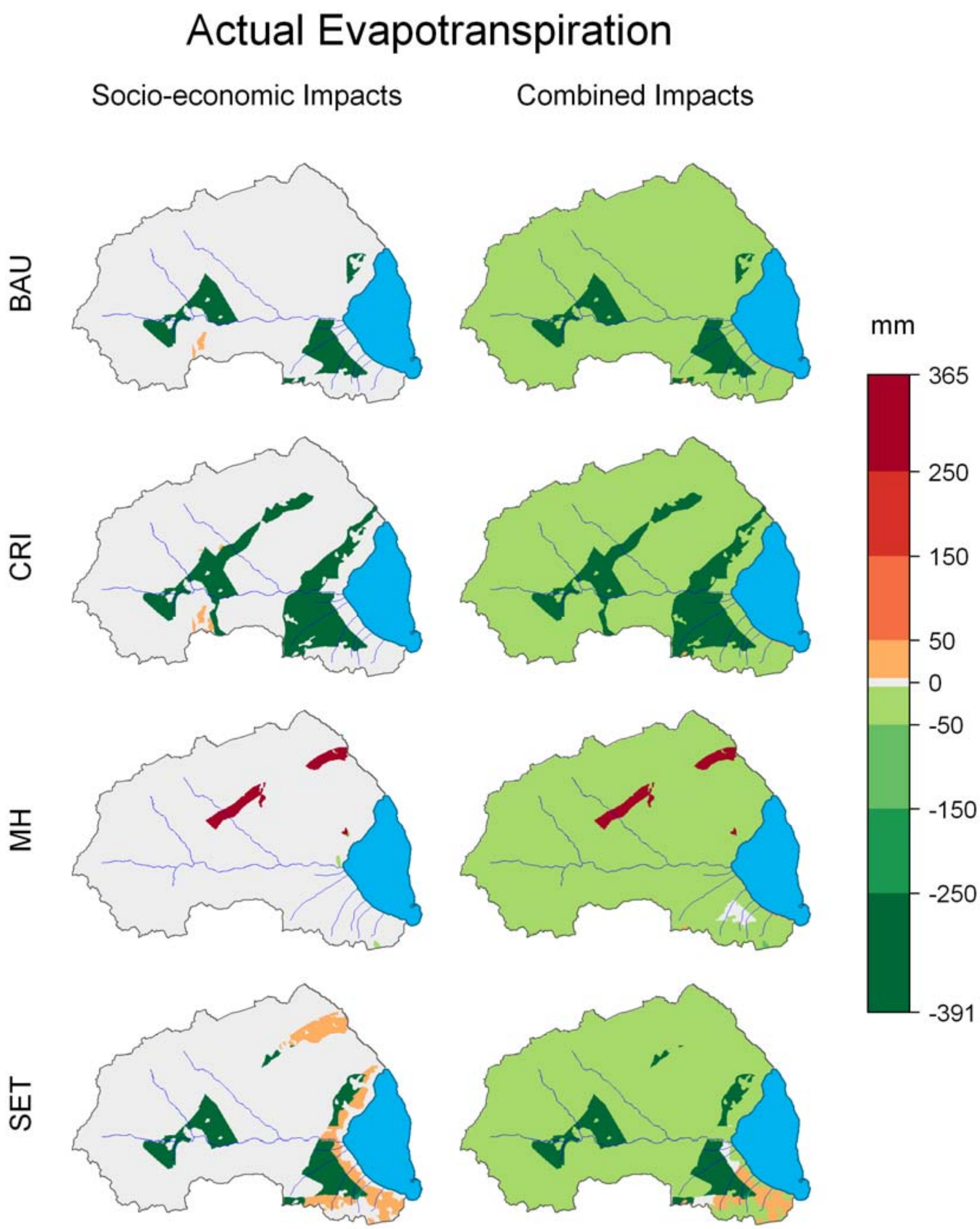


Figure 3.2.10: Maps showing long-term average annual spatial changes [mm] in actual evapotranspiration (ET_a) for the Mar Menor catchment. Left: socio-economic impacts; Right: combined impacts.

Impacts for individual rivers

The spatial changes in the catchment of the Mar Menor were evaluated also for the long-term average annual changes in discharge (Q) and nutrient inputs (NO_3-N, NH_4-N and PO_4-P) for the individual streams flowing into the lagoon (compare with LAGOONS, 2013, page 41, Figure 4.1.1,). The combined scenario impacts are shown as bars, and the socio-economic scenario impacts only – as circles in Figure 3.2.11.

The Albujon wadi is the only stream in the catchment having a permanent flow. It brings most of the freshwater and nutrient inputs to the lagoon, and therefore even though the simulated percental changes in Q, NO_3-N, NH_4-N and PO_4-P are rather small for the Albujon compared to those of the other wadis, its importance for the lagoon is much higher.

The average annual discharge of the Albujon wadi is nearly equally influenced by the combined and socio-economic changes for two scenarios causing a decrease in Q (CRI: 10% and SET: 17%), whereas in the BAU and MH scenarios, both causing an increase in Q (20% and 5%, respectively), the socio-economic impacts are slightly stronger.

In contrary to that, the discharge in all small streams decreases for all four scenarios under the combined climate and socio-economic changes. This is because these streams are not affected by changes in the effluent release from the WWTP but only by changes in land use. If to look at the socio-economic impacts only (circles), it is obvious that the changes, assumed for the MH scenario, have no impact on average annual discharge in any of these streams. This is because their implementation (changes in agricultural land and irrigated area) was solely in the catchment of the Albujon wadi. The land use changes, assumed for the other scenarios, were also partly implemented in the catchments of these small streams. The reduction of irrigated area and the conversion of agricultural land into fallow in areas close to the lagoon under the SET scenario took place mainly in the catchments of these streams. Therefore the impacts on runoff for the SET scenario are significant in most of the small streams.

A similar difference in impacts between the Albujon wadi and the other inflowing streams can be observed for the NH_4-N and PO_4-P loads, too. While the Albujon wadi is impacted by both, changes in diffuse sources and point sources, the other streams are influenced by changes in land use and applied fertilizers only. The contribution of point sources to the NH_4-N and PO_4-P loads in the catchment of the Albujon wadi is extremely high. Therefore, the assumed changes in the effluent quantity and quality strongly affect the total NH_4-N and PO_4-P loads of this river. Besides, no differences between the combined and the socio-economic impacts are visible. On the contrary, we can observe that for the other small streams in most cases the combined impacts are stronger. This is because climate plays a more important role in their catchments, and has a considerably high impact on runoff and thus on diffuse pollution.

In the case of the average annual NO_3-N loads, we can observe a more homogeneous picture among scenarios and streams. It can be noted, that this nutrient component is influenced equally strong in all catchments mainly by diffuse pollution. Therefore all streams show decreasing trends for the combined impacts and all four scenarios. This observation is a result of the projected decreasing precipitation and consequently runoff in the Mar Menor catchment in future. The SET scenario again looks outstanding, and shows the strongest decrease in average annual loads, especially for the non-permanent flowing streams. The size of the

converted areas within their catchments under the SET scenario is the biggest among all scenarios and hence the impacts of these land use changes are the largest.

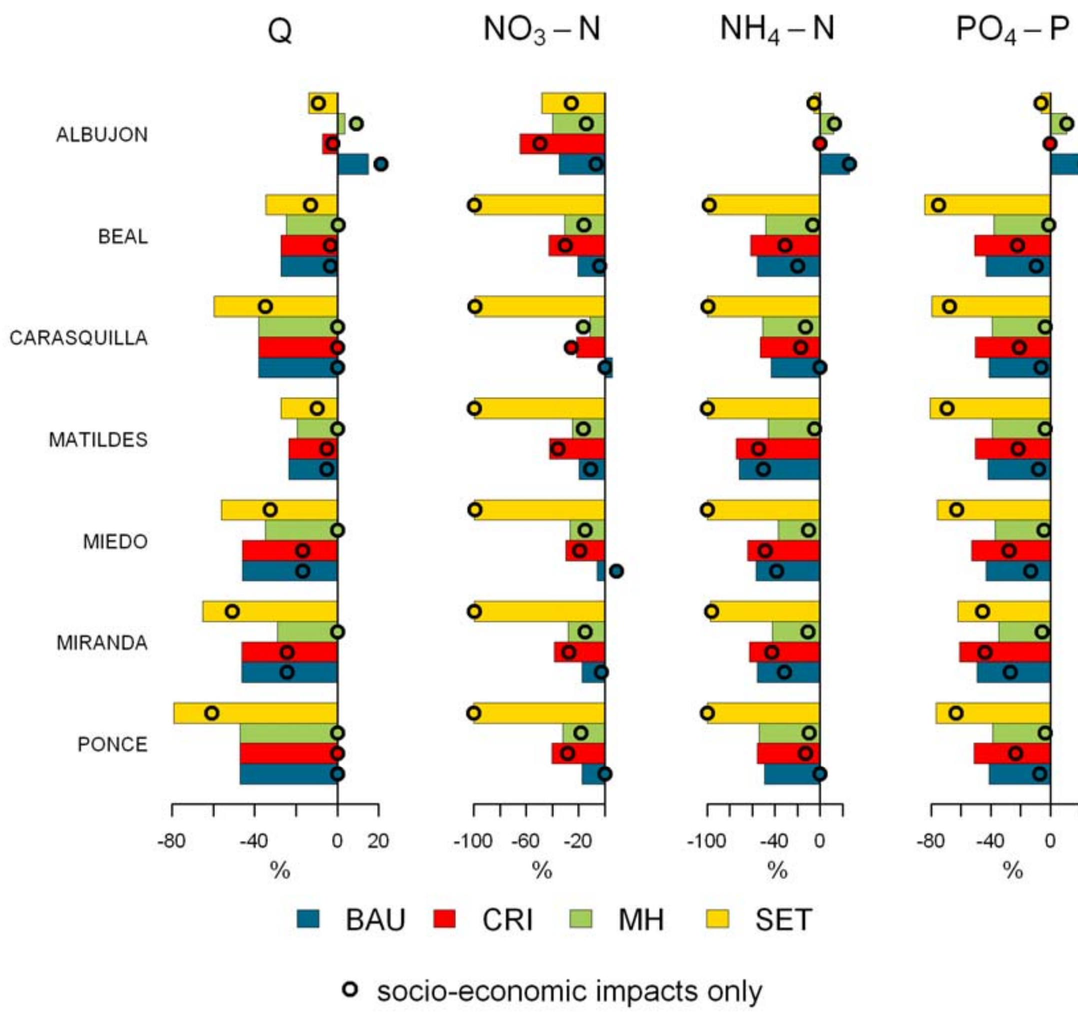


Figure 3.2.11: Relative changes [%] in long-term mean annual discharge (Q) and nutrient loads (NO_3-N, NH_4-N and PO_4-P) showing the combined (bars) and socio-economic (circles) impacts for individual tributaries of the Mar Menor.

3.2.4 Summary

In summary, it can be concluded that due to the fact that the Mar Menor catchment is highly managed the socio-economic changes (land use and management) have a nearly equal and partly even stronger impact on the analyzed variables as climate change (see Figure 3.2.12). In some cases, the socio-economic impacts can be opposite to the combined impacts. Also, the socio-economic impacts might be so strong that in some cases the direction of trend is hardly changing when climate change is added. The assumed changes, regarding population and tourism in the BAU scenario for example, cause an increase in total inflow of 12%, whereas the combined impacts show a decrease of 3% only.

In general, it can be stated that the long-term average annual total inflow and nitrate nitrogen loads to the lagoon as well groundwater recharge and actual evapotranspiration rates in the catchment are all projected to decrease (Figure 3.2.12) for each of the four combined socio-economic scenarios, and GWR and NO_3-N show the strongest impacts (up to -78%). Whereas, the combined impacts on ammonium nitrogen and phosphate phosphorus loads to the lagoons show different changes for the four scenarios, depending on the applied socio-economic changes, as these two nutrient components originate mainly from point sources, which are not affected by climate change.

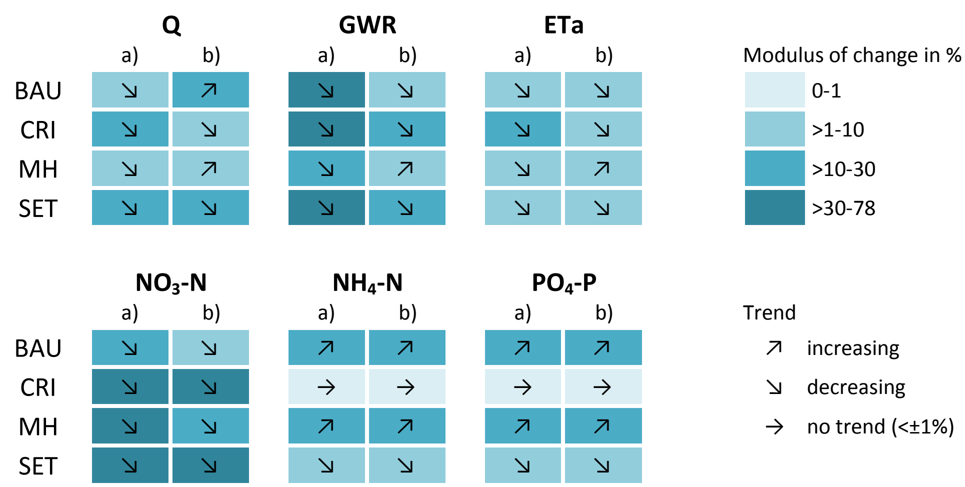


Figure 3.2.12: Summary of trends for analysed parameters (discharge - Q, groundwater recharge - GWR, actual evapotranspiration - ET_a, nitrate nitrogen - NO_3-N, ammonium nitrogen - NH_4-N, phosphate phosphorus - PO_4-P) in the Mar Menor catchment caused by potential future changes: (a) – combined impacts, (b) – socio-economic impacts.

3.3 Catchment of the Tyligulskyi Liman

3.3.1 Water quantity – annual and monthly changes

Total inflow to the lagoon

The simulated average total inflow of fresh water to the Tyligulskyi Liman is 3.8 m^3/s for the reference conditions driven by the s10 scenario, but it is estimated to drastically decrease under the selected climate scenario in the future period p1 (Figure 3.3.1). All reference and socio-economic scenarios simulated for the period 2011-2040 show an obvious decrease in total inflow to the lagoon compared to the reference period 1971-2000 by more than 60% (left graph). This is mainly due to climate impact with higher temperatures (+1.1°C) leading to higher evapotranspiration, and notably lower precipitation (-8.7%) in this selected climate scenario (compare section 2.2.2). Looking at the socio-economic impacts only (upper right graph) we can see that the four management scenarios show smaller changes in an opposite direction, and cause an increase of the total inflow to the lagoon up to +7% for the SET scenario. These increasing trends mainly result from the assumed changes in water management practices for the four scenarios. Both the abstraction of groundwater (irretrievable use) and the installation of ponds within the river network have remarkable influences on the discharge of the inflowing rivers. Changes in water management and less significant human impacts and water consumption, as assumed for the different socio-economic scenarios (compare Table 2.4), lead to higher water availability within the catchment, but cannot compensate the intense impacts of the projected climate changes on water resources (lower right graph).

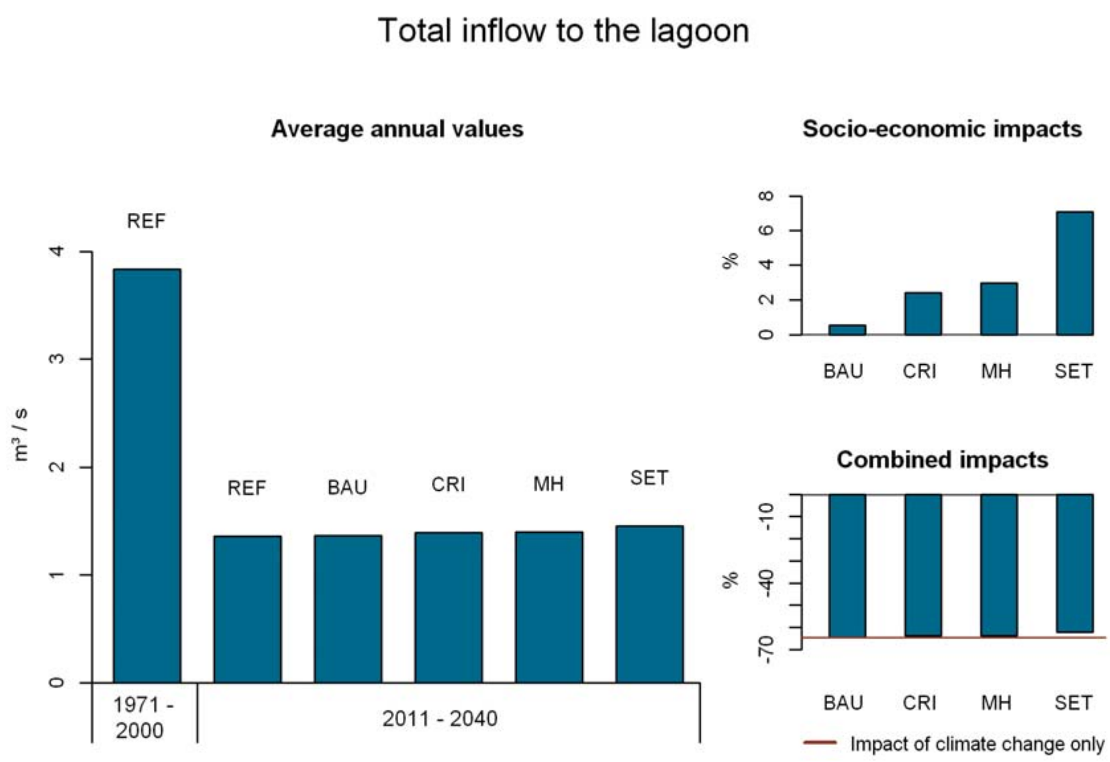


Figure 3.3.1: Impacts on total inflow (Q) to the Tyligulskyi Liman. Left: long-term mean annual discharges [m^3/s] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on Q for each scenario.

Groundwater recharge

Figure 3.3.2 shows the average absolute annual values of groundwater recharge in the Tyligulskyi Liman catchment for the reference climate (1971-2000) and management conditions (REF) as well as under future climate (2011-2040) and the same and different socio-economic assumptions (left graph). Similarly as we have already seen for the total discharge to the lagoon, a significant climate impact on groundwater recharge is obvious for the future period p1 (relative change is about -60%), which is becoming even higher under the MH and SET scenarios (lower right graph). The highest impact of management changes on GWR can be observed for the SET scenario (-16%), whereas changes in the MH scenario are about -6% (upper right graph). Changes in groundwater recharge due to socio-economic impacts mainly result from changes in land use patterns and vegetation cover within the catchment, and especially within the conservation corridor with natural vegetation assumed around the Tyligul River. For the MH scenario a slight increase in the forest areas (+10%) as well as a conversion of agricultural land to grassland around the river are assumed, which lead to lower groundwater recharge due to higher evapotranspiration rates in those areas. This effect is strengthened under the SET scenario, where an increase of forested areas by +40% is assumed, and the buffer zone around the river is converted to fallow. It was already mentioned by Kim and Jackson (2012) that agricultural fields have the highest groundwater recharge rate compared to other vegetation covers and land use classes. Therefore, each conversion of such areas to other land use classes results in lower GWR rates.

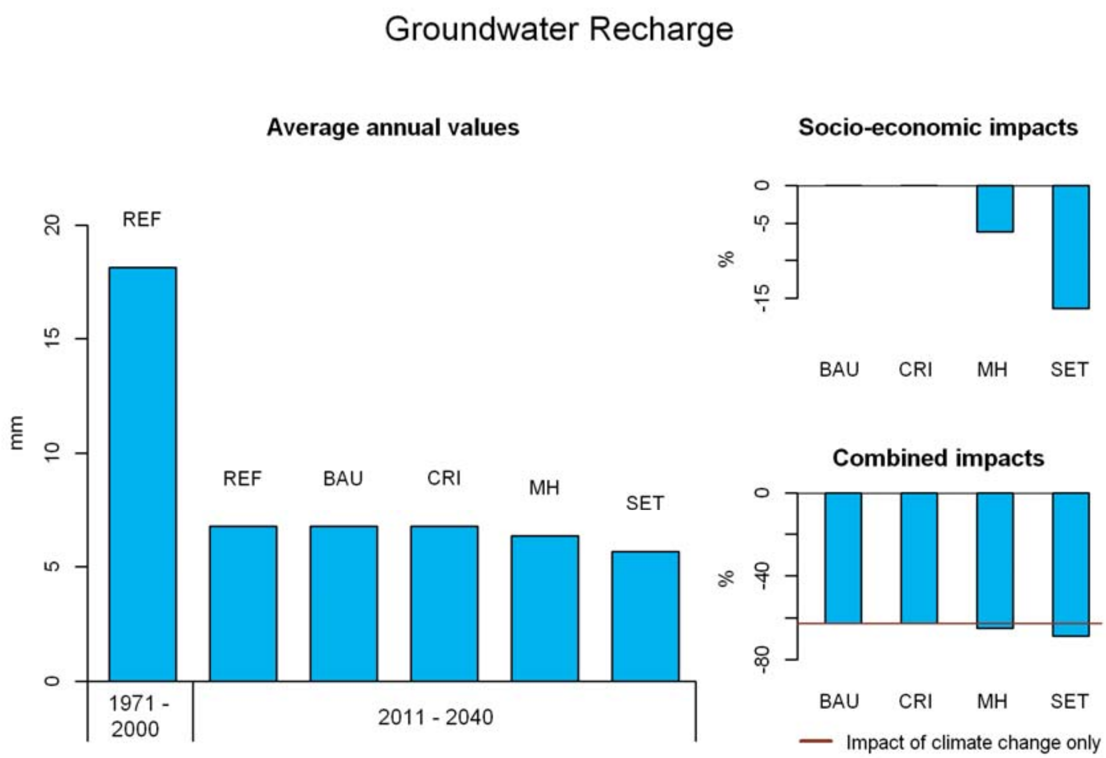


Figure 3.3.2: Impacts on groundwater recharge (GWR) in the Tyligulskyi Liman catchment. Left: long-term mean annual recharge rates [mm] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on GWR for each scenario.

Actual evapotranspiration

Potential impacts of climate and land use changes on actual evapotranspiration in the Tyligulskyi Liman catchment are shown in Figure 3.3.3. Under the reference climate (1971-2000) and socio-economic conditions (REF) the average annual actual evapotranspiration is 488 mm, which is reduced to about 470 mm per year for all management scenarios in the future period 2011-2040 driven by s10 climate scenario (left graph). This is mainly due to lower precipitation and resulting lower water availability in the catchment. The socio-economic impacts only are quite low and do not exceed relative changes by 1% (upper right graph). They are generated solely by changes in land use composition, which were not assumed for the BAU scenario. A slight relative decrease (-0.02%) of ET_a for the CRI conditions is due to deforestation on a half of the forested areas in the Tyligulskyi Liman catchment, accompanied by a conversion of these parts to fallow with usually lower leaf area index and transpiration rates. Higher changes, but in the opposite direction, can be detected for the MH (+0.3%) and SET (+0.6%) scenarios, where cropland is reduced by 10% and 20%, respectively, and the forested areas are assumed to extend by 10% and 40%, respectively. The remaining former cropland areas are converted to grassland or fallow. All these changes result in higher ET_a rates than under the reference socio-economic conditions. Due to the quite high absolute values of annual Et_a, the relative changes do not exceed 4%, even for the combined impacts.

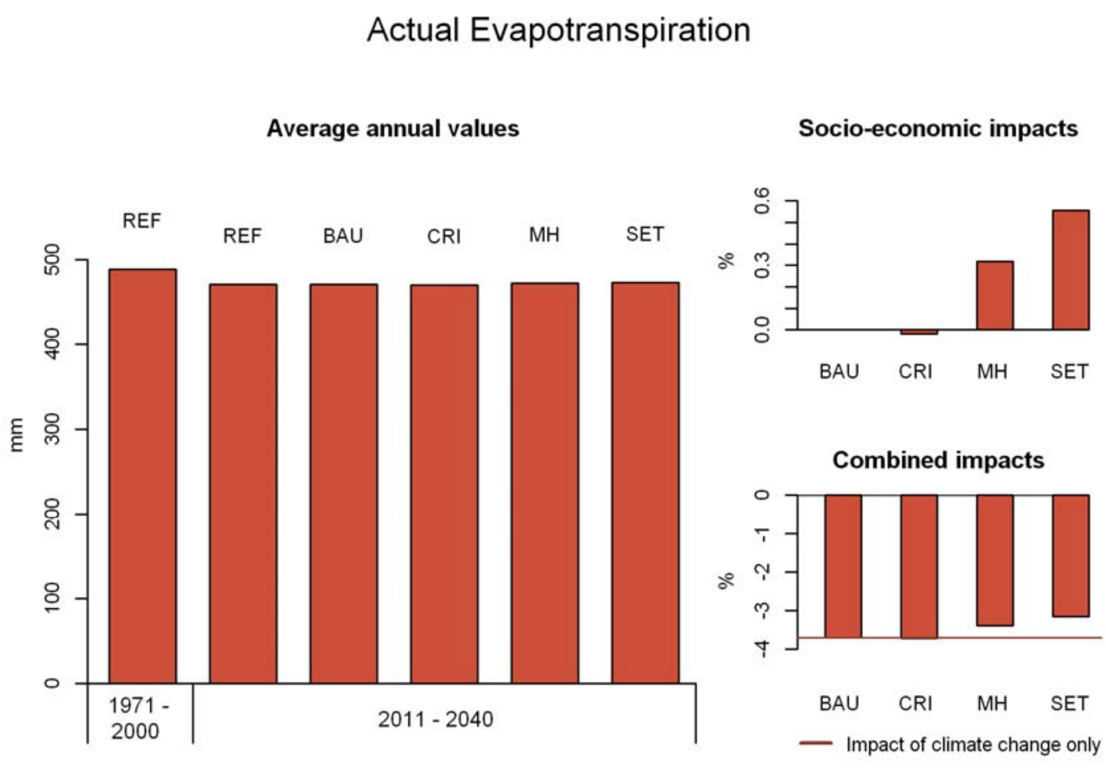


Figure 3.3.3: Impacts on actual evapotranspiration (ET_a) in the Tyligulskyi Liman catchment. Left: long-term mean annual evapotranspiration rates [mm] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on ET_a for each scenario.

Average monthly changes in discharge, groundwater recharge and evapotranspiration

Figure 3.3.4 shows the relative seasonal changes of water flow components discussed above for the Tyligulskyi Liman catchment as long-term average values. Looking at the total inflow to the lagoon (upper left graph) we can see that the direction of changes caused by the combined and socio-economic scenarios is the same as for the average annual values, but with some spread within the year. While the average combined impact on river discharge (solid lines) was projected to be about -65% resulting from lower precipitation and higher temperatures (Figure 3.3.1), the monthly changes vary between -30 and -80%, with minimal changes in February and July, and the highest relative changes in April (missing snow melt peak) and in September until November (lower precipitation). The positive trends for water inflow to the Tyligulskyi Liman caused by changes in water management practices (dashed lines) have the highest influence in June and during winter months, especially for the SET scenario, where the uninstallation of ponds (-75%) and decrease in water abstraction (-15%) are most effective, and lead to up to +21% increase of the total inflow to the lagoon in June.

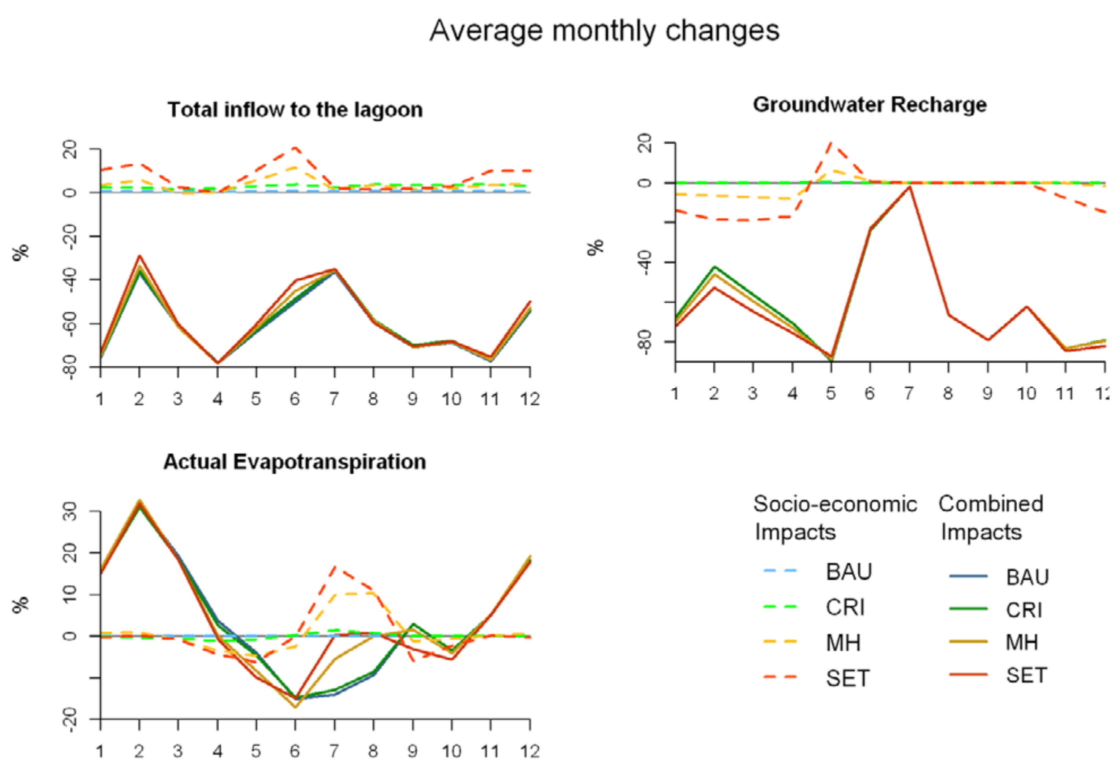


Figure 3.3.4: Long-term mean monthly relative changes [%] of Q, GWR and ET_a in the Tyligulskyi Liman catchment showing the socio-economic impacts (dashed lines) and the combined impacts (solid lines) for each scenario.

The projected average monthly changes in groundwater recharge due to the combined impacts of climate and socio-economic scenarios for the Tyligulskyi Liman catchment are the highest in winter months and reduced to ±0% in July (upper right graph of Figure 3.3.4). The socio-economic impacts on GWR can be seen only for the MH and SET scenarios in winter and spring

time and vary between -19% in March and +20% in May due to the monthly availability of water as well as usual seasonal variations in vegetation cover and leaf area index.

Seasonal changes of actual evapotranspiration in the Tyligulskyi Liman catchment caused by climate and/or management changes have the most diverse patterns (lower graph in Figure 3.3.4). Although only small average changes of about -3.5% were projected for the combined impacts (Figure 3.3.3), the monthly changes (solid lines in Figure 3.3.4) range from -17% up to +33%. The absolute average monthly changes vary between -17 mm and +4 mm per month. As actual evapotranspiration is generally low in the colder winter months with reduced leaf area index and vegetation cover, already small absolute changes (in mm) result in quite high relative changes (in %), whereas higher absolute decrease of ET_a in summer months means lower relative changes. The decrease of actual evapotranspiration in summer months due to climate changes can be partly compensated by changes in land use patterns as assumed for the SET and MH scenarios, which cause an increase in ET_a by up to 17% in July. In general, changes in evapotranspiration induced by altered land use composition can be observed only during the vegetation period from April to October when the water transpiration processes are most intensive.

3.3.2 Water quality – annual changes

The incoming nutrient loads to a lagoon are highly connected to the volume and availability of inflowing river waters. Therefore, it is not surprising that the combined impacts on average annual loads of nitrate nitrogen, ammonium nitrogen and phosphate phosphorus under the reference and future climate conditions (Figures 3.3.5 - 3.3.7) show the same behaviour as the combined impacts on the total discharge to the Tyligulskyi Liman described above (Figure 3.3.1). The main river Tyligul, as well as other smaller rivers draining to the lagoon, is characterized by long and recurrent periods with low flow or even fully dry conditions in summer. The occurrence of such periods is intensified by the projected climate change with higher temperatures and lower precipitation. The fully missing discharge to the Tyligulskyi Liman consequently means the missing nutrient inputs as well.

However, the influence of socio-economic scenarios only, without considering climate change, shows another picture compared to their effects on total discharge to the lagoon. This can be mainly explained by changes in point and diffuse nutrient sources assumed for the different management scenarios. The socio-economic and combined impacts on nutrient loads coming to the Tyligulskyi Liman are presented in detail in the following subsections.

Nitrate nitrogen loads

The left graph in Figure 3.3.5 shows the average daily total sum of nitrate nitrogen loads entering the lagoon by the inflowing rivers. Driven by the reference climate (1971-2000) and reference management conditions, the total load to the lagoon accounts for 31 kg/day. This load is reduced by more than 50% due to climate change only (right lower graph). On the one hand, this is caused by lower precipitation and higher temperatures, which diminish the volume of inflowing waters, and, consequently, the according NO_3-N load to the lagoon. On the other hand,

the reduced precipitation available for leaching through soil profile diminishes nutrient leaching through soils, and ultimately the diffuse pollution from agricultural fields.

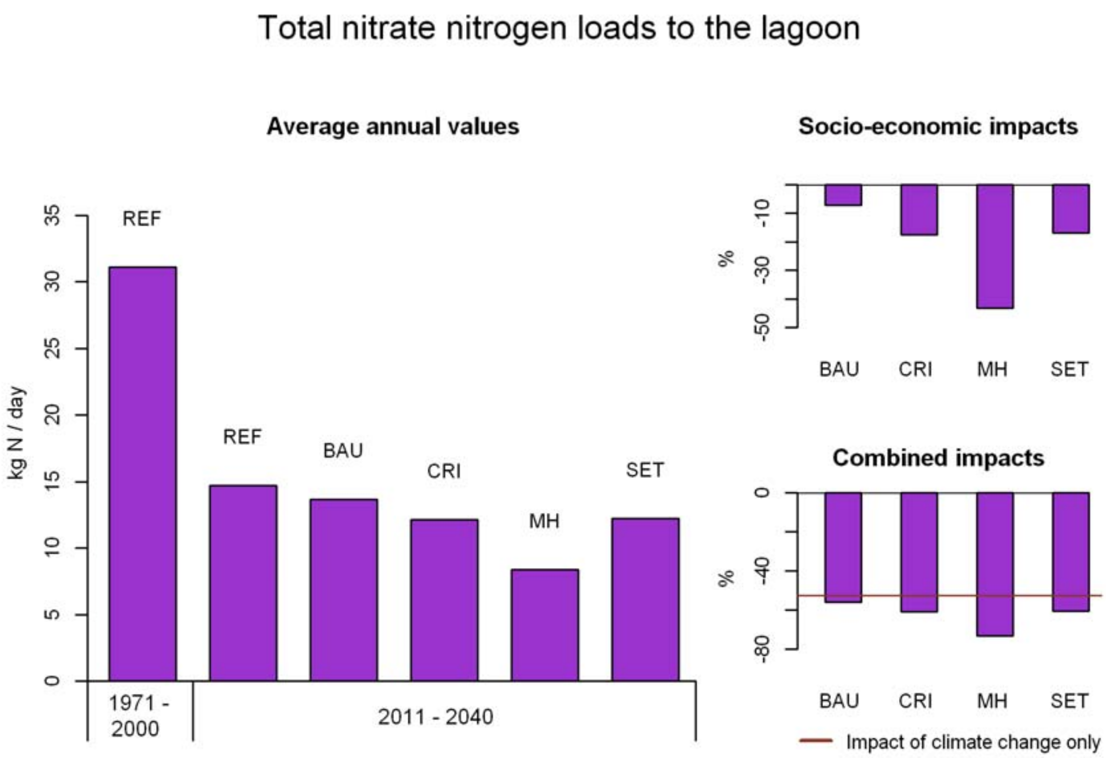


Figure 3.3.5: Impacts on total nitrate nitrogen (NO_3-N) input to the Tyligulskyi Liman. Left: long-term mean annual loads [kg N/day] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on NO_3-N for each scenario.

The decreasing trend due to climate change impacts is intensified by the assumed socio-economic changes, which act in the same direction (right upper and lower graphs). The highest NO_3-N reduction (-43%) is achieved in the MH scenario due to reduction of point source pollution by 50%. Although the assumed mineral fertilization in the MH scenario is five times higher than under the reference conditions, the applied fertilizer amounts are still low and cannot notably increase diffuse pollution from agricultural areas (according to Deliverable 5.1 (LAGOONS, 2013) mineral nitrogen fertilizers applied under reference conditions amounts to 11 kg N /(ha*year)). In general, it seems that the reduction of point source pollution is the most important measure for the decrease of nitrate nitrogen loads coming to the river in this case study area. The relative socio-economic impacts on NO_3-N loads (-7% in BAU, -18% in CRI, -43% in MH and -17% in SET, respectively) reflect the assumed percental changes in the total volume of point source effluents (-8%, -20%, -50% and -35%, respectively), except for the SET scenario. In this scenario an increase of total water inflow to the lagoon is expected, to be caused by extensive reduction of total pond volume in the catchment. The increased amount of inflowing water (accompanied by nutrient flows) partly compensates the assumed quite high decrease of point source pollution (-35%), and finally results in a decrease of NO_3-N by 17% only.

Ammonium nitrogen loads

The total ammonium nitrogen loads coming to the Tyligulskyi Liman behave similar to the nitrate nitrogen loads in this catchment and show almost the same percental changes as NO_3-N (right graphs in Figure 3.3.6). Under the reference conditions (REF) and the reference climate (1971-2000) the average daily NH_4-N loads entering the lagoon are 12.8 kg/day. They are projected to decrease drastically under the future climate conditions (2011-2040) to about 3-6 kg/day depending on the management assumptions (left graph in Figure 3.3.6). This reduction in NH_4-N load is mainly due to the decreasing runoff and discharge reaching the Liman. Additionally, it could be affected by lower amounts of NH_4-N leaching from soils due to reduced precipitation (-8.7%), as well as by enhanced nitrification processes (oxidation of ammonium to nitrite and nitrate) in warmer (+1.1°C) and dryer soil conditions as expected for the near future. But this relationship cannot be investigated when simply looking at the total NH_4-N loads finally reaching the lagoon, as the routed water and loads are affected by impacts of pond management and temporary drying-up of the rivers.

Analysing the socio-economic impacts only (upper right graph) it is obvious that the percental changes of NH_4-N induced by socio-economic impacts correspond to those of NO_3-N, and can be explained by the effects of lower amount of pollution from point sources (BAU, CRI, MH), partly overlaid by the influence of decreasing pond volume and resulting increase of discharge (SET).

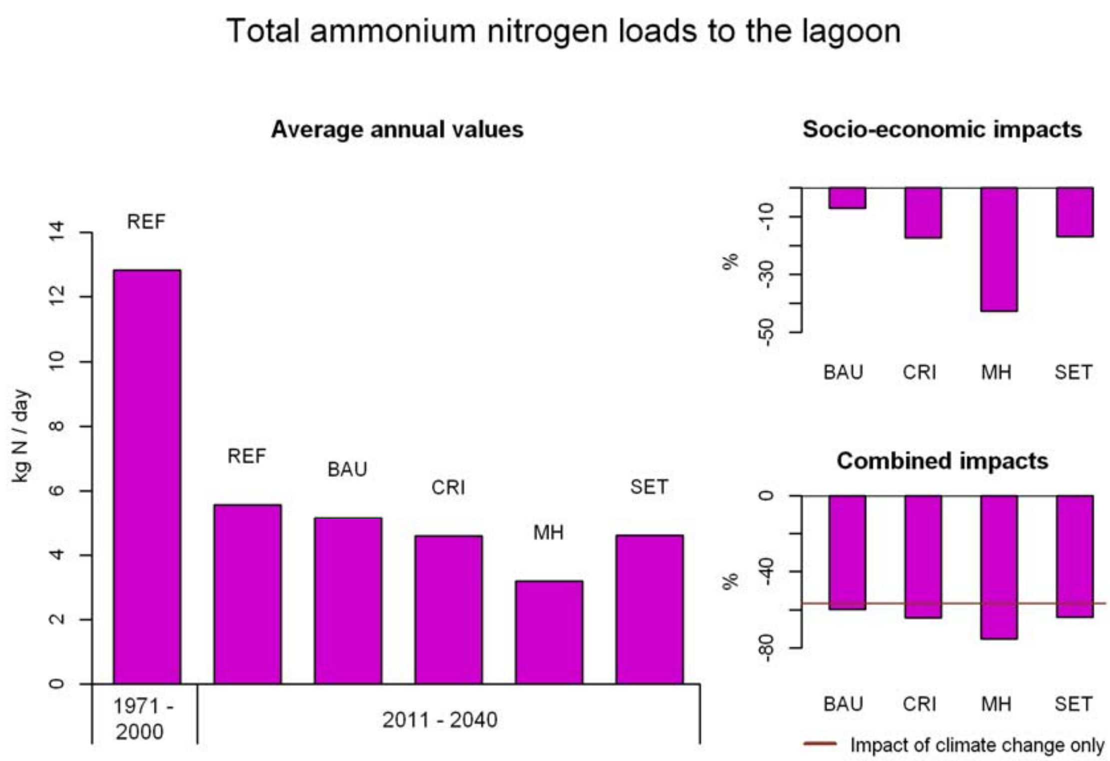


Figure 3.3.6: Impacts on total ammonium nitrogen (NH_4-N) input to the Tyligulskyi Liman. Left: long-term mean annual loads [kg N/day] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on NH_4-N for each scenario.

Phosphate phosphorus loads

Figure 3.3.7 shows in its left graph the average daily total sum of phosphate phosphorous loads entering the Tyligulskyi Liman, simulated driven by assumed reference and scenario climate and management conditions. Under the reference conditions (REF) and reference climate (1971-2000) the average daily PO_4-P load entering the lagoon is 21.4 kg/day. It is projected to be reduced by more than 60% in the period 2011-2040 due to climate change impact only (right lower graph). The decline is mainly caused by the reduction of water discharge carrying lower amounts of PO_4-P loads in future periods compared to the reference period, and could be strengthened by reduced erosion and leaching processes under decreased precipitation.

This reducing effect is intensified by the impacts of the four socio-economic scenarios applied in this study, similar to NO_3-N and NH_4-N. The reduction is highest for the MH scenario, lower for the CRI and SET scenarios, and the lowest for the BAU scenario (upper right graph). This is mainly due to the reduction of point source pollution overlaid by pond management measures. An increase in fertilizer application as assumed for the MH (five times higher than in the reference conditions) and SET (two times higher) scenarios seems to be not very serious in view of diffuse nutrient sources, as the original mineral phosphorus amounts applied for the reference conditions are only 3 kg P /ha.

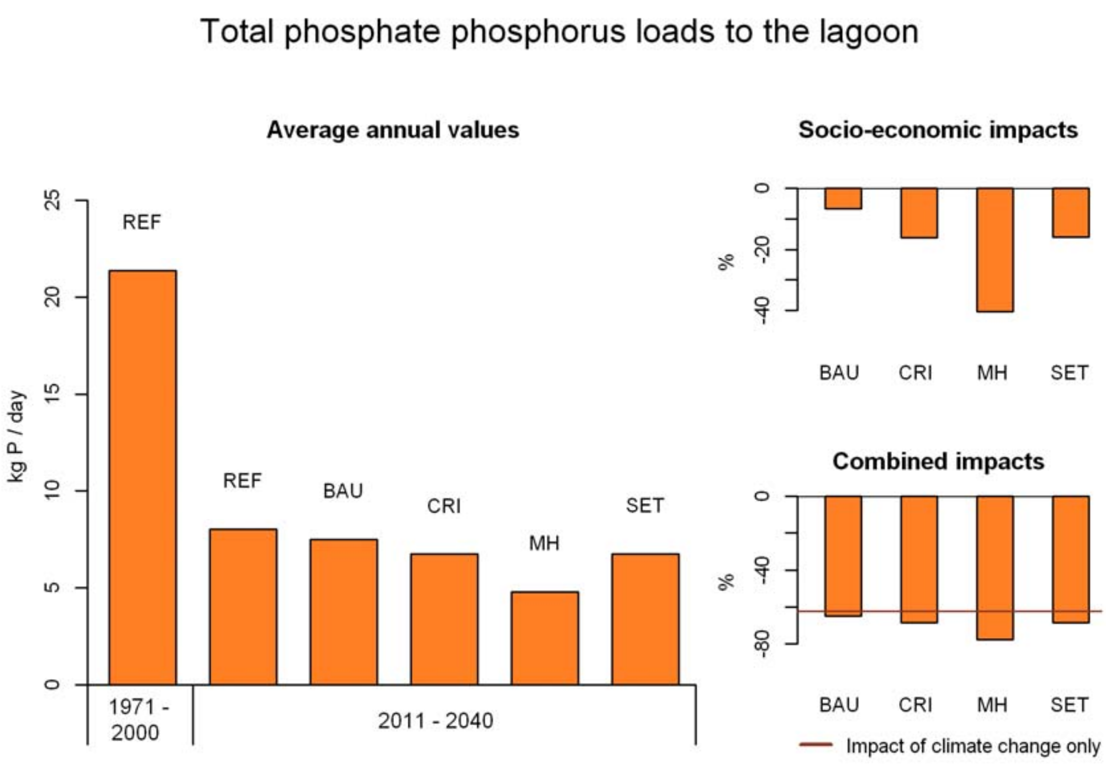


Figure 3.3.7: Impacts on total phosphate phosphorus (PO_4-P) input to the Tyligulskyi Liman. Left: long-term mean annual loads [kg P/day] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on PO_4-P for each scenario.

3.3.3 Spatial changes

In addition to the analysis of changes in total inputs coming from the draining rivers to the Tyligulskyi Liman caused by assumed future scenarios, a spatial analysis of changes was performed as well, which is presented below. This section includes maps of the Tyligulskyi Liman catchment showing long-term average changes in surface and subsurface runoff (RUN), groundwater recharge (GWR) and actual evapotranspiration (ET_a) for each of the four socio-economic scenarios. For every variable, the single socio-economic impacts as well as the combined climate change and socio-economic impacts are presented on maps based on the hydrotope-level resolution. The effects of the socio-economic changes only are obvious for areas with an assumed altered land use and vegetation cover, whereas the combined impacts cause changes over the whole catchment. The impacts of changing climate can diminish or strengthen the impacts of land use change only. At the end of this section a graph is added showing the long-term average annual changes of Q, NO_3-N, NH_4-N and PO_4-P inputs to the Tyliguslkyi Liman analyzed for the single rivers entering this water body.

Figure 3.3.8 shows spatial changes in surface and subsurface water flow in mm/y for the future period 2011-2040 compared to the reference period 1971-2000 driven by climate scenario s10. Two next Figures 3.3.9 and 3.3.10 depict spatial changes in groundwater recharge and actual evapotranspiration between the same scenarios. For both periods the simulated outputs were averaged over the whole 30 year period and mapped.

BAU scenario

As for the BAU scenario no changes were assumed in land use pattern, no socio-economic impacts on Q, GWR and ET_a can be detected on the left maps in the three figures. The combined impacts are depicted on the right maps showing the single climate change impacts. Due to higher temperature and decreased precipitation the runoff is decreasing in all hydrotopes of the catchment, but with different intensities, influenced by characteristics of soil types and vegetation cover in the catchment as well as by natural variations in temperature regime and precipitation distribution. It is visible that in the northern part, with normally higher precipitation level and higher share of forests, the reduction in runoff is smaller than in the dryer southern areas around the Tyligulskyi Liman and near the river.

Looking at the climate change impacts on groundwater recharge (Figure 3.3.9, BAU scenario, right), we can see that a decrease in GWR is projected for the future period. The highest changes are visible in the northern part of the catchment. They are weaker in the middle course of the Tyligul River, and show some increase again around the Tyligulskyi Liman.

The highest negative changes in ET_a under the changing climate as projected by s10 climate scenario (Figure 3.3.10, BAU scenario, right) can be observed in the northern part of the catchment due to reduction of available water for evapotranspiration. In contrast, evaporation from water bodies increases due to higher temperatures.

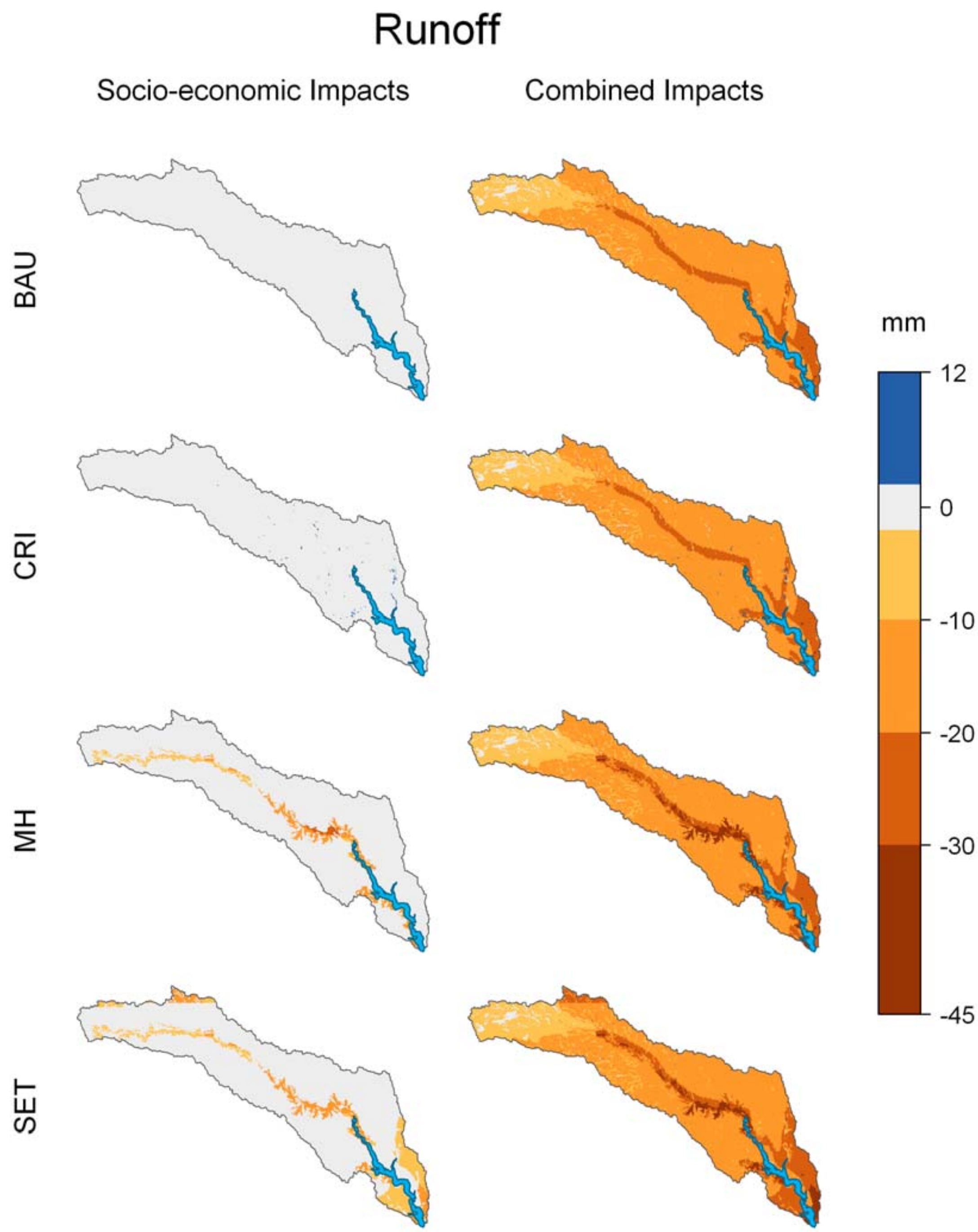


Figure 3.3.8: Maps showing long-term average annual spatial changes [mm] in surface and subsurface runoff (RUN) for the Tyligulskyi Liman catchment. Left: socio-economic impacts; Right: combined impacts.

CRI scenario

In the CRI scenario a deforestation is assumed, and 50% of all forested areas (3.6% of the total catchment area) in the drainage basin are converted to fallow. These areas react with some increase in surface and subsurface runoff (max. +12 mm/year), which can even reverse the solely climate change impact in these areas, a negligible increase in GWR (≤1 mm/year), and a

decrease in evapotranspiration (max. -16 mm/year) for the single socio-economic impacts (Figures 3.3.8 – 3.3.10, CRI left). The converted former forested areas in this scenario with the lower leaf area index cause reduced transpiration rates, and hence more water is available for runoff to the river network. Only a very small and negligible portion of this additional available water goes to the groundwater pool.

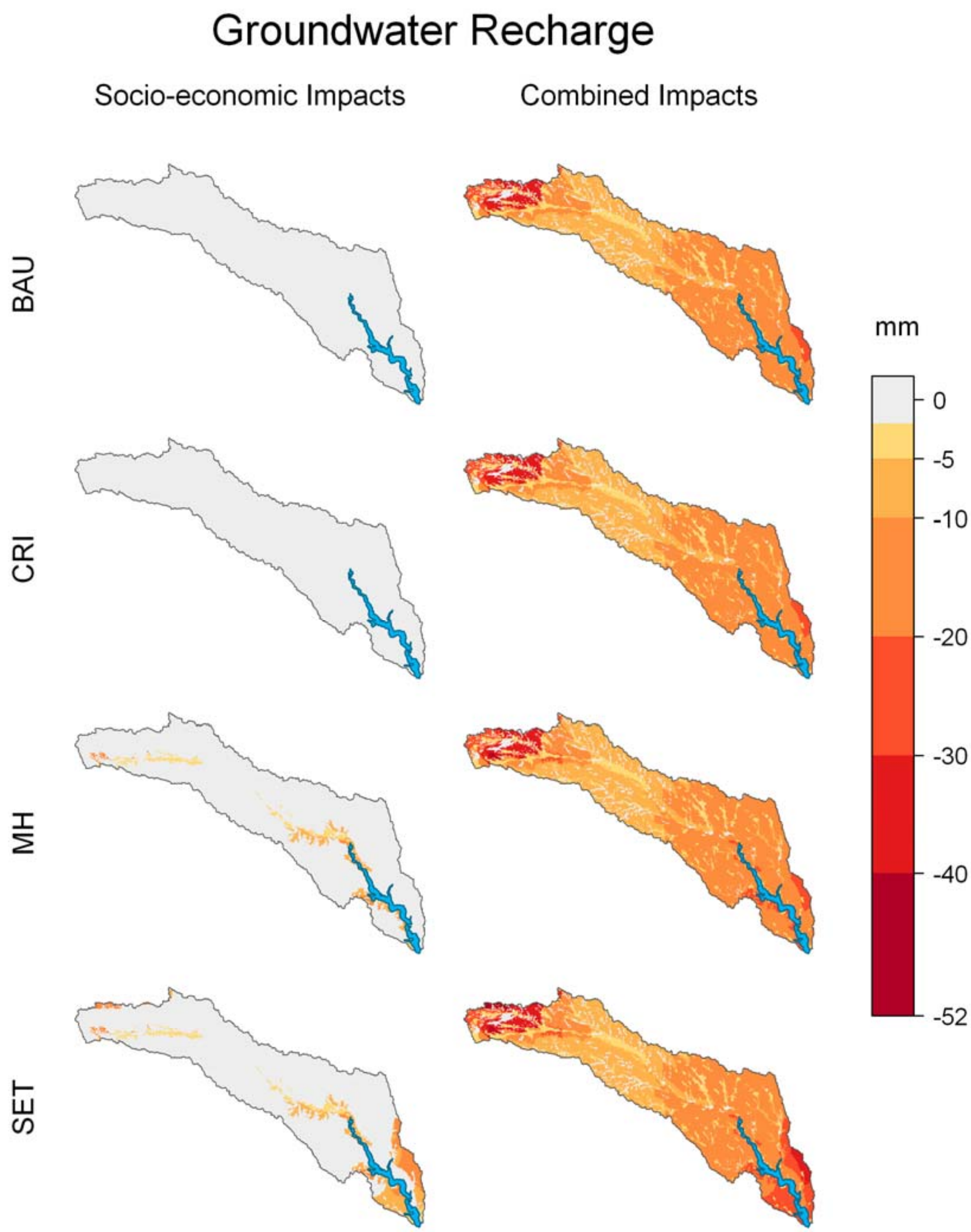


Figure 3.3.9: Maps showing long-term average annual spatial changes [mm] in groundwater recharge (GWR) for the Tyligulskyi Liman Catchment. Left: socio-economic impacts; Right: combined impacts.

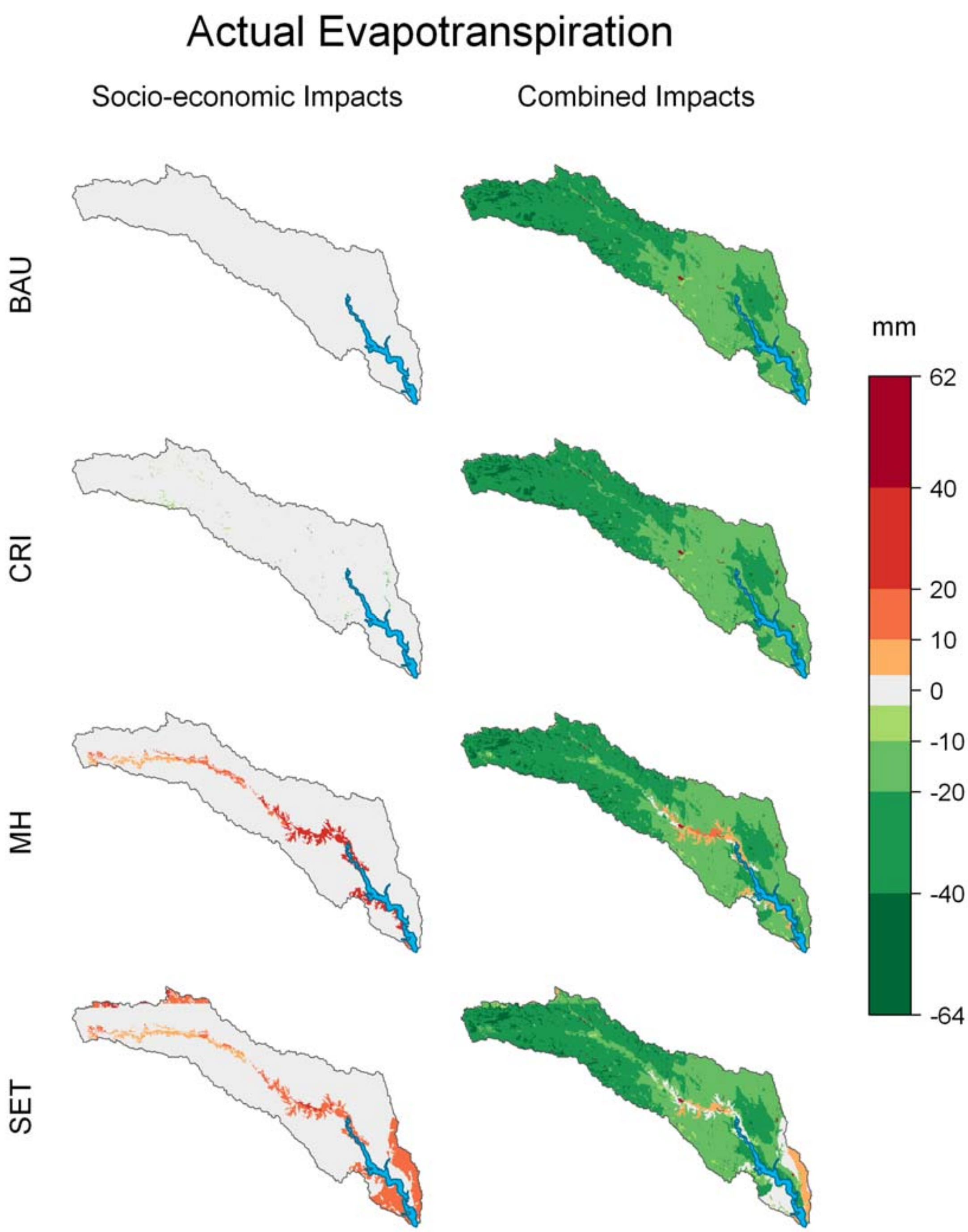


Figure 3.3.10: Maps showing long-term average annual spatial changes [mm] in actual evapotranspiration (ET_a) for the Tyligulskyi Liman Catchment. Left: socio-economic; Right: combined impacts.

MH scenario

In the MH scenario an increase in forests by 10% is assumed, cropland is reduced by 10% and most of the formerly agricultural areas are converted to meadows, which are located within a conservation corridor around the Tyligul River as a buffer zone against diffuse pollution and erosion. The effects of these land use changes can be seen in Figures 3.3.8 to 3.3.10 (MH, left).

The conversion of cropland to permanent vegetation (meadow or forests) leads to a reduction of runoff as well as groundwater recharge in these areas, whereas evapotranspiration rates increase due to higher transpiration potential of these vegetation types with their higher leaf area and vegetation period. These effects intensify the negative climate change impacts on runoff and groundwater recharge, but reverse the impact on ET_a in the areas around the lower course of the Tyligul River (MH, right). The permanent grassland vegetation in this region increases ET_a rates more than they would be decreased by climate change impacts.

SET scenario

The impacts of the socio-economic changes induced by the SET scenario are shown in the last rows of Figures 3.3.8 – 3.3.10 (SET, left). In this scenario 20% of cropland is converted to forest (mainly in the northern part of the catchment, due to climatic conditions) or fallow (in the corridor around the Tyligul River). The conversion of cropland to fallow or forest reduces the amount of surface and subsurface runoff, and intensifies the negative trend in runoff caused by climate change impacts. Simultaneously, the evapotranspiration rates increase due to higher area of permanent vegetation and longer vegetation period. In the areas where cropland is transformed to fallow the GWR decreases, and it is reduced even more in afforested areas and under new fallow land around the Tyligulskyi Liman itself. In these zones the evapotranspiration potential is increased most due to the higher leaf area index. The positive changes in evapotranspiration due to change of vegetation cover in the southern areas around the lagoon are higher than the negative changes induced by climate change.

Impacts for individual rivers

The spatial changes were evaluated also for the long-term average annual changes in discharge (Q) and nutrient inputs (NO_3-N, NH_4-N, PO_4-P) for the individual rivers flowing into the lagoons (Figure 3.3.11). The combined impacts are shown as bars, and the socio-economic impacts only as circles.

Figure 3.3.11 shows the relative changes in discharge and nutrient loads coming to the Tyligulskyi Liman from six tributaries. The changes were estimated by comparing the long-term average model outputs driven by the socio-economic scenarios with the outputs achieved under the reference management conditions for the same time period 2011-2040 (socio-economic impacts only), and with the outputs achieved with reference land use map and management for the reference time period 1971-2000 under the same climate scenario s10 (combined impacts).

As we have already seen above for the annual average sums entering the lagoon, the changes in Q, NO_3-N, NH_4-N and PO_4-P under the combined scenarios are all negative (almost or more than -50%), and this is mainly due to climate change impacts.

The changes induced by the socio-economic scenarios only are less pronounced. Especially the changes in discharge are very minor, with some exceptions for the MH and SET scenarios, where more significant changes in ponds volume were assumed.

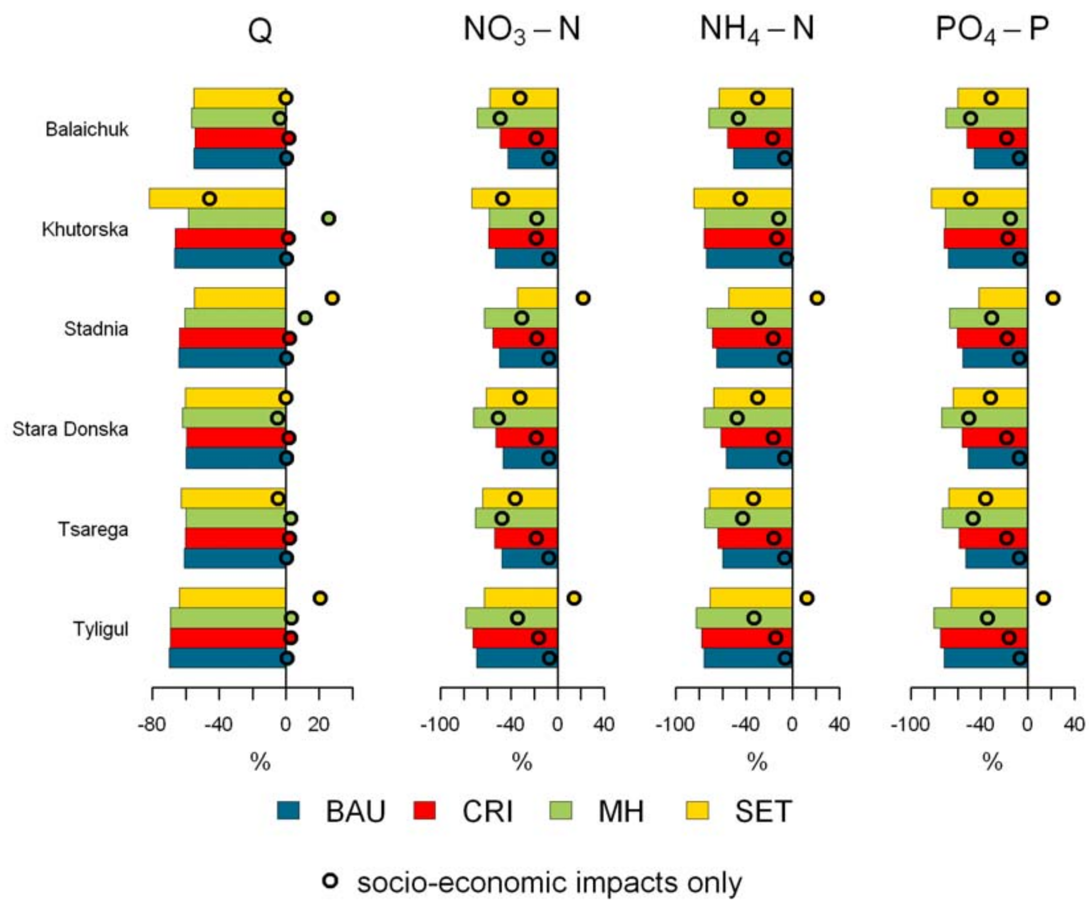


Figure 3.3.11: Relative changes [%] in long-term mean annual discharge (Q) and nutrient loads (NO_3-N, NH_4-N and PO_4-P) showing the combined (bars) and socio-economic (circles) impacts for the main tributaries of the Tyligulskyi Liman.

Compared to the river discharge behaviour under the socio-economic scenarios, the percental changes in nutrient loads are quite high. They are slightly different between the rivers, but almost no differences can be detected between the diverse nutrient components per river. The rivers with the highest relative increase in discharge due to changes in pond management (e.g. Stadnia or Tyligul) even show positive trends in nutrient loads for those scenarios (SET), as the loads are mainly connected to the inflowing water volumes.The more water is routed to the lagoon, the more nutrients can be transported. The reduction in point source pollution by 35% in the SET scenario is not sufficient to reduce nutrient loads in such cases, in contrast to the MH scenario (point sources -50%) for the Khutorska River, where an increase of discharge by 25.8% can be detected accompanied by a decrease of nutrient loads by about -12%.

These positive socio-economic impacts for the SET scenario detected in the two rivers coming to the lagoon might be a reason for the quite moderate changes in total nutrient loads coming to the Tyligulskyi Liman under the SET scenario conditions. The differences between rivers are due to the diverse distribution of point sources (which are connected to population density per subbasin), the pond volumes per river each within the catchment, as well as to the specific discharge regimes of the watercourses, which often run dry during the year.

3.3.4 Summary

The combined climate and socio-economic impacts on model outputs driven under the selected "best fitting" scenario, as well as the solely socio-economic impacts for the Tyligulskyi Liman catchment are summarized in Figure 3.3.12. For simplification the relative changes are classified into four groups representing the strength of change. The direction of change is illustrated by arrows showing the increasing or decreasing trends.

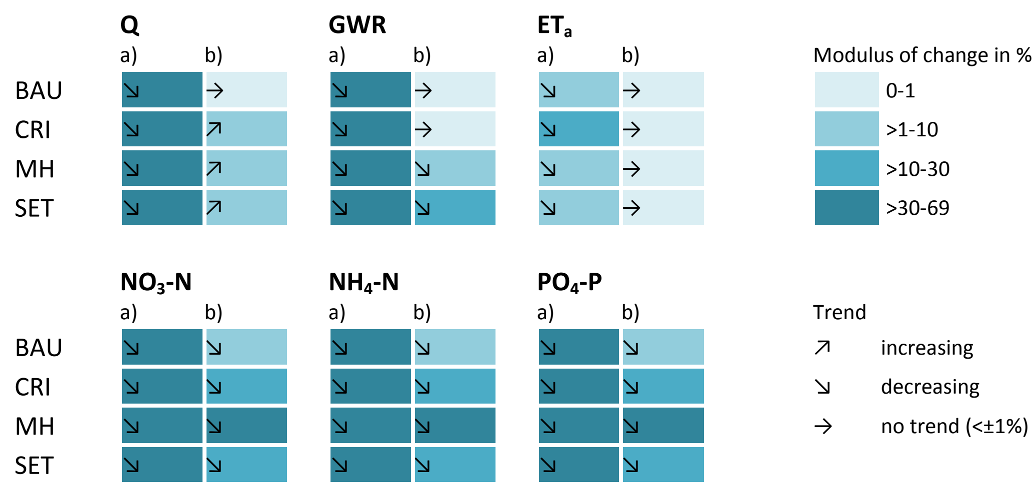


Figure 3.3.12: Summary of trends for analyzed parameters (Discharge - Q, groundwater recharge - GWR, actual evapotranspiration - ET_a, nitrate nitrogen - NO_3-N, ammonium nitrogen - NH_4-N, phosphate phosphorus - PO_4-P) in the Tyligulskyi Liman catchment caused by potential future changes: (a) – combined impacts, (b) – socio-economic impacts .

Looking at the single impacts of the socio-economic scenarios in the catchment of the Tyligulskyi Liman (Figure 3.3.12, upper row, b) we can conclude that the total freshwater inflow to the lagoon is projected to increase in three scenarios of four (from 1 to 10% for CRI, MH and SET). The BAU scenario shows an increase lower than +1%. The simulated changes are induced by a combination of various factors. The reduction of the effective volume of ponds located in the river network leads to an increase in river discharge (MH and SET). The same effect provide the decreases in irretrievable water use and water abstraction from groundwater for human or agricultural consumption (in BAU, CRI and SET), as well as the conversion of forests to fallow land (CRI). The afforestation (in MH and SET) leads to a decreasing groundwater recharge and slightly higher evapotranspiration rates at the same time. The combined impacts (a) on water flows in rivers, soils and air show all decreasing trends due to higher temperatures and less available water following the expected decrease in precipitation.

All three water quality variables investigated in this study are projected to decrease under the four applied socio-economic scenarios (Figure 3.3.12, lower row, b). The nutrient loads coming to the Tyligulskyi Liman are strongly influenced by the operation of ponds (as it is obvious for water quantity), but also by the pollution from point sources in the catchment. The reduction of nutrients is the strongest for the MH scenario, which has the most effective combination of changes in point source pollution, buffer zones along the Tyligul River, and pond management. The three nutrients under observation behave quite similar in this area and the differences

between the relative changes are small. No individual behaviour or nutrient specific processes could be revealed. This is because the regulation of river water flows (including dissolved nutrients) by ponds is the prevailing factor in this case, and it overlays the effects of nutrient processes in soils of the catchment. The combined impacts (a) on water quality variables show even higher decreasing trends, as less water (and dissolved nutrients) is routed through the river network in the projected warmer and dryer climate conditions.

The catchment of the Tyligulskyi Liman has a strong vulnerability to land use and management changes. The impacts of socio-economic and environmental changes on water quantity and quality are quite significant, as this area and its discharge regime are strongly influenced by human activities. The sensitivity is higher for water quality than for water quantity outputs. However, the impacts of potential climate change as projected by the “best fitting” scenario for this catchment are high, and lead to a strong decrease in both, water quantity and quality components. The results are associated with a quite high uncertainty resulting from the high diversity of climate change projections in this catchment (due to its location close to the border of the covered European area), as well as from the challenges of a proper model setup and calibration (due to the lack of appropriate spatial and temporal observation data as described in our previous report LAGOONS, 2013).

3.4 Catchment of the Vistula Lagoon

3.4.1 Water quantity – annual and monthly changes

The changes in total discharge (Q), groundwater recharge (GWR) and actual evapotranspiration (ET_a) were analysed under different socio-economic and combined scenarios for the catchment of the Vistula Lagoon. Figures 3.4.1 - 3.4.3 depict the absolute changes in water flows (left) as well as the relative changes of these variables under the four socio-economic scenarios compared to the reference management conditions driven by the best-fitting climate scenario s10 (right graphs). The changes can be distinguished between those caused by the solely socio-economic impacts (right above) and those caused by the combined climate and socio-economic impacts (right below). A detailed climate change impact assessment until the end of the 21st century for the multi-river Vistula Lagoon catchment under a set of 15 different climate scenarios (15 RCM/GCM combinations) can be found in Hesse et al. (2014)

Total inflow to the lagoon

The average total inflow is projected to be 210 m^3/s for the reference climate (1971-2000) and management (REF) conditions. This reference discharge is simulated to increase by 5.9% and reach 222 m^3/s in the near future period (2011-2040) only due to climate impacts (Figure 3.4.1).

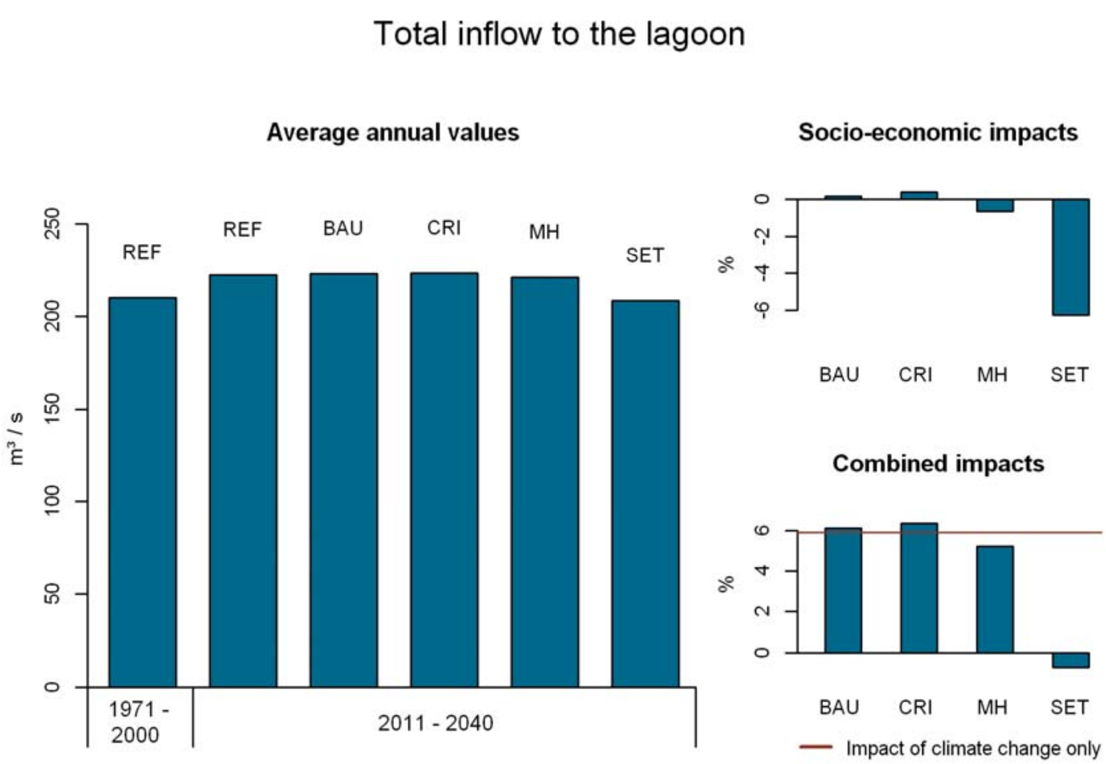


Figure 3.4.1: Impacts on total inflow (Q) to the Vistula Lagoon. Left: long-term mean annual discharges [m^3/s] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on Q for each scenario.

The applied climate scenario s10 shows the long-term average climate change signals of +0.8°C for temperature and +3.8% for precipitation, and mainly the increase in precipitation leads to the increase in total freshwater inflow to the lagoon.

The climate change impact is practically not influenced by the BAU, CRI and MH scenarios, but compensated or even slightly reversed under the SET scenario conditions. All these socio-economic impacts on river discharges result only from changes in land use composition, as no changes in water management were assumed in the Vistula Lagoon catchment. In the BAU scenario cropland area is only slightly increased (by +1.4%), and some parts of grassland and forests are decreased accordingly. This change in vegetation cover causes a negligible increase in total discharges (+0.2%). The increase is because the surface and subsurface runoff is usually higher and plant transpiration rates are lower on cropland compared to the perennial vegetation, like forest and grassland, with their permanent and higher leaf area indices. In the CRI scenario cropland is reduced by -10% and the forested land shrinks by -20% forming large areas of fallow land in the catchment. These relative large changes have contradicting effects on river discharge: the transformation of forest to fallow causes an increase in discharge, whereas the transformation of cropland to fallow reduces runoff generation due to evapotranspiration effects. So, the resulting change is only +0.4%. The land use changes as assumed in the MH scenario result in a slightly decreasing total inflow to the Vistula Lagoon (-0.7%), mainly due to a slight extension of forested areas with a higher water loss from the catchment due to some increase in plant transpiration.

The largest socio-economic impacts on the total freshwater inflow to the lagoon can be observed for the SET scenario (-6.3%). In this scenario 50% of the cropland is converted to fallow land and forests (+25%). Both latter land use classes have a higher evapotranspiration potential than agricultural fields, so that less water is available for surface, subsurface and groundwater flow to form the river discharge. The depletion of water flows is higher than the climate change induced increase, so that the combined impact of the SET scenario shows a negative trend of -0.7%.

Groundwater recharge

The effects of scenarios on groundwater recharge are similar. Figure 3.4.2 shows the average absolute annual values of groundwater recharge in the Vistula Lagoon catchment for the reference climate (1971-2000) and management conditions (REF) as well as under future climate (2011-1040) and four socio-economic scenarios (left graph). The long-term average annual groundwater recharge in the catchment is simulated to be 109 mm/year under the reference conditions, and it is increased for the period 2011-2040 by 7.2% due to climate change impact only, resulting from the higher precipitation in the catchment.

Looking at the socio-economic impacts, we can see that there are only negligible changes in groundwater recharge visible for the BAU scenario (+0.5%), due to transformation of forest to cropland, and for the MH scenario (-0.4%), due to the increase of forested areas by 5%. More notable changes can be observed when the creation of fallow land was implemented in the CRI and SET scenarios. This was accompanied by a loss of agricultural area of -10% or -50%, respectively, usually being the land use class with the highest groundwater recharge potential (Kim and Jackson, 2012). The assumed transformation of land use patterns in the CRI and SET

scenarios decreases the positive trend in GWR caused by climate change impacts for the CRI scenario, and even reverses this trend under the SET scenario conditions. The large fallow land areas assumed in these two scenarios have a higher evapotranspiration potential than the former cropland, and decrease leaching of groundwater in such area. This effect is even strengthened in the SET scenario by an increase of forests by +25%, as such vegetation has the higher leaf area indices and plant transpiration rates.

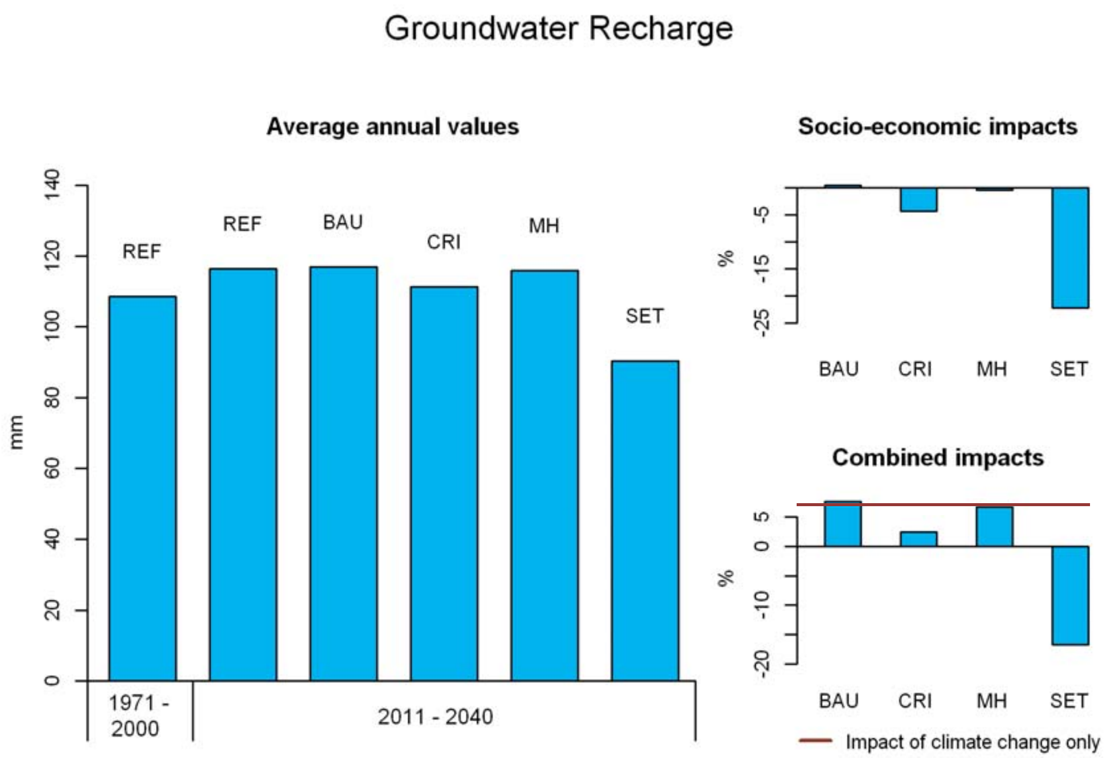


Figure 3.4.2: Impacts on groundwater recharge (GWR) in the Vistula Lagoon catchment. Left: long-term mean annual recharge rates [mm] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on GWR for each scenario.

Actual evapotranspiration

The potential impacts of expected climate and socio-economic changes on the actual evapotranspiration in the Vistula Lagoon catchment are illustrated in Figure 3.4.3. Driven by the reference climate of the s10 scenario (1971-2000) under assumption of the reference management conditions (REF) the long-term average annual ET_a is estimated to be 488 mm. It is projected to be increased by 1.6% to 495 mm only due to the specific climate change signals of s10 scenario for this basin (graph left). The increasing average temperature (+0.8°C) and precipitation (+3.8%) intensify actual evapotranspiration processes from soil and by plants, as warmer air can hold higher air humidity, and the higher precipitation causes higher water availability for volatilization.

The projected rise in the actual evapotranspiration is affected by the implemented socio-economic measures mainly for the SET scenario. Looking at the land use change impacts on ET_a, we can see that the BAU and CRI scenarios cause only small and negligible changes of -0.2 and -0.1% mainly due to the assumed reduction in forested areas in these scenarios. Although the reductions in forest vegetation are quite different for the both scenarios (BAU: -3%, CRI: -20%), the resulting changes are almost the same. This can be explained by an extension of fallow land in the CRI scenario, which nearly fully compensates the decreasing effect of deforestation on ET_a flows. The changes in land use patterns as assumed for the MH scenario cause an increase in ET_a of about 0.5%. This increase is mainly due to afforestation (+5%). In general, forest has higher transpiration rates than other vegetation types in the catchment.

The highest land use change impacts can be seen for the SET scenario. In this scenario 50% of cropland is transformed to fallow or forest areas. Both these new vegetation types have a higher evapotranspiration potential than the former cropland and cause a relative change of the long-term average ET_a flows of +4.4% (upper right graph). Taking into account the climate change impact and looking at the combined effects (lower right graph) we can see that the both impacts are added for the SET scenario leading to an average relative change of about 6%. This change corresponds to an absolute difference in average annual ET_a of 29 mm/year for the SET scenario in future climate compared to the reference conditions.

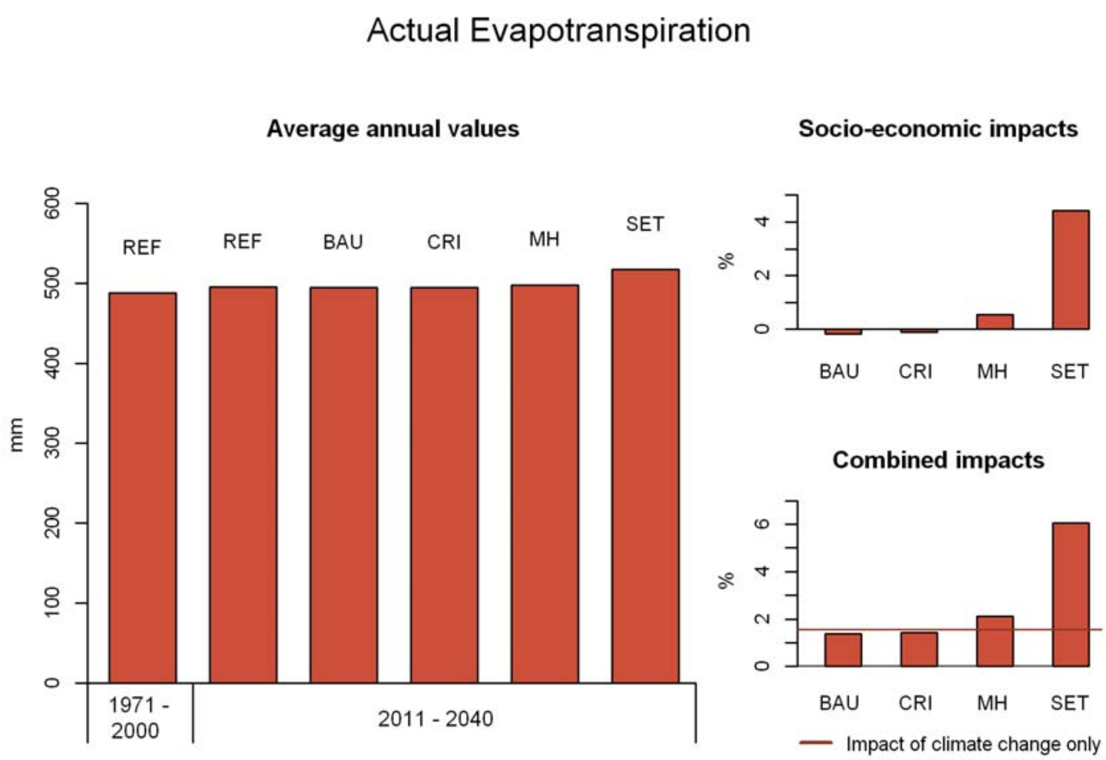


Figure 3.4.3: Impacts on actual evapotranspiration (ET_a) in the Vistula Lagoon catchment. Left: long-term mean annual evapotranspiration rates [mm] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on ET_a for each scenario.

Average monthly changes of discharge, groundwater recharge and evapotranspiration

The average seasonal dynamics of the relative changes in water flows in the Vistula Lagoon catchment are depicted in Figure 3.4.4.

Regarding the total inflow to the lagoon (upper left graph), a quite high diversity of relative changes can be observed for the combined impacts (solid lines). This is mainly due to climate change, and the monthly changes for the three combined scenarios with BAU, CRI and MH vary between -12% in April (missing snow melt peak) and +21% in September (increase in precipitation). In general, it is visible that the increase in river discharge entering the Vistula Lagoon is mainly caused by higher precipitation in autumn and winter time. The curve for the combined changes with the SET scenario (red solid line) is located below the other solid lines showing a weaker increase in discharge in autumn/winter, and a stronger decrease in spring/summer. This is due to extensive changes in land use patterns: development of new forested areas and enlarged fallow land. The both extended land use classes are characterised by higher evapotranspiration rates resulting from the higher leaf area indices and more permanent vegetation cover.

The impacts of socio-economic scenarios only (dashed lines) are minor for the BAU, CRI and MH scenarios throughout the year, and show a notable decrease in all months for the SET scenario, with an average change of -7% ranging between -3.5% in March and -11.8% in September.

The projected average monthly changes in groundwater recharge due to the combined impacts of climate and land use changes (solid lines in the upper right graph of Figure 3.3.4) show a high diversity between the monthly values. The changes vary between -50% in April and +60% in July and September. These changes are highly influenced by changes in the monthly precipitation with a short lag time.

GWR rates are usually higher in winter (about 15 mm/year on average) and lower in summer time (about 1 mm). The large relative changes in summer months are not so important, as they are due to the low absolute values of groundwater recharge in this season, and even small changes of less than 1 mm can cause high percentages of change. The largest negative absolute change due to climate impact only (not shown in the graph) is projected in April (-5 mm), and the largest positive absolute trend can be observed in November (+5 mm), but in summer months the absolute changes are between -0.05 and 0.5 mm driven by the s10 climate scenario.

The socio-economic impacts on GWR (dashed lines) are most evident for the SET scenario, with the highest absolute change in November (-5.7 mm). The moderate absolute decrease in GWR between September and April is due to change in land use patterns in the SET scenario, characterized by more areas with permanent vegetation. The same, but with lower values, can be seen for the CRI scenario. The 20% decrease in GWR simulated in the MH scenario in June is negligible, as it corresponds to an absolute value of -0.2 mm.

The seasonal changes in actual evapotranspiration in the Vistula Lagoon catchment resulting from land use change impacts only (dashed lines in the lower graph of Figure 3.4.4) are most visible between May and September. The amplitude of absolute changes for the SET scenario showing the highest impacts is between -5.4 mm in May and +12.6 mm in August. This is due to

the differences between the specific plant growth parameters and leaf area indices of the vegetation types assumed in the REF and SET model runs.

The base (t_b) and optimum temperatures (t_o) for plant growth, for example, are different between the fallow vegetation (t_b=8°C and t_o=25°C) and winter wheat (t_b=0°C and t_o=15°C), and the latter was considered as the main crop on the agricultural fields. This causes a later starting but longer lasting growing season, resulting in the negative relative changes of ET_a in spring (May), but positive changes in the late summer and autumn (September) period.

Large negative relative changes are projected in January (-20%) and December (-52%) for the combined impacts (solid lines). The ET_a rates in the winter season are low in general (< 1 mm), so that very small absolute changes (-0.084 and -0.004 mm, respectively) result in such high relative values in percent. The highest absolute changes in ET_a due to climate change impacts can be observed in April (+6.6 mm) and July (-7 mm), partly reversing the impacts of land use change only on ET_a rates in the Vistula Lagoon catchment.

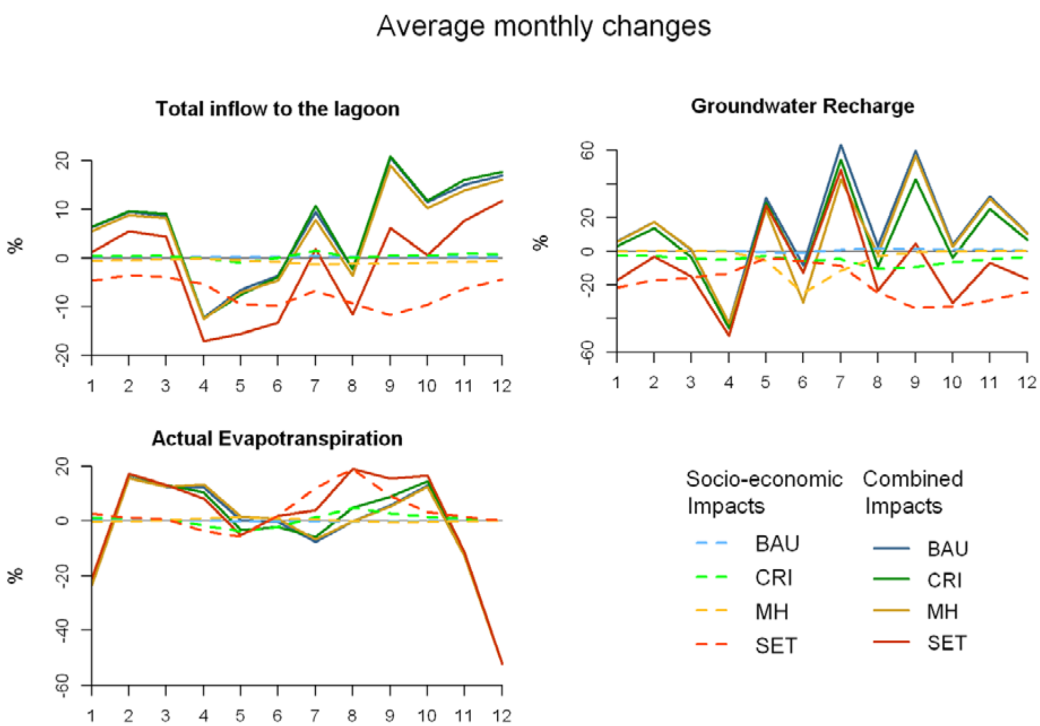


Figure 3.4.4: Long-term mean monthly relative changes [%] of Q, GWR and ET_a in the Vistula Lagoon catchment showing the socio-economic impacts (dashed lines) and the combined impacts (solid lines) for each scenario.

3.4.2 Water quality – annual changes

Figures 3.4.5 – 3.4.7 show the long-term average daily sums of total nutrient loads brought to the Vistula Lagoon by the inflowing rivers. The nutrient loads in rivers are calculated as the product of concentration and discharge. Therefore, changing concentrations due to alterations in point or diffuse nutrient sources as well as changing river discharge due to climate impact or effects of altered land use patterns can affect the nutrient loads in the catchment in various

ways. The socio-economic and combined impacts of potentially changed future conditions on nutrient loads coming to the Vistula Lagoon are presented for three dissolved riverine nutrient forms in the following subsections.

Nitrate nitrogen loads

The left graph in Figure 3.4.5 shows the average daily total sums of nitrate nitrogen loads entering the lagoon from the rivers. Driven by the reference climate (1971-2000) and the reference management conditions (REF) the average daily total load to the Vistula Lagoon accounts for 19.6 t. This load is projected to reduce to 19.1 t on average (-2.4%) under climate change impact of the s10 climate scenario. The seasonal changes in NO_3-N load are mostly related to the precipitation trend and to the increasing water leaching through soils of the catchment. An increase in loads can be observed in the winter months (conforming to the discharge behaviour), but on average a slight decrease can be detected due to the missing snow melt peak in spring (LAGOONS, 2013).

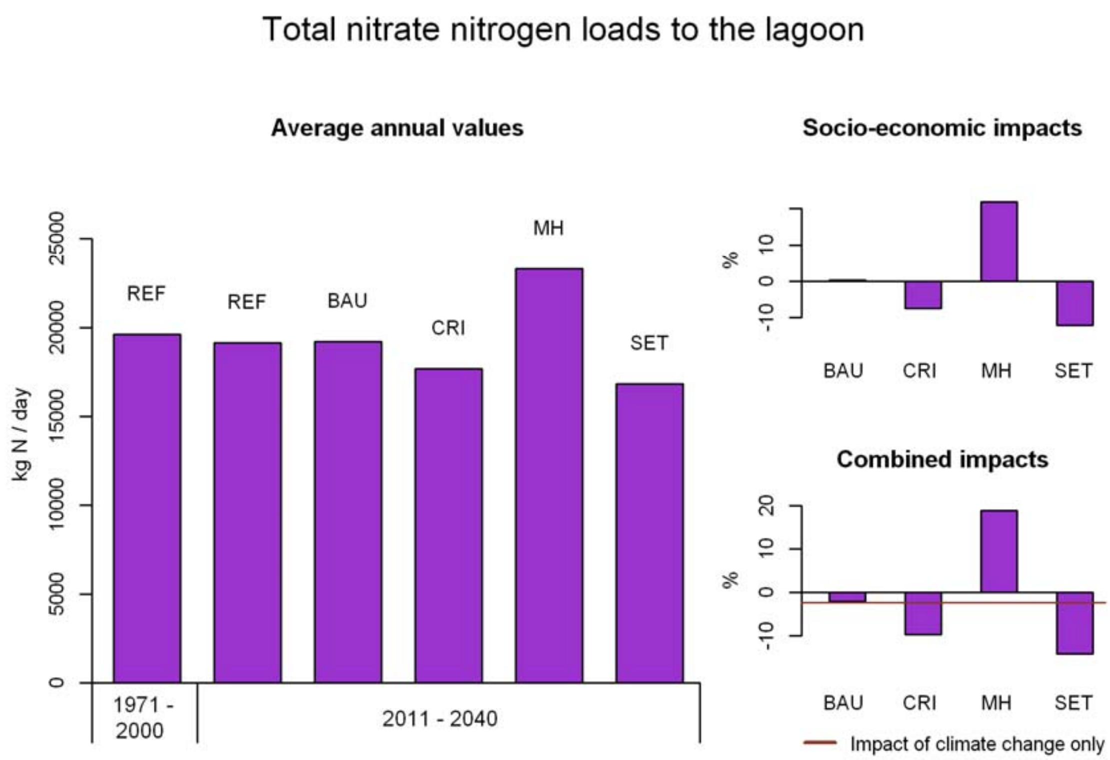


Figure 3.4.5: Impacts on total nitrate nitrogen (NO_3-N) input to the Vistula Lagoon. Left: long-term mean annual loads [kg N/day] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on NO_3-N for each scenario.

Except the BAU scenario, the socio-economic impacts on the NO_3-N loads are more intense and cause larger relative changes than the impact of climate change (right graphs in Figure 3.4.5). The highest change is projected for the MH scenario (+21.8%) due to an increased diffuse pollution resulting from the significant change in fertilizer application on agricultural fields (N_{org}+300%, N_{min}+100%) assumed in this scenario. A decrease in NO_3-N loads is projected for the CRI (-7.5%) and SET (-12.1%) scenarios, due to the fact that both are mainly characterized

by the transformation of cropland to fallow, which is not fertilized. In the CRI scenario the reduction of cropland amounts to -10%, accompanied by the decrease of point sources (-30%) and applied fertilizers (-10%). The relative decrease in load is only slightly higher for the SET scenario, where 50% of cropland is transformed to fallow, but the fertilization with N_{min} increases by 10% on the remaining fields. The socio-economic impacts caused by the BAU scenario (+1.4% increase in cropland, and +10% increase in mineral fertilizers) are negligible (+0.3% increase in load). This small positive impact is reversed by the climate impact, so that the resulting combined impact for the BAU scenario on NO_3-N loads is negative (-2.1%).

Ammonium nitrogen loads

The direction of changes in the total ammonium nitrogen load coming to the Vistula Lagoon caused by the socio-economic impacts of the four scenarios is similar to the changes in nitrate nitrogen, as they both are influenced by the same management changes (area of the agricultural fields, fertilization and point sources) (Figure 3.4.6, upper right graph). The BAU scenario projects a negligible increase in NH_4-N loads by 0.8% due to slightly increased cropland area, the CRI and SET scenarios result in a decrease by -9.6% and -21.6%, respectively, due to a decrease in fertilized agricultural area (-10/-50%) and in point source emissions (-30/-35%), additionally influenced by specific changes in N_{min} fertilizer application (-10/+10%). The same as for the NO_3-N loads, an increasing trend in total NH_4-N loads coming to the Vistula Lagoon can be observed for the MH scenario (+13.3%), too, resulting from the assumed intensification of fertilizer application in this model setup.

However, there is an obvious difference between the projected NO_3-N and NH_4-N loads for the climate change only and combined scenarios in the Vistula Lagoon catchment. While the climate change impact on the nitrate load is rather minor (-2.4%), a significant climate change impact is simulated for the ammonium nitrogen loads (-41.7%) (lower right graph).

Under the reference conditions (REF) and reference climate (1971-2000) the average daily NH_4-N load entering the lagoon is 17.2 t/day. The load is projected to be drastically reduced under the future climate conditions (2011-2040) to the long-term average load of 10 tons per day (left graph). Most likely, this decrease is connected to the projected higher temperatures in the period 2011-2040, as mineralization processes and emergence of ammonium in soils are temperature related, and ammonium appears mainly in case of soil temperatures outside the range between 5 and 40°C. If spring and autumn temperatures are higher than in the reference period, less NH_4-N will be emerged from mineralization. Additionally, less leached with water or lost with sediments NH_4-N will enter the river network due to the missing or lower snow melt peak in spring. The decrease in future NH_4-N loads could also be indirectly linked to the rising temperature, because the higher temperatures increase evaporation potential in the region, cause lower water content in soils, and inhibit ammonium emergence during mineralization (which is defined in the model to occur at soil water contents above 80%). Seasonal changes of NH_4-N loads due to climate change impacts of different climate scenarios (including the best-fitting scenario s10) are illustrated in LAGOONS (2013).

Due to the strong climate change impact on the simulated future ammonium loads the combined impacts on this nutrient are all negative (between -34% and -54%), depending on the applied socio-economic scenario (lower right graph in Figure 3.4.6).

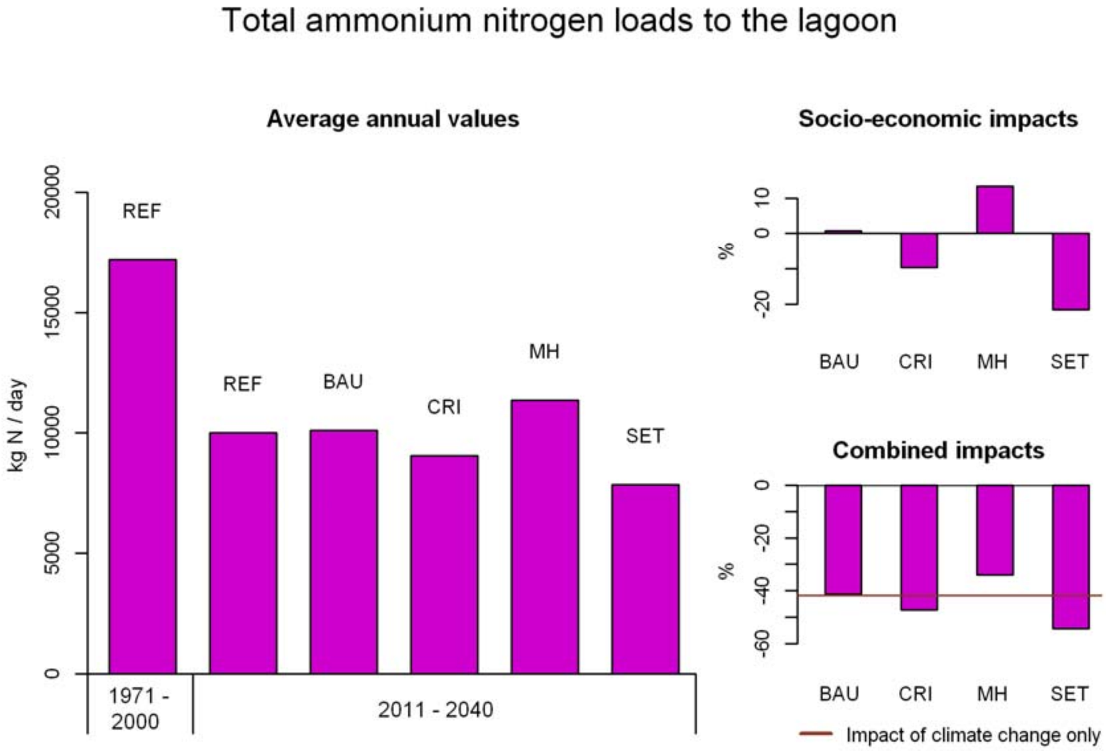


Figure 3.4.6: Impacts on total ammonium nitrogen (NH_4-N) input to the Vistula Lagoon. Left: long-term mean annual loads [kg N/day] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on NH_4-N for each scenario.

Phosphate phosphorus loads

Figure 3.4.7 (left graph) shows the average daily total sum of phosphate phosphorous loads coming to the Vistula Lagoon as simulated by the different reference and scenario climate and management conditions. Under the reference conditions (REF) and reference climate (1971-2000) the average daily PO_4-P load entering the lagoon is 1.7 tons per day, which is projected to be slightly increased in the future period 2011-2040 with the same management measures by 3.7% to 1.8 t/day due to solely climate change impacts. This increase in load is probably connected to increasing leaching processes with higher precipitation, washing more PO_4-P from sandy and highly permeable soils in the catchment used for agriculture (LAGOONS, 2013).

The socio-economic scenarios cause changes in different directions ranging from minor to moderate (upper right graph). An increase in PO_4-P loads coming to the lagoon is caused by the BAU (+1.7%) and MH (+17%) scenarios. The increase in the BAU scenario is due to a slight increase in agricultural area (+1.4%) and P_{min} fertilization (+10%), and in the MH scenario it is caused by the same reasons, but with a higher intensity (cropland +2%, fertilization +100%). The CRI and SET scenarios show decreasing trends: -17.3% and -11.5%, correspondingly, as in both scenarios a conversion of agricultural land into fallow is assumed, as well as a reduction of point source emissions. The conversion of cropland is assumed with a higher percentage in the

SET scenario (-50%) than in the CRI scenario (-10%), but due to the impact of fertilization (CRI: -10%, SET: +10%) the lower PO_4-P loads are generated for the CRI scenario.

The combined impacts show the same behaviour as the solely socio-economic ones, but the positive changes (BAU, MH) are slightly increased, and the negative ones (CRI, SET) slightly decreased. But the climate change impacts are not able to reverse or compensate any impacts cause by changes in management measures and land use patterns.

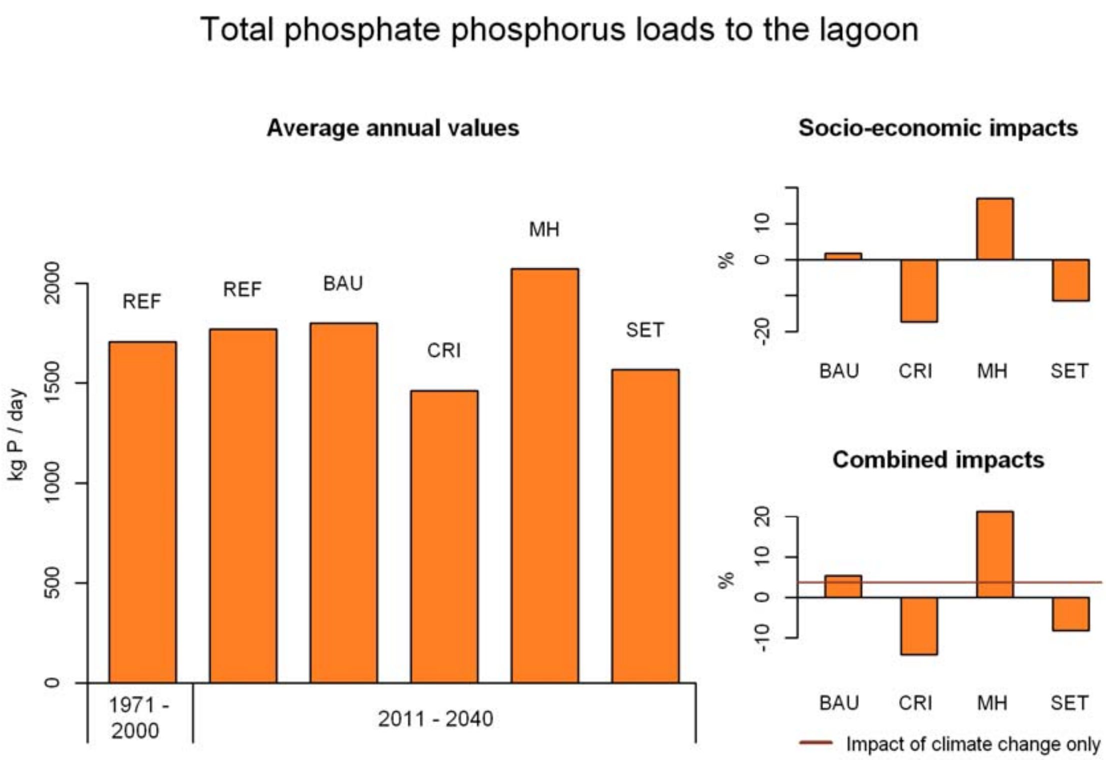


Figure 3.4.7: Impacts on total phosphate phosphorus (PO_4-P) input to the Vistula Lagoon. Left: long-term mean annual loads [kg P/day] for the reference conditions (REF) and the four scenarios (BAU, CRI, MH and SET); Right: relative changes [%] showing the socio-economic impacts (upper graph) and the combined impacts (lower graph) on PO_4-P for each scenario.

3.4.3 Spatial changes

For the spatial analysis of changes caused by the applied climate and socio-economic scenarios the following section includes maps of the Vistula Lagoon catchment showing long-term average changes in surface and subsurface runoff (RUN), groundwater recharge (GWR) and actual evapotranspiration (ET_a) for each of the four socio-economic scenarios. For every variable, both the single socio-economic impacts as well as the combined climate, land use and management change impacts are presented on maps with the hydrotope-level resolution. The effects of solely socio-economic changes are evident for areas with altered land use and vegetation cover, whereas the combined impacts are spread more over the whole catchment. The climate change impacts can diminish or strengthen the impacts caused by the socio-economic changes. Figures 3.4.8 to 3.4.10 show spatial changes in long-term average RUN, GWR and ET_a for the future

period 2011-2040 compared to the reference period 1971-2000 driven by climate scenario s10. For both periods, the simulated spatial annual outputs were averaged over the whole 30 year period. Then the differences per hydrotope were calculated and mapped.

BAU scenario

In the BAU scenario an increase in cropland by 1.4% is assumed (corresponding to +194 km^2). To achieve this change percentage, a reduction of forested areas by -3% (-152 km^2) as well as a small decrease of set-aside (-9% ≙ 0.5 km^2), pasture (-6% ≙ 39 km^2) and wetland (-5% ≙ 2.5 km^2) land use classes were implemented. These changes in land use patterns affect only small parts of the catchment, but cause diverse responses in RUN (Figure 3.4.8), GWR (Figure 3.4.9) and ET_a (Figure 3.4.10), depending on the transformed land use class and soil conditions (socio-economic impacts, BAU, left). The deforestation of deciduous and mixed forests leads to higher surface and subsurface runoff in this area, accompanied by an increase in groundwater recharge and a decrease in actual evapotranspiration, due to a lower leaf area index of the deforested areas, causing the reduced transpiration rates. Hence, more water is available for runoff to the river network or leaching to the groundwater pool. The creation of cropland from the fallow land, pasture or wetland, in contrast, mostly causes decreasing RUN and ET_a, and slightly increasing GWR.

The combined impacts of the BAU scenario and changing climate affect larger areas of the catchment (right maps), and show a high heterogeneity, mainly due to the natural variations in precipitation distribution. In the central part of the basin, there are also some areas with only minor changes in RUN, GWR and ET_a. The large north-western and north-eastern areas are characterized by an increase in surface and subsurface runoff caused by higher precipitation in these regions. The GWR increases mostly in the west around the Vistula Lagoon, and in some eastern parts, additionally influenced by soil conditions. The changes in ET_a due to climate change impacts can be mainly seen in forested areas. Here an increase is projected, as warmer air (+0.8°C) can hold higher air humidity and the higher precipitation (+3.8%) causes higher water availability for volatilization in these areas with their high evapotranspiration potential.

CRI scenario

In the CRI scenario 10% of the cropland (≙1389 km^2) and 20% of the forests (≙1012 km^2) are converted to fallow land. Both changes cause an increase in surface and subsurface runoff (Figure 3.4.8, CRI, left). The increase in runoff on the former forested areas is due to a lower evapotranspiration caused by a decreased vegetation biomass and leaf area index on fallows. The increase in runoff on the former cropland (small absolute values) can be explained by the specific annual plant growth dynamics, and connected seasonal variations in transpiration potential of the fallow land compared to cropland. The transformation of cropland to fallow results in a decrease of GWR (Figure 3.4.9, CRI, left) and in an increase of ET_a (Figure 3.4.10, CRI .left), whereas the transformation of forests into fallow has opposite effects. This is the result of the specific plant growth parameters and transpiration potentials of the different vegetation types, too.

The combined spatial impacts of the CRI scenario intensify the increasing trend for RUN in some parts of the catchment, but compensate or even reverse the average socio-economic impacts on

GWR and ET_a in the drainage basin. As the climate change impacts do not occur in all parts of the catchment evenly, the overall land use and climate change impacts can often be seen side by side with opposite directions, but the local changes are not compensated by each other.

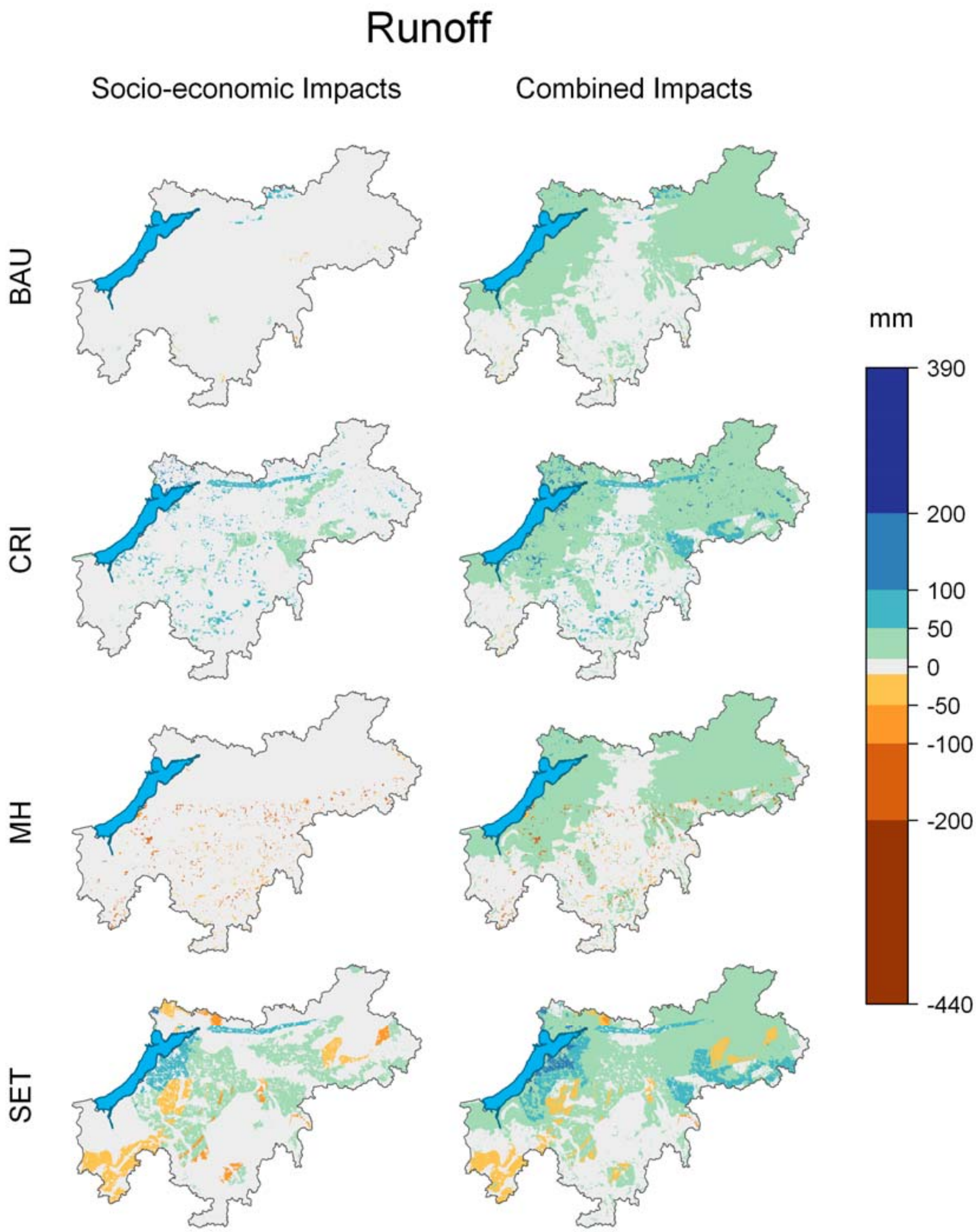


Figure 3.4.8: Maps showing long-term average annual spatial changes [mm] in runoff (RUN) for the Vistula Lagoon Catchment. Left: socio-economic impacts; Right: combined impacts.

MH scenario

The MH scenario is characterized by an increase in cropland by 2% (≙ 278 km^2) and the extension of forested areas by 5% (≙ 253 km^2). These land use changes had to be balanced in the land use map by some reduction in set-aside, grassland and wetland areas. As such land use classes are not defined in the less detailed land use map of the Russian part of the catchment (see LAGOONS, 2013), the corresponding changes in the land use types were only made in the Polish part of the catchment. This is the reason why the spatial changes due to the socio-economic impacts of the MH scenario are only detectable in the southern Polish part of the drainage basin.

In this region mainly a decrease in surface and subsurface runoff is detected, especially for afforested areas (Figure 3.4.8, MH, left). There are only little parts where the runoff increases after transformation of grassland in cropland. The ET_a increases with afforestation, but decreases in new cropland due to specific plant transpiration potentials of the different vegetation types (Figure 3.4.10, MH, left). The GWR shows the same partitioning but with the opposite direction: it increases under cropland but decreases under forests (Figure 3.4.9, MH, left).

The maps of combined spatial impacts (MH, right) most often simply add the climate and socio-economic impacts side by side, only locally on small fields the climate impacts on RUN are reversed and those on ET_a are strengthened. For the GWR both options, intensification as well as weakening of the projected climate change impacts, can be detected.

SET scenario

The spatial impacts of the socio-economic changes induced by the SET scenario are shown in the last rows of the Figures 3.4.8 - 3.4.10 (SET, left). In this scenario 50% of cropland (≙ 6946 km^2) is converted to fallow land and forests. By that, the forested areas increase by 25% (≙ 1266 km^2). The rest of the changed cropland is assumed to become a set-aside (5685 km^2). These land use changes cause wide-ranging changes in RUN, GWR and ET_a, with opposite directions of change for surface and subsurface runoff. The transformation of cropland to fallow results in an increasing runoff in the central part of the basin with a high seasonality. The increase (small absolute values) can be explained by the specific annual plant growth processes of the fallow land (cover crop) compared to cropland (winter wheat). The transformation of cropland to forest reduces the surface and subsurface runoff due to the higher interception and transpiration rates of forest. The both land use changes cause decreasing groundwater recharge and increasing ET_a rates. The decrease/increase is higher under the new forests than under the new fallow land, as the plant transpiration potential of forest is usually higher than that of set-aside.

The right maps show the combined impacts of climate change projected by the selected s10 scenario applied together with the SET scenario and compared to the reference conditions. For areas where cropland was transformed to fallow land, the climate change impacts are strengthened, and the runoff increases even more than under climate change only with the increase in precipitation. The transformation to forest can reverse the climate change impact and decrease surface and subsurface runoff. A reversal of climate change impacts can also be

observed for the GWR in transformed agricultural areas. The climate change impacts on ET_a, in contrast, are intensified by the land use changes assumed under the SET scenario conditions.

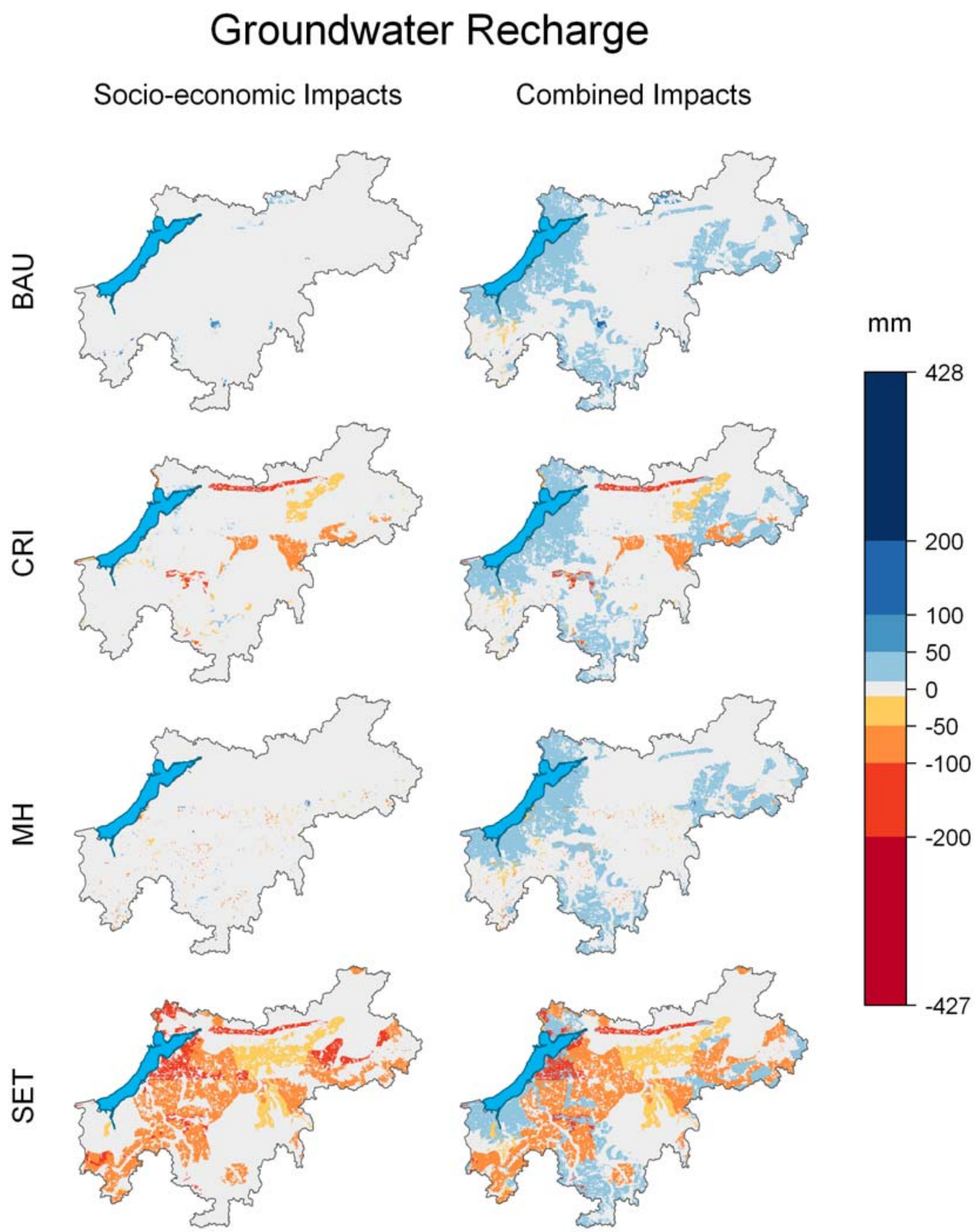


Figure 3.4.9: Maps showing long-term average annual spatial changes [mm] in groundwater recharge (GWR) for the Vistula Lagoon Catchment. Left: socio-economic impacts; Right: combined impacts.

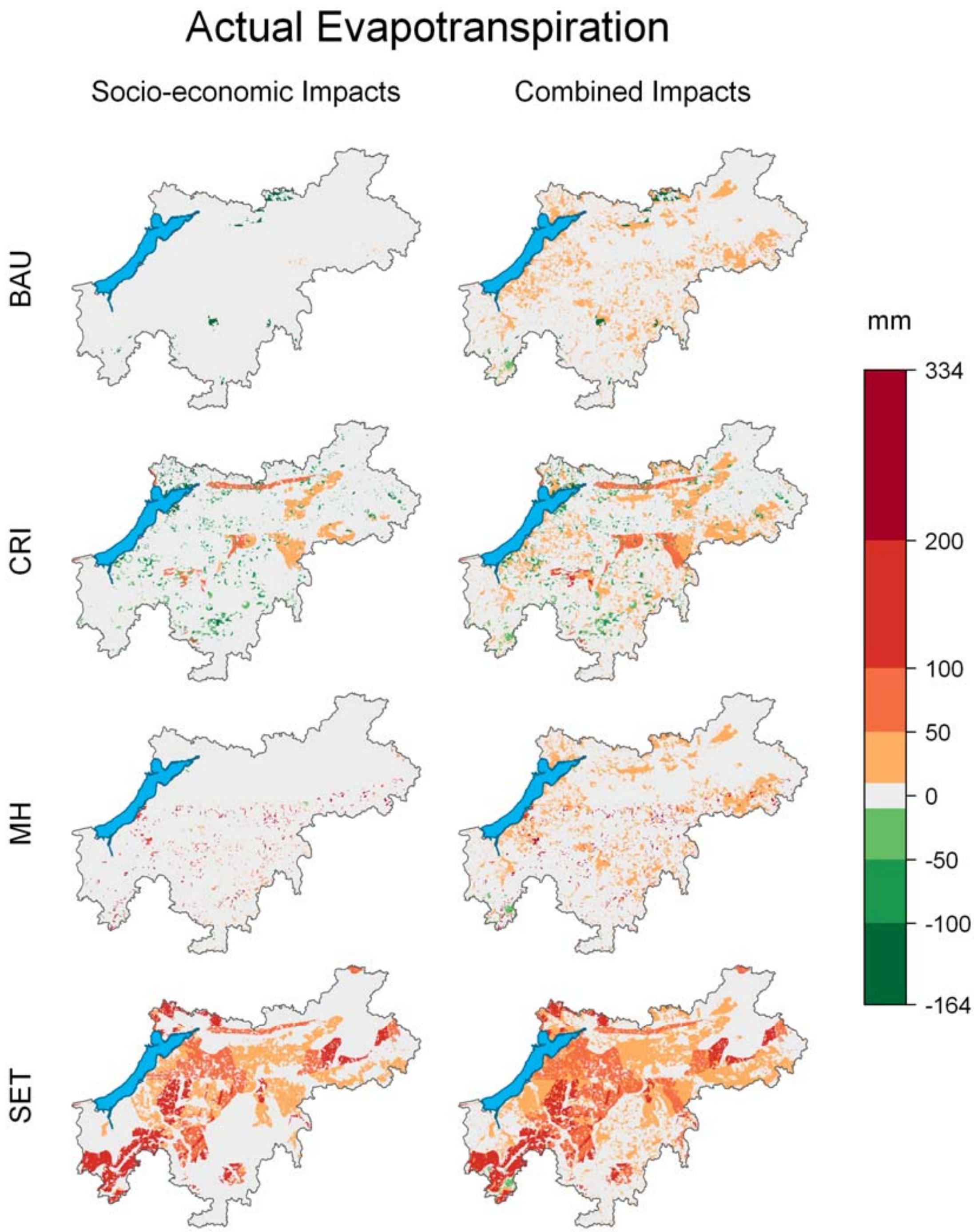


Figure 3.4.10: Maps showing long-term average annual spatial changes [mm] in actual evapotranspiration (ET_a) for the Vistula Lagoon Catchment. Left: socio-economic; Right: combined impacts.

Impacts for individual rivers

The spatial changes were evaluated also for the long-term average annual changes in discharge (Q) and nutrient loads (NO_3-N, NH_4-N and PO_4-P) coming to the Vistula Lagoon by the individual rivers (Figure 3.4.11). The combined impacts on the four variables are shown as bars, and the

solely socio-economic impacts as circles. The analysis was performed for 12 main rivers of different importance coming to the lagoon. Their long-term average observed discharges range between 0.3 (Vileyka) and 86.5 m^3/s (Pregolya) (LAGOONS, 2013). The scenario impacts were estimated by comparing the long-term average model outputs driven by the socio-economic scenarios with the outputs achieved under the reference management conditions for the same time period 2011-2040 (socio-economic impacts only), and with the outputs achieved with reference land use map and management for the reference time period 1971-2000 under the same climate scenario s10 (combined impacts).

In general, the combined and socio-economic impacts on the specific river discharges mostly reflect the average impacts on the total inflow to the Vistula Lagoon described in section 3.4.1. The socio-economic impacts of the BAU, CRI and MH scenarios are quite low, and cannot compensate the increase in Q caused by the projected climate change, so that almost all combined impacts for these scenarios have a positive direction.

Only the SET scenario with a wide-ranging transformation of cropland to fallow or forest has more significant effects on Q. The majority of rivers react with a strong decrease in river discharge. The solely specific climate change impacts on the discharge in the several subcatchments are lowered, compensated or even reversed by the SET scenario application. The diversity in the magnitude of changes for the different river basins can be explained by the heterogeneity and distribution of land use transformation areas as well as by the uneven precipitation changes within the multi-river Vistula Lagoon drainage basin.

The relative changes in nutrient loads coming with the different rivers show a high diversity between the tributaries, scenarios as well as between variables. The observed changes, especially for the NO_3-N and PO_4-P loads, are mainly caused by changes in land use composition and management, and are less influenced by the climate change impacts. The combined percental impacts almost in all cases have the same magnitude and direction as the socio-economic ones, and climate impacts only marginally influence these trends. But changes in NH_4-N loads do not correspond to this behaviour, as this variable is more influenced by temperature and water content in soil. The differences in impacts between rivers are due to diverse land use patterns and point source distribution, as well as the diversity in projected climate change within the catchment. Especially the share of cropland per river drainage area is a very important factor influencing nutrient loads coming with the rivers.

The changes in nitrate and phosphate loads are mostly low for the BAU scenario, but more significant in the CRI, MH and SET scenarios. The NO_3-N load decreases under the CRI and SET scenarios due to a reduction of agricultural area, which is most significant in the SET scenario (-50%). The increase in fertilizer application assumed for the MH scenario causes the higher nitrate loads in almost all analysed river subcatchments. An increase in fertilization affects PO_4-P as well, and causes increased phosphate loads under the MH scenario. The socio-economic changes of the MH scenario lead to an increase in the NH_4-N loads, too, but this effect is almost compensated or even reversed by climate change impacts in many of the river basins (e.g. Pasleka and Pregolya).

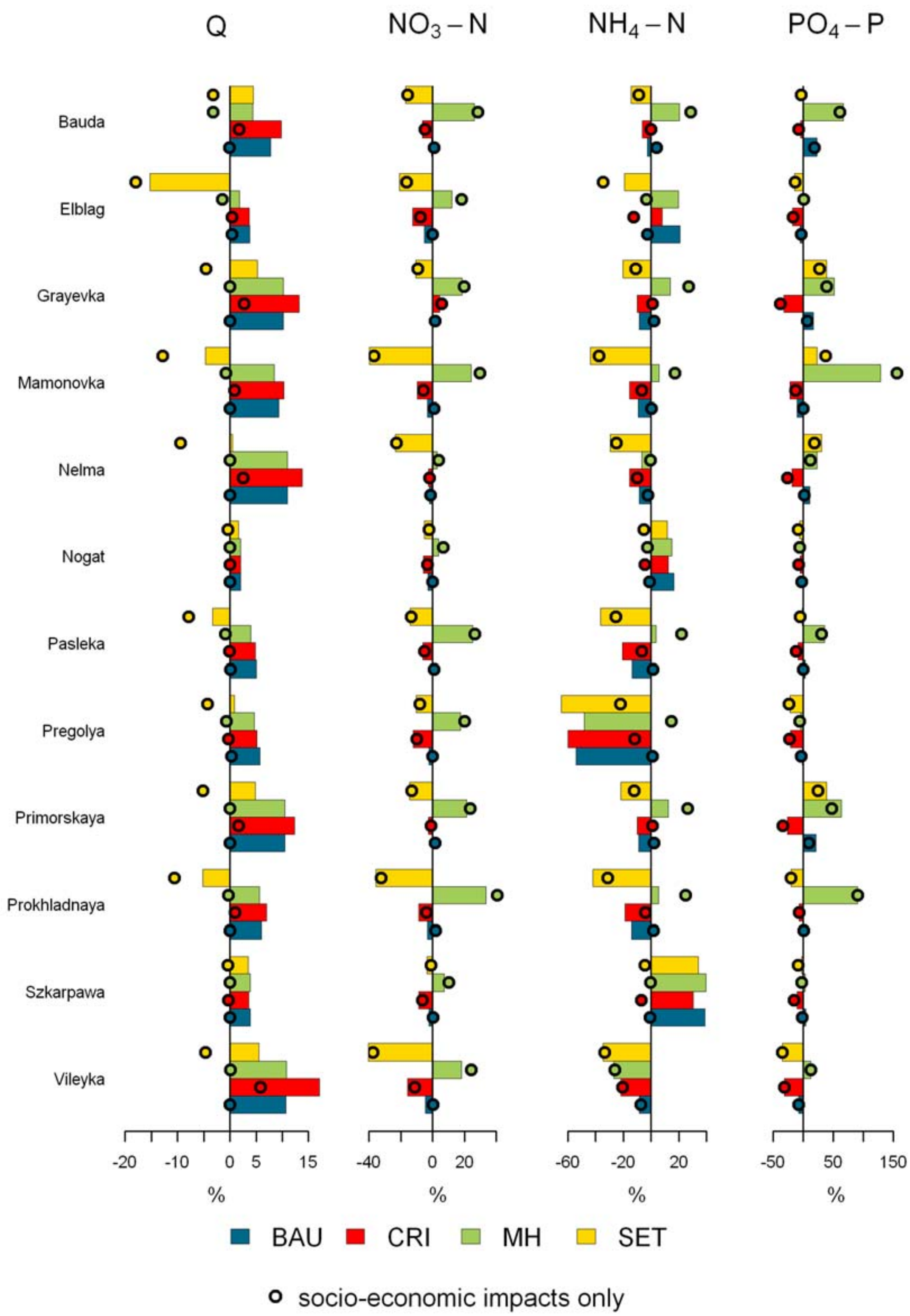


Figure 3.4.11: Relative changes [%] in long-term mean annual discharge (Q) and nutrient loads (NO_3-N, NH_4-N and PO_4-P) showing the combined (bars) and socio-economic (circles) impacts for individual tributaries of the Vistula Lagoon.

There are three rivers (Szkarpawa, Nogat and Elblag) showing an opposite (increasing) climate change impact on NH_4-N loads compared to the rest of the subcatchments and the total catchment on average. These rivers are located in the lowest part of the drainage basin, are highly influenced by the groundwater level and retained and slow flowing river waters. Therefore it can be assumed that the soil water content is usually higher in this area, and it would even increase with the increasing precipitation projected by climate change. Such favourable conditions for NH_4-N emergence in future (in SWIM model NH_4-N is defined to be emerged when soil water content is higher than 80%) lead to the increase in ammonium loads in these rivers.

3.4.4 Summary

The combined climate ("best fitting" s10 climate scenario) and socio-economic (BAU, CRI, MH and SET) impacts on the selected model outputs as well as the solely socio-economic impacts of the four scenarios for the Vistula Lagoon catchment are summarized in Figure 3.4.12. For simplification, the relative changes are classified into four groups representing the strength of change. The direction of change is illustrated by arrows (trend to increase or decrease).

Looking at the impacts of the socio-economic changes only in the catchment of the Vistula Lagoon (Figure 3.4.12 b) we can conclude that the average total freshwater input to the lagoon is only negligibly influenced by the BAU, CRI and MH scenarios (less than ±1%), but it is decreasing for the SET scenario. The impacts on water quantity in this case are due to land use change only, as alterations in water management were not assumed for any of these scenarios. An increase of forested areas in the MH (+5%) and SET (+25%) scenarios contributes to an overall decrease in discharge and groundwater recharge, and to an increase in actual evapotranspiration, which is less pronounced in the MH scenario (less than 1% change) but obvious in the SET scenario. In the CRI and SET scenarios the reduction of cropland area to fallow causes a reduction of groundwater recharge, as fallow has lower GWR rates due to increased evapotranspiration of the perennial set-aside vegetation.

The combined impacts (Figure 3.4.12 a) on water flows in the catchment show the increasing trends in all three water flow components under the BAU, CRI and MH scenarios with changing climate due to higher water availability with the increased precipitation. In the combined SET scenario, the climate change effects are highly influenced by land use change impacts, leading to a compensation of the change in Q, reversion of the change in GWR and intensification of the change in ET_a.

The water quality variables in the Vistula Lagoon catchment are influenced by the socio-economic changes in different directions. Changes in agricultural practices and area of cropland have the highest influence on the nutrient loads, as they affect diffuse pollution in the catchment. The nutrient loads are reduced in the CRI scenario, in which lower fertilization amounts and a moderate reduction of the agricultural land are assumed, as well as in the SET scenario, where slightly higher fertilization rates and a 50% reduction of the agricultural area were defined. An increase in nutrient loads is projected for the MH scenario with a slight increase in cropland area and much higher rates of mineral and organic fertilizers on agricultural fields. For the BAU scenario the changes in nutrient loads are negligible, and all lower than 2%.

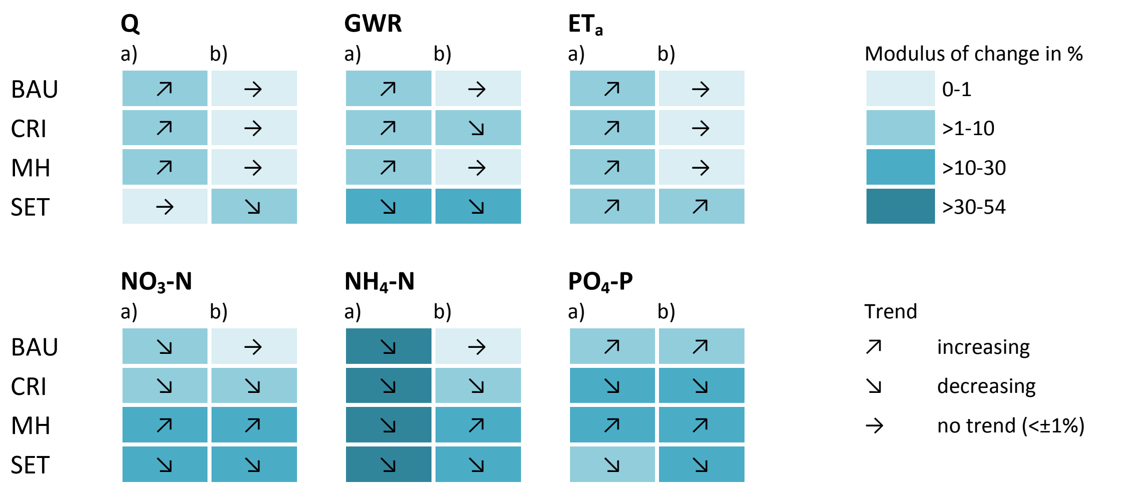


Figure 3.4.12: Summary of trends for analysed parameters (discharge - Q, groundwater recharge - GWR, actual evapotranspiration - ET_a, nitrate nitrogen - NO_3-N, ammonium nitrogen - NH_4-N, phosphate phosphorous - PO_4-P) in the Vistula Lagoon catchment caused by potential future changes: (a) – combined impacts, (b) – socio-economic impacts.

The combined impacts on water quality variables NO_3-N and PO_4-P almost resemble the socio-economic impacts only. The changes in nutrient loads in this case are only minimally influenced by the additional impacts of climate change. However, the NH_4-N loads are highly impacted by climate change and all combined impacts on the ammonium load show a strong decreasing trend due to the expected future temperature changes.

The simulation results show that the catchment of the Vistula Lagoon is influenced by both, expected change in climate as well as socio-economic changes. Climate is projected to be warmer and wetter in future, leading to moderate changes in water flow components. However, changes in land use and agricultural practices (including fertilization) can have significant effects on water quantity and quality, so that every measure should be well debated before its implementation. Although the changes in cropland and forest areas assumed for the CRI and SET scenarios are quite high and maybe not realistic, they help to understand the system and processes in the catchment better, and to derive reasonable adaptation measures in order to adapt to potential future trends in the catchment.

4 SUMMARY AND CONCLUSIONS

In Chapter 3 the results of the socio-economic and combined impact assessment on various water and nutrient components were presented for each case study area individually, whereas this chapter aims to summarize the combined impacts on the main model outputs and to compare these between the four case study areas. For that, the relative changes are classified into four categories representing the strength of change: from the small impact below 1% until the significant impact between 51 and 100%. So, Figure 4.1 presents the long-term average annual changes in total water inflow (Q) and nutrient (NO_3-N, NH_4-N and PO_4-P) loads to the lagoons driven by the combined scenarios as 3-dimensional plots, which allows us to compare the impacts on a certain component (y-axis) between catchments (z-axis) and scenarios (x-axis). The projected impacts are quite divers in terms of trend direction (increase/decrease) and impact intensity (percental change), and they are also quite divers between the catchments and scenarios.

The total water inflows to the Ria de Aveiro, the Mar Menor and the Tyligulskyi Liman are projected to decrease for each of the four scenarios, mainly as a result of decreasing precipitation in the future scenario period 2011-2040. The strongest decrease in precipitation and therefore also in water inflow is simulated for the Tyligulsyki Liman. On the contrary, an increase in future precipitation in the catchment of the Vistula Lagoon leads to an increase in total inflow for the BAU, CRI and MH scenarios, whereas in the SET scenario this increase compensates the impacts of land use change, and there is practically no trend in total inflow in this case.

The combined impacts on the total nitrate nitrogen load to the lagoons show a decrease for all scenarios and all four case study areas, except for the MH scenario in the Vistula Lagoon catchment. The overall decrease in the NO_3-N loads can be related to both climate change (for the Ria de Aveiro, Mar Menor and Tyligulskyi) and changes in management and land-use (for all four case study areas, and especially for the Vistula). The land use and the management changes, assumed for most catchments and scenarios (conversion of agricultural land to fallow, grassland or forest and reduction of applied fertilize) lead to a decrease in nitrate nitrogen loads. Solely, a significant increase in the applied fertilizer rates in the Vistula Lagoon catchment, assumed for the MH scenario, and increase in precipitation lead to an overall increase in the total NO_3-N load to this lagoon. Similar as for the water inflow, the projected changes in the nitrate nitrogen loads to the four lagoons show the strongest decrease for the Tyligulskyi Liman, climate change impact and overall decrease of freshwater inflow (carrying the nutrient loads) to this lagoon.

The simulated changes in the total ammonium nitrogen and phosphate phosphorus loads show divers patterns for the four catchments.

In the case of the NH_4-N loads, an increase for all four scenarios in the Ria de Aveiro catchment, and for the BAU and MH scenarios in the Mar Menor catchment was simulated. A decrease is projected for all four scenarios in the Tyligulskyi Liman and the Vistula Lagoon catchments, as well as for the SET scenario in the Mar Menor catchment. The reasons for these trends are explained in details in Chapter 3.

The phosphate phosphorus loads are projected to decrease for all scenarios in the Ria de Aveiro and the Tyligulskyi Liman catchments mainly due to climate change, as well as for the CRI and

SET scenarios in the Vistula Lagoon catchment, and the SET scenario in the Mar Menor catchment due to the combined effects of climate and socio-economic changes. In the case of the BAU and MH scenarios the combined changes lead to an increase in PO_4-P loads to the Mar Menor and the Vistula Lagoon. Again, the detailed reasons for every trend are explained in Chapter 3.

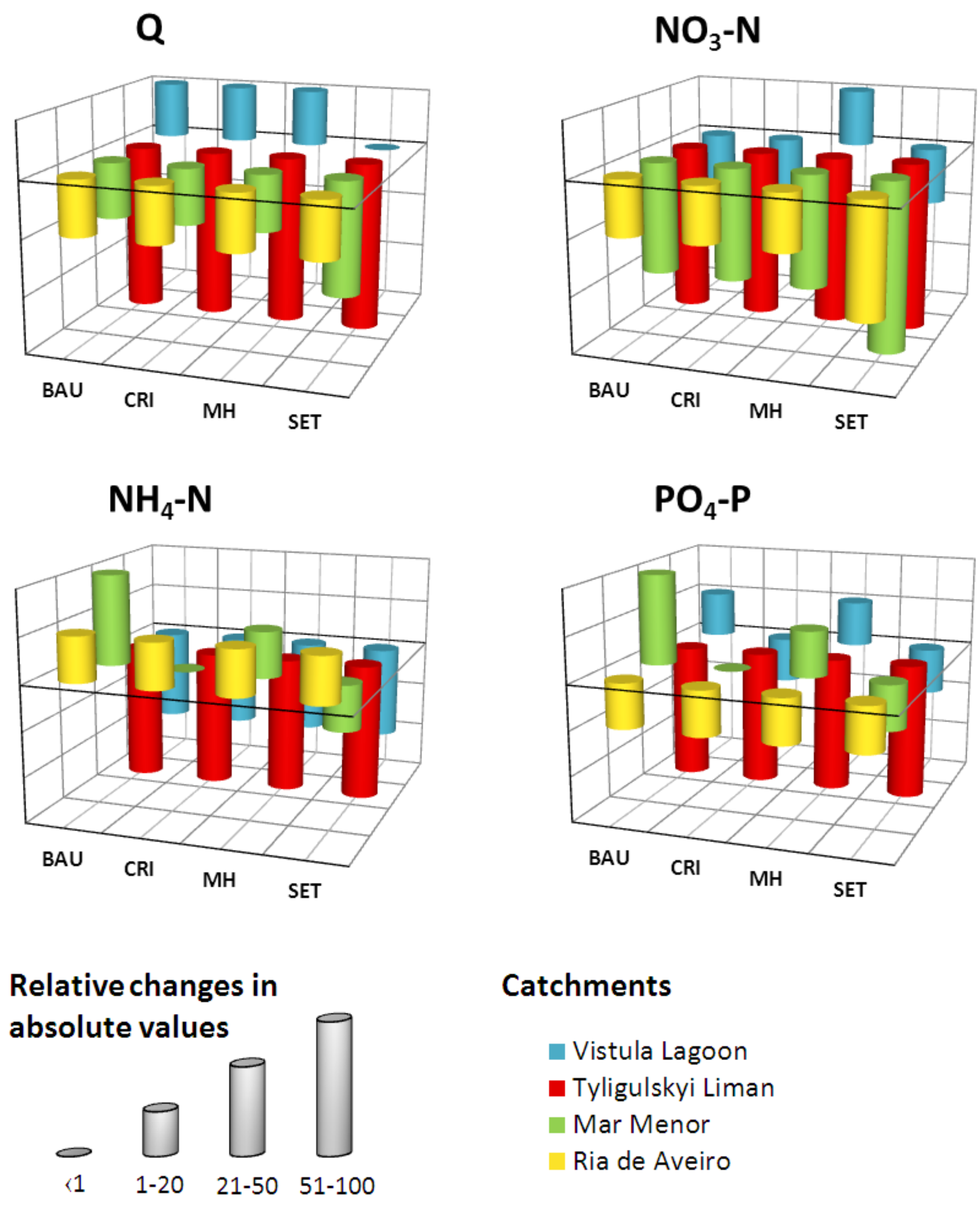


Figure 4.1: Summary of trends for discharge (Q), nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), and phosphate phosphorus (PO_4-P) in the four case study areas caused by combined climate and socio-economic (BAU, CRI, MH, SET) scenarios.

However, we cannot assume that the results of the combined climate and socio-economic impact assessment for the four lagoon catchments presented in this report deliver universally valid and strict results, and that all impacts projected for a certain scenario will be realised in future in case the scenario assumptions would be fulfilled. The assessment comes along with some uncertainty, which should be kept in mind when the results are analysed and interpreted. The uncertainties are related to A) data availability and quality for the model setup and calibration/validation, B) ability of climate and eco-hydrological models to represent the simulated interrelated processes in the atmosphere and in a landscape, and C) reliability of climate and socio-economic scenarios applied for the impact assessment. These uncertainties are shortly discussed below.

A) A hydrological or eco-hydrological model used for impact assessment should be calibrated and validated in advance. For that, appropriate homogeneous and complete spatial datasets (DEM, land use and soil maps) and time series (daily climate parameters and regularly observed discharge and nutrient concentrations) are necessary for a successful model setup and calibration/validation. However, in our case in all four study areas some data were missing, or data coverage in time and/or space was problematic. Especially water quality data were insufficient in spatial and temporal dimensions in order to properly calibrate the SWIM model for water quality characteristics. Therefore, in all four cases, the model calibration for water flows and water quality variables was a very complicated task. Nevertheless, despite of all difficulties and data gaps, SWIM was calibrated and validated with satisfactory or good results for the drainage areas of all four lagoons (see LAGOONS, 2013), and the model could be applied for climate and land use change impact assessment.

B) Models are always a simplification of reality, and natural processes taking place in atmosphere, soils, water bodies and vegetation, as well as interrelations between them, are represented in models with a certain degree of accuracy. This is due to a restricted memory of computers and computation times as well as simply due to a limited human knowledge and understanding of processes. The models are characterised by a certain level of abstraction. They are never and cannot be a full copy of a system. Comparing simulated and observed global and regional climate data, several studies show the restricted ability of current climate models to satisfactorily reproduce the real local measurements (Anagnostopoulos et al., 2010; Koutsoyiannis et al., 2008; Kundzewicz and Stakhiv, 2010). Similar constraints can be also found in the hydrological and eco-hydrological models. The SWIM model, for example, is a semi-distributed model simulating processes at a hydrotope-level resolution, trying to cover the heterogeneity within a catchment to a certain extent, but it is not able to deliver locally exact projections. The different models come with different model uncertainties regarding the representation of processes, which depend on their level of complexity. To overcome the limitations and weaknesses of a single eco-hydrological or climate model, it could be useful to apply several models with the same input parameter sets (model intercomparison) for a more comprehensive assessment of uncertainties and elicitation of robust outputs (Warszawski et al., 2013; Schewe et al., 2013).

C) A further large uncertainty is connected to the scenarios themselves applied for the impact assessments. Different models come along with different scenarios, and nobody knows the most probable future climate and socio-economic development in a region, or at the national level, as it is influenced by several unpredictable factors. A common method to overcome these

problems regarding the climate scenarios is to use different global (GCM) and regional climate models (RCM) to produce and apply a set of scenarios in order to investigate the range of uncertainty. This method is preferable in comparison with applying just one climate scenario as driver (Tebaldi and Knutti, 2007; Giorgi et al., 2001). But it is still limited, and the uncertainty remains high in case of a distinct diversity in the different future climate projections, as detected, for example, for the Tyligulskyi Liman catchment in our study (LAGOONS, 2013). Nevertheless, even with possibly improved climate models, the uncertainty on future socio-economic pathways hinders perfect regional hydrological and water-quality projections, so that they still are highly uncertain (Wilby, 2010). To deal with this uncertainty, it would be favourable to apply the socio-economic scenarios with ranges, instead of exact percentages of change. This would support a more comprehensive assessment of the uncertainties related to the socio-economic assumptions.

Due to the lack of more detailed information on case-specific observations and measurements, as well as to time constraints and limited working capacity, not all possible methods to reduce uncertainties could be applied in this study. The climate and land use change impact assessment presented here delivers first results and rough estimation on probable future developments in the four case study areas. For future research, in order to diminish and better assess (but not to eliminate) uncertainty, it could be recommended to apply a set of climate scenarios and 2-3 eco-hydrological models, as well as socio-economic scenarios with ranges, for a better and more reliable combined climate and land use change impact assessment. Additionally, it would be helpful to get improved RCM scenario sets for some areas (e.g. Tyligulskyi Liman catchment). These methods would help to identify probable future risks and threats more realistically, and to virtually test possible adaptation measures, as efforts to cope with the probable future climate conditions and their impacts are needed.

Despite of all the uncertainties connected to the combined climate and land use change impact assessment presented here, some general conclusions can be drawn:

a) Except for the Mar Menor catchment and the SET scenario in the Vistula Lagoon drainage basin, the impacts of climate change on water quantity are generally stronger than the impacts of the socio-economic changes.

b) The socio-economic scenarios cause changes in different directions and magnitudes regarding water flows in the catchment, and no common trend among scenarios and/or case study areas can be detected.

c) In general, the socio-economic changes have higher impacts on nutrient loads entering the lagoons than on the total freshwater inflow to the water bodies.

d) The combined impacts on nutrient loads show diverse directions in three of the four catchments; only in the drainage basin of the Tyligulskyi Liman a decreasing trend in nutrient loads is projected for all socio-economic scenarios due to a strong climate change impact.

5 REFERENCES

Aich, V., Liersch, S., Vetter, T., Huang, S., Tecklenburg, J., Hoffmann, P., Koch, H., Fournet, S., Krysanova, V., Müller, E. N., and Hattermann, F. F. (2014) Comparing impacts of climate change on streamflow in four large African river basins. *Hydrological Earth System Sciences*, 18, 1305-1321, DOI:10.5194/hess-18-1305-2014.

Anagnostopoulos, G. G., Koutsoyiannis, D., Christofides, A., Efstratiadis, A. and Mamassis, N. (2010) A comparison of local and aggregated climate model outputs with observed data. *Hydrological Sciences Journal*, 55(7), 1094-1110, DOI: 10.1080/02626667.2010.513518.

Bates, B.C., Z.W. Kundzewicz, S. Wu and J.P. Palutikof, (eds.) (2008) Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Giorgi, F., Hewitson, B., Christensen, J.H., Hulme, M., von Storch, H., Whetton, P., Jones, R., Mearns, L. and Fu, C. (2001) Regional climate information – evaluation and projections, Chapter 10, Climate change 2001: the scientific basis. Contribution of working group I to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, 583–638.

Hattermann, F.F., Wattenbach, M., Krysanova, V. and Wechsung, F. (2005) Runoff simulations on the macroscale with the ecohydrological model SWIM in the Elbe catchment-validation and uncertainty analysis. *Hydrological Processes*, 19(3), 693–714.

Kim, J.H. and Jackson, R.B. (2012) A Global Analysis of Groundwater Recharge for Vegetation, Climate, and Soils. *Vadose Zone Journal* 11, 1, DOI:10.2136/vzj2011.0021RA.

Hesse, C., Krysanova, V., Päzolt, J.and Hattermann, F.F. (2008) Eco-hydrological modelling in a highly regulated lowland catchment to find measures for improving water quality. *Ecological Modelling*, 218, 135-148.

Hesse, C.; Krysanova, V.; Voß, A. (2012) Implementing In-Stream Nutrient Processes in Large-Scale Landscape Modeling for the Impact Assessment on Water Quality. *Environmental Modeling & Assessment* 17(6), S. 589-611, DOI: 10.1007/s10666-012-9320-8.

Hesse, C., Krysanova, V., Stefanova, A., Bielecka, M. and Domnin, D.A. (2014) Assessment of climate change impacts on water quantity and quality of the multi-river Vistula Lagoon catchment. *Hydrological Sciences Journal*, DOI: 10.1080/02626667.2014.967247

Krysanova, V., Mueller-Wohlfeil, D.I. and Becker, A., (1998) Development and test of a spatially distributed hydrological / water quality model for mesoscale watersheds. *Ecological Modelling*, 106, 261-289.

Krysanova, V., Wechsung, F., Arnold, J., Srinivasan, R. and Williams, J. (2000) SWIM (Soil and Water Integrated Model): User Manual. In: PIK Report No. 69, Potsdam.

Krysanova, V., Hattermann, F., Huang, S., Hesse, C., Vetter, T., Liersch, S., Koch, H. and Kundzewicz, Z. (2014) Modelling climate and land-use change impacts with SWIM: lessons learnt from multiple Applications. *Hydrological Sciences Journal*, DOI: 10.1080/02626667.2014.925560

Kundzewicz, Z.W. and Stakhiv, E.Z. (2010). Are climate models "ready for prime time" in water resources management applications, or is more research needed? *Hydrological Sciences Journal*, 55 (7), 1085-1089.

LAGOONS (2012a) The Vistula Lagoon – Current knowledge base and knowledge gaps. LAGOONS Report D2.1a, 99pp.

LAGOONS (2012b) The Ria de Aveiro Lagoon – Current knowledge base and knowledge gaps. LAGOONS Report D2.1b, 52pp.

LAGOONS (2012c) The Mar Menor Lagoon – Current knowledge base and knowledge gaps. LAGOONS Report D2.1c, 65pp.

LAGOONS (2012d) The Tyligulskyi Lagoon – Current knowledge base and knowledge gaps. LAGOONS Report D2.1d, 54pp.

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

LAGOONS (2014a) Final scenarios. LAGOONS Report D4.2, 45pp.

LAGOONS (2014b) Modelling results and recommendations. LAGOONS Report D6.2, 182 pp.

Liersch, S., Cools, J., Kone, B., Koch, H., Diallo, M., Reinhardt, J., Fournet, S., Aich, V. and Hattermann, F.F. (2012) Vulnerability of rice production in the Inner Niger Delta to water resources management under climate variability and change. *Environmental Science & Policy*, 34, 18-33.

Meehl, G.A., T.F. Stocker and Co-authors (2007) Global climate projections. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt,M. Tignor andH.L.Miller, Eds., CambridgeUniversity Press, Cambridge,747-846.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., Dankers, R., Eisner, S., Fekete, B., Colón-González, F.J., Gosling, S.,N., Kim, H., Liu, X., Masaki, Y, Portmann, F.T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L., Kabat, P. (2013) "Multi-model assessment of water scarcity under climate change", Proceedings of the National Academy of Sciences, 111, 9, 3245-3250. DOI:10.1073/pnas.1222460110

Stefanova, A., Krysanova, V., Hesse, C. and Lillebo, A.I. (2015) Climate change impact assessement on water inflow to a coatal lagoon – Ria de Aveiro watershed, Portugal. *Hydrological Sciences Journal* (accepted)

Tebaldi, C. and Knutti, R. (2007). The use of the multi-model ensemble in probabilistic climate projections. Philosophical Transactions of the Royal Society, 365, 2053-2075

Vetter, T., Huang, S., Yang, T., Aich, V., Wang, X., Gu, H., Krysanova, V. and Hattermann, F.F. (2013) Intercomparison of climate impacts and evaluation of uncertainties from different sources using three regional hydrological models for three river basins on three continents. In: Proceedings of the IMPACTS World conference.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., Schewe, (2013) "The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP)", Proceedings of the National Academy of Sciences, 111, 9, 3228-3232. DOI:10.1073/pnas.1312330110

Wilby, R.L. (2010) Evaluating climate model outputs for hydrological applications. *Hydrological Sciences Journal*, 55 (7), 1090-1093.