NEXOGENESIS
STREAMLINING WATER RELATED POLICIES

Deliverable 3.6

Sensitivity/Uncertainty Analysis Report

Lead: IHE
Date: February 2024

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Project Deliverable

Project Number	Project Acronym	Project Title
101003881	NEXOGENESIS	Facilitating the next generation of effective and intelligent water-related policies, utilising artificial intelligence and reinforcement learning to assess the water-energy-food-ecosystem (WEFE) nexus

Instrument:	Thematic Priority
H2020 RIA	LC-CLA-14-2020

Start Date of the project	Duration
01 September 2021	48 months

Organisation name of lead contractor for this deliverable	Document version
IHE	1

Dissemination level	Deliverable Type
Public	**Report**

Authors (organisations)
Janez Sušnik, Sara Masia, Henry Amorocho Daza (IHE); Nikos Mellios, Giannis Kourtis (UTH); Stefano Terzi, (EURAC).
Reviewers (organisations)
Antonio Trabucco (CMCC)

NEXOGENESIS STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Abstract

This Deliverable demonstrates the application of the uncertainty analyses in system dynamics models of the water-energy-food-ecosystems nexus of the five NEXOGENESIS case studies. For each of the case studies (Nestos-Mesta, Lielupe, Jiu, Adige, Inkomati-Usuthu), both model parametric and scenario uncertainty are assessed, with results presented for every case. These results demonstrate that the uncertainty approach has been successfully implemented in the SDMs. This is critical, as this information will feed into the development of the NEXOGENESIS NEPAT decision support tool. It also means that policy makers and planners will, for this first time in the WEFE context, have more information at their disposal to evaluate uncertainties associated with model results. Rather than relying on a single model forecast, a wide spectrum of potential futures is now provided. As a result, policies and strategies can be developed that are flexible to a wider range of potential outcomes, making them more robust under development in an uncertain future.

List of abbreviations

BAU – business as usual

CLD – Causal Loop Diagram

CS – Case Study

D – Deliverable

ES – Ecosystems Services

GHG – Greenhouse Gas

LRB – Lielupe River Basin

NEPAT – NExus Policy Assessment Tool (the new name for the SLNAE)

NBS – Nature Based Solutions

RCP – Representative Concentration Pathway

PCF – Precipitation Correction Factor

PV - PhotoVoltaic

SDM – System Dynamics Modelling

SH – stakeholder

SFD – Stock Flow Diagram

NEXOGENESIS
STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

SLNAE – Self Learning Nexus Assessment Engine

SSP – Shared Socio-economic Pathway

WEFE – Water-Energy-Food-Ecosystems

WS – workshop

Keywords

Case studies; System dynamics; uncertainty analysis; WEFE nexus.

Disclaimer

All results presented in this Deliverable are draft at the time of writing. They are not intended for scientific recommendations or policy advice, and are all subject to change.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Table of Contents

Contents

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

1. Introduction and purpose of the Deliverable

Deliverable 3.6 shows how uncertainty is characterised within NEXOGENESIS, and presents output from the five case studies (Nestos-Mesta; Lielupe; Jiu; Adige; Inkomati-Usuthu) to demonstrate that uncertainty characterisation and assessment has been implemented in the system dynamics models. Thus, the purpose of the Deliverable is to present the results of the uncertainty assessment coming from the five case study system dynamics models.

First by way of introduction, a brief recap of the case studies, including the developed conceptual maps and system dynamics model (SDM) structure is presented (though not in depth as much of this is covered in earlier Deliverables, which are referenced). Following this, a second recap on the methodological approach of uncertainty assessment in the NEXOGENESIS SDMs is provided. Again, this is a summary of more detailed information provided in an earlier Deliverable, and is provided for completeness of information rather than a detailed report.

Section 4 then presents in depth the results of the uncertainty assessment in the five case studies. For each case study, results from the different sectors (water, energy, food, land, ecosystems, climate) are presented. In addition, results for both parametric and scenario uncertainty are presented, giving considerable detail as to the progress made in NEXOGENESIS systems modelling.

Section 5 describes the utility of the uncertainty analysis, and how they may be put to good use by stakeholders in policy and decision making, while Section 6 concludes by commenting on how the uncertainty work will be used in the remainder of NEXOGENESIS.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

2. Case study conceptual maps / causal loop diagrams, and System Dynamics Model descriptions

In NEXOGENESIS, system dynamics has been selected as the modelling approach of choice. The rationale for this, and a detailed description of the system dynamics modelling approach are given in Deliverable 3.2 “Final report on the complexity science and integration methodologies”. This information will not be repeated here. Likewise,

Detailed descriptions of the conceptual models and system dynamics models for all case studies are found in Deliverable 3.4 and are not repeated here. Please refer to Deliverable 3.4 for full details. This Deliverable presents results derived from those described SDMs.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101003881

3. Sensitivity and uncertainty assessed in NEXOGENESIS

In NEXOGENESIS, two main sources of uncertainty are tested: parametric uncertainty and scenario uncertainty. Parametric uncertainty deals with exploring the uncertainty in a given model variable and assessing its overall impact to model results. For example, crop yields estimated from a number of different external models, and provided via WP2 data, often give a range of values for the same variable (e.g. irrigated maize yield per hectare). As a result, it is worth exploring the entire input model ensemble variability (or uncertainty), and assessing the impact of this on SD model outputs. Similarly, for other inputs such as surface water runoff, there is uncertainty around the external models' values being used as input to the SDMs. Therefore, this range of model uncertainty will be explored in the NEXOGENESIS SD models. This concept is illustrated schematically in Figure 1. Here, a variable, X, is given by multiple external models provided from WP2. These models give a range of values for this variable over time. At each time point, the range in model values gives a minimum and a maximum. Between the minimum and maximum values, one can assume, in the absence of better information, a uniform statistical distribution of values, illustrated by the inset in Figure 45. In this concept, all values between minimum and maximum have equal probability of occurrence. Outside this range, the probability is zero. Stochastic Monte-Carlo sampling of a uniform distribution between minimum and maximum for this parameter is propagated through the SD models, with all affected variables being impacted by the value selected on each Monte-Carlo simulation. In this way, by performing a sufficient number of sample runs (e.g. 100), the uncertainty associated with a given parameter, as well as its impact across the entire SDM output can be assessed.

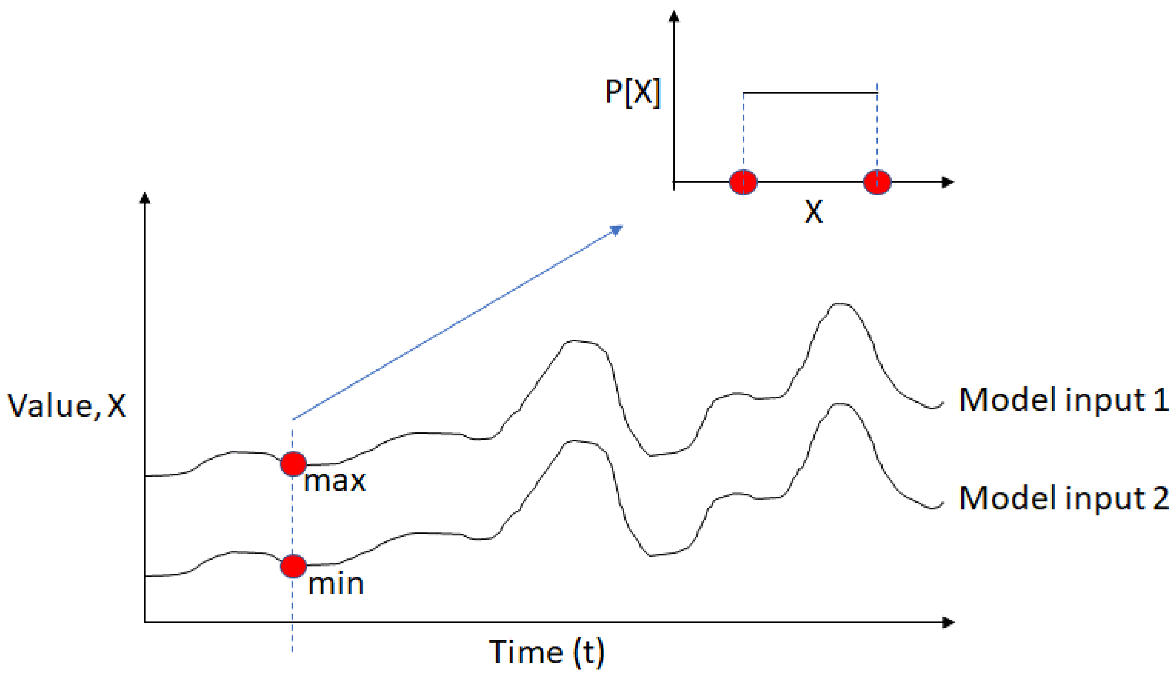


Figure 1: illustration of the concept behind model parametric uncertainty in NEXOGENESIS SDMs. The concept illustrated is repeated at every model timestep.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Scenario uncertainty deals with assessing the difference between future projections of a system development. The future is unknown. While broad trends can be described, the details are subject to uncertainty. For example, the Shared Socioeconomic Pathways (SSPs) describe a number of plausible development narratives for society based on assumptions around, for example, fertility rates, levels of cooperation or competition, etc. These different SSPs give rise to a variety of estimations around population trends, the level of demand for certain products, the supply and availability of different materials, and so on. Likewise, the climate system future is also uncertain, depending to a large extent on how society chooses to source its energy in the future (NB: there is therefore some relationship between the SSPs and climate pathways, given by the Representative Concentration Pathways; RCPs). Different climate projections, depending to a large extent on the emission of greenhouse gases from burning of fossil fuels and agricultural production, lead to differences in, for example, precipitation patterns, temperature patterns, crop yields, and crop water requirements. The differences between SSPs and RCPs represent scenario uncertainty, which will be captured in NEXOGENESIS by testing four different scenario combinations: RCP26-SSP2; RCP26-SSP4; RCP85-SSP2; RCP85-SSP4.

Sensitivity testing will assess the impact on model outputs by changing one parameter at a time and observing the impacts. In each Case Study, a number of important input parameters will be identified. These will then be changed by, for example, +/-20% from the original, baseline value. The impact of these changes on model output parameters will be observed and reported. Outputs that are more sensitive to change will display a greater level of variability to changes in the input parameter that is changed, and vice versa.

Deliverable 3.5 “Sensitivity and uncertainty analysis” outlines in greater detail the uncertainty assessment, scenario analysis, and sensitivity tests carried out in NEXOGENESIS.

All analyses in this Deliverable are conducted based on case-study specific data that have been scaled appropriately and provided via Work Package 2 to meet the requirements of NEXOGENESIS model development and case study needs. These data, both biophysical and socioeconomic, are explained and detailed at length in Deliverables D2.2, 2.3, and 2.4. Some data derive from local case-study sources to fill data gaps not covered by the WP2 data.

NEXOGENESIS
STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101003881

4. Uncertainty and sensitivity results from the Case Studies

4.1 Case Study #1: Nestos/Mesta River Basin

In the following sections, sample uncertainty outcomes in a range of parameters of the Nestos system dynamics model are showcased. The uncertainty analysis conducted is two-fold: parametric and scenario-based. Parametric uncertainty refers to the uncertainty associated with the values of the model parameters, and it arises from the imperfect knowledge or variability of true values of these parameters. Parametric uncertainty acknowledges that these parameter values might not be precisely known and that their uncertainty can influence the model's predictions or outcomes. Therefore, it's essential to understand and quantify parametric uncertainty to assess the reliability and robustness of model results. To illustrate parametric uncertainty, the RCP2.6-SSP2 scenario is employed to exemplify the variability linked to both input and output parameters of the model. Scenario-based uncertainty involves uncertainty arising from different potential scenarios or future conditions. Scenario-based uncertainty acknowledges that the future is uncertain, and that the actual outcome depends on which scenario unfolds. Therefore, assessing scenario-based uncertainty involves analyzing the variability in outcomes across different scenarios and understanding the implications of this uncertainty for decision-making. Under these lines, the outcomes between different scenarios are contrasted, specifically comparing the RCPs (2.6 and 8.5) and the SSPs (2 and 4).

In the Nestos-Mesta case study, we focus on analyzing the uncertainty of selected parameters related to river water and food production at the sub-basin level. Consequently, we chose key sub-basins in both countries. In Bulgaria, sub-basin W430 was chosen because it is the last sub-basin before the water enters Greek territory. In Greece, we selected sub-basin W970, as it is the final sub-basin before the water flows into the Aegean Sea. To address the uncertainty of other ecosystem-related parameters, such as mean species abundance and carbon mass in vegetation, we perform the analysis at a regional level. This approach represents the uncertainty for the entire system of sub-basins within both the Bulgarian and Greek territories. In the Nestos-Mesta CS, the key parameters tested are:

- River basin runoff in sub-basin W430 - BG
- River basin runoff in sub-basin W970 - GR
- River nitrogen concentration in sub-basin W430 - BG
- River nitrogen concentration in sub-basin W970 - GR
- Maize grown alone production in sub-basin W430 - BG
- Maize grown alone production in sub-basin W970 - GR
- Potatoes production in sub-basin W430 - BG
- Potatoes production in sub-basin W970 - GR

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

- Mean species abundance for birds - BG
- Mean species abundance for mammals - BG
- Mean species abundance for amphibians - BG
- Carbon mass in vegetation - BG
- Mean species abundance for birds - GR
- Mean species abundance for mammals - GR
- Mean species abundance for amphibians - GR
- Carbon mass in vegetation – GR

These were selected because they represent key parameters of interest for the transboundary case study and encompass essential nexus sectors.

4.1.1 Parametric uncertainty

As the Nestos case study involves transboundary considerations and the model operates at a sub-basin level (with 7 river basins in Bulgaria and 4 in Greece), certain parametric uncertainty findings, particularly regarding water aspects, are highlighted in W430 (the final Bulgarian river basin before the river crosses into Greek territory) and W970 (the downstream last Greek river basin before the river flows into the Aegean Sea). In all figures, Month 1 corresponds to January 2015.

Within the Water sector, Figures 46 and 47 present the outcomes of parametric uncertainty concerning the runoff of W430 and W970 river basins, respectively. The solid red lines represent the minimum values, while the solid blue lines represent the maximum values of a series of runoff model outcomes. The dotted black lines indicate the sample values at each timestep, derived from a uniform distribution. This figure description applies to the entire range of figures presented concerning parameter uncertainty, regardless of the specific parameter being examined.

As evident from the two figures, there is considerable uncertainty between the runoff parameter values, with large differences between minimum and maximum values across the simulation time horizon, in both river basins. This is expected, given that runoff estimations derived from various models over a 35-year time horizon inherently involve a high degree of uncertainty. The probability distribution for runoff at different time intervals is shown in Figures 2 and 3, for BG - W430 and GR - W970 river basins, respectively.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

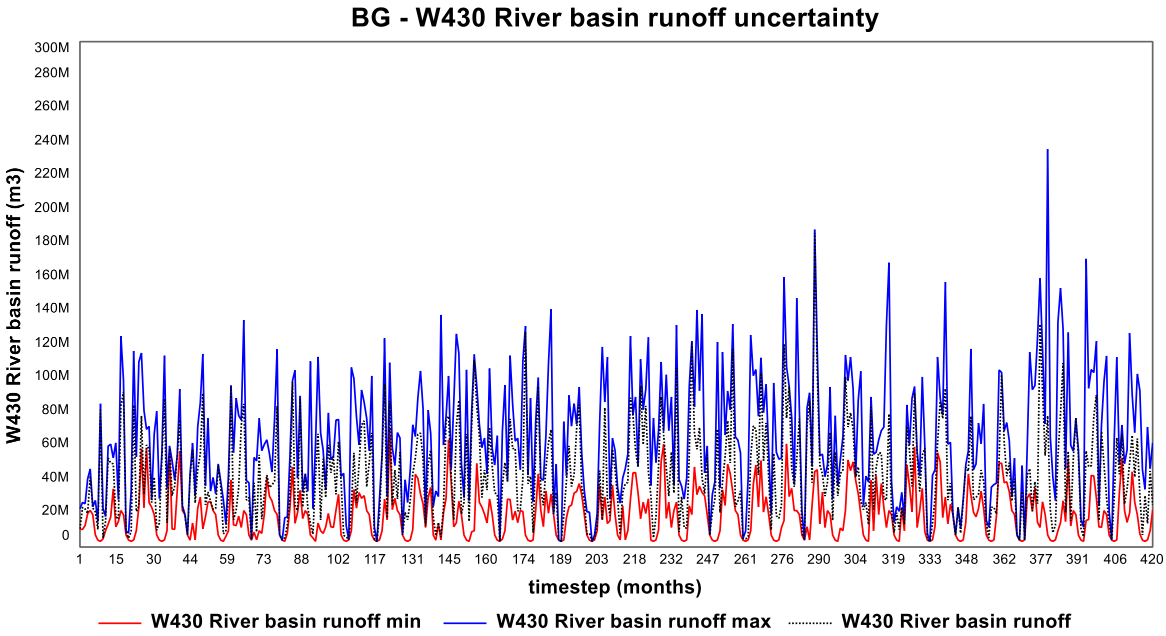


Figure 2: Uncertainty for the BG – W430 River basin runoff parameter for the RCP2.6-SSP2 scenario in the Nestos case study.

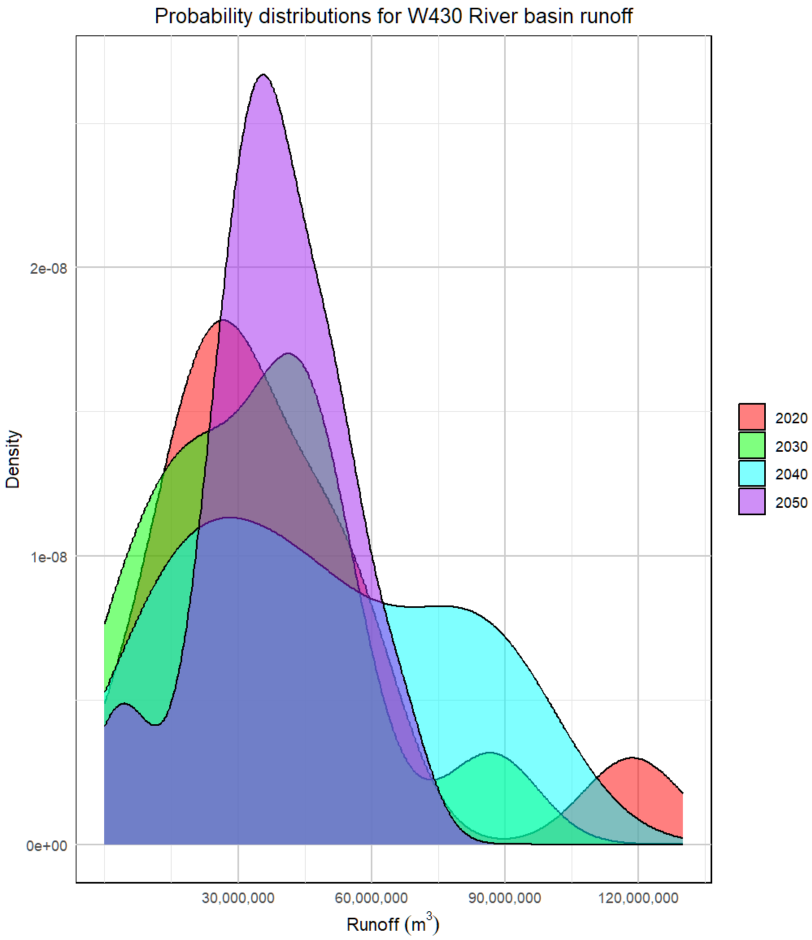


Figure 3: Probability distributions for the BG - W430 River basin runoff at different time intervals

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

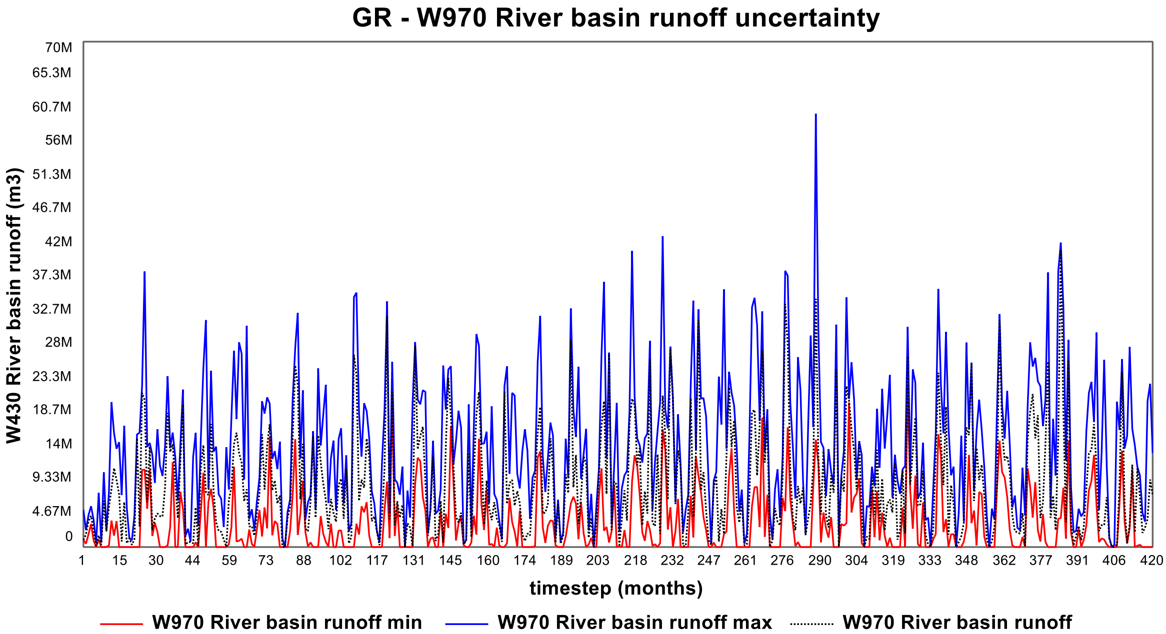


Figure 4: Uncertainty for the GR – W970 River basin runoff parameter for the RCP2.6-SSP2 scenario in the Nestos case study.

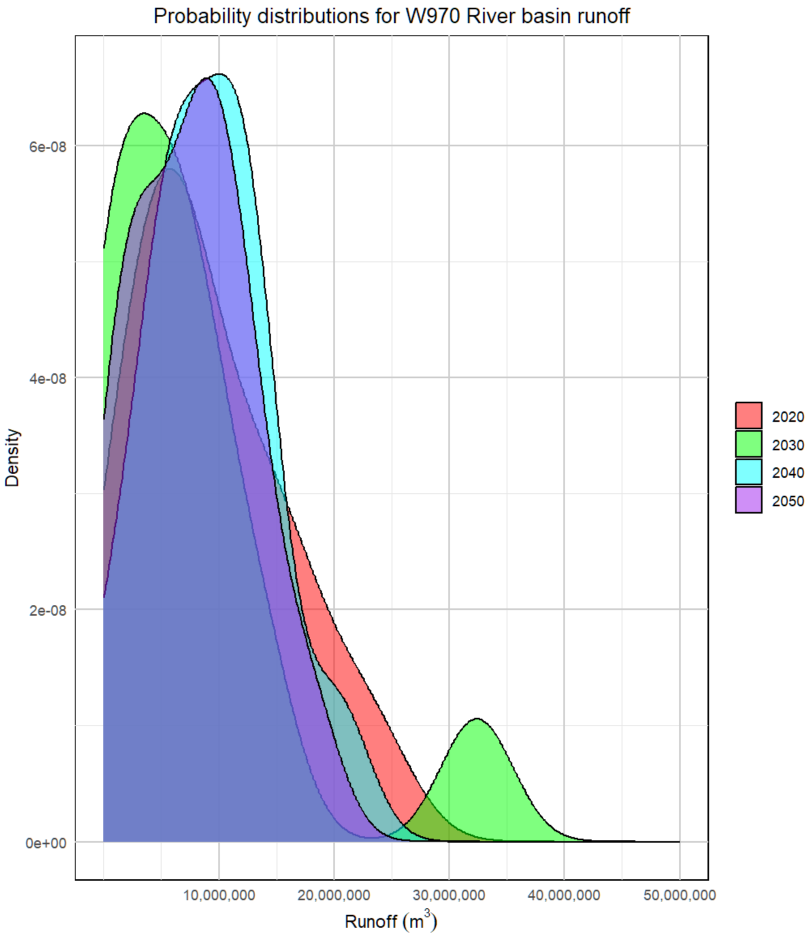


Figure 5: Probability distributions for the GR - W970 River basin runoff at different time intervals

Another crucial element of the water resources in the Nestos case study' involves the uncertainty stemming from the estimation of river nitrogen concentration. Figures 6 and 7

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

depict the results of parametric uncertainty regarding the river nitrogen concentration in the W430 and W970 river basins, respectively. This uncertainty arises from the amount of nitrogen application in the crop types within the river basins, from the leaching factor affecting the river, and of course from the runoff uncertainty which affects river water discharge volume.

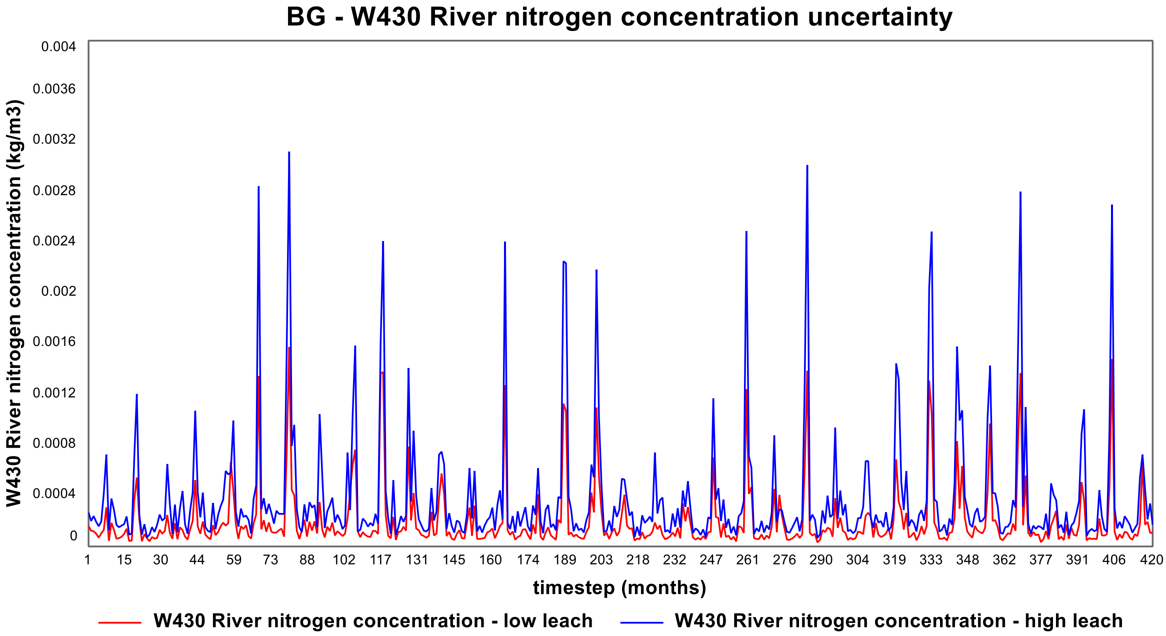


Figure 6: Uncertainty for the BG – W430 River nitrogen concentration parameter for the RCP2.6-SSP2 scenario in the Nestos case study.

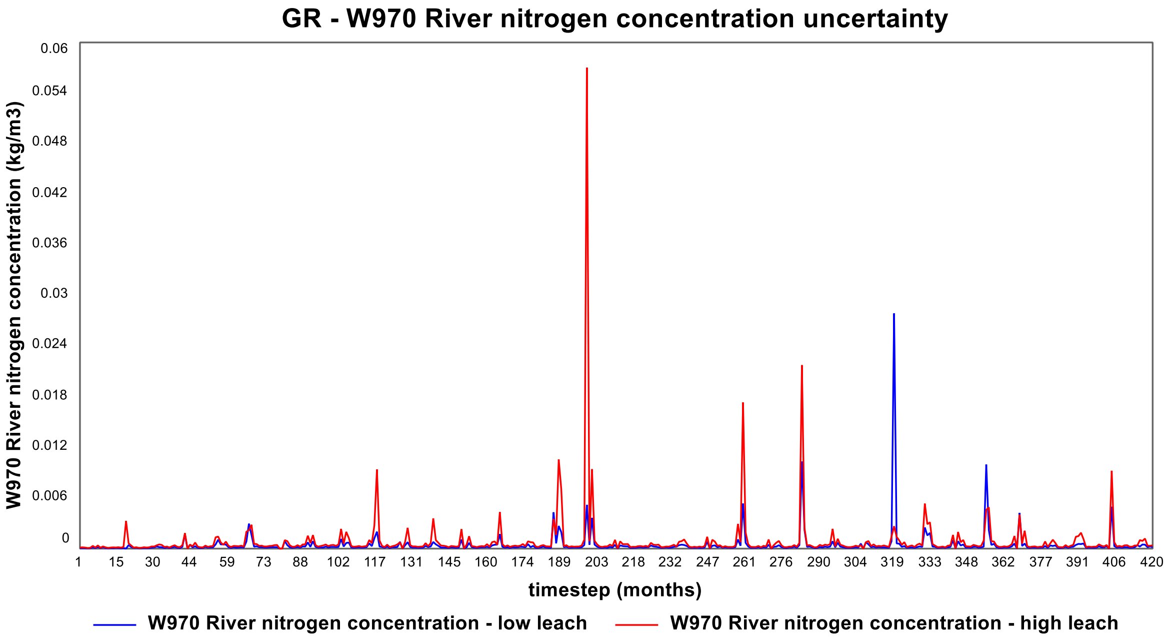


Figure 7: Uncertainty for the GR – W970 River nitrogen concentration parameter for the RCP2.6-SSP2 scenario in the Nestos case study.

In the Food domain, Figures 8 and 9 depict the results of parametric uncertainty regarding maize production for W430 and W970, respectively. Additionally, Figures 10 and 11 illustrate

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

the outcomes of parametric uncertainty concerning potato production for both river basins. It's important to note that within both the Bulgarian and Greek river basins, models provide crop productivity estimates based on climate and other environmental conditions for rice, sorghum, and soybeans, in addition to maize and potatoes. Estimates for all other crop productions are sourced from national statistical authorities.

The considerable fluctuation in production uncertainty arises from both the estimation of production factors for each crop (kg/m^2) by the models and the estimation of crop areas projected until the time horizon of 2050.

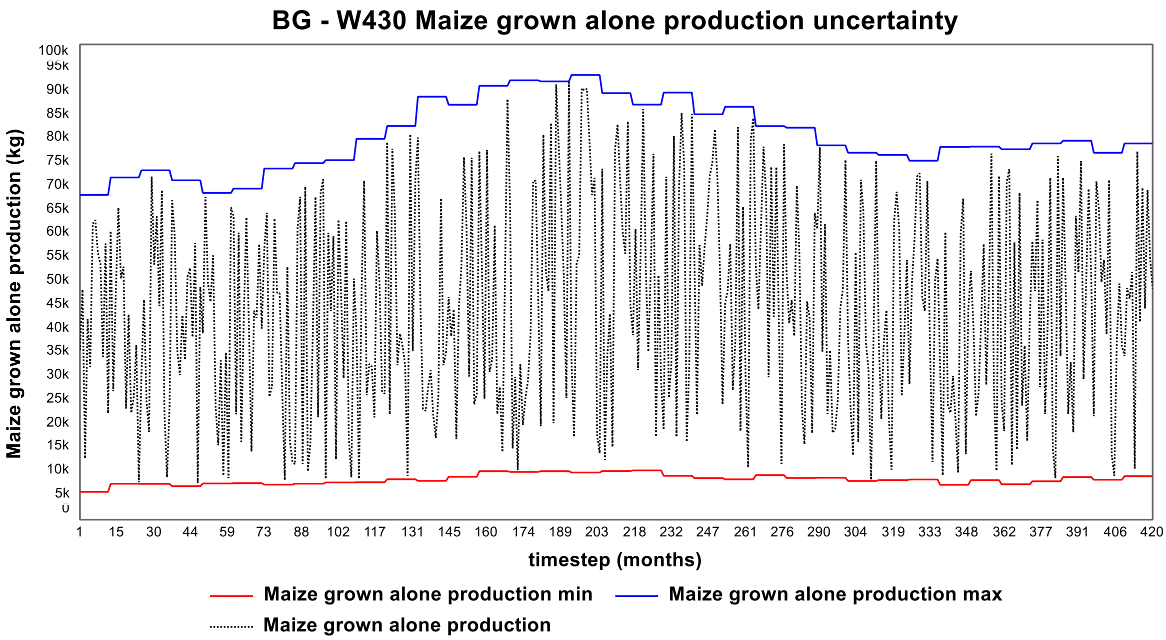


Figure 8: Uncertainty for BG – W430 River basin maize grown alone production parameter for the RCP2.6-SSP2 scenario in the Nestos case study.

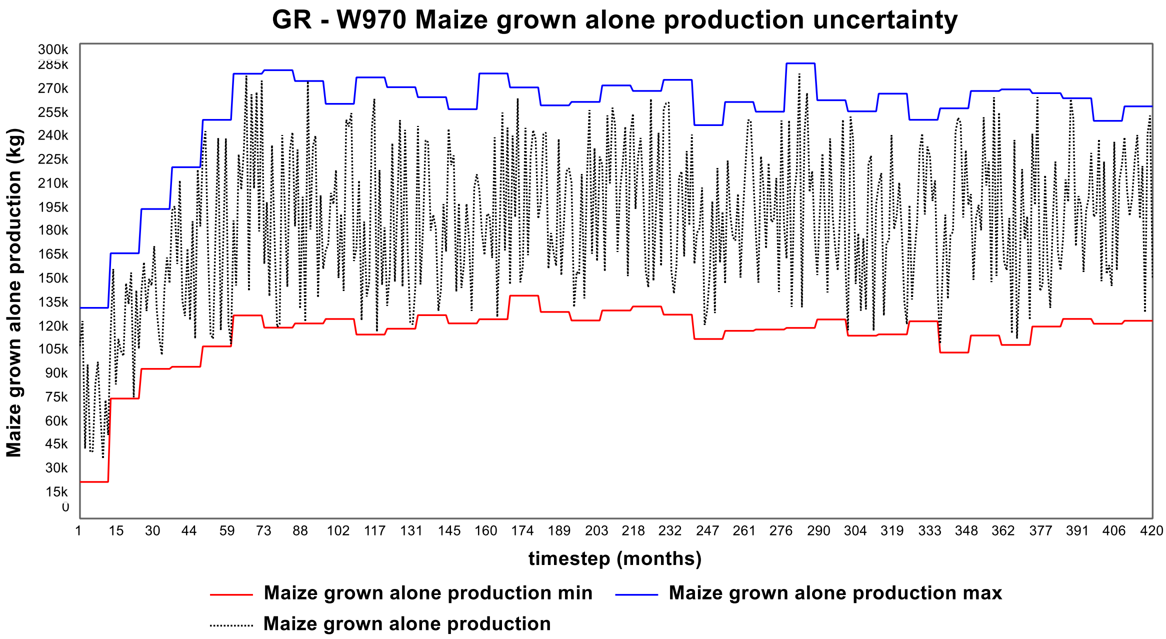


Figure 9: Uncertainty for GR – W4970 River basin maize grown alone production parameter for the RCP2.6-SSP2 scenario in the Nestos case study.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

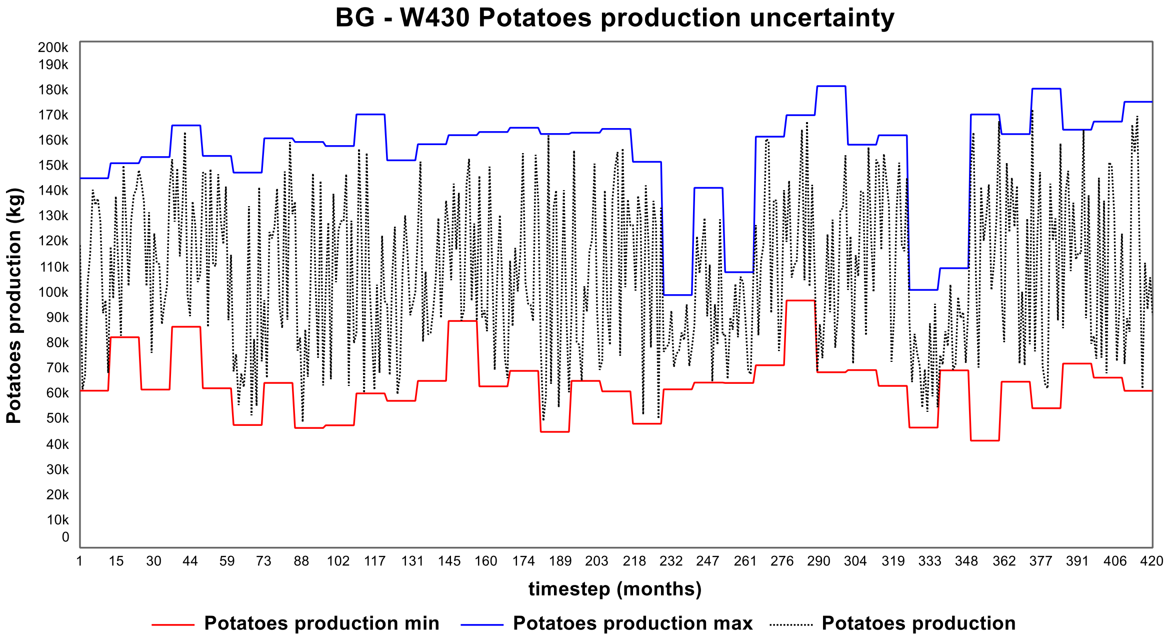


Figure 10: Uncertainty for BG – W430 River basin potatoes production parameter for the RCP2.6-SSP2 scenario in the Nestos case study.

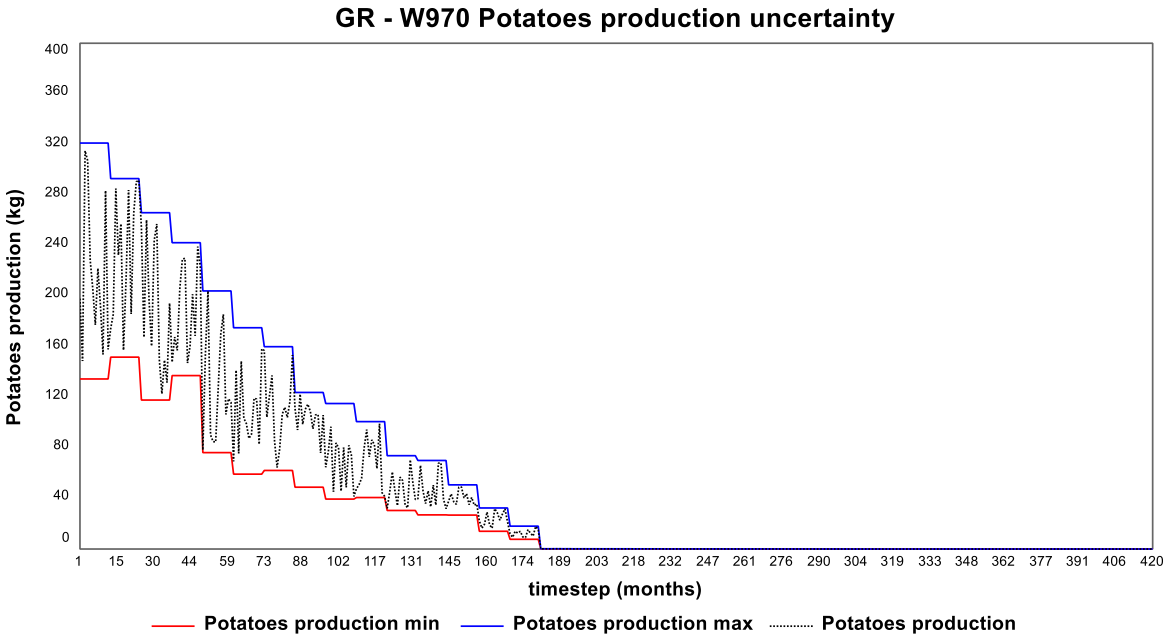


Figure 11: Uncertainty for GR – W970 River basin potatoes production parameter for the RCP2.6-SSP2 scenario in the Nestos case study.

Within the Ecosystems sector, parametric uncertainty affects the mean species abundance (birds, mammals, and amphibians) and carbon mass in vegetation across the entire Bulgarian and Greek river basins territories. Figures 12-15 illustrate the uncertainty outcomes related to the mean species abundance for birds, mammals, amphibians, and the carbon mass in vegetation for the Bulgarian territory, while Figures 58-61 illustrate the respective parameters'

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

uncertainty for the Greek territory. The probability distribution for carbon mass in vegetation at different time intervals is shown in Figures 16 and 17, for BG and GR, respectively.

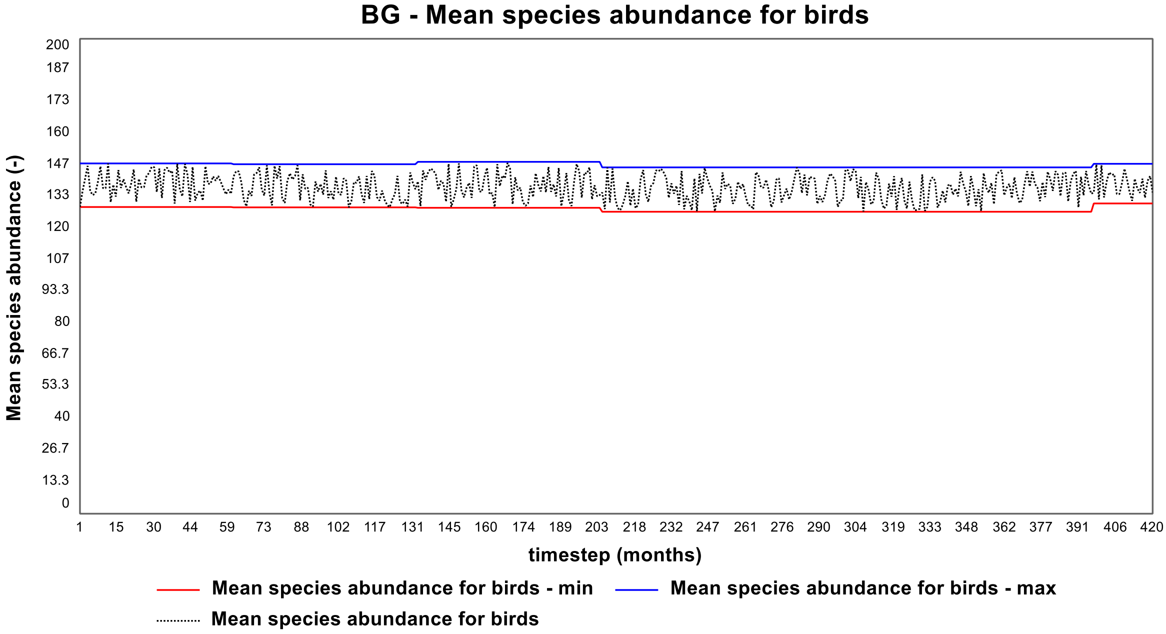


Figure 12: Uncertainty for the mean species abundance for birds' parameter for the RCP2.6-SSP2 scenario in the Bulgarian river basins territory.

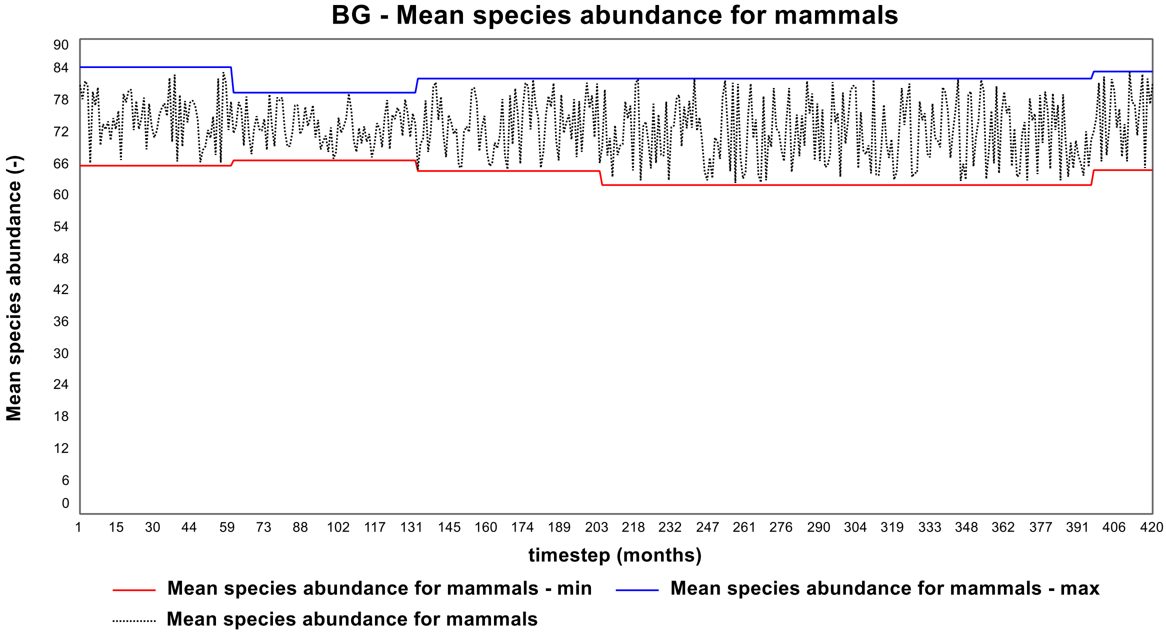


Figure 13: Uncertainty for the mean species abundance for mammals' parameter for the RCP2.6-SSP2 scenario in the Bulgarian river basins territory.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

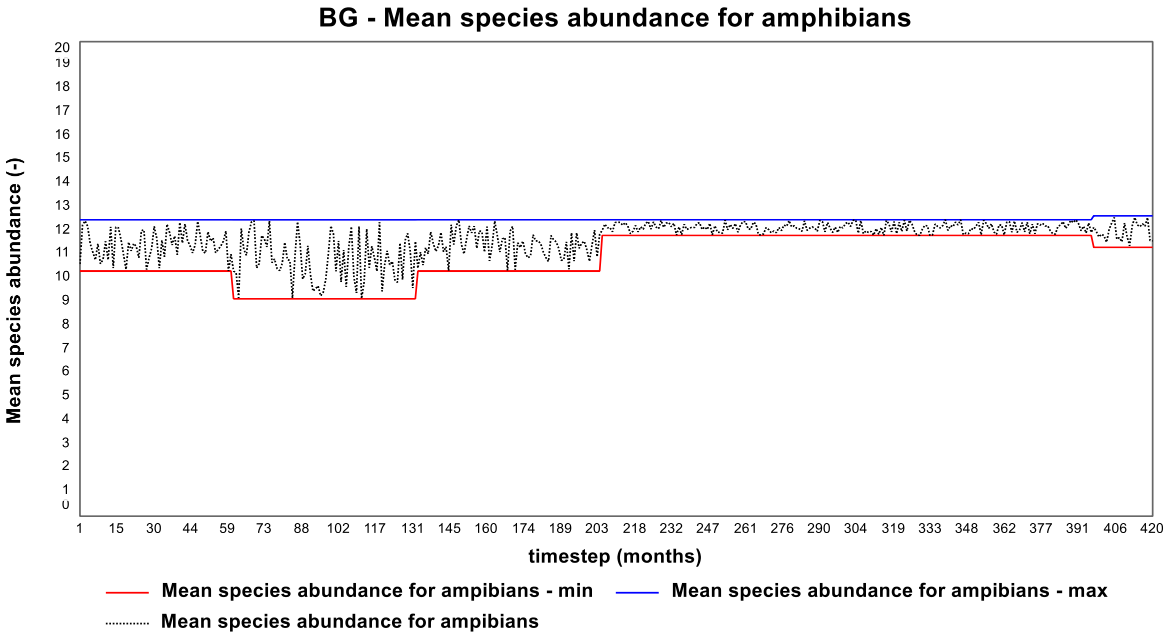


Figure 14: Uncertainty for the mean species abundance for amphibians' parameter for the RCP2.6-SSP2 scenario in the Bulgarian river basins territory.

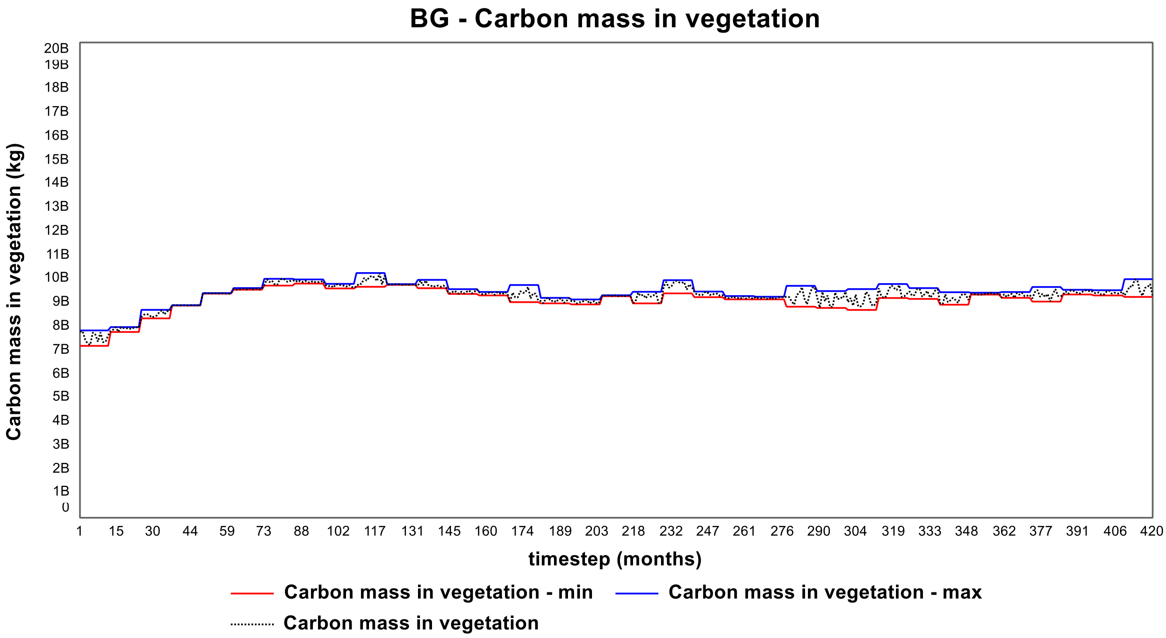


Figure 15: Uncertainty for the carbon mass in vegetation parameter for the RCP2.6-SSP2 scenario in the Bulgarian river basins territory.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

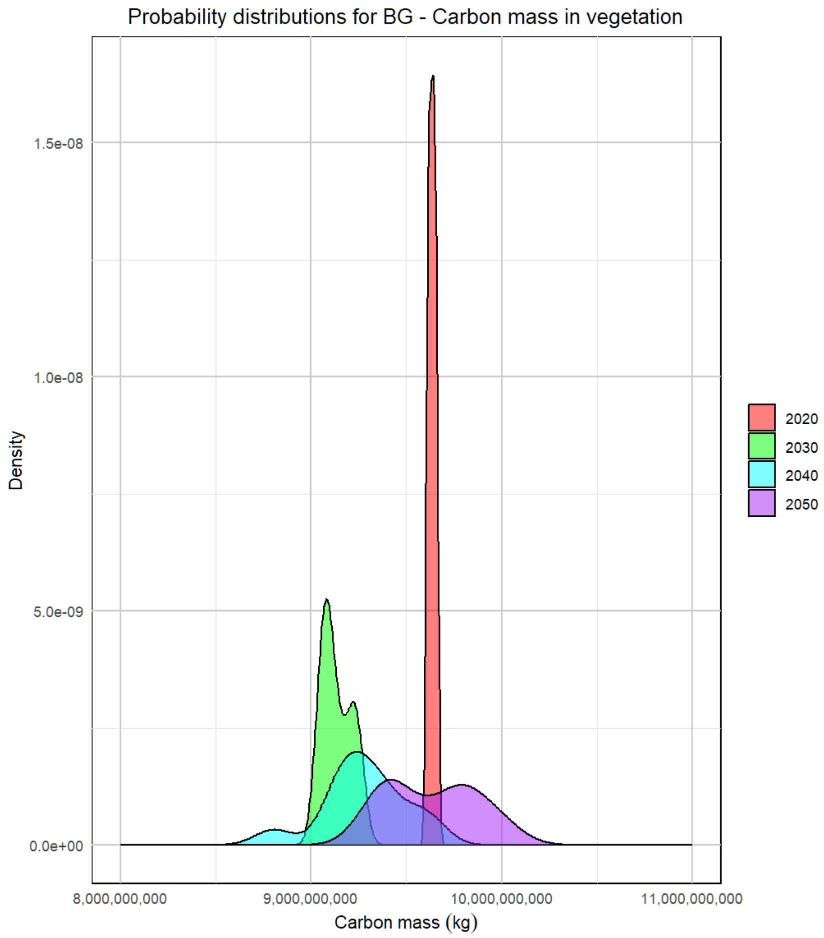


Figure 16: Probability distributions for the BG – Carbon mass in vegetation at different time intervals

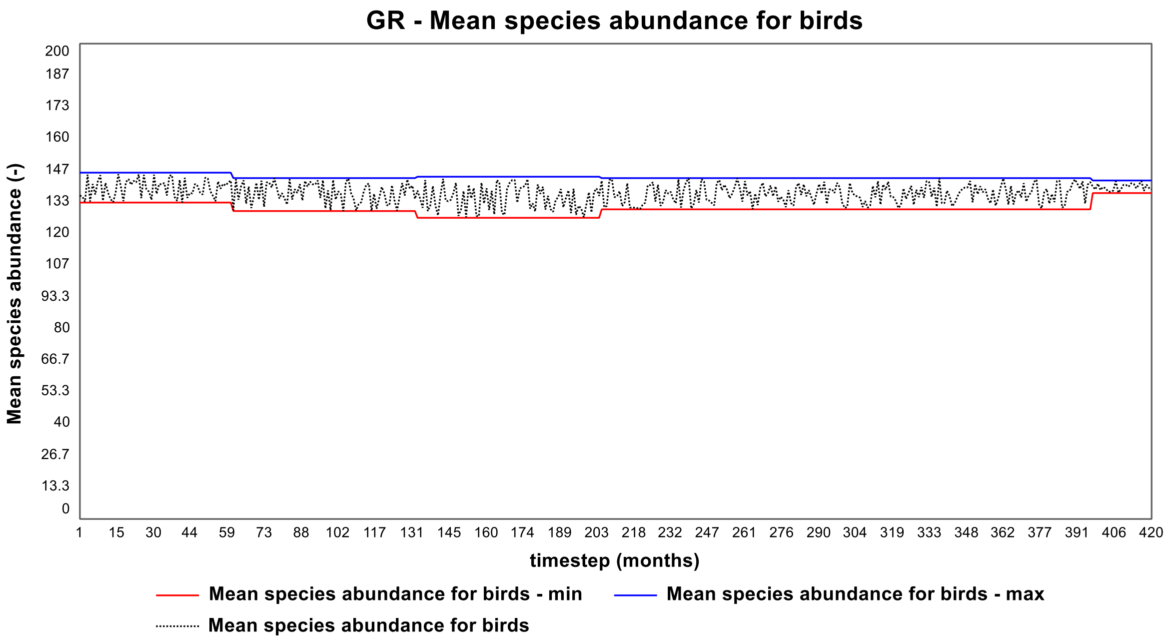


Figure 17: Uncertainty for the mean species abundance for birds' parameter for the RCP2.6-SSP2 scenario in the Greek river basins territory

NEXOGENESIS
STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

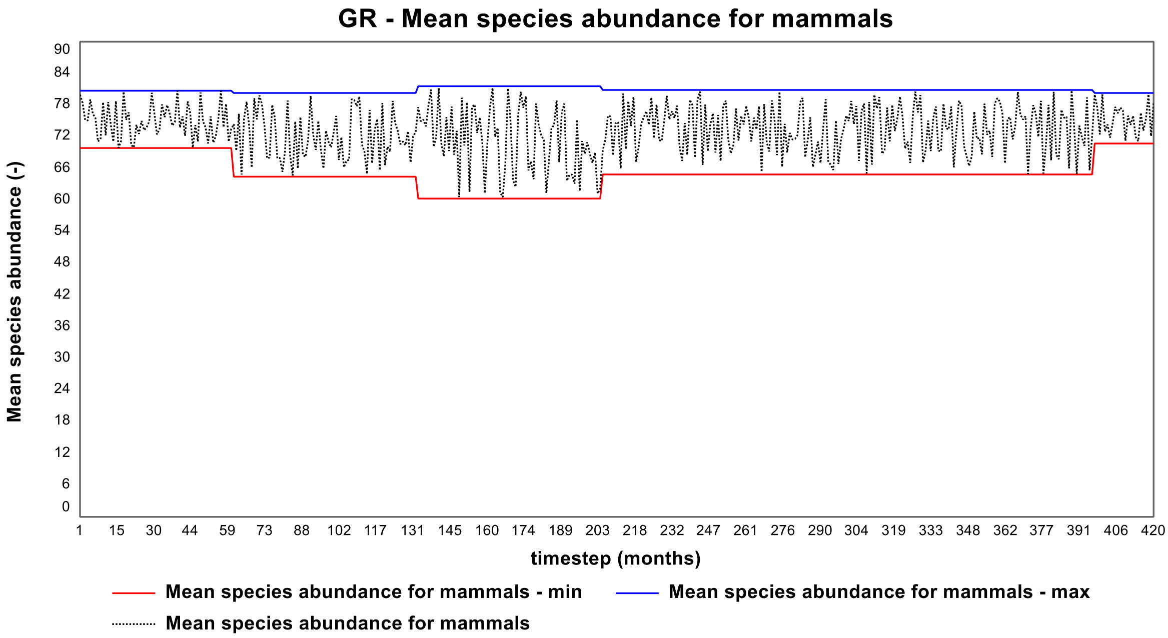


Figure 18: Uncertainty for the mean species abundance for mammals' parameter for the RCP2.6-SSP2 scenario in the Greek river basins territory.

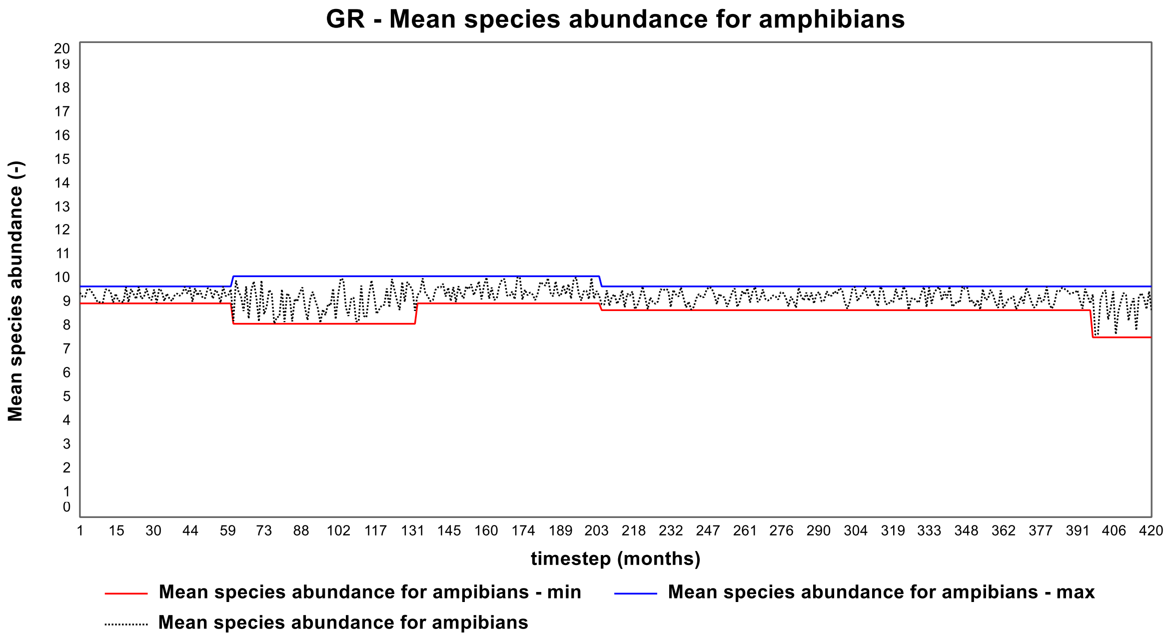


Figure 19: Uncertainty for the mean species abundance for amphibians' parameter for the RCP2.6-SSP2 scenario in the Greek river basins territory.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

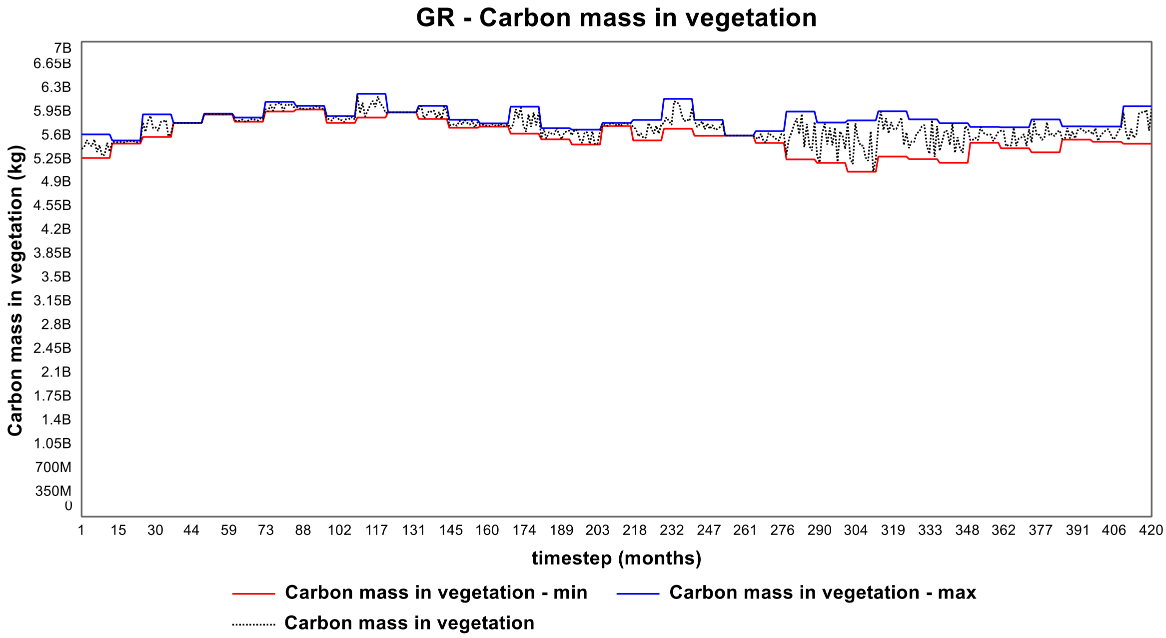


Figure 20: Uncertainty for the carbon mass in vegetation parameter for the RCP2.6-SSP2 scenario in the Greek river basins territory.

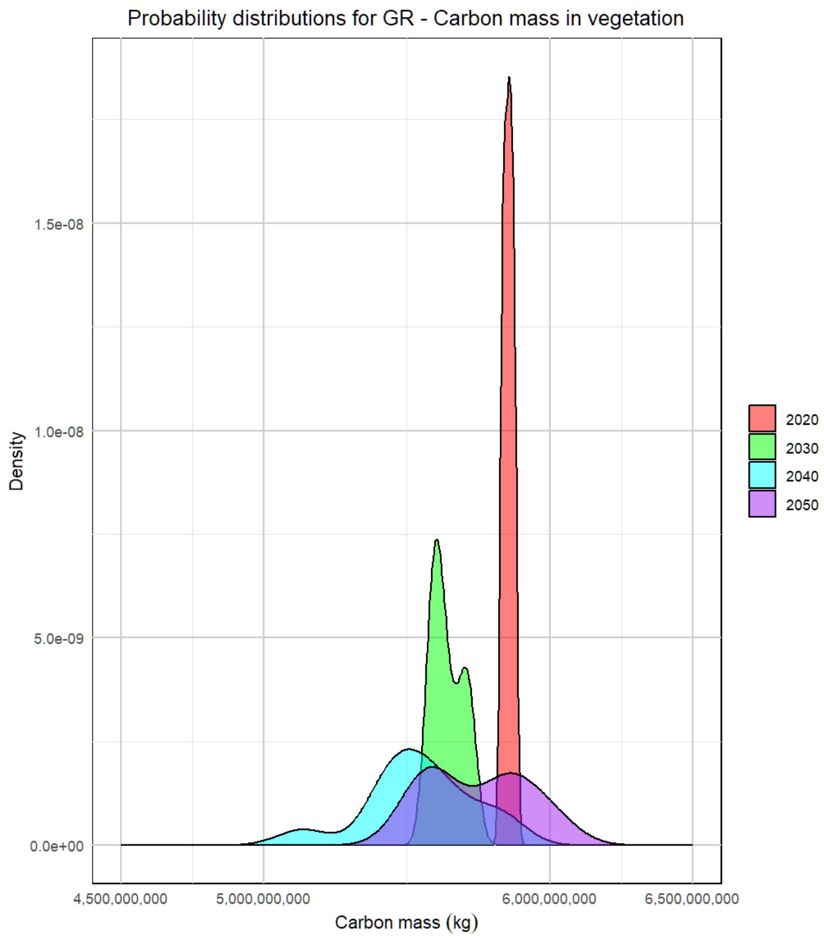


Figure 21: Probability distributions for the GR – Carbon mass in vegetation at different time intervals.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

In the sectors of energy and climate, a formal parametric uncertainty analysis was not conducted, as the data were sourced from reputable national statistical authorities and pertinent literature. However, it's important to note that numerous energy and climate parameters are directly influenced by uncertainties surrounding factors such as population dynamics, crop cultivation areas, livestock numbers, and others. Consequently, the presence of uncertainty stemming from these factors is inherent in a diverse array of energy and climate parameters, such as energy demand and CO^2 emissions from agriculture-livestock, among others.

4.1.2 Scenario uncertainty

This section highlights key uncertainty findings showcasing the disparity in outcomes for identical parameters across different climate scenarios, specifically contrasting the RCP climate scenarios (RCPs 2.6 and 8.5) and the socio-economic scenarios (SSP2 and SSP4).
Concerning population projections across the entire river basins in Bulgarian and Greek territories, Figures 22 and 23 depict the varying trajectories of population dynamics under the SSP2 and SSP4 scenarios, respectively. Notably, both territories exhibit a positive population trend across both SSP scenarios, with SSP2 indicating a more pronounced incline and respective larger population growth, compared to SSP4.

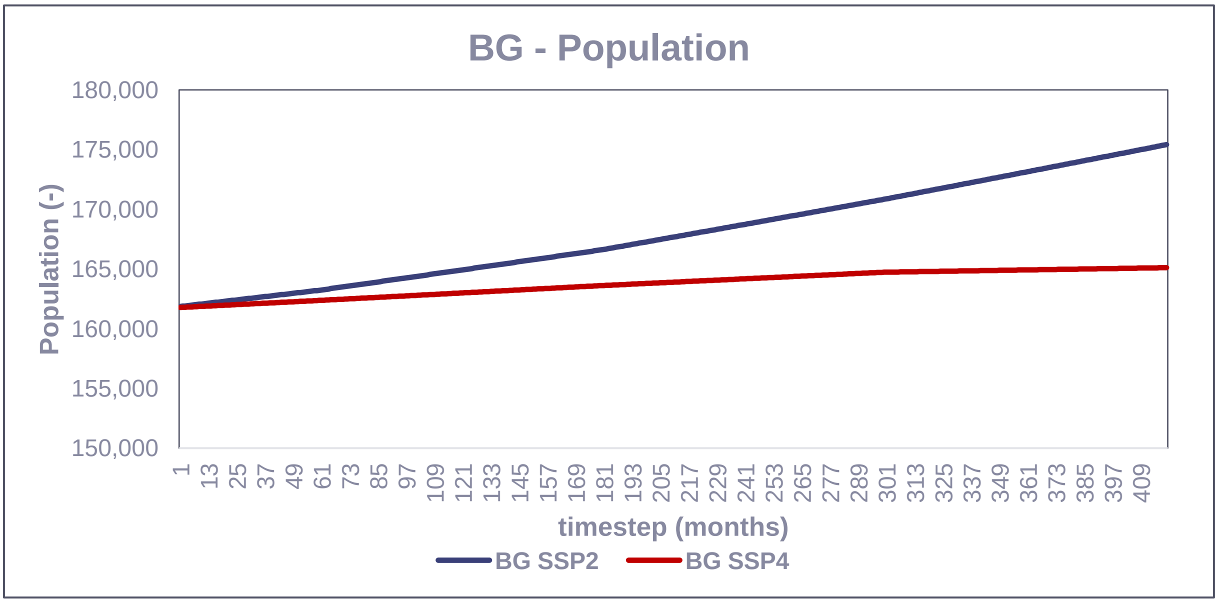


Figure 22: The difference in population projections between SSPs 2 and 4 in the Bulgarian river basins territory.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

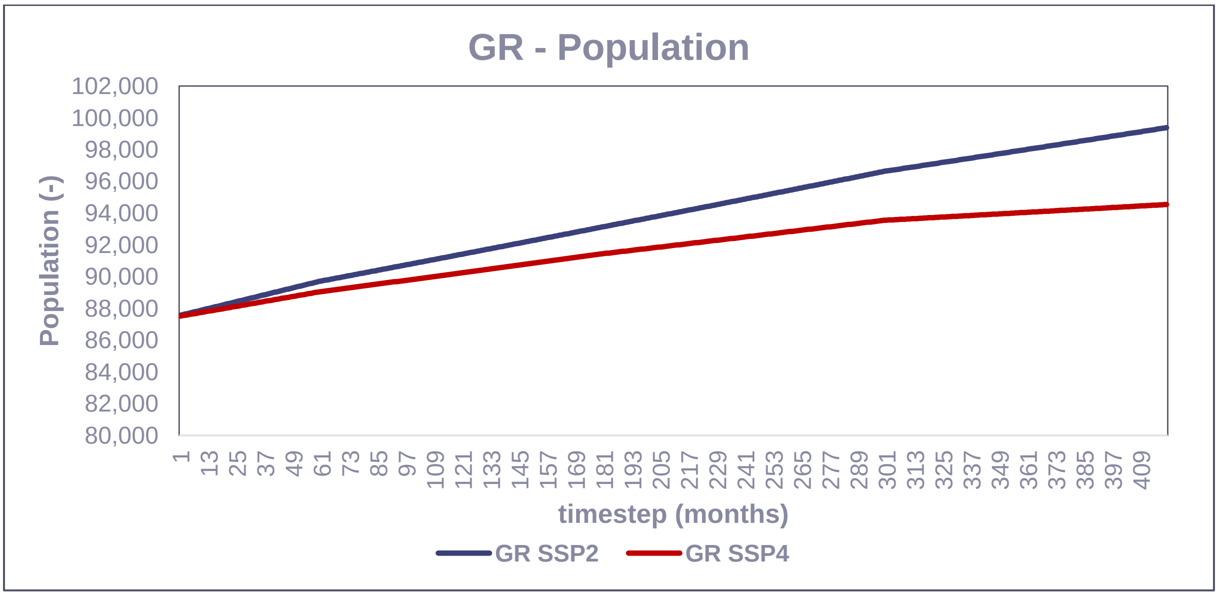


Figure 6233: The difference in population projections between SSPs 2 and 4 in the Bulgarian river basins territory.

In the domain of Water, the dynamics of “Water withdrawal from agriculture”, and “Water withdrawal from livestock”, are influenced by different SSPs (Figures 24-27), while “River water volume” in W430 and W970 river basins are influenced by different RCPs (Figures 28 and 29). As evident in both Bulgaria and Greece, there is a minimal disparity in total water abstraction for irrigation and livestock purposes between the SSP scenarios. This can be attributed to the singular parameter influencing water withdrawals: the varying projections of crop areas and livestock heads according to the SSP2 and SSP4 scenarios. In contrast, the river water volume in W430 and W970 exhibits a notable discrepancy between the two RCP scenarios. This difference arises from the varying climatic projections influencing precipitation patterns according to the two RCP scenarios, while water abstractions from agriculture and livestock are affected by the crop areas and livestock heads evolution over time.

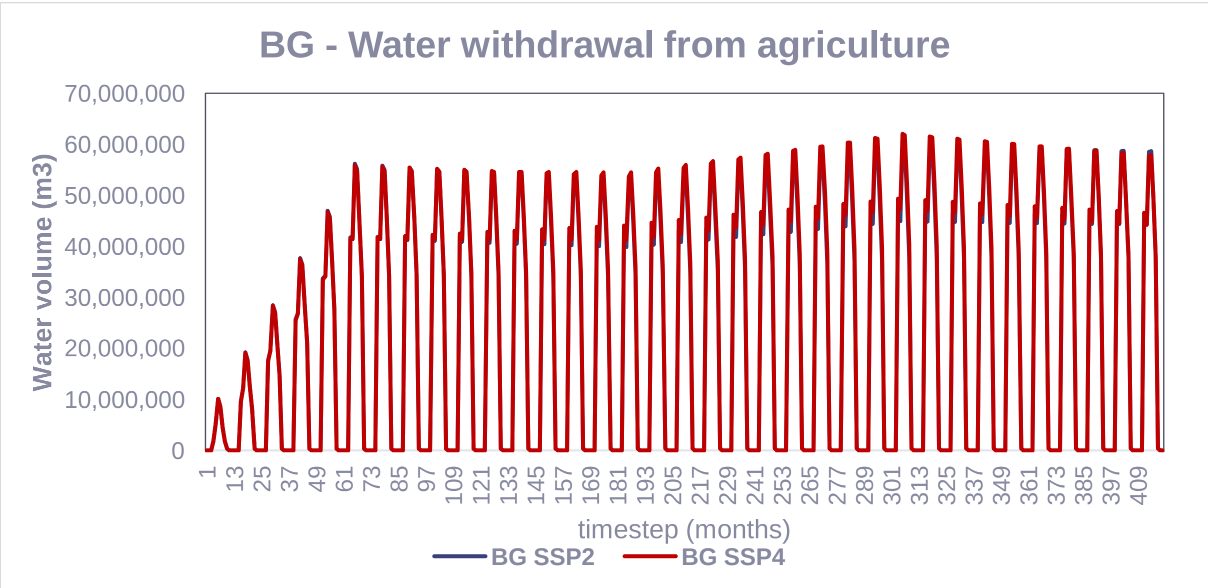


Figure 24: The difference in projections regarding water withdrawal from agriculture between SSPs 2 and 4 in the Bulgarian river basins territory.

NEXOGENESIS
STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101003881

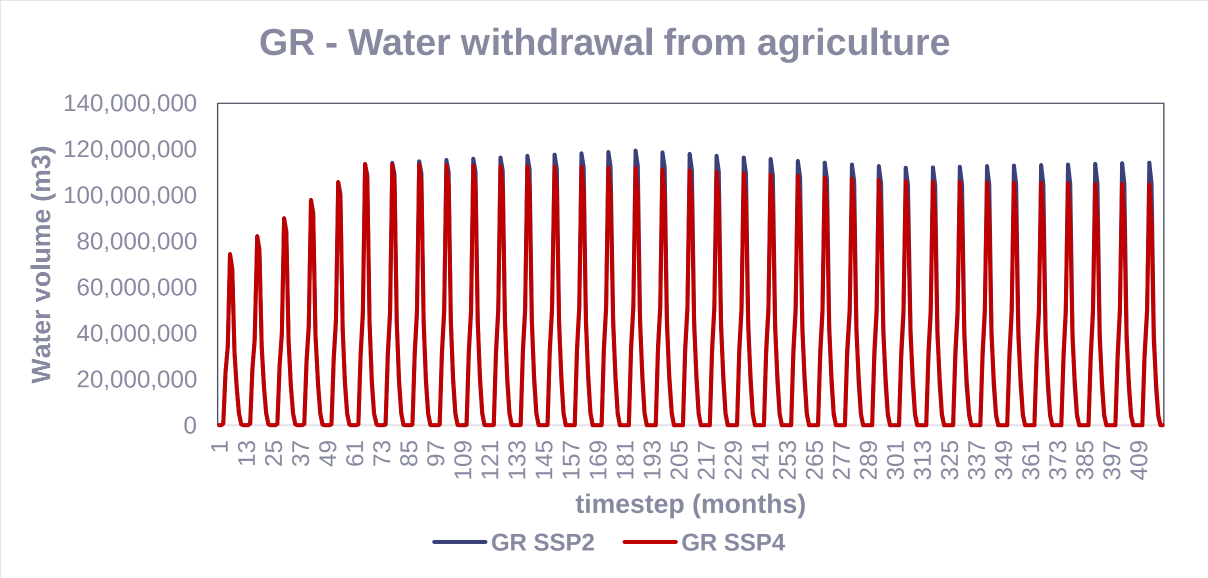


Figure 25: The difference in projections regarding water withdrawal from agriculture between SSPs 2 and 4 in the Greek river basins territory.

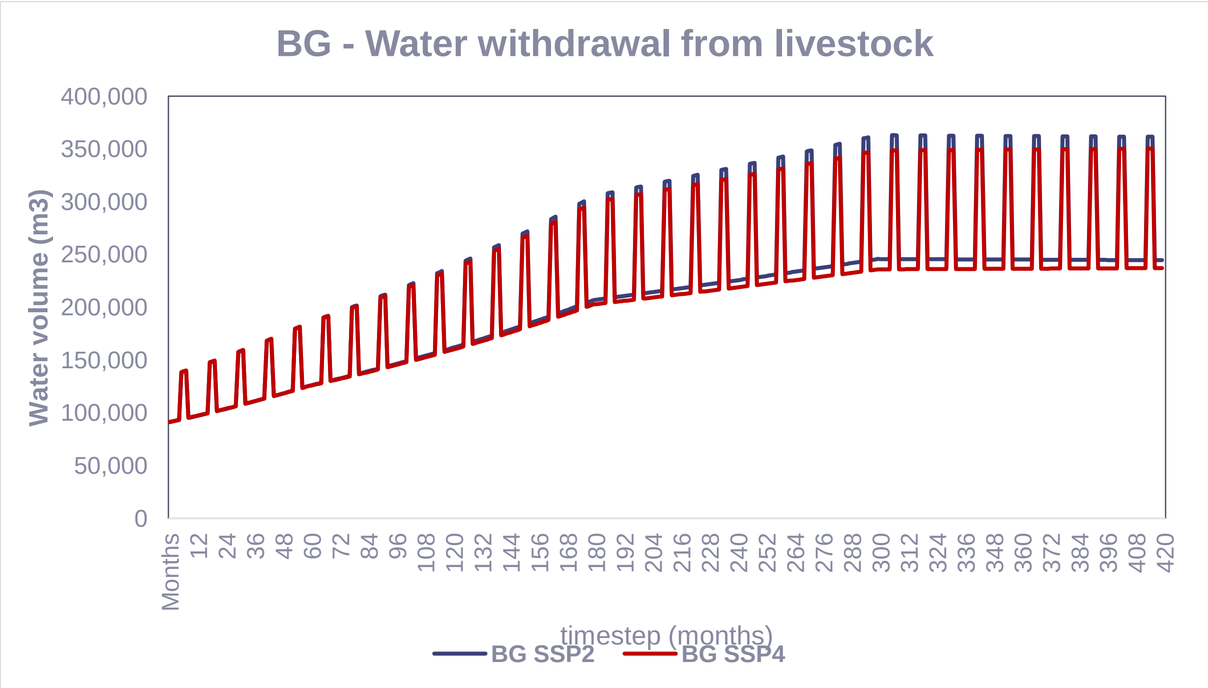


Figure 26: The difference in projections regarding water withdrawal from livestock between SSPs 2 and 4 in the Bulgarian river basins territory.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

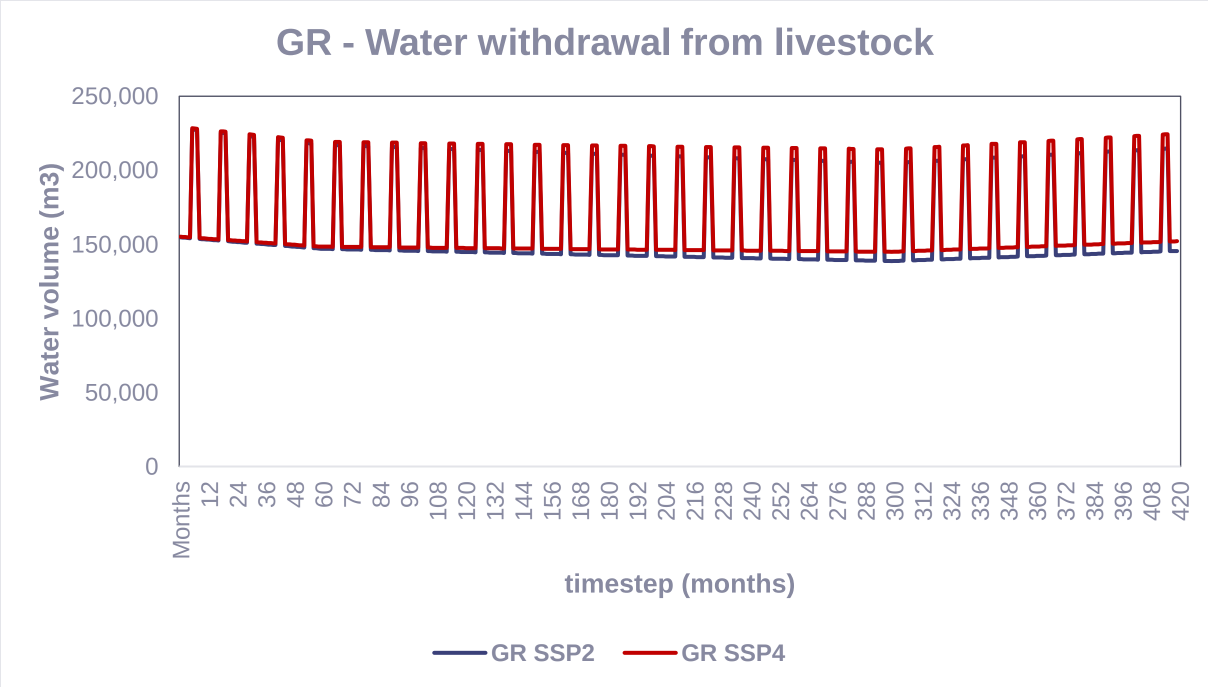


Figure 27: The difference in projections regarding water withdrawal from livestock between SSPs 2 and 4 in the Greek river basins territory.

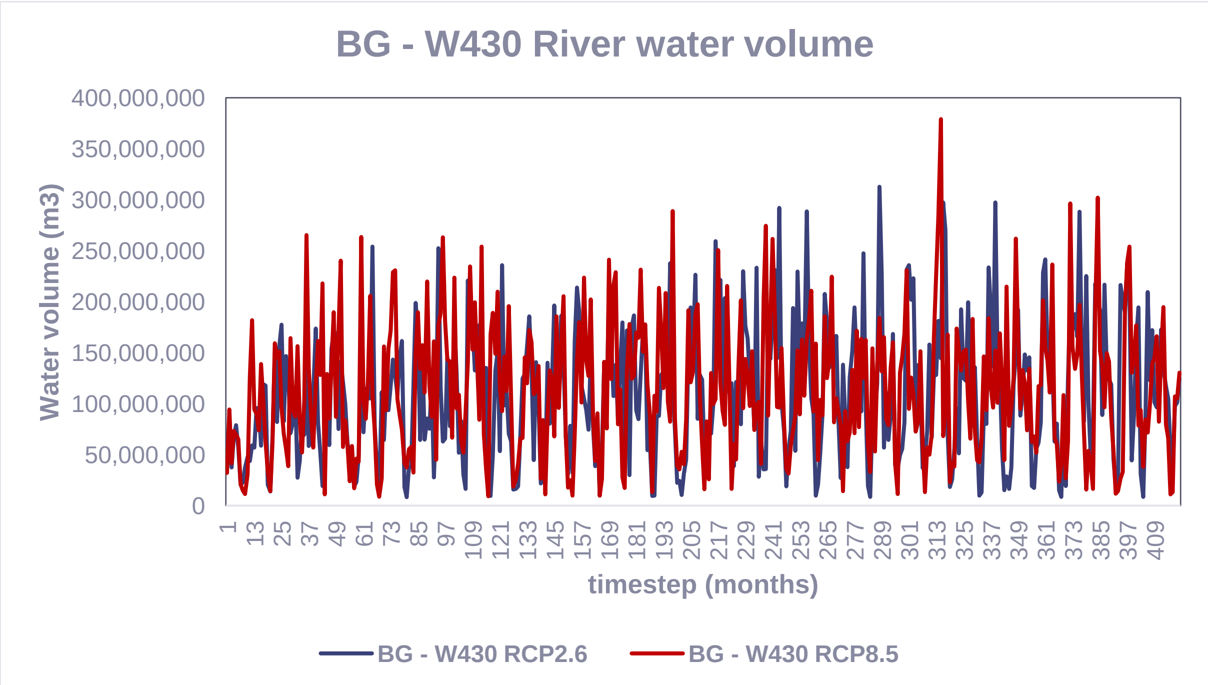


Figure 28: The difference in projections regarding BG – W430 river water volume between RCPs 2.6 and 8.5.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

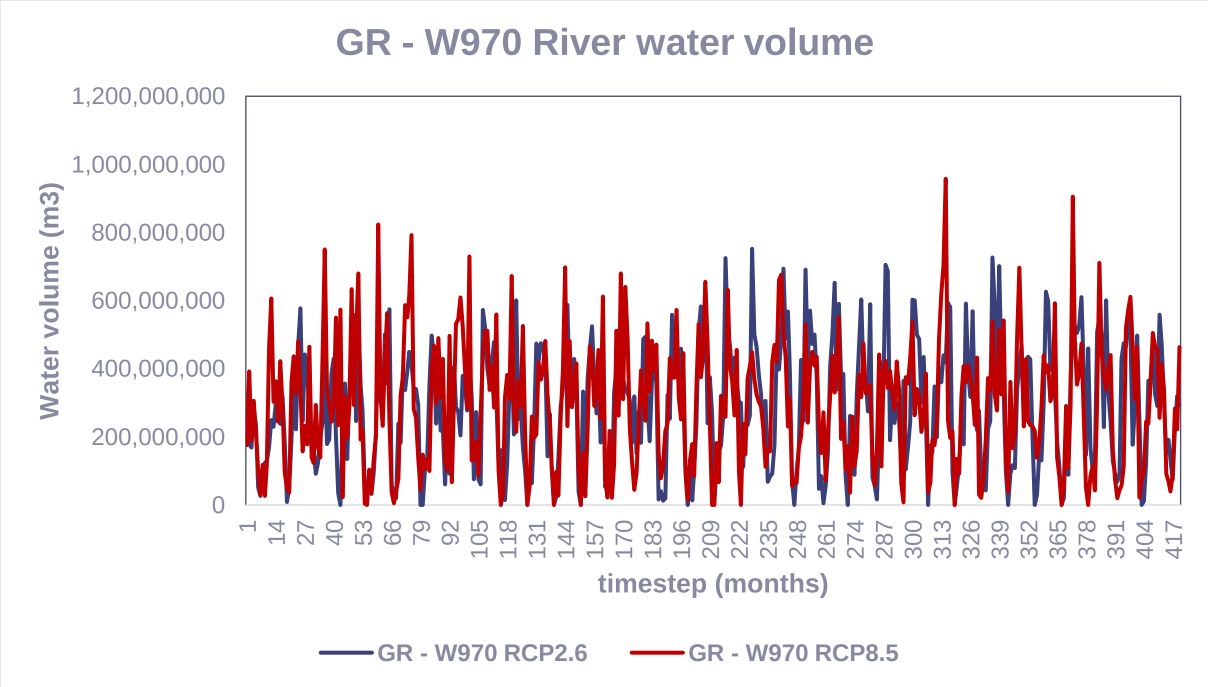


Figure 29: The difference in projections regarding GR – W970 river water volume between RCPs 2.6 and 8.5.

Concerning river nitrogen concentration fluctuation in the two specific basins of Bulgaria and Greece (illustrated in Figures 30 and 31), a substantial disparity is observed between RCP2.6 and 8.5. This discrepancy arises from several factors. Firstly, river water volume is influenced by projections under the two RCP scenarios. Secondly, water abstractions from agriculture and livestock are contingent upon the evolution of crop areas and livestock numbers over time, thus impacting river discharge after water exploitation. Finally, the leaching factor of nitrogen from agricultural fields into the river introduces uncertainty, particularly regarding the uncertainty attributed to the amount of nitrogen applied to each type of crop areas and simulated leaching thereafter.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

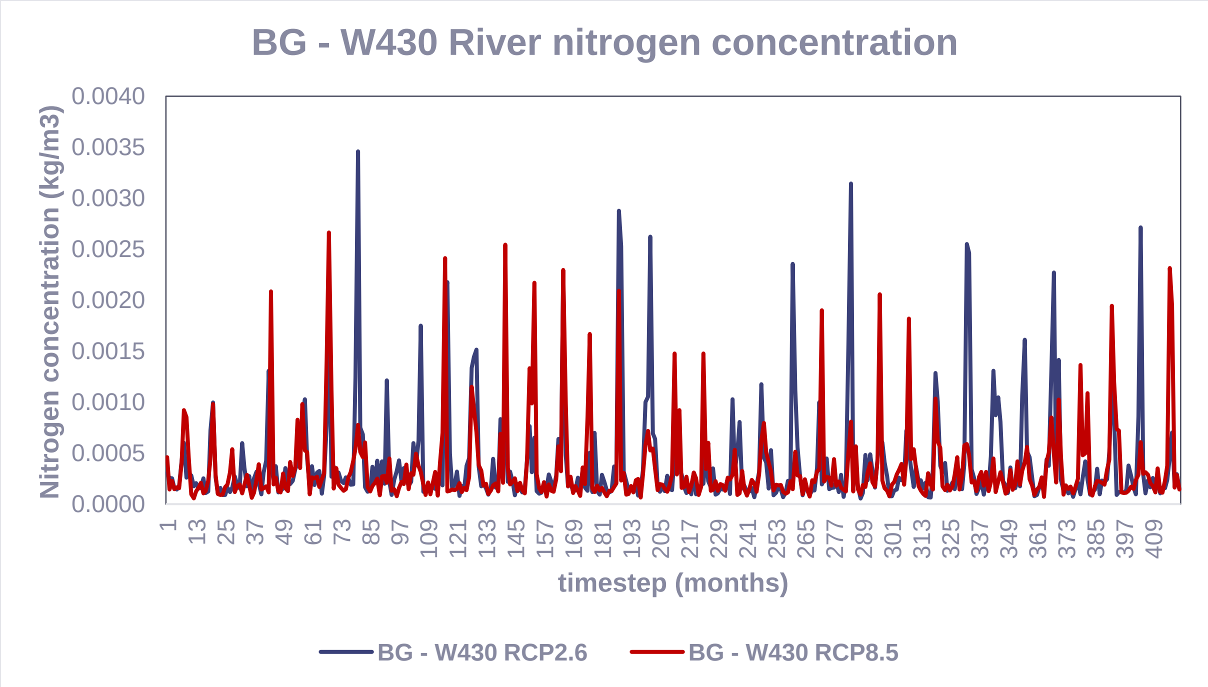


Figure 30: The difference in projections regarding BG – W430 river nitrogen concentration between RCPs 2.6 and 8.5.

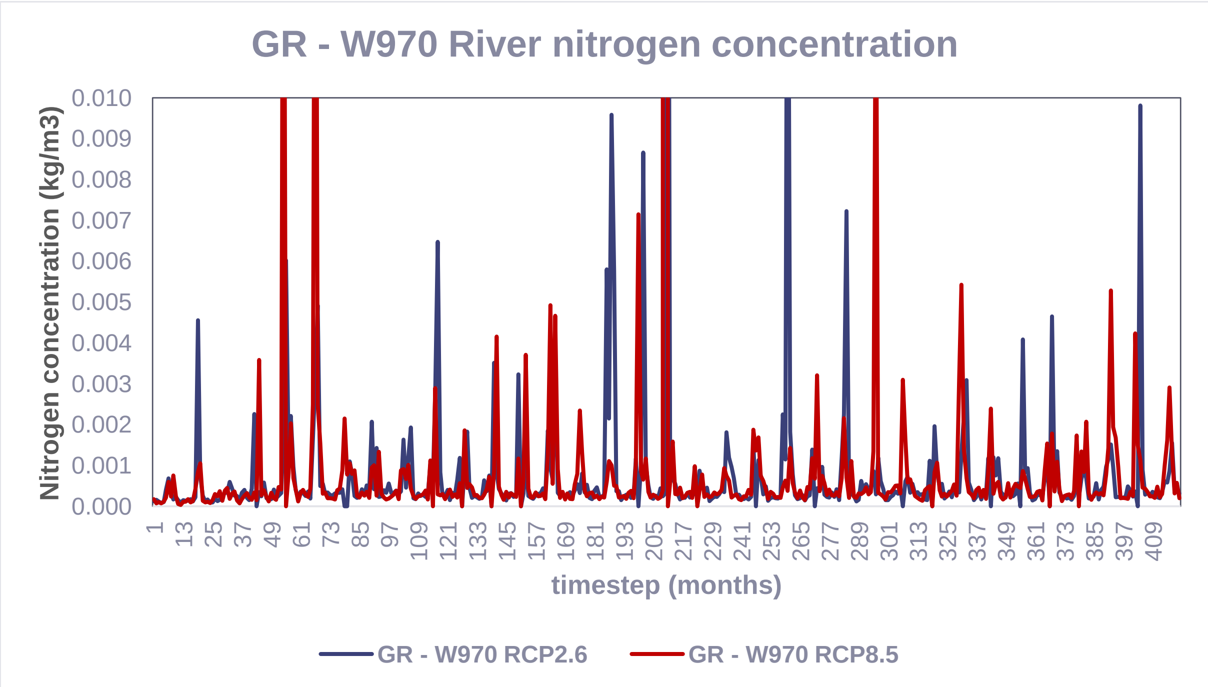


Figure 31: The difference in projections regarding GR – W970 river nitrogen concentration between RCPs 2.6 and 8.5.

In the Food domain, the production of crop and livestock food in both country sides of the Nestos basin exhibits a marginal variation across the two SSP scenarios, as depicted in Figures 32-35.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

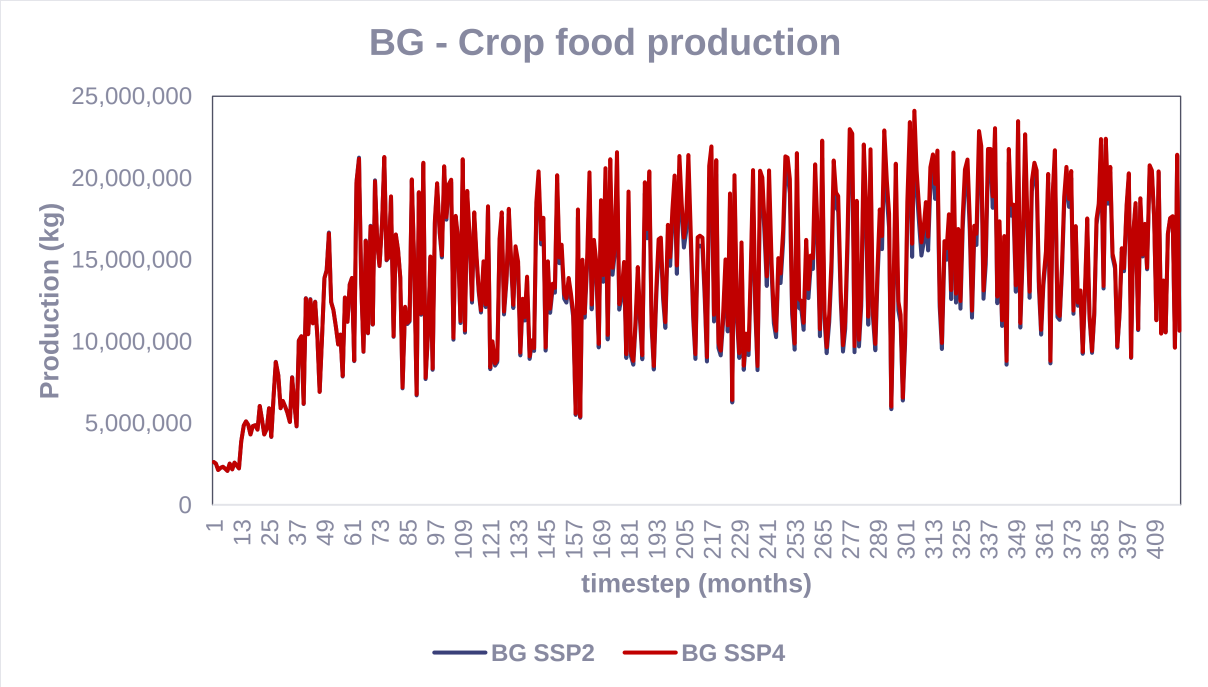


Figure 32: The difference in projections regarding crop food production between SSPs 2 and 4 in the Bulgarian river basins territory.

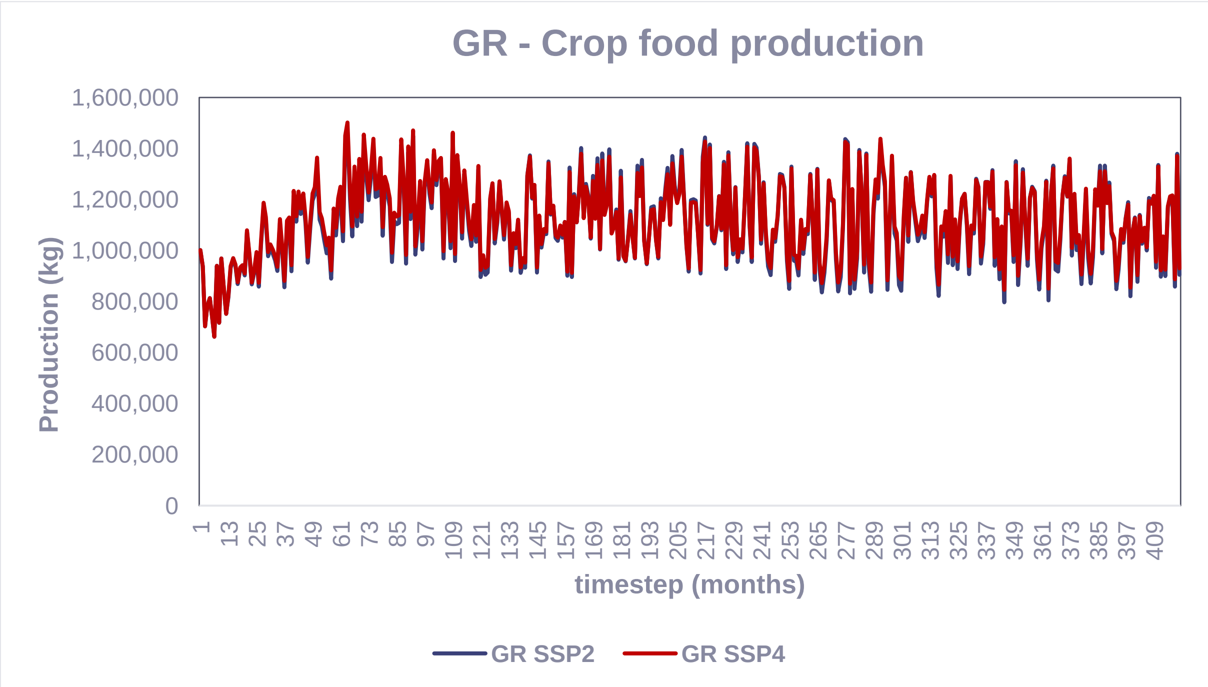


Figure 33: The difference in projections regarding crop food production between SSPs 2 and 4 in the Greek river basins territory.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

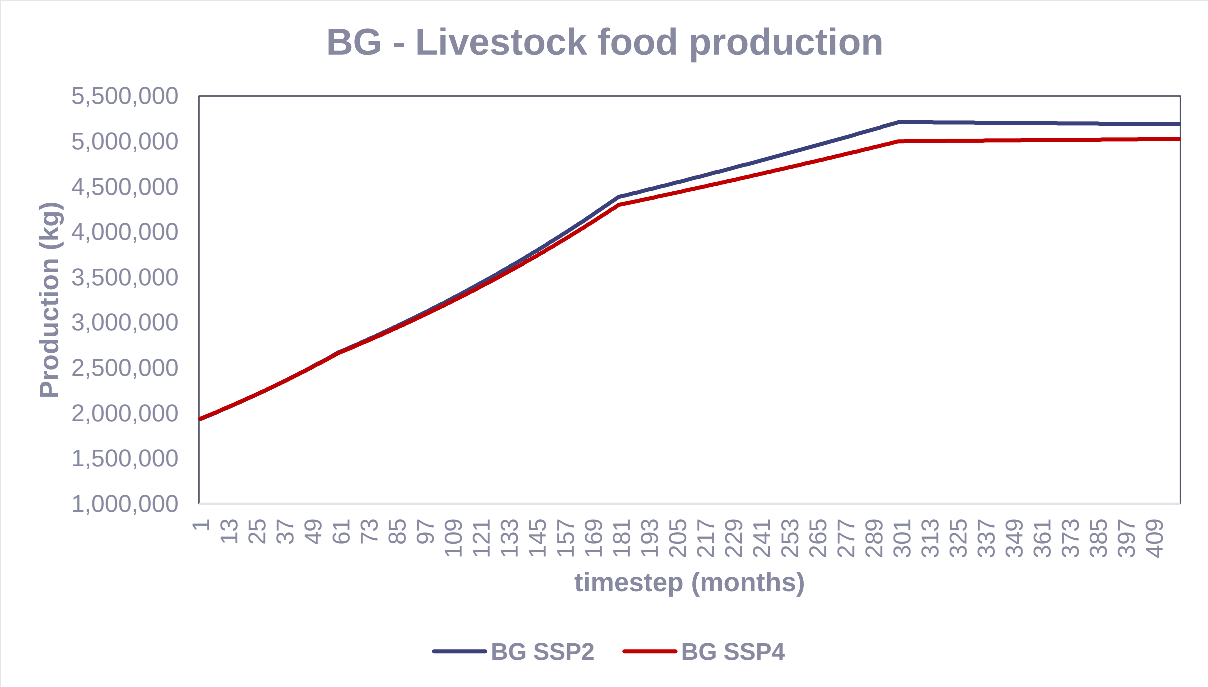


Figure 34: The difference in projections regarding livestock food production between SSPs 2 and 4 in the Bulgarian river basins territory.

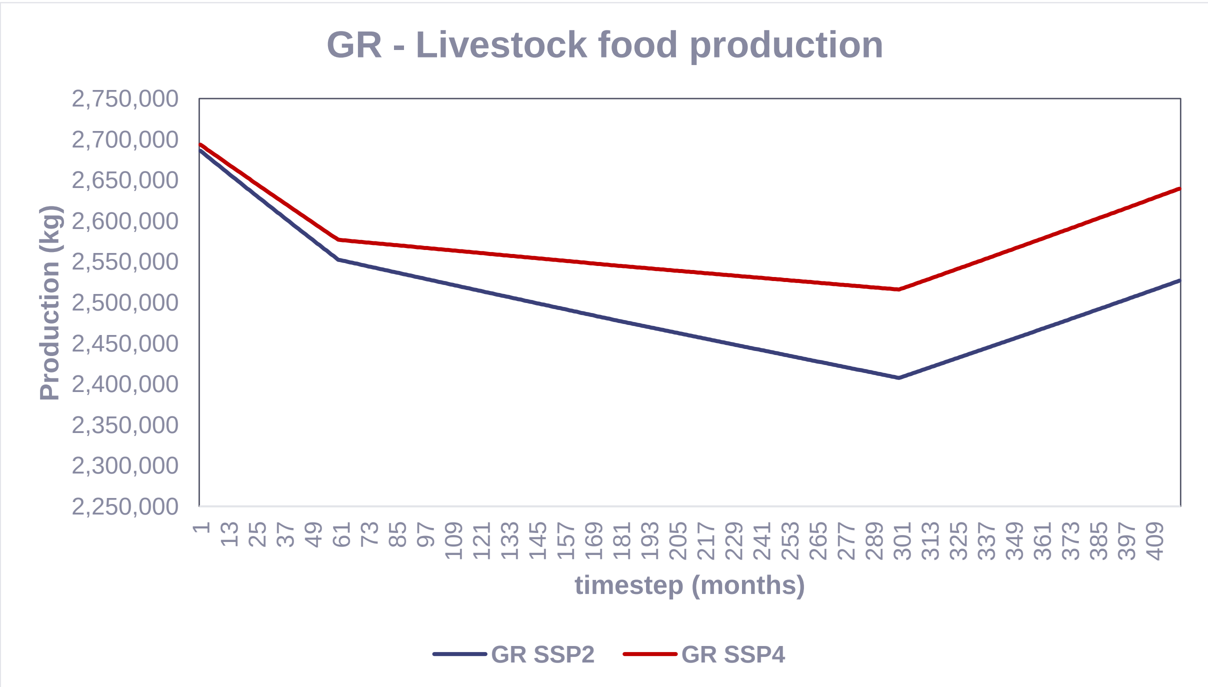


Figure 35: The difference in projections regarding livestock food production between SSPs 2 and 4 in the Greek river basins territory.

In the domain of food demand, variations in population projections between SS2 and SSP4 (depicted in Figures 36 and 37 for the two countries) serve as the driving force. These discrepancies in population projections lead to noticeable differences in total food demand for the Nestos case study, culminating in a significant divergence by the simulation's conclusion.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Consequently, effective planning of food production hinges largely on monitoring the trajectory of population growth, a pivotal metric for local planners and policymakers.

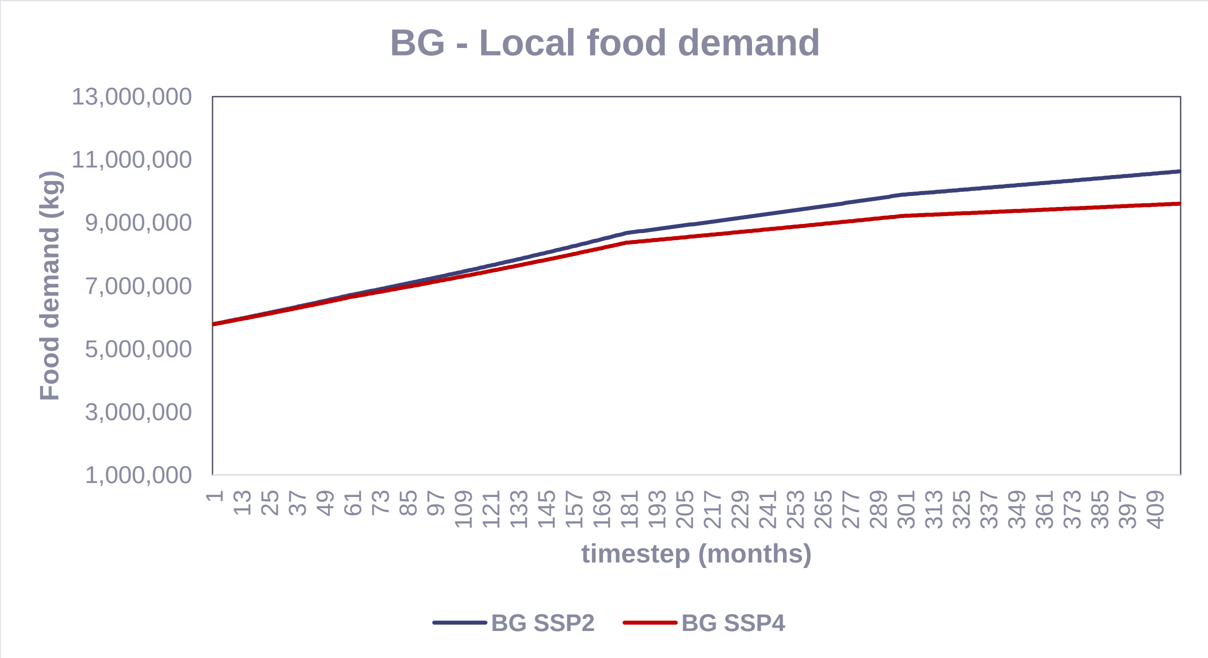


Figure 36: The difference in projections regarding local food demand between SSPs 2 and 4 in the Bulgarian river basins territory.

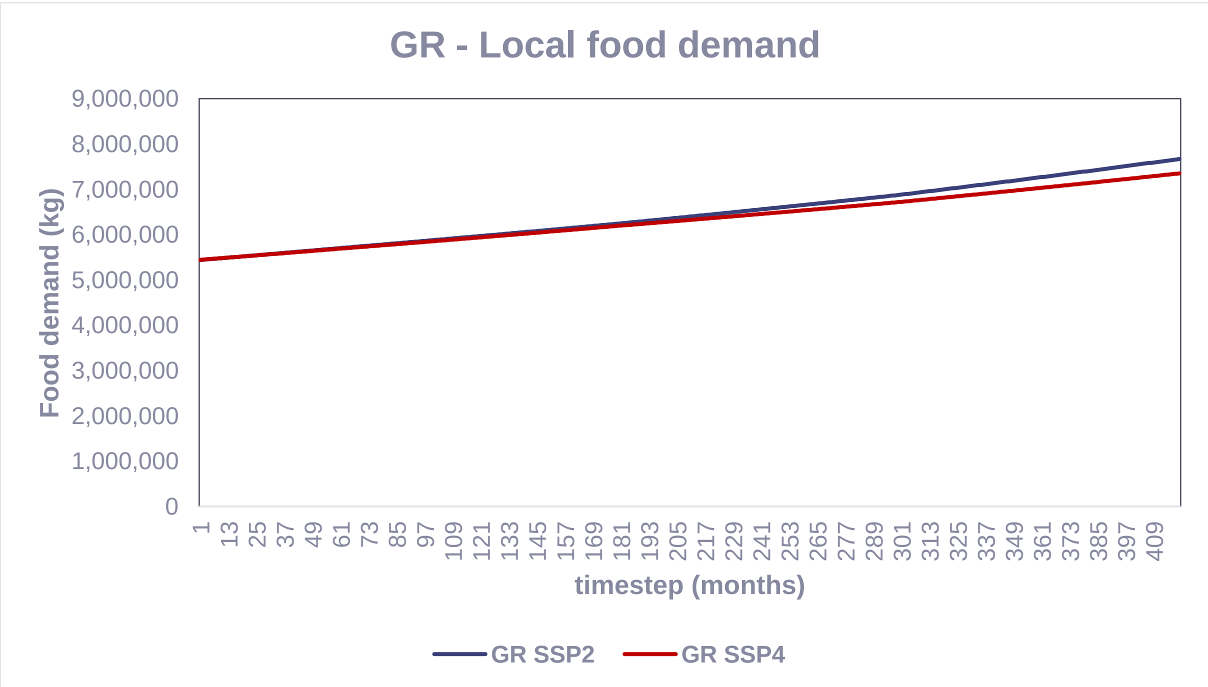


Figure 37: The difference in projections regarding local food demand between SSPs 2 and 4 in the Greek river basins territory.

Within the energy sector, the total local electricity generation, the total local electricity demand, and the overall energy balance are influenced by the SSP scenarios, as illustrated in Figures 38-43, for the two country sides of the river basin. Conversely, the RCPs hold no significance

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

in this sector. Notably, the electricity generation curves (depicted in Figures 38 and 39) exhibit some divergence, indicating a lower level of electricity generation under SSP4 for Bulgaria and a higher level of electricity generation under SSP4 for Greece.

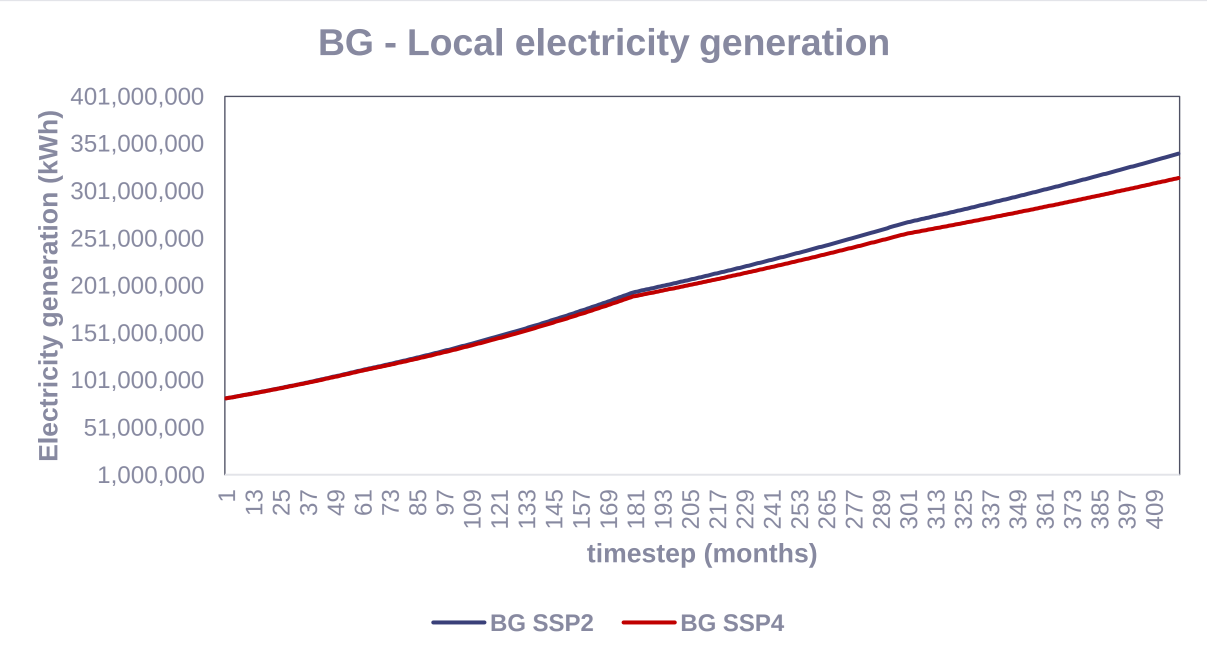


Figure 38: The difference in projections regarding local electricity generation between SSPs 2 and 4 in the Bulgarian river basins territory.

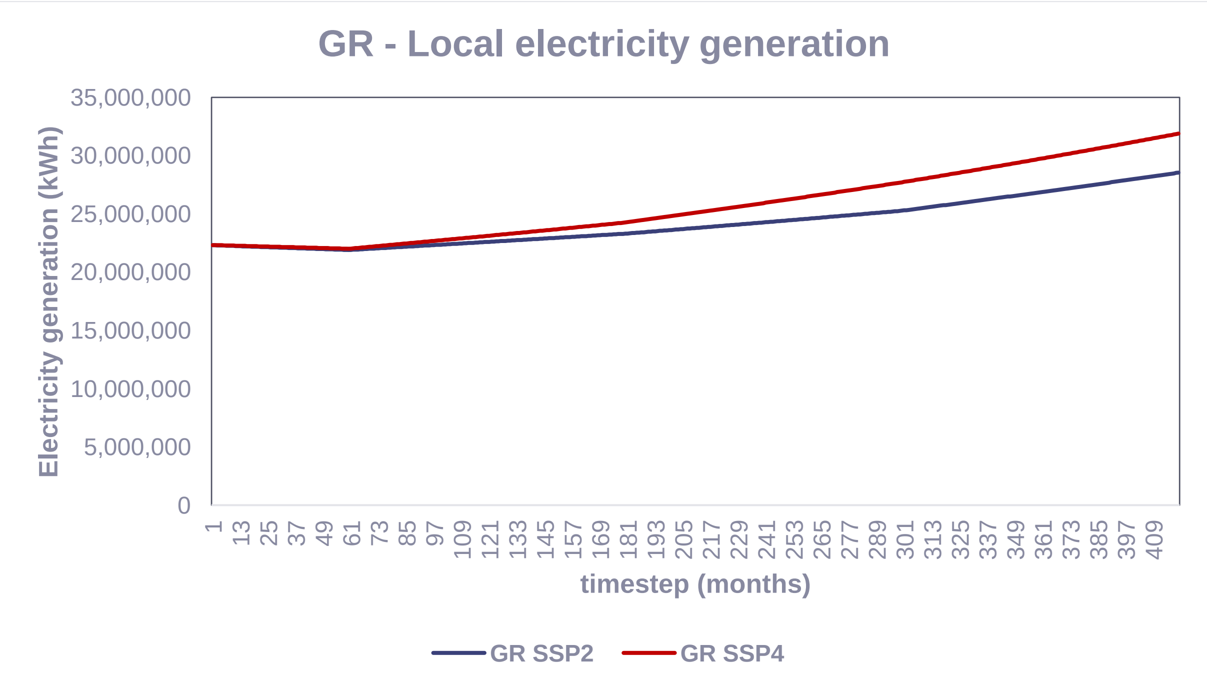


Figure 39: The difference in projections regarding local electricity generation between SSPs 2 and 4 in the Greek river basins territory.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

The electricity demand shows a similar trend as with electricity generation, with SSP4 indicating a lower level of demand in Bulgaria and a higher in Greece, as illustrated in Figures 40 and 41.

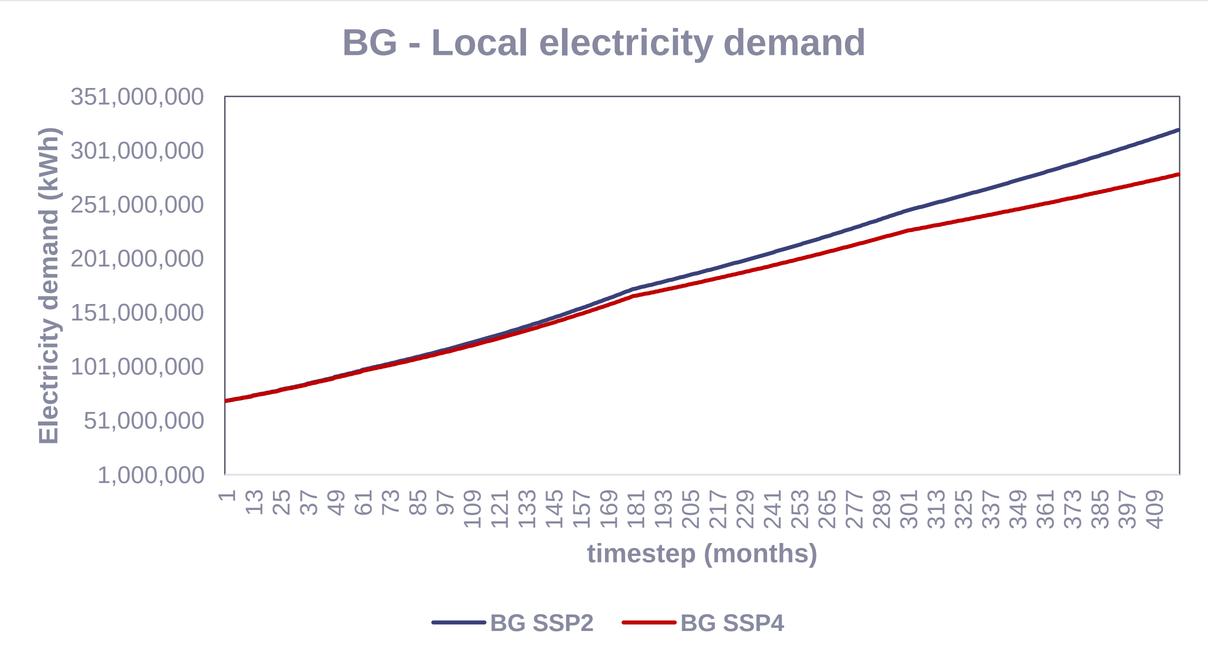


Figure 40: The difference in projections regarding local electricity demand between SSPs 2 and 4 in the Bulgarian river basins territory.

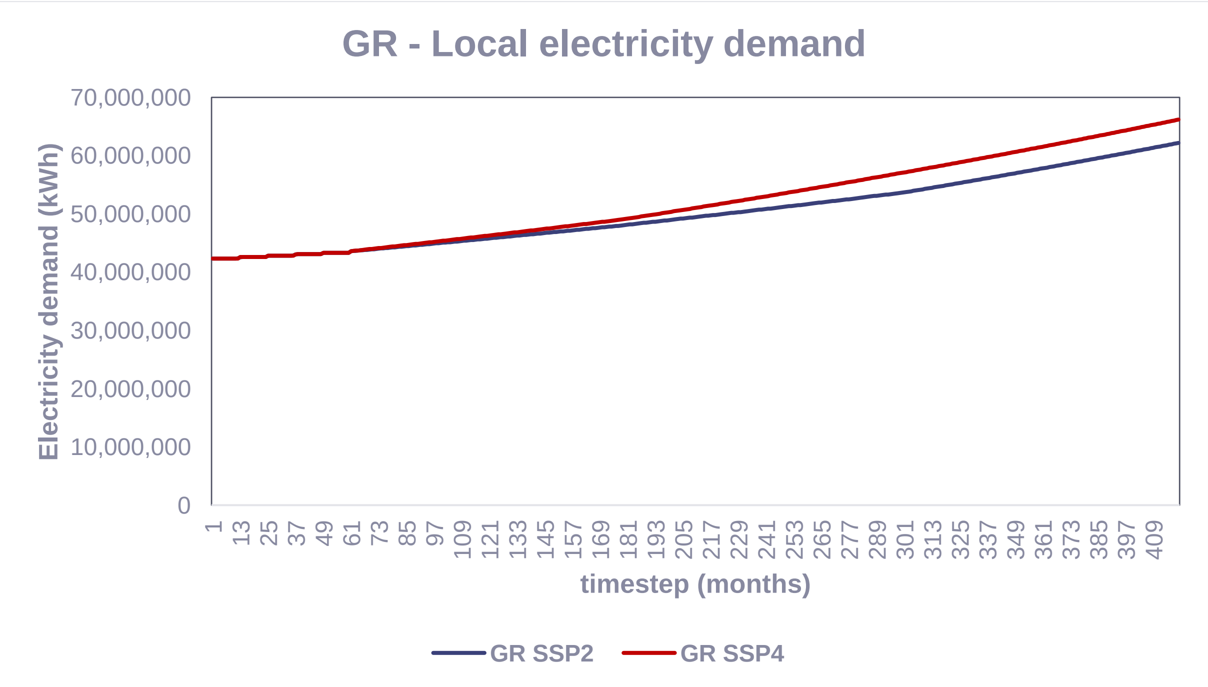


Figure 41: The difference in projections regarding local electricity demand between SSPs 2 and 4 in the Greek river basins territory.

Regarding the local electricity balance (i.e. the difference between the supply and demand), the Bulgarian river basins territory shows a positive trend (Figure 42), with SSP4 affecting more

NEXOGENESIS STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

the positive balance, while the Greek river basins territory shows a negative trend (Figure 43), with SSP4 affecting slightly more the negative balance.

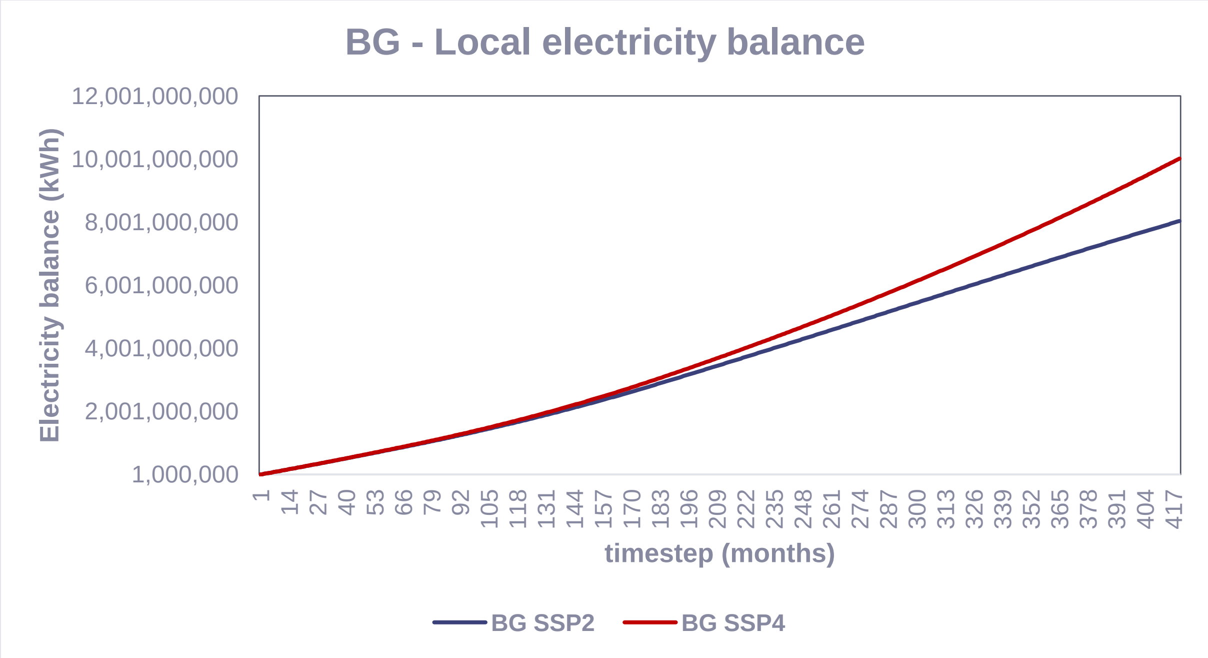


Figure 42: The difference in projections regarding local electricity balance between SSPs 2 and 4 in the Bulgarian river basins territory.

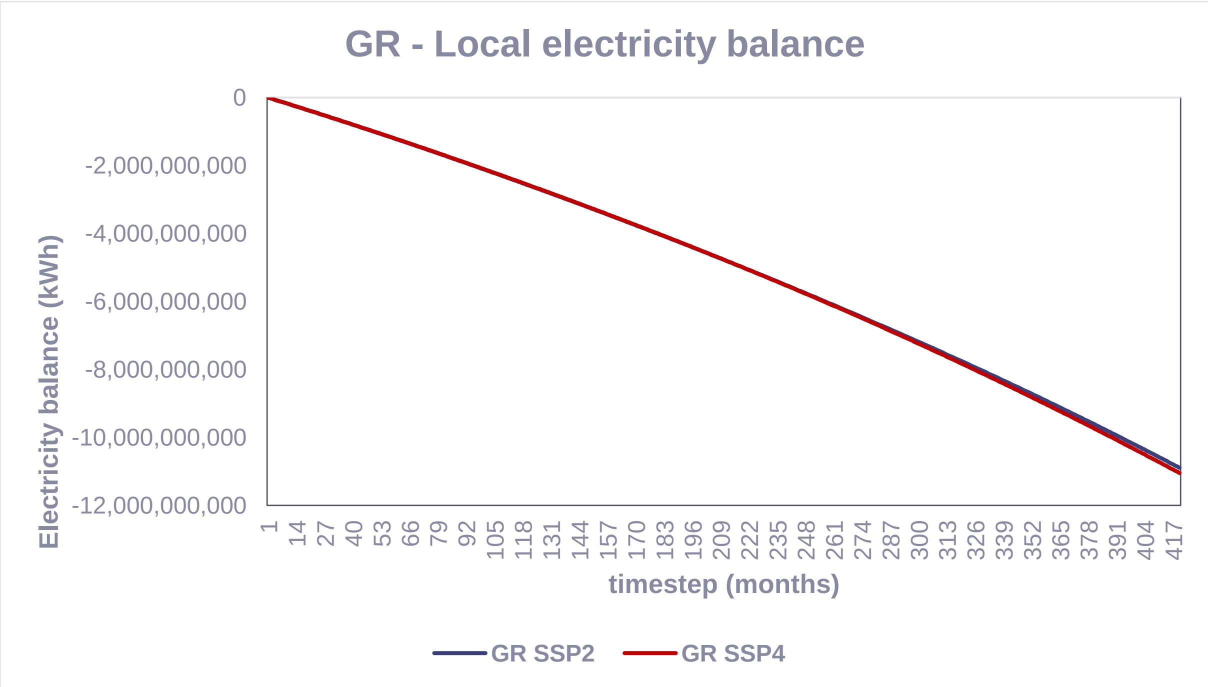


Figure 43: The difference in projections regarding local electricity balance between SSPs 2 and 4 in the Greek river basins territory.

In the Ecosystems sector, the carbon mass in vegetation is influenced by RCPs. Figures 44 and 85 depict the results for carbon mass in vegetation, for river basins across the two

NEXOGENESIS STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

countries. This parameter is higher for RCP8.5 for the two territories from month 160 and onwards.

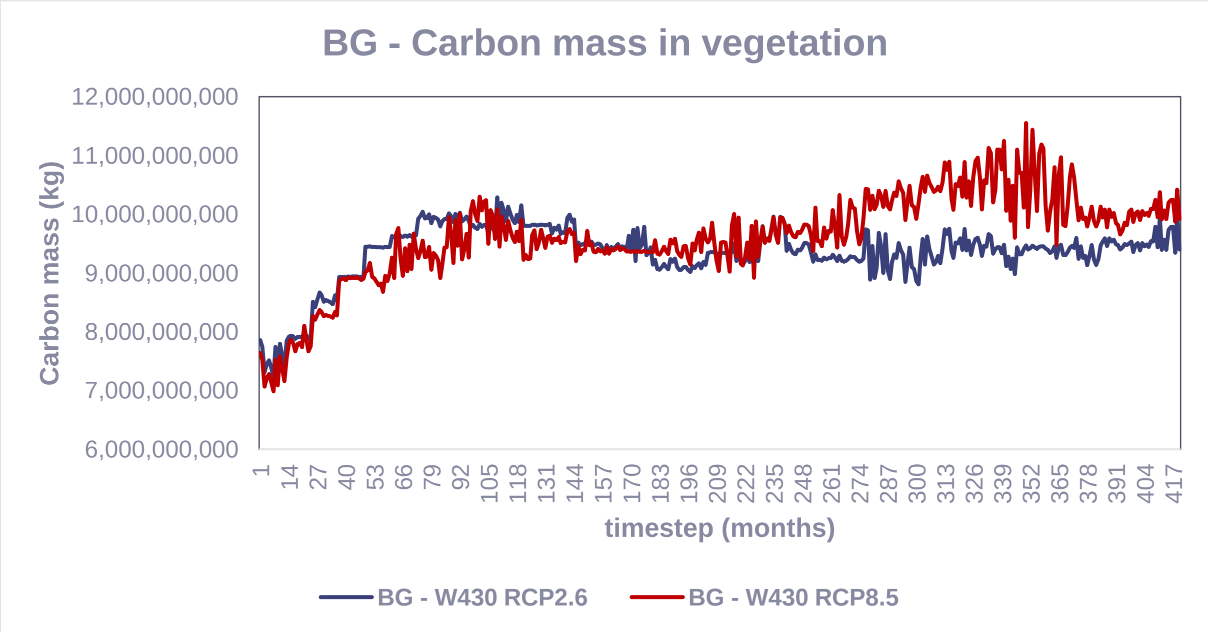


Figure 44: The difference in projections regarding carbon mass in vegetation between RCPs 2.6 and 8.5 for the Bulgarian river basins territory.

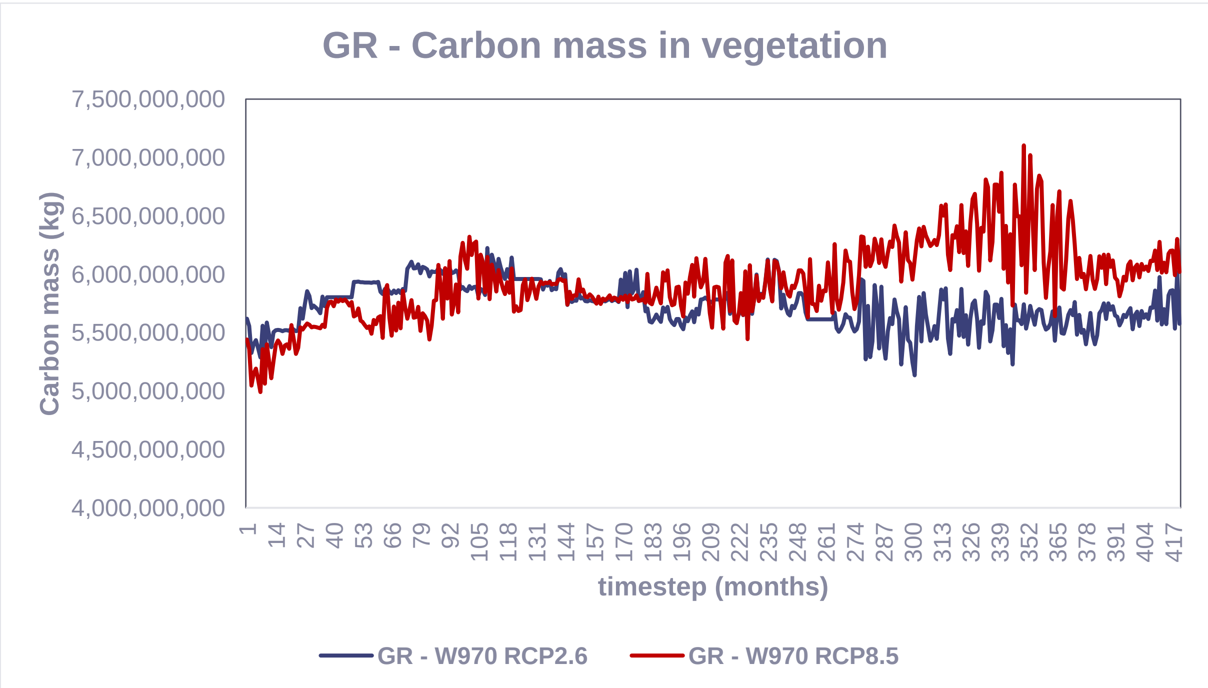


Figure 45: The difference in projections regarding carbon mass in vegetation between RCPs 2.6 and 8.5 for the Greek river basins territory.

In the climate sector, the overall local emissions are influenced by the SSPs trends. In Figures 46 and 47 concerning the Bulgarian and Greek parts respectively, SSP2 slightly outperforms SSP4 in emissions. Although these differences are relatively minor, suggesting limited impact

NEXOGENESIS STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

of the SSPs on emissions locally for the parameters considered in the model, it's crucial to acknowledge that emissions from various other sectors of the economy, apart from agriculture and livestock, are not included in this analysis.

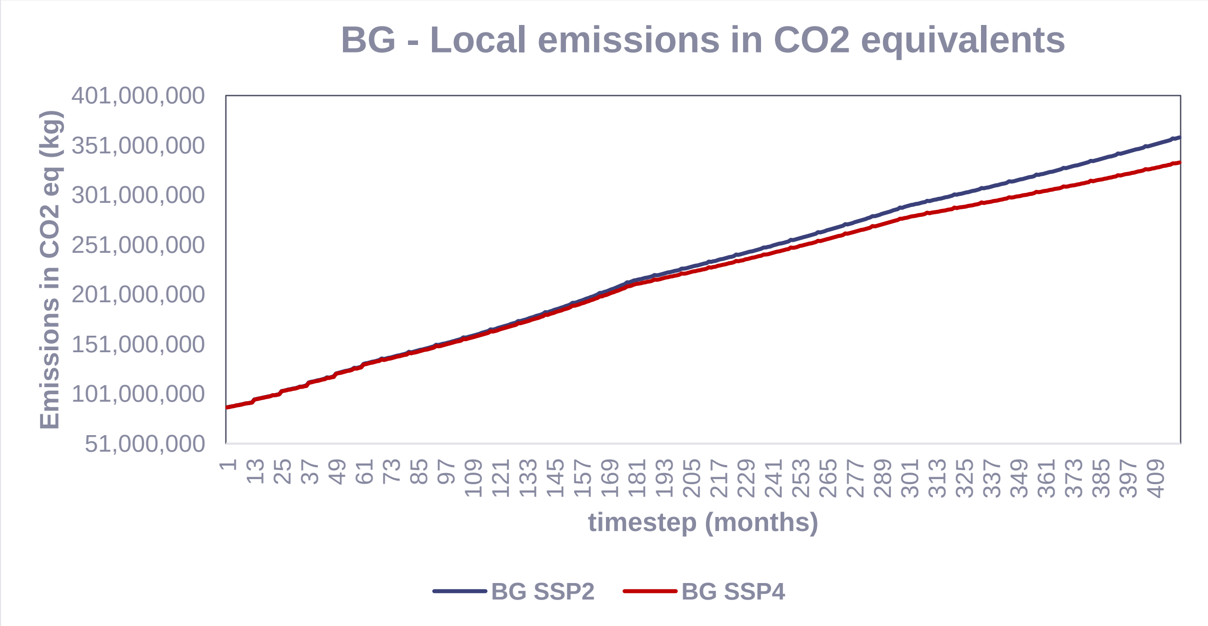


Figure 46: The difference in projections regarding local emissions between RCPs 2.6 and 8.5 for the Bulgarian river basins territory.

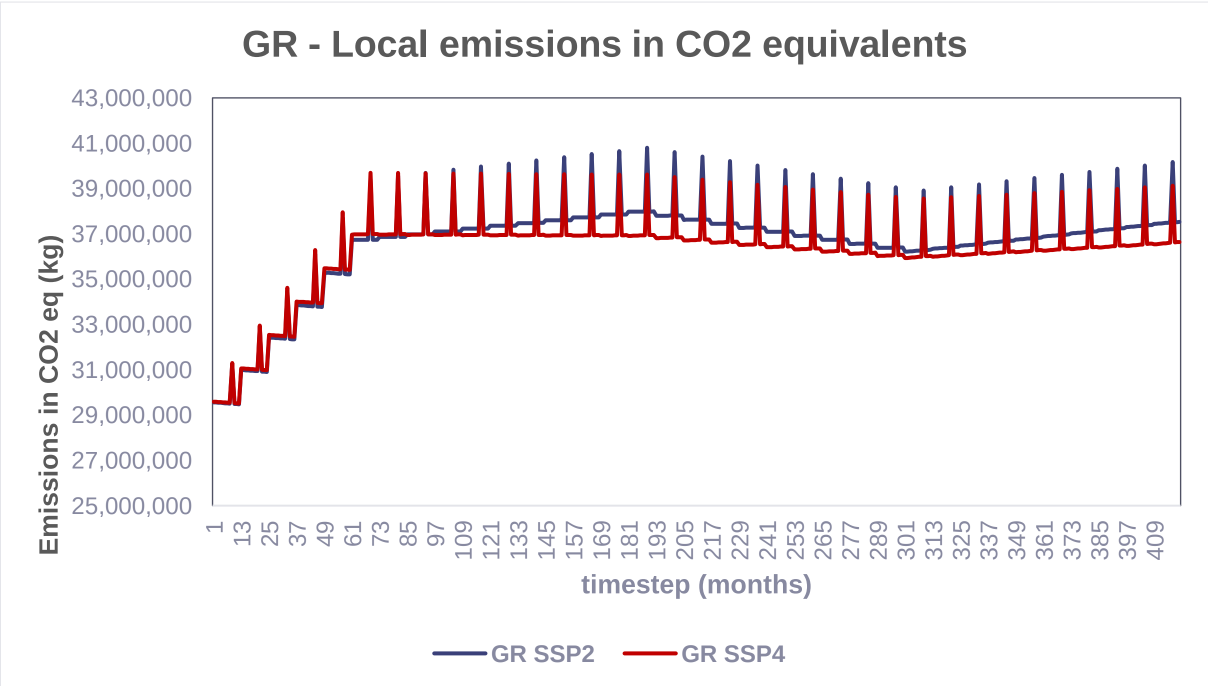


Figure 47: The difference in projections regarding local emissions between RCPs 2.6 and 8.5 for the Greek river basins territory.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

4.1.3 What-if and stress tests

In the Nestos/Mesta case study and for the RCP2.6-SSP2 scenario, the following what-if / stress tests are conducted:

i. Doubling and halving the runoff in the 7 sub-basins belonging to Bulgaria and the 4 belonging to Greece, to assess implications on surface water resources (SWR). Changes in precipitation patterns are considered the primary factor influencing these variations. Doubling the runoff could enhance water availability, potentially alleviating stress on surface water resources. On the other hand, halving runoff may exacerbate water shortages, especially during critical consumption periods.

ii. Doubling and halving energy production, to evaluate impacts on energy balance in both Bulgarian and Greek territories, despite local energy production feeding the national grid network. Although this scenario is not entirely realistic, it helps identify potential vulnerabilities in the energy supply and demand system under extreme variations.

iii. Doubling and halving crop and livestock food production, by altering crop areas and livestock numbers, to analyze effects on the food balance in both countries. Increased production could lead to surpluses and opportunities for trade, while decreased production may threaten food security and necessitate imports.

iv. Doubling and halving population size, to understand effects on both energy and food balance. A larger population may increase demand for energy and food, while a smaller population may reduce these demands, impacting the economic and logistic aspects of supply.

These scenarios explore extreme but unlikely changes, serving as stress tests for the supply and demand systems. The goal is not to predict realistic outcomes but to understand the potential impacts of significant what-if variations. As with parametric uncertainty, this analysis compares these tests against baseline projections to assess relative impacts on key outputs.

Figures 48 and 49 display the results of what-if stress tests on surface water resources (SWR) in the Bulgarian and Greek part of the Nestos/Mesta transboundary river basin respectively, under the RCP2.6SSP2 climate change scenario. Both graphs effectively illustrate the sensitivity of surface water resources in the Bulgarian and Greek parts to variations in precipitation. The significant differences between the "doubling" and "halving" scenarios emphasize the vulnerability of the region's water resources to climate variability and the importance of managing water resources effectively. The simulation mean provides a baseline for comparison, allowing assessment of the potential consequences of hydrological shifts, whether from increased or decreased rainfall.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

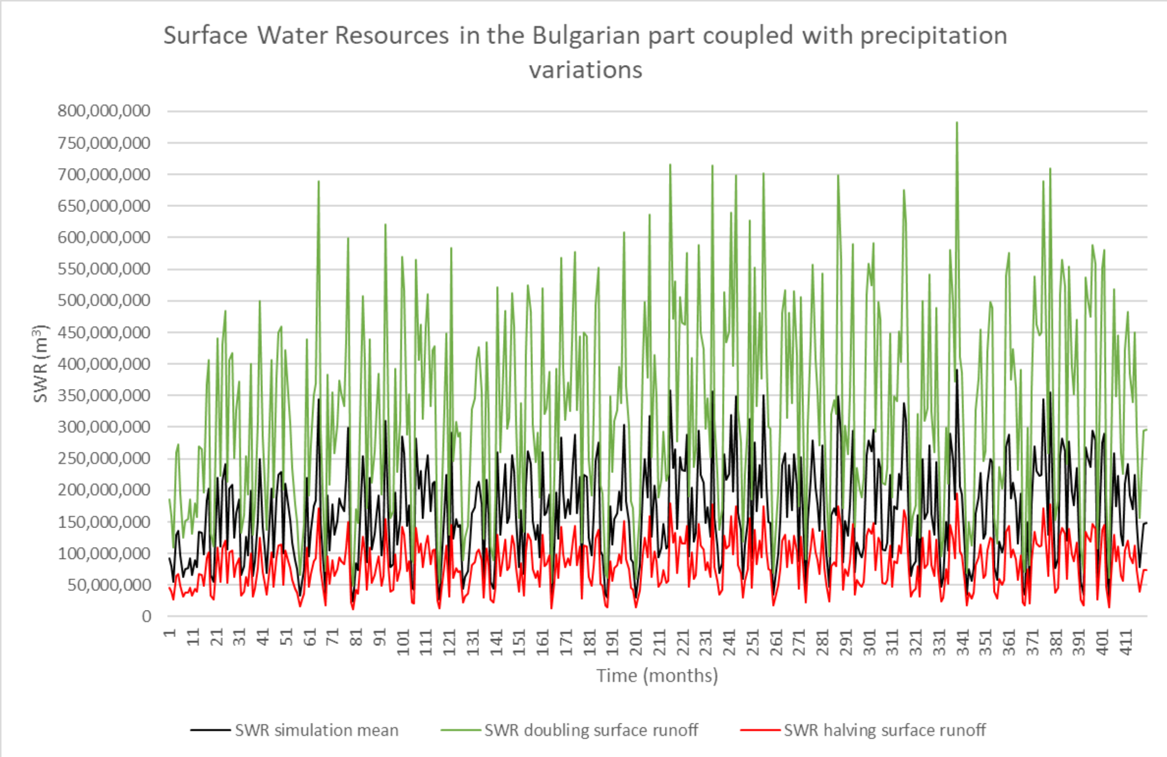


Figure 48: Temporal pattern of Surface Water Resources in the Bulgarian part under the RCP2.6SSP2 scenario. The black line represents the average simulation, while the green line shows the trend with doubled surface runoff, and the red line indicates the trend with halved surface runoff.

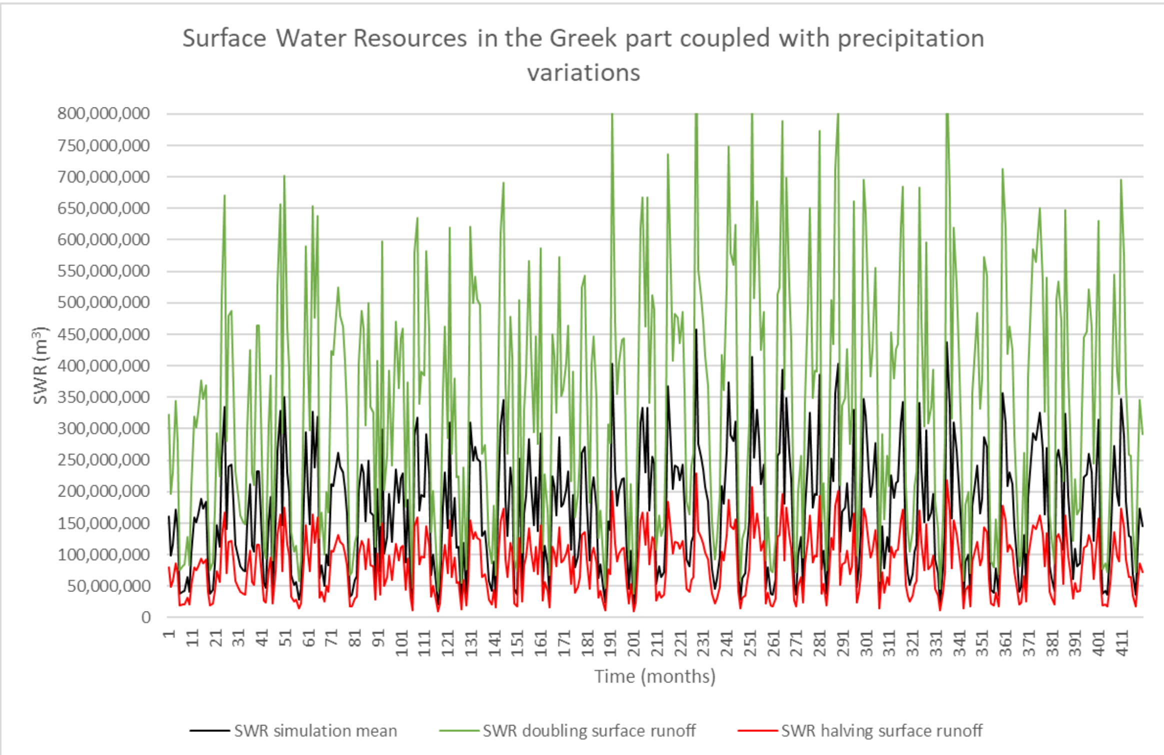


Figure 49: Temporal pattern of Surface Water Resources in the Greek part under the RCP2.6SSP2 scenario. The black line represents the average simulation, while the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

green line shows the trend with doubled surface runoff, and the red line indicates the trend with halved surface runoff.

Figures 50 and 51 present electricity balance stress test results for the Bulgarian and Greek parts of the Nestos/Mesta basin under the RCP2.6SSP2 climate change scenario. In Bulgaria, the baseline scenario shows slight growth, while doubling energy production significantly improves the balance, and halving it leads to a decline over time. Conversely, Greece's baseline scenario shows a negative trend, with only energy production doubling resulting in a positive electricity balance trend. The RCP2.6SSP2 scenario itself, representing a relatively low emissions pathway, also plays a role, with its impact varying regionally due to other factors like climate change effects on hydropower resources and specific national energy policies.

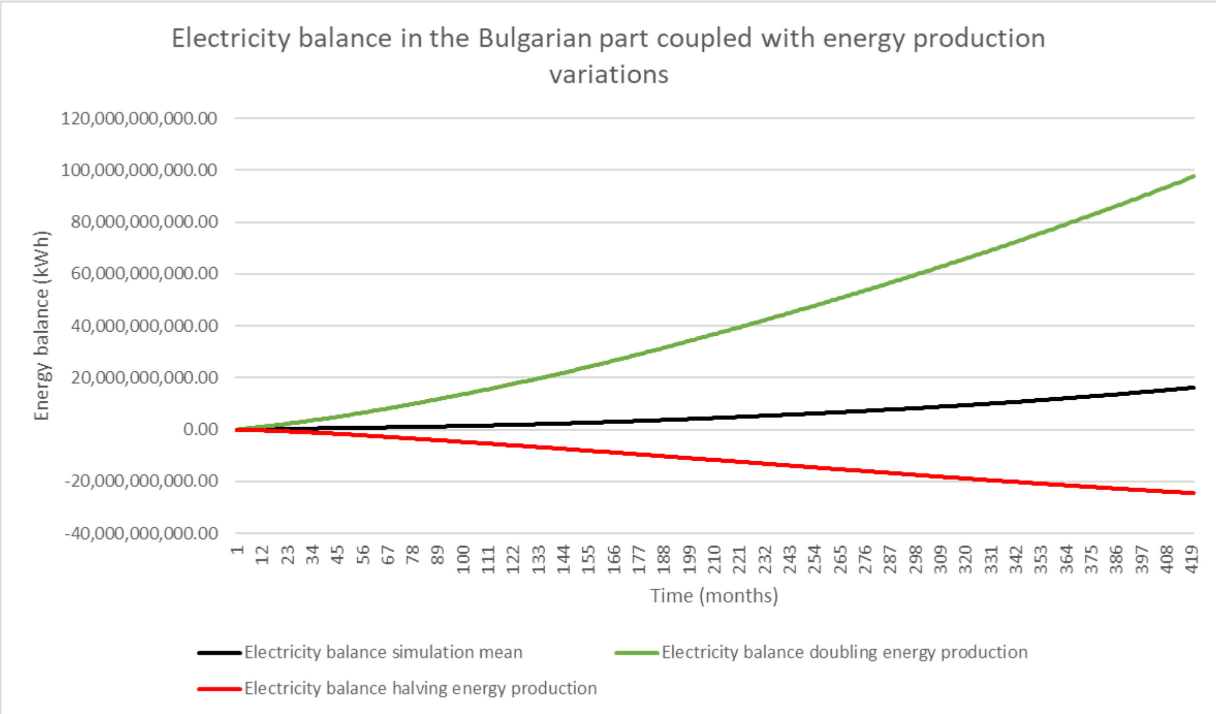


Figure 50: Energy balance in the Bulgarian part under the RCP2.6SSP2 scenario. The black line represents the average simulation, while the green line shows the trend with doubled energy production, and the red line indicates the trend with halved energy production.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

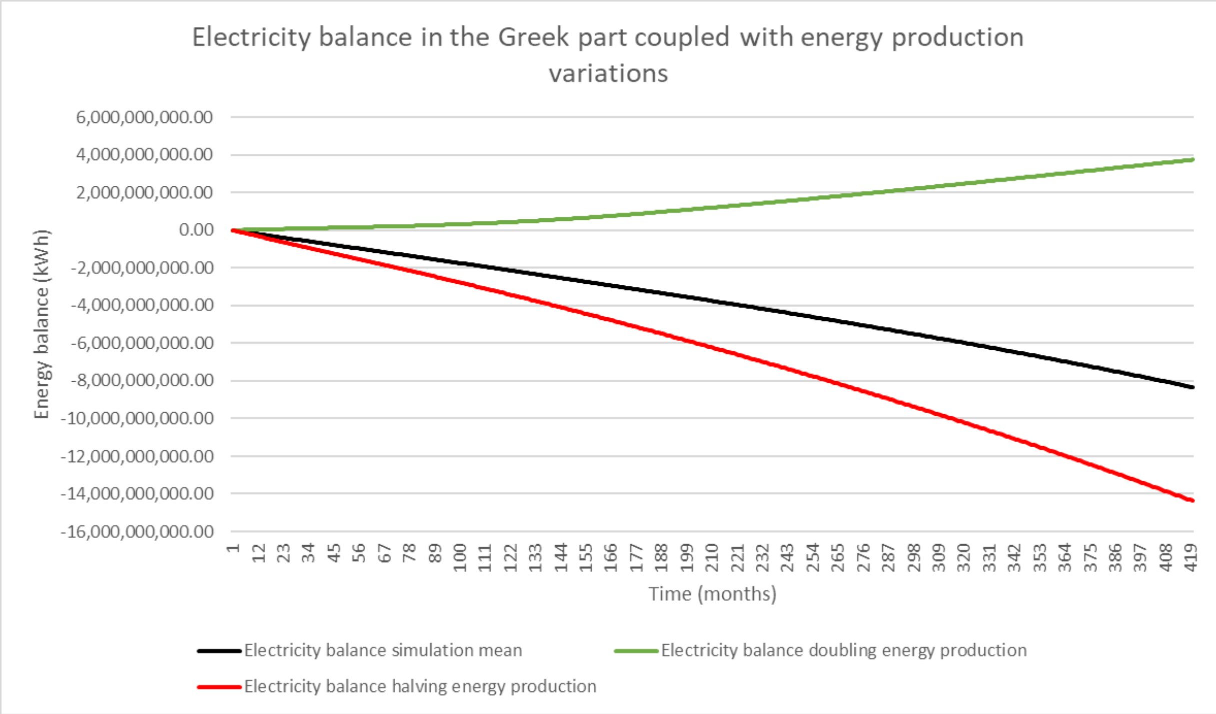


Figure 51: Energy balance in the Greek part under the RCP2.6SSP2 scenario. The black line represents the average simulation, while the green line shows the trend with doubled energy production, and the red line indicates the trend with halved energy production.

Figures 52, 53 and 54 55 show food balance stress tests for Bulgaria and Greece within the Nestos/Mesta basin under the RCP2.6SSP2 climate scenario. Both regions demonstrate resilience to halving crop areas and livestock, maintaining a positive food balance. This suggests a significant food production surplus relative to consumption,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

indicating potential for self-sufficiency regardless of the production reductions modeled.

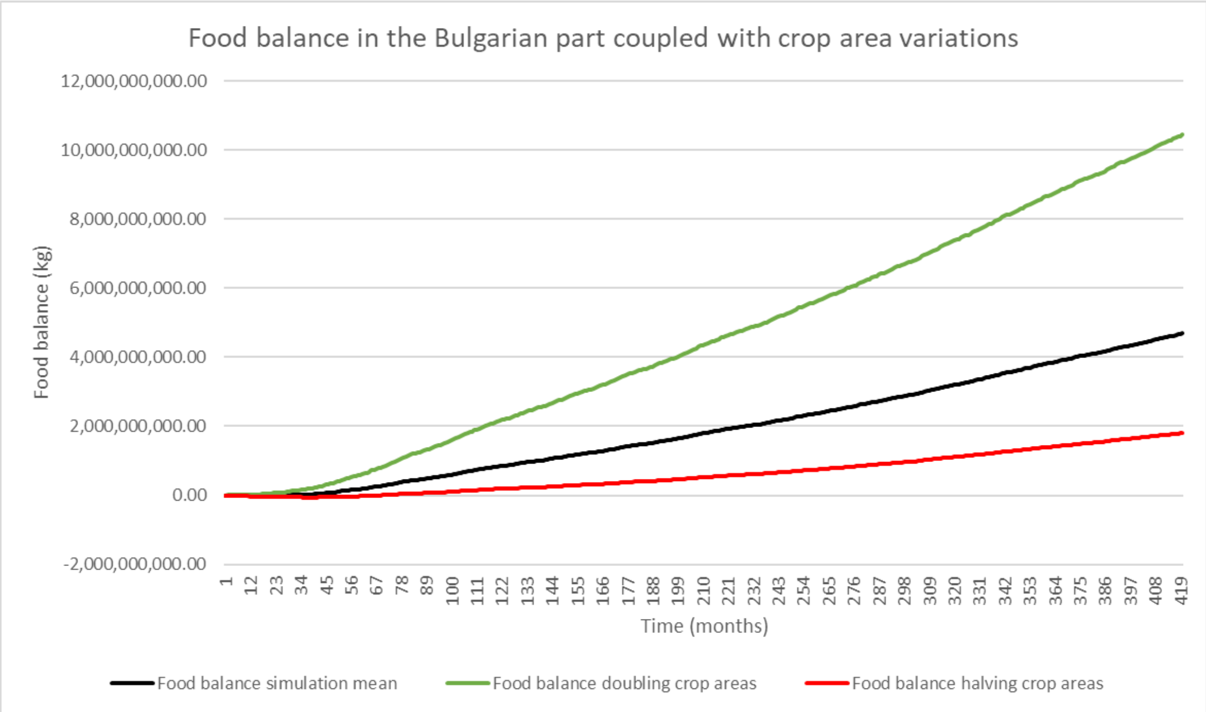


Figure 52: Food balance in the Bulgarian part under the RCP2.6SSP2 scenario. The black line represents the average simulation, while the green line shows the trend with doubled crop areas, and the red line indicates the trend with halved crop areas.

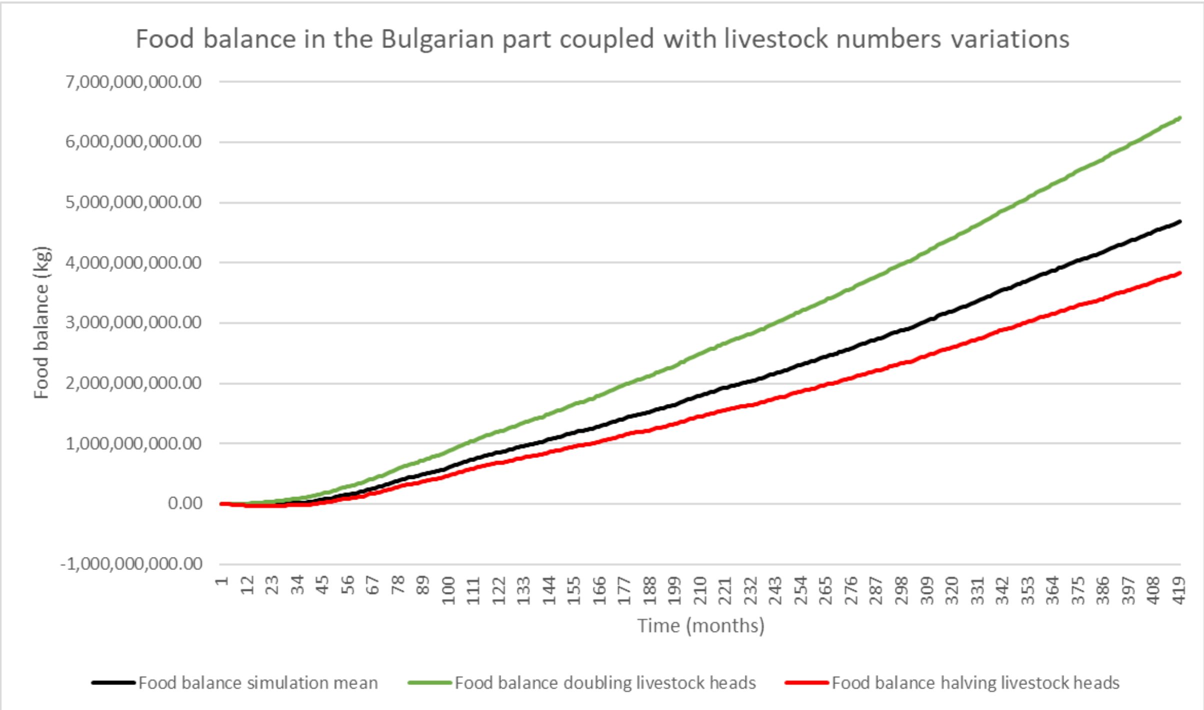


Figure 53: Food balance in the Bulgarian part under the RCP2.6SSP2 scenario. The black line represents the average simulation, while the green line shows the trend

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

with doubled livestock numbers, and the red line indicates the trend with halved livestock numbers

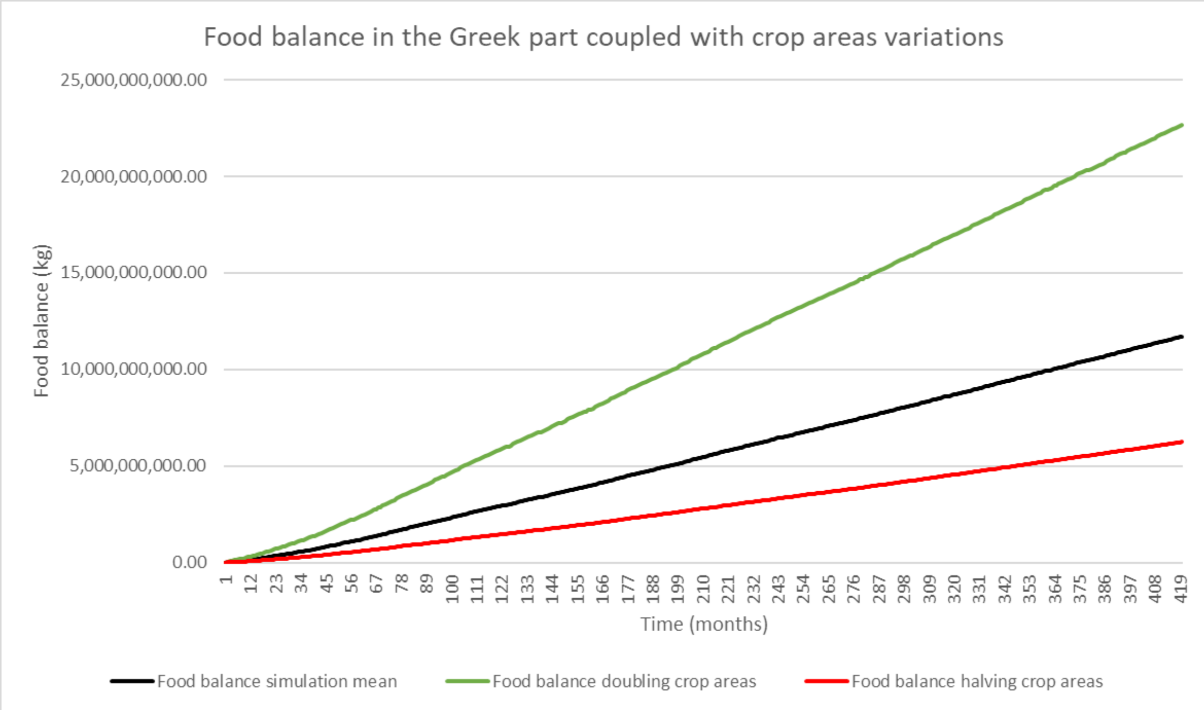


Figure 54: Food balance in the Greek part under the RCP2.6SSP2 scenario. The black line represents the average simulation, while the green line shows the trend with doubled crop areas, and the red line indicates the trend with halved crop areas.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

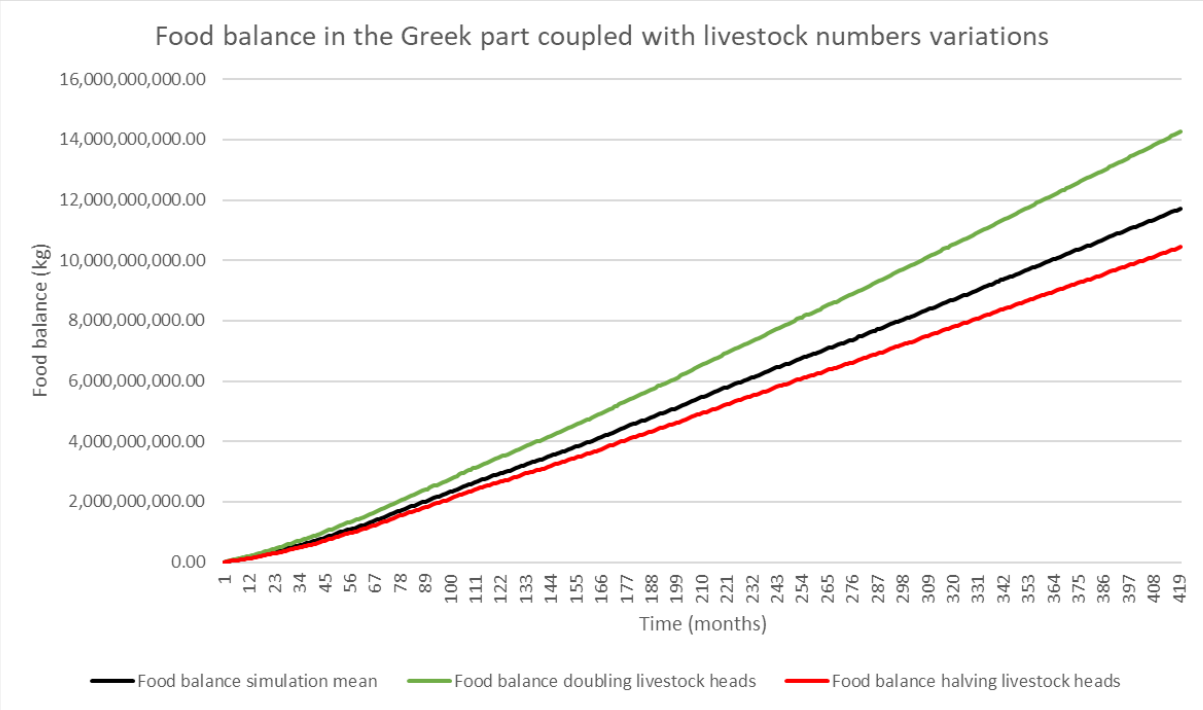


Figure 55: Food balance in the Greek part under the RCP2.6SSP2 scenario. The black line represents the average simulation, while the green line shows the trend with doubled livestock numbers, and the red line indicates the trend with halved livestock numbers.

Stress tests assessed the vulnerability of electricity and food balances in the Nestos/Mesta basin to changes in population growth, using the RCP2.6-SSP2 scenario as a baseline. This baseline projects negative population growth rates in both Bulgaria and Greece until 2050. Figures 56-59 illustrate the sensitivity of electricity and food balances to deviations from this baseline, specifically examining scenarios where population growth is halved and doubled. The results likely reveal the extent to which existing food and energy surpluses or deficits are impacted by changes in population size and its associated increase or decrease in demand. A negative growth rate suggests existing production exceeds consumption, but a doubling of this rate might strain resources, causing negative impacts on both electricity and food balances. Conversely, halving the already negative growth rate could further enhance existing surpluses. The figures are crucial for understanding the basin's resilience to population

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

shifts and informing policies related to resource management and infrastructure planning.

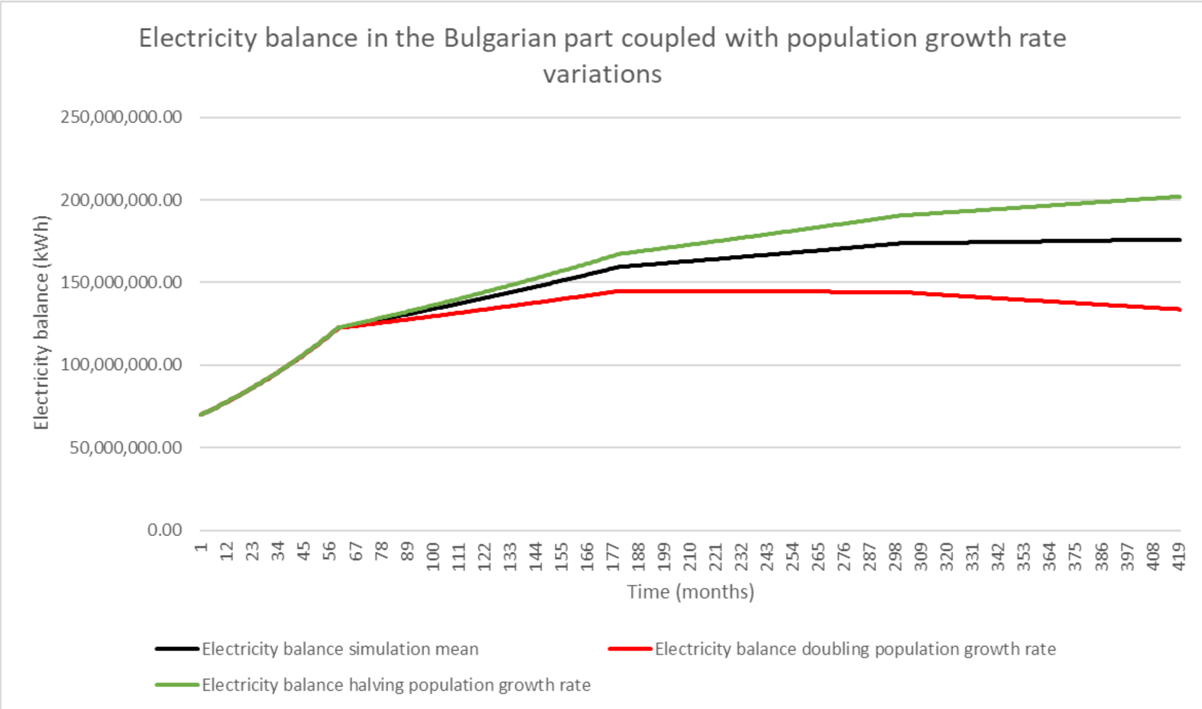


Figure 56: Electricity balance in the Bulgarian part under the RCP2.6SSP2 scenario. The black line represents the average simulation, while the green line shows the trend with halving population growth rate, and the red line indicates the trend with doubled population growth rate.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

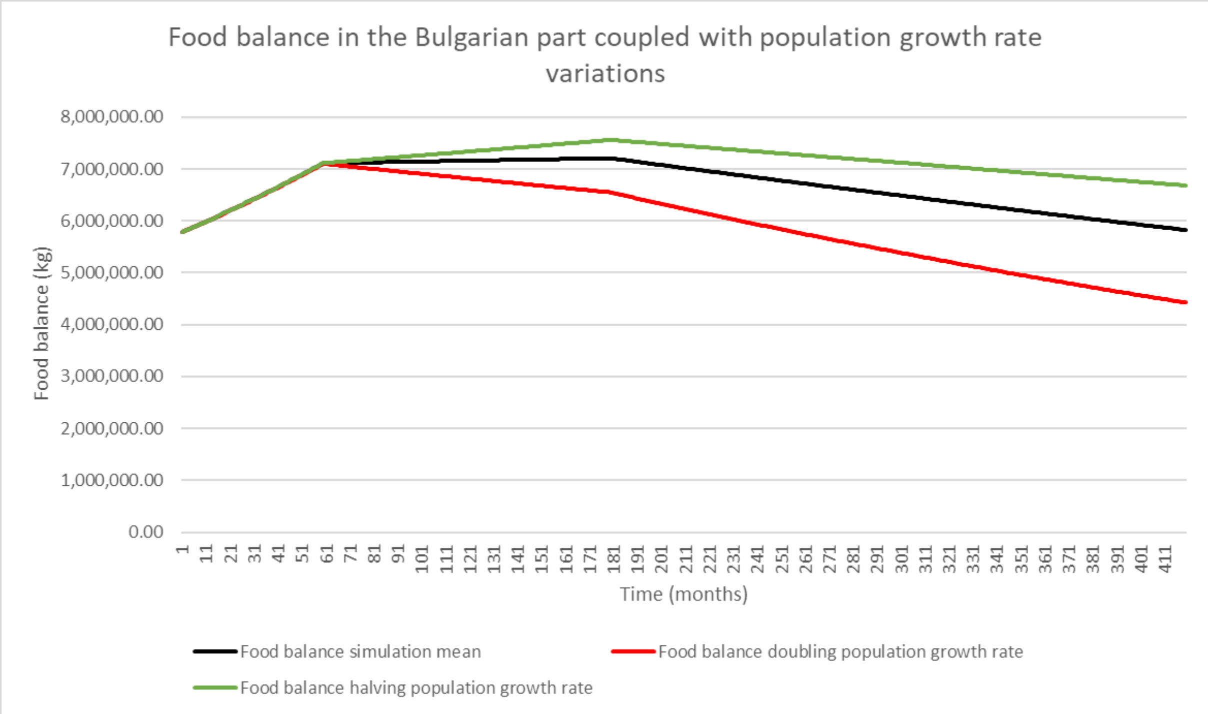


Figure 57: Food balance in the Bulgarian part under the RCP2.6SSP2 scenario. The black line represents the average simulation, while the green line shows the trend with halving population growth rate, and the red line indicates the trend with doubled population growth rate.

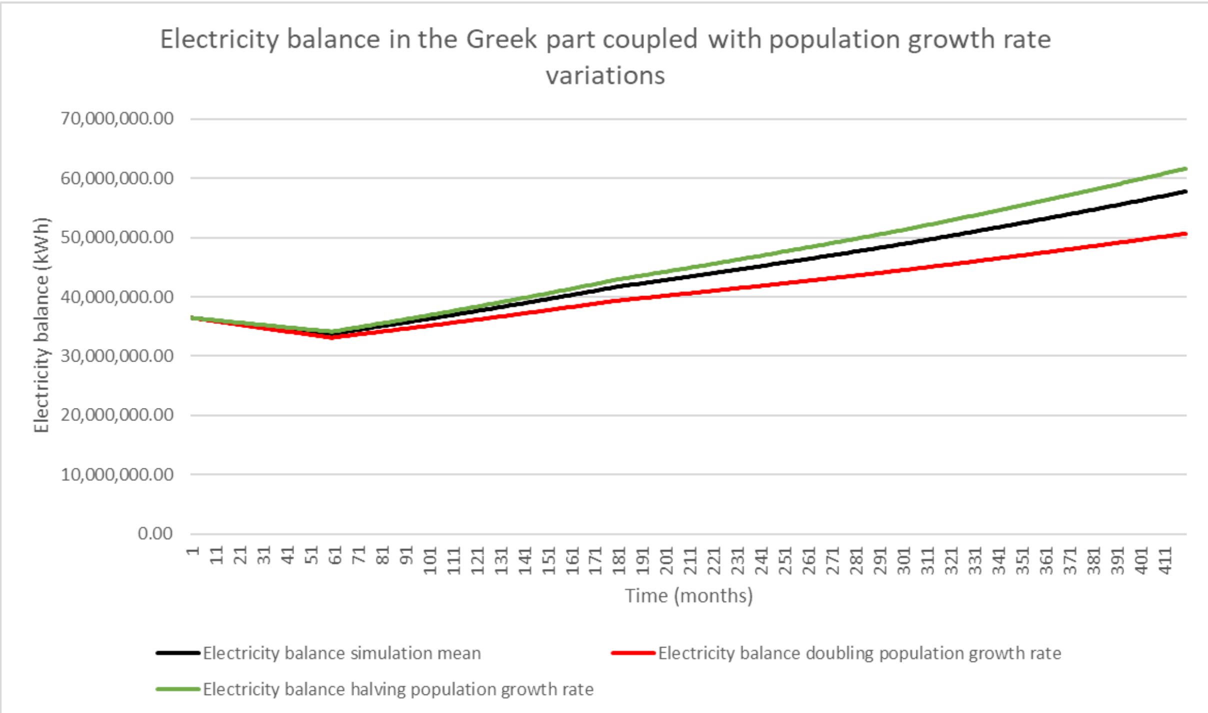


Figure 58: Electricity balance in the Greek part under the RCP2.6SSP2 scenario. The black line represents the average simulation, while the green line shows the trend with halving population growth rate, and the red line indicates the trend with doubled population growth rate.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

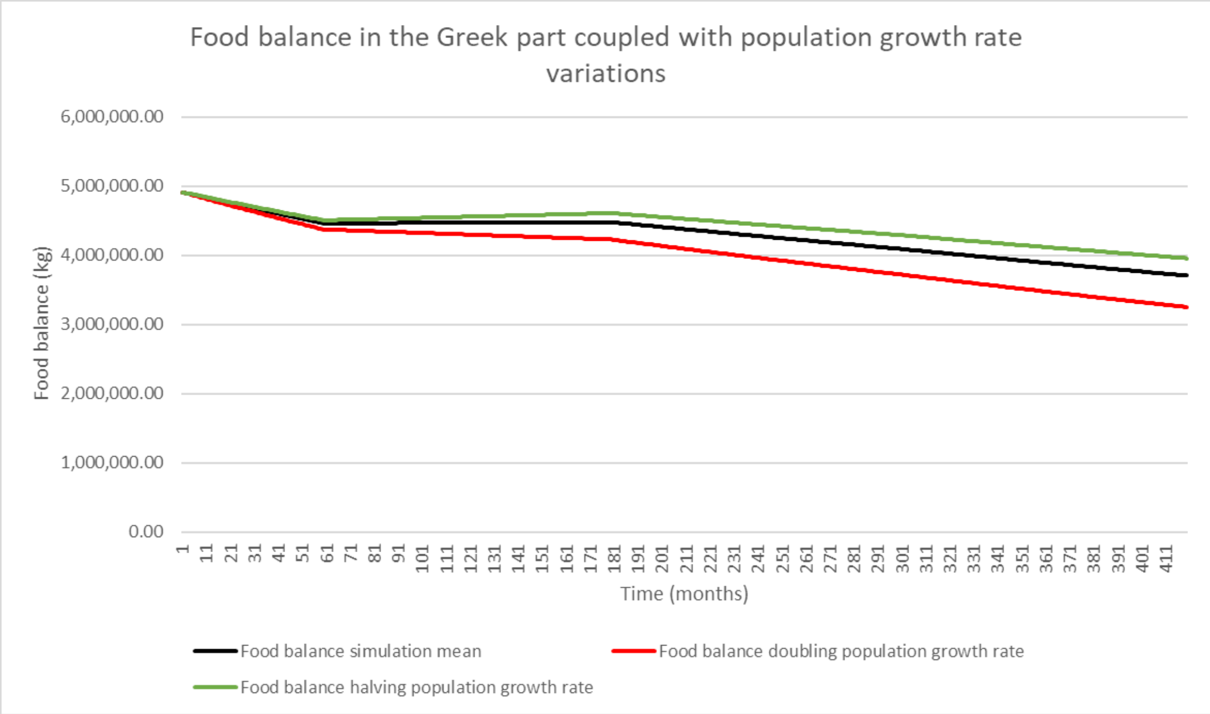


Figure 59 Food balance in the Greek part under the RCP2.6SSP2 scenario. The black line represents the average simulation, while the green line shows the trend with halving population growth rate, and the red line indicates the trend with doubled population growth rate.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

4.2 Lielupe River Basin

As previously introduced in Chapter 3, the proposed SD model aims to capture two sources of uncertainty, i.e. parametric and scenario, for assessing the WEFE Nexus in the Lielupe River Basin (LRB). It is important to clarify that all input variables in the model are treated as parameters. However, for some parameters, we have trends across multiple scenarios, particularly those derived from WP2-provided data. Table XX presents the full list of input variables used in the model, including those from WP2 and other sources.

Table 1. Summary of variables - Lielupe River Basin Case Study

Sector	Variables	Source
Climate	CO2 emissions per MWh produced - natural gas	Other sources (government and NGO reports) and academic literature
Climate	CO2 emissions per MWh produced - solar PV	Other sources (government and NGO reports) and academic literature
Climate	CO2 emissions per MWh produced - wind turbines	Other sources (government and NGO reports) and academic literature
Climate	GHG emissions in well-drained agriculture land	Other sources (government and NGO reports) and academic literature
Climate	GHG emissions in undrained agriculture land	Other sources (government and NGO reports) and academic literature
Ecosystems	Species richness amphibians	WP2 Data
Ecosystems	Species richness mammals	WP2 Data
Ecosystems	Species richness birds	WP2 Data
Ecosystems	Carbon mass in vegetation - deciduous forest	WP2 Data
Ecosystems	Carbon mass in vegetation - evergreen forest	WP2 Data
Ecosystems	Carbon mass in vegetation - grasslands	WP2 Data
Ecosystems	Carbon mass in vegetation - croplands	WP2 Data
Food	Nitrogen content in manure	Other sources (government and NGO reports) and academic literature
Food	Relative yield ratio field peas (Organic/Conventional farming practice)	Other sources (government and NGO reports) and academic literature
Food	Relative yield ratio maize (Organic/Conventional farming practice)	Other sources (government and NGO reports) and academic literature
Food	Relative yield ratio rapeseed (Organic/Conventional farming practice)	Other sources (government and NGO reports) and academic literature
Food	Relative yield ratio summer wheat (Organic/Conventional farming practice)	Other sources (government and NGO reports) and academic literature
Food	Relative yield ratio winter wheat (Organic/Conventional farming practice)	Other sources (government and NGO reports) and academic literature
Food	Crop yield - field peas	WP2 Data
Food	Crop yield - maize	WP2 Data
Food	Crop yield - rapeseed	WP2 Data
Food	Crop yield - summer wheat	WP2 Data
Food	Crop yield - winter wheat	WP2 Data
Nature-based solutions	Nitrate leaching rate	Other sources (government and NGO reports) and academic literature

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Nature-based solutions	Bioreactor nitrogen removal efficiency	Other sources (government and NGO reports) and academic literature
Nature-based solutions	Constructed wetland nitrogen removal efficiency	Other sources (government and NGO reports) and academic literature
Nature-based solutions	Riparian buffers nitrogen removal efficiency	Other sources (government and NGO reports) and academic literature
Nature-based solutions	Organic farming nitrogen removal efficiency	Other sources (government and NGO reports) and academic literature
Population	Domestic per capita nitrogen generation rate	Other sources (government and NGO reports) and academic literature
Population	Population	WP2 Data
Renewable energy	Solar PV generation capacity per area	Other sources (government and NGO reports) and academic literature
Water	Surface water flow	WP2 Data

4.2.1. Parametric uncertainty

This section aims to show uncertainty quantification across the sectors identified in the LRB SD model (Figure 60, See also section 2.2.2). Results below were estimated based on a global sensitivity analysis of 25 model parameters (10 stochastic time series and 15 rate converters) using a Sobol sequencing sample of 1000 iterations, with a monthly time step over 420 months (i.e. 35 years – 2015-2050). Stella Professional 3.3 was used to develop the uncertainty analysis. Sub sections below show the dynamic uncertainty range of key model's variables after performing the global sensitivity evaluation.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

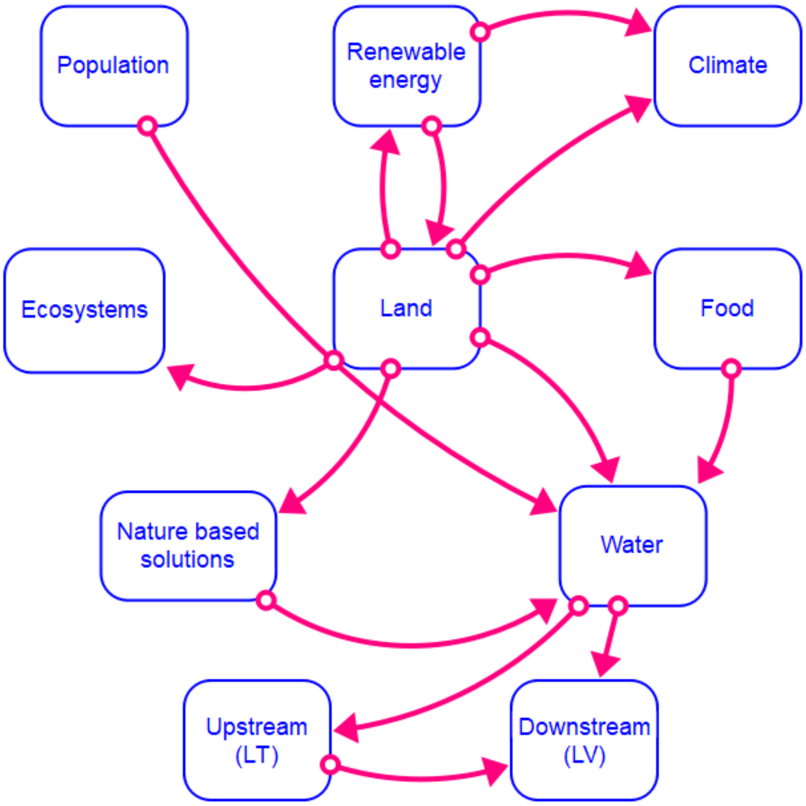


Figure 50. Lielupe River Basin SD WEFE Nexus Overview

4.2.1.1 Land sector

There is uncertainty regarding changes in land use. In Lielupe River Basin total arable land may increase at the expense of grasslands, and vice versa. Figure 61 captures these trends over time. Long-term trends show a slight average increase in agricultural areas. However, it is important to note that the range of prediction uncertainty significantly increases over time.

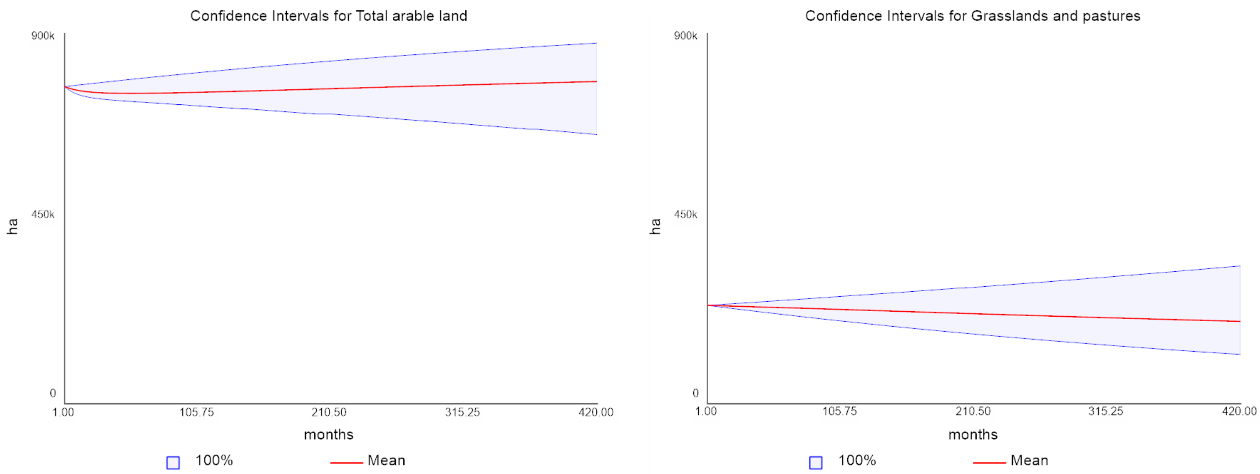


Figure 61. Dynamic confidence intervals for arable land and grasslands in Lielupe River Basin

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

4.2.1.2 Population sector

Changes in population are expected to affect, among others, the total domestic nitrogen generation rate. Sensitivity analysis outputs show a trend of long-term and slight decrease in the domestic nitrogen generation rate (Figure 62) driven by an expected population reduction. However, results show a relatively wide range of variability driven by variations in the range of the nitrogen per capita generation rate.

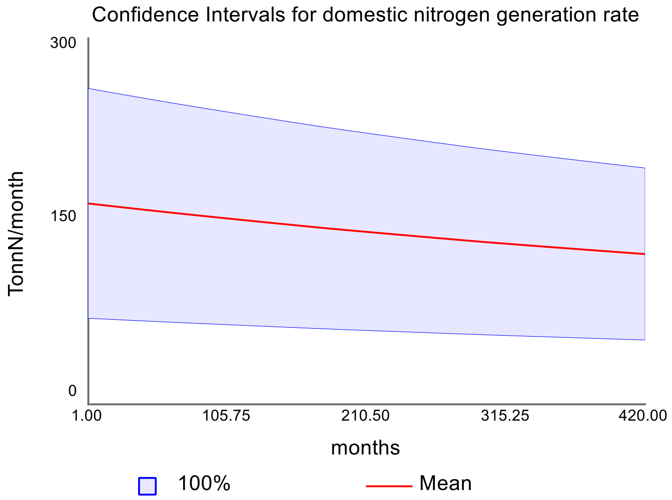


Figure 62. Dynamic confidence intervals for domestic nitrogen generation rate in the Lielupe River Basin

4.2.1.3 Renewable energy sector

This sector shows estimates of long-term renewable energy generation in the LRB (Figure 63). Wind energy is expected to dominate Solar PV with an average generation capacity of 4.8 million MWh/month against 238 thousand MWh/month in 2050. This is based on the current higher relative wind energy capacity installed and the low rates of PV generation in the Baltic region. However, renewable energy generation can vary significantly based on the rate of expansion of renewable energy installed capacity.

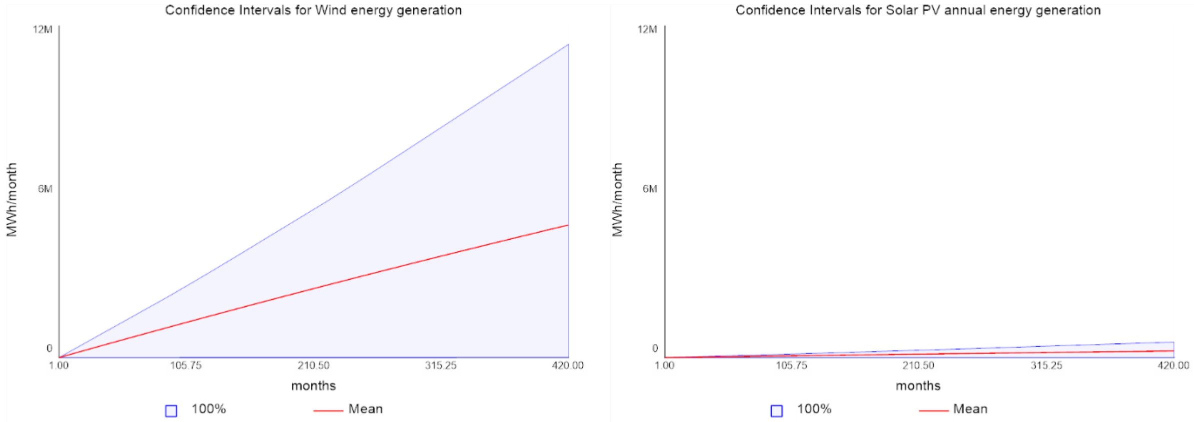


Figure 63. Dynamic confidence intervals for wind and solar PV energy generation in the Lielupe River Basin

NEXOGENESIS
STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

4.2.1.4 Climate sector

Climate sector aims to capture changes in GHG emissions across LRB. Figure 92 (left), shows an estimation of the reduction of CO2e emissions derived from generating energy from renewable sources in the river basin. The average trend shows an exponential growth in the emissions savings in the long-term (e.g. 770M CO2e in 2050). However, the order of magnitude of such savings will vary significantly based on the renewable energy expansion rates, as well as on the uncertainty of the rate of energy/emissions ratio of both conventional and renewable energy sources considered in the basin. 64 (right), shows an estimation of the cumulative emissions associated to cropland. Results show a linear increase of cumulative GHG emissions over time (e.g. 113m CO2e in 2050). Variations in land use and emissions rate imply that the emissions confidence interval widens significantly over the years.

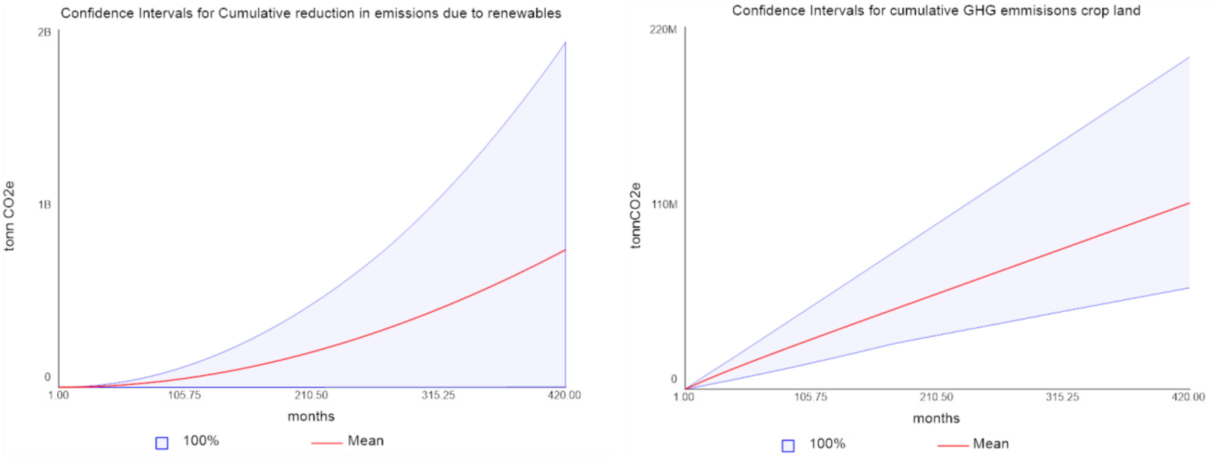


Figure 64. Dynamic confidence intervals for cumulative reduction in CO2e emissions due to renewables and CO2e emissions from cropland

4.2.1.5 Ecosystems sector

The Ecosystems sector captures the relation between changes in total biomass in vegetation and biodiversity in the basin. Figure 65 (left) shows an average trend of growth and stabilisation of total carbon biomass in vegetation in the basin. However, the ranges of prediction slightly increase over time. Figure 65 (right) shows the species richness of birds and mammals over time, exhibiting the same observed behaviour of the total vegetation biomass. Yet, it is worth mentioning that despite ranges of prediction also widen over time, their magnitude remains relatively constant.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

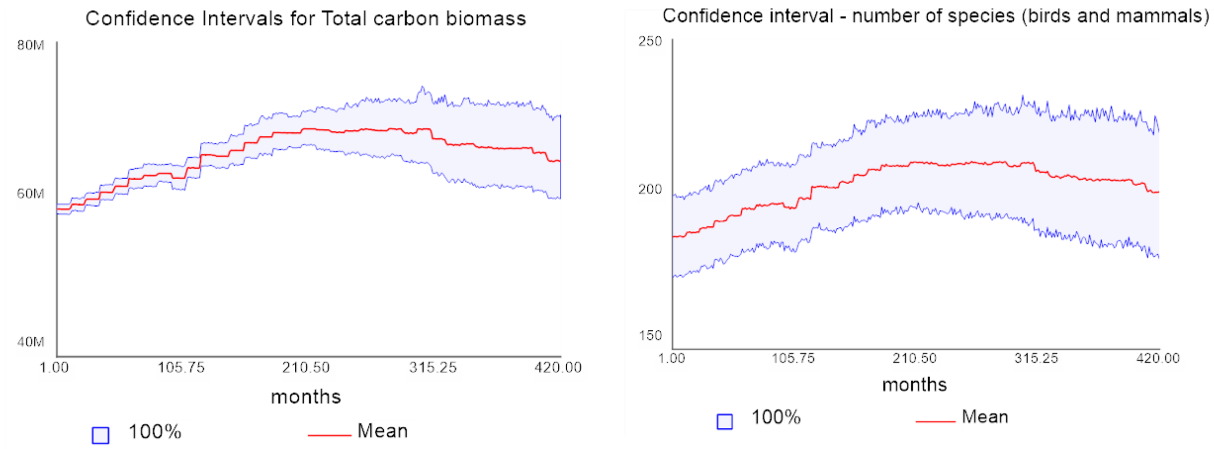


Figure 65. Dynamic confidence intervals for total carbon biomass and species richness of birds and mammals in the Lielupe River Basin

4.2.1.6 Food sector

This sector shows long-term crop production estimates in the basin. The main crop in the basin is wheat (see Figure 66). Summer and Winter wheat production are also disaggregated in B and C graphs of Figure . Average wheat production is expected to remain relatively stable yet with oscillations driven mostly by volatility in winter wheat production. It is worth mentioning that the range of total production is very wide due to the high variance of wheat crop yield estimated by WP2 (average 200k, min 72k, max 345k tonnes/month).

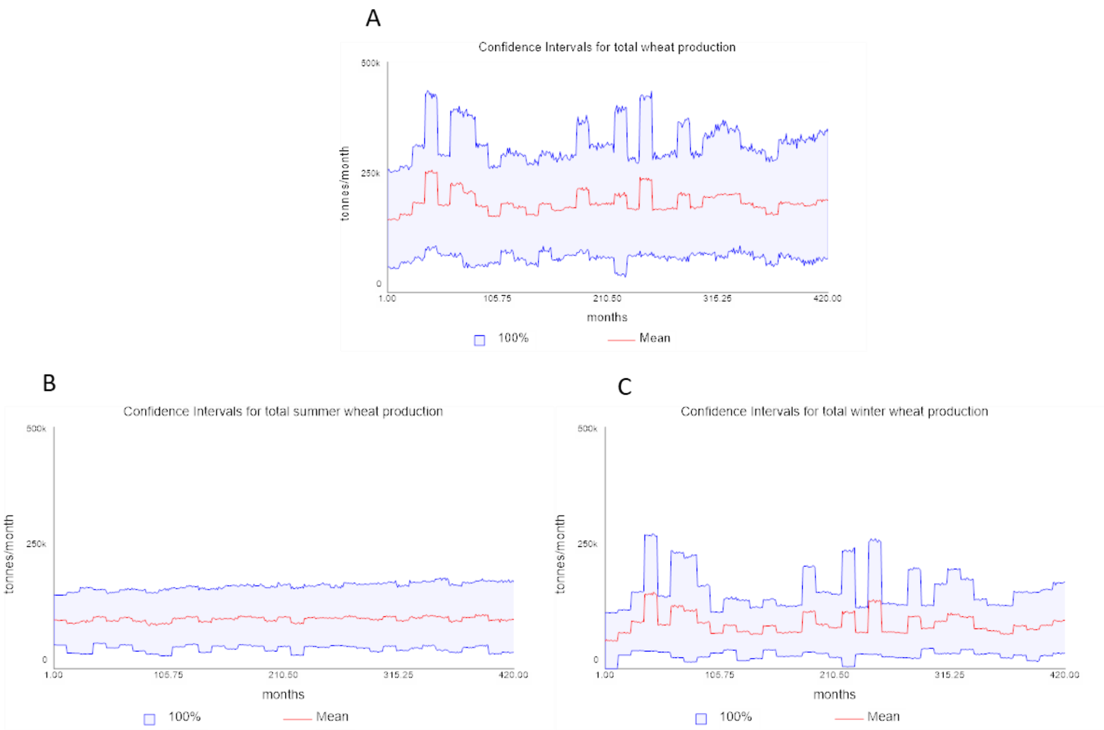


Figure 66. Dynamic confidence intervals for wheat crop production in the Lielupe River Basin

Other crops such as maize, rapeseed, and field peas are also important in the basin (see Figure). Average crop production of these crops is expected to remain relatively stable, yet

NEXOGENESIS
STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

with a slight oscillating behaviour. Maize shows a high variance, resembling the case of wheat. However, rapeseed and field peas production exhibit a narrow range of variability.

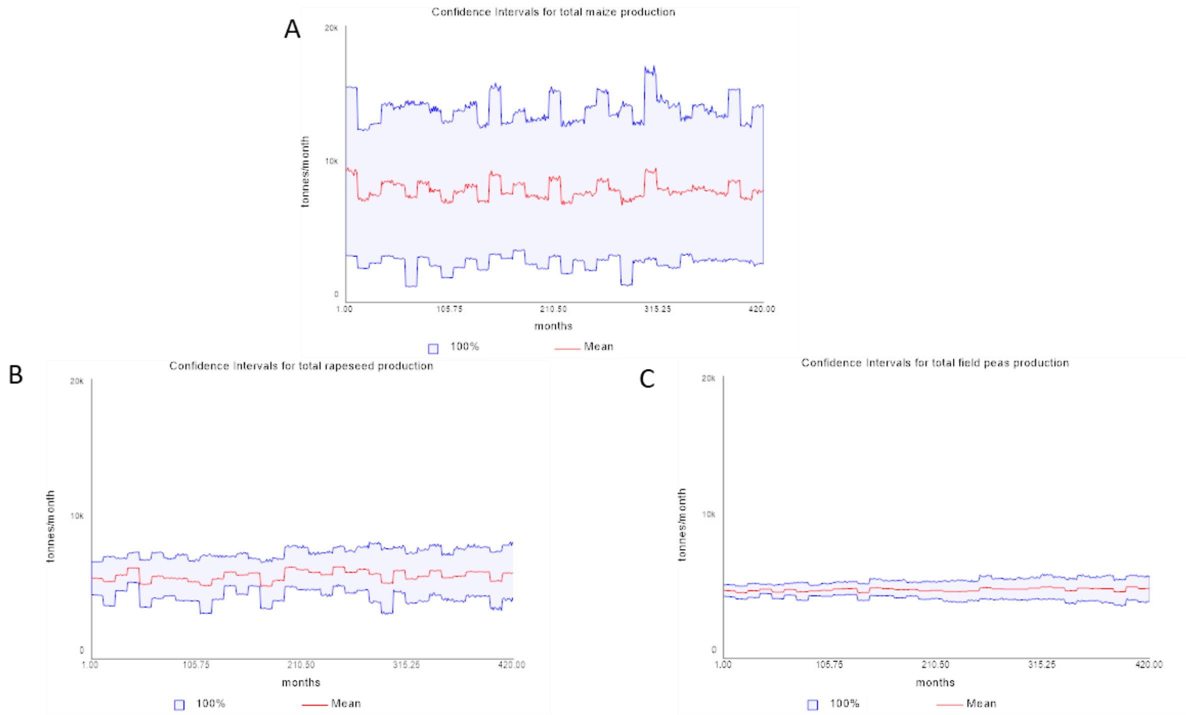


Figure 67. Dynamic confidence intervals for maize, rapeseed and field peas crop production in the Lielupe River Basin

4.2.1.7 Nature-based solutions sector

This sector aims to capture the possible benefits of a large-scale implementation of nature-based solutions (NBS) in the basin to control nutrient pollution. Figure 68 (A-B) shows total crop nutrient leaching in water under a business-as-usual (BAU) scenario (A) versus implementing NSB in the basin (B). In a BAU scenario, average nitrogen emissions exhibit a logistic growth behaviour, that is, first increasing from 1300 tons N/month and later stabilising around 2100 tons N/month. In contrast, by implementing NBS, average nitrogen concentration exhibits a behaviour of exponential decay, starting at 1300 tons N/month and later stabilising around 500 tons N/month in the long term. However, when global parametric uncertainty is considered, the ranges of nutrient loads and relative reduction of leaching due to NBS are wide. For example, the 90% confidence interval of relative nutrient leaching reduction due to NBS for 2050 ranges from 25 to 95%.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

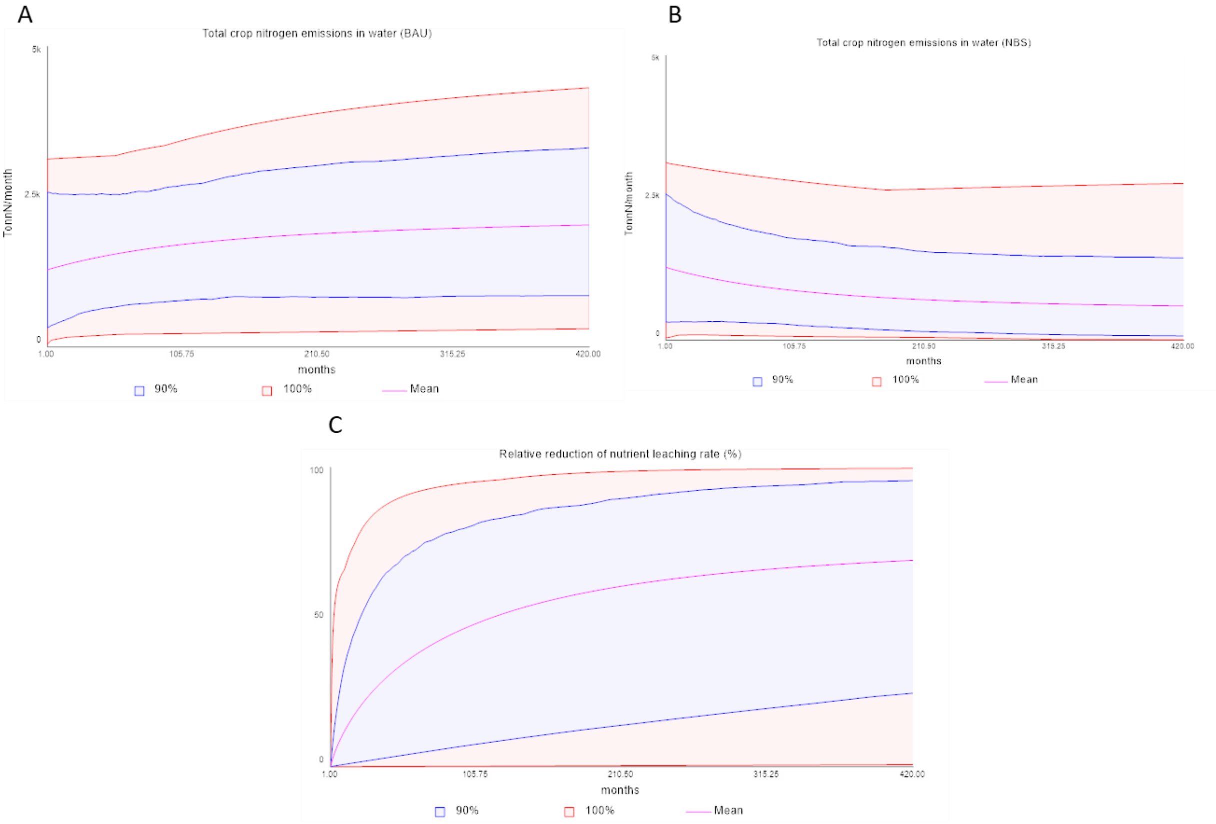


Figure 68. Total crop nutrient loads in water under a business-as-usual (BAU) scenario (A) versus implementing NSB in the basin (B)

4.2.1.8 Water sector

This sector aims to capture the water quality dynamics in the basin, particularly in terms of nutrient concentration. A stochastic river flow data series was estimated based on WP2's hydrological model outcomes (see Figure 69). River flow is highly seasonal with peak flows in winter and low flow in summer (see Figure 69). This, in conjunction with the nutrient loads calculated in the NBS module, allows a dynamic and stochastic estimation of nutrient concentration in the Lielupe River (see Figure 69). Nutrient concentration behaviour over time responds to flow variation in an inverse way, i.e. low flow conditions are associated with nutrient concentration peaks, and vice versa.

NEXOGENESIS
STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

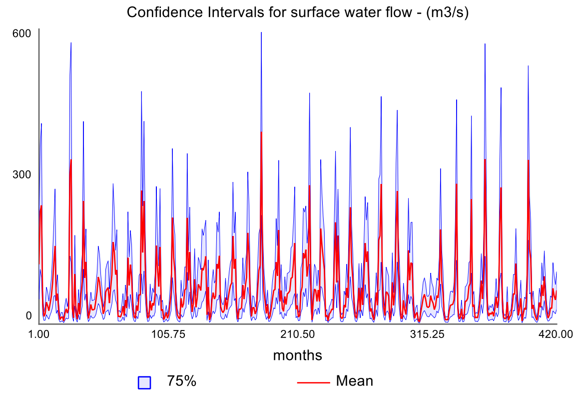


Figure 69. Dynamic confidence interval of surface water flow in the Lielupe River Basin

Despite nutrient concentration behaviour being strongly driven by flow, it is possible to estimate the relative long-term nutrient concentration reduction by implementing NBS in the basin. Figure 70 contrasts the nutrient concentration time series of a BAU and an NBS scenario. In a NBS scenario, seasonal nitrogen concentration peaks inevitably still exist but are substantially lowered by implementing a NBS expansion in the basin. Figure -C further illustrates this point by showing a dynamic confidence interval reduction of nitrogen concentration in the basin. The average nitrogen concentration reduction for 2050 would reach 43% with a 90% confidence interval ranging from 12 to 70%.

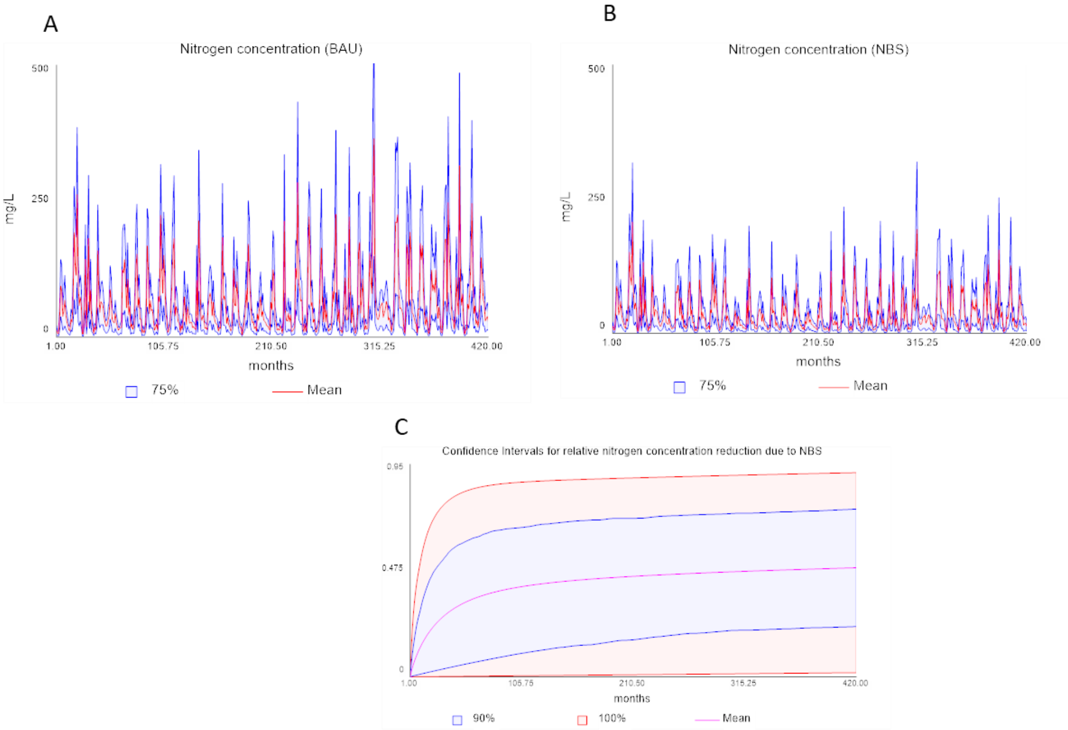


Figure 70. Nitrogen concentration in water under a business-as-usual (BAU) scenario (A) versus implementing NSB in the basin (B).

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

4.2.2. Scenario uncertainty

Scenario uncertainty relates to alternative global trends or future world narratives that might affect the LRB WEFE system. This model considers estimations coming from climate scenarios RCP 2.6 and RCP 8.5, as well as from socioeconomic scenarios SSP2 and SSP4. Scenario uncertainty does not directly affect all sectors described in section 2.2.2. Sectors including uncertainty coming from climate or socioeconomic scenarios are described below.

4.2.2.1 Population sector

Population growth will be affected under different scenarios. Figure 71 shows the expected cumulative population growth rate under two socioeconomic scenarios i.e. SSP2 and SSP4. Both scenarios exhibit the same behaviour of compounded population reduction over the long term, however, SSP44 shows a more drastic reduction.

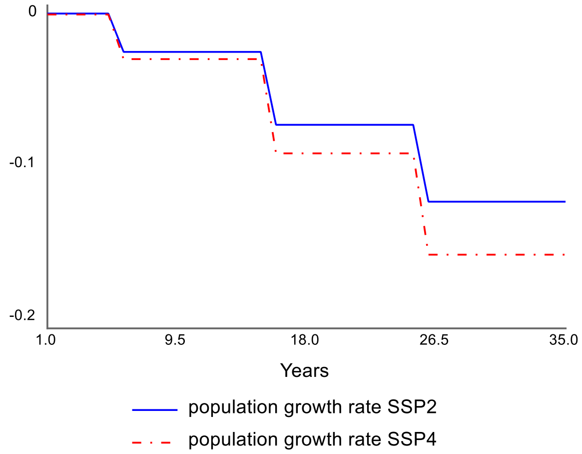


Figure 71. Cumulative population growth rate under different socioeconomic scenarios

4.2.2.1 Food sector

This section presents an assessment of the effect of climate scenarios on crop yield for the LRB. Figure 72 shows confidence intervals for the main cereal crops in the basin i.e. wheat and maize. Estimations under RCP 2.6 are in the first column while estimations corresponding to RCP 8.5 are on the right. Both columns exhibit oscillating trends with high volatility. However, both crop yield scenarios are virtually in the same confidence interval over time.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

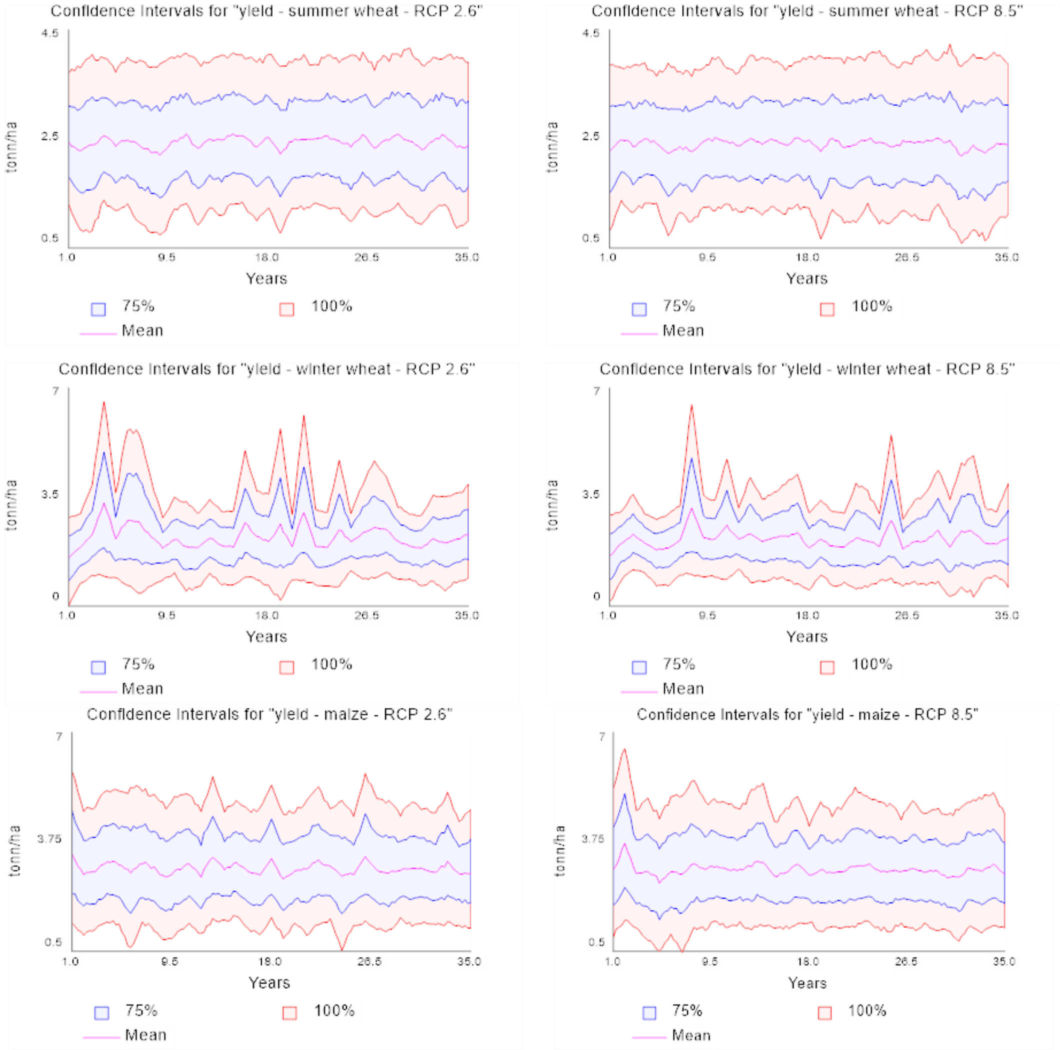


Figure 72. Dynamic confidence intervals for cereals (wheat and maize) crop production in the Lielupe River Basin under two RCP emission scenarios

Figure 73 shows confidence intervals for other crops in the basin i.e. rapeseed and field peas. As in the previous figure, both scenarios and crops exhibit oscillatory yet stationary behaviour of yield over time, yet the rapeseed crop yield exhibits less volatility than field peas. However, it is worth mentioning that crop yields remain in the same confidence interval range regardless of the climate scenario.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

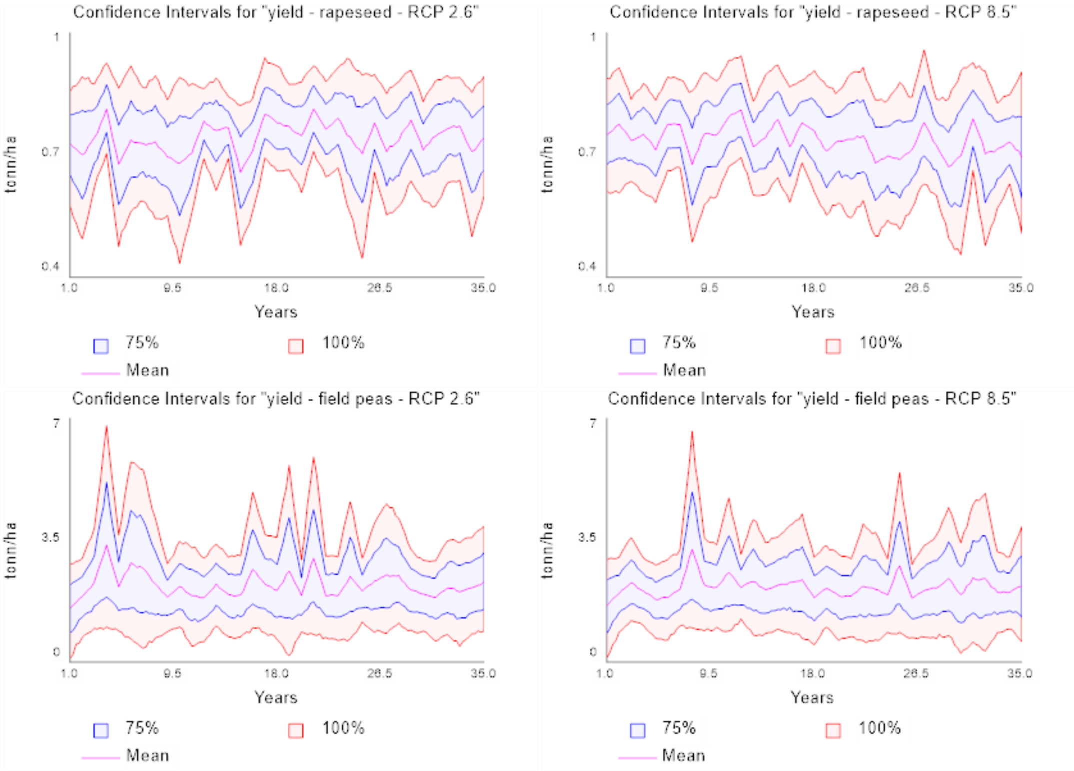


Figure 73. Dynamic confidence intervals for rapeseed and field peas crop production in the Lielupe River Basin under two climate scenarios

4.2.2.2 Ecosystems sector

This section compares the effect of different climate change scenarios on LRB biodiversity. Figure 74 presents a dynamic confidence interval of species richness of mammals, birds, and amphibians under RCP2.6 (left) and RCP6.0 (right) scenarios. Please note that, at the moment of writing this report, the RCP8.5 climate scenario impacts on biodiversity are not yet publicly available for analysis. However, we report the available RCP6.0 as it is a scenario of high radiating forcing, yet less extreme than RCP 8.5. Species richness of amphibians and birds shows a trend of slight long-term growth under the two RCP scenarios under consideration. Mammal species, on the other hand, show a slight increase under RCP 2.6 scenario but remain steady under RCP6.0.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

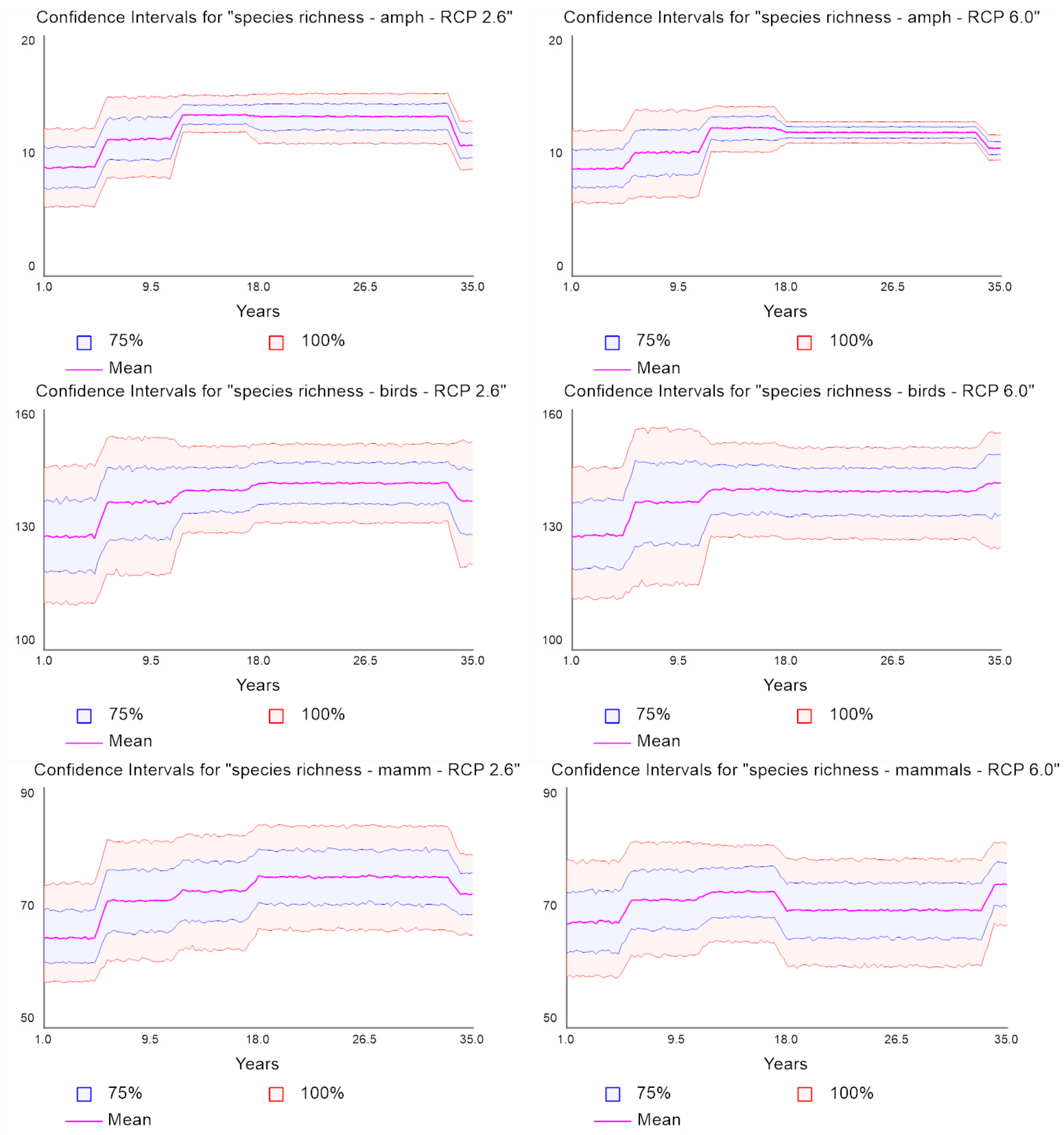


Figure 74. Dynamic confidence interval species richness of mammals, amphibians and birds in the Lielupe River Basin under two climate scenarios

Figure 75 compares the dynamic behaviour of total carbon mass in vegetation confidence intervals under RCP 2.6 and RCP 8.5. Here it is possible to observe that RCP 2.6 exhibits a behaviour of slight growth and decay after reaching a peak around half of the timespan. RCP 8.5, on the contrary, shows a trend of slight linear growth in biomass over time. Also, variance is narrower under RCP2.6 compared with RCP8.5, this comes on a first stance, from the fact that more predictive models are available under RCP8.5, as reported from WP2. Yet, the lower bound of RCP8.5 covers the RCP2.6 confidence interval.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

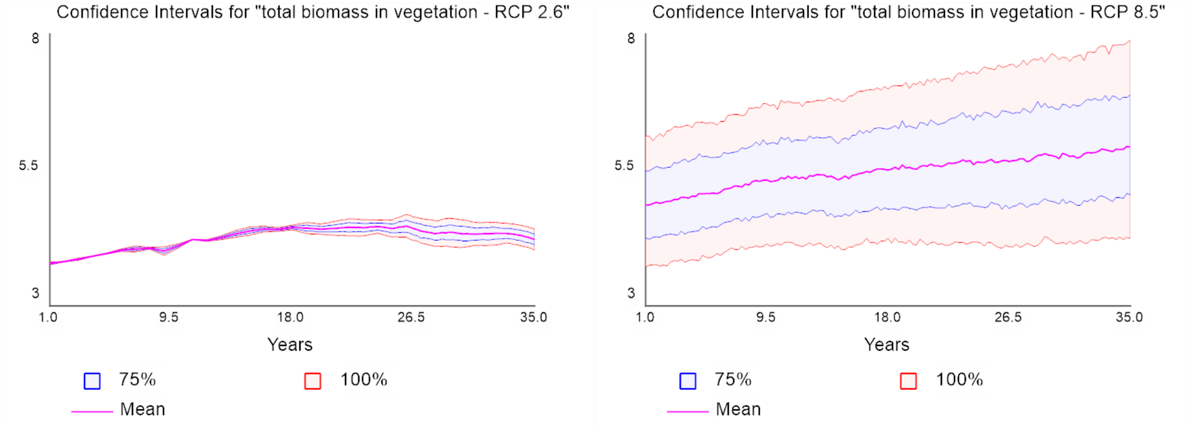


Figure 75 Dynamic confidence interval for total carbon mass in vegetation in the Lielupe River Basin under two climate scenarios

4.2.2.2 Water sector

Here are presented changes in surface water flow under different climate scenarios i.e. RCP2.6 and RCP8.5 (see Figure 76). As previously, discussed in section 4.2.1.8, river flows in both scenarios exhibit a heavily marked seasonality of peak flows in winter and low flows in summer. Also, both surface water flows are in the same range with peaks of 500 m3/s, average high values of 100 m3/s and long-term mean flow of 25 m3/s.

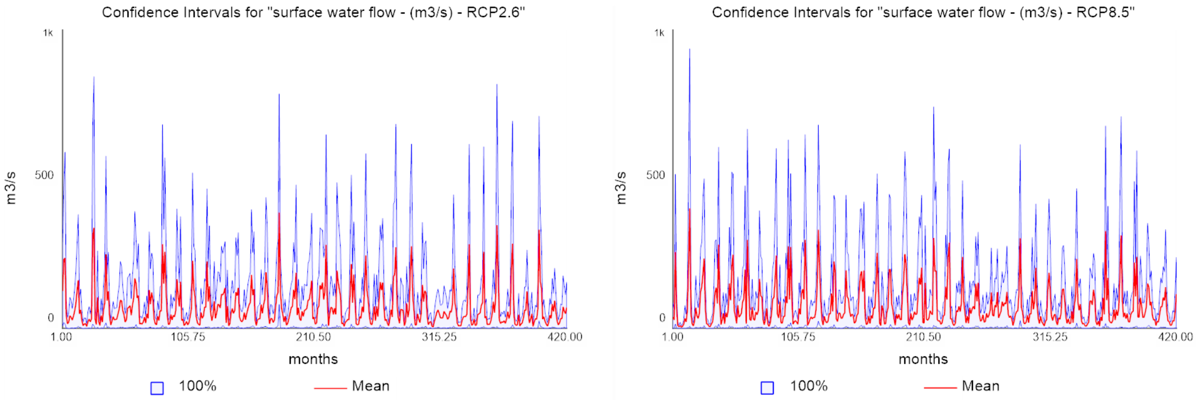


Figure 76. Dynamic confidence interval of surface water flow in the Lielupe River Basin under two climate scenarios

4.2.3 What-if and stress tests

What-if and stress tests focus on the impact of the core policies on various output variables of interest. The analysis also considers the intrinsic variability estimated by parametrical uncertainty. However, more importantly, it shows how policy futures can drive changes in nexus outputs amidst deep uncertainty.

More specifically, we propose a robust analysis of two important policy levers for the Lielupe CS: (1) The long-term fraction of arable land in which NBS will be implemented, (2) The decision of allowing or not to convert arable land back to grasslands. For policy lever (1), a uniform distribution is proposed to be tested in the range of 0 to 1. 0 meaning that no arable land incorporates NBS, and 1 meaning that the whole arable undergoes an NBS transition. For policy lever (2), an ad-hoc distribution taking values 0 or 1, is proposed. 0 meaning that no

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

transition to grasslands is allowed, and 1 otherwise. If allowed, the model assumes a 10% transformation of arable land to grasslands according to current policy objectives in the basin.

The proposed *policy variability* is meant to be tested in several simulations. Here, we propose running the Lielupe SD model 1000 times following a Sobol sequence sampling. Additionally, both policy levers are considered independently for the upstream (Lithuania—LT) and downstream (Latvia—LV) countries. Table 1 illustrates the parameters for the analysis for the first 10 runs of the simulation.

Run ID	Fraction of Land with NBS (LV)	Fraction of Land with NBS (LT)	Allow conversion of arable land to grasslands (LV)	Allow conversion of arable land to grasslands (LT)
Run 1	0.5	0.5	0	0
Run 2	0.25	0.75	1	1
Run 3	0.75	0.25	0	0
Run 4	0.375	0.625	1	1
Run 5	0.875	0.125	0	0
Run 6	0.125	0.375	1	1
Run 7	0.625	0.875	0	0
Run 8	0.3125	0.3125	1	1
Run 9	0.8125	0.8125	0	0
Run 10	0.0625	0.5625	1	1

This open policy exploration helps us identify impacts in various nexus sectors. For example, in the water sector, the combination of the selected policies broadly affects water quality measured as total nitrogen discharged in the river basin (See Figure 77). The graphs illustrate that the considered policies are overall expected to lower nitrogen pollution, but the extent of such reduction depends on the combination of values for the policies, showing a broad range of long-term reduction between 10% and 60%.

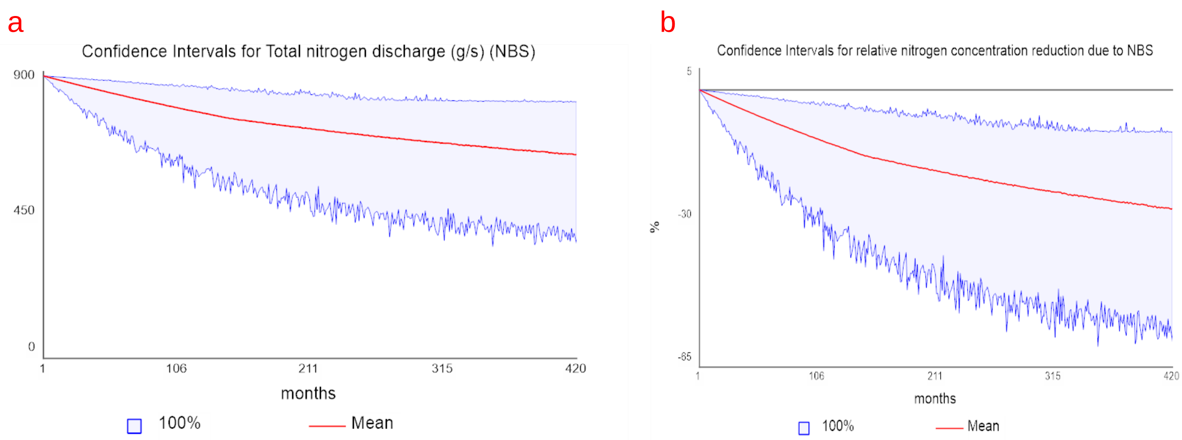


Figure 77. Dynamic confidence interval of a) total nitrogen discharge due to NBS and b) relative nitrogen concentration reduction due to NBS in the Lielupe RB.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Regarding local food availability, simulation results show that the proposed policies do not have an evident effect on changing the total crop production per month in the river basin. As can be observed in Figure 78, local food availability oscillates over the years exhibiting a behaviour that follows crop yield trends (see subsection 4.2.2.1 Food sector) instead of being affected by the policy levers above.

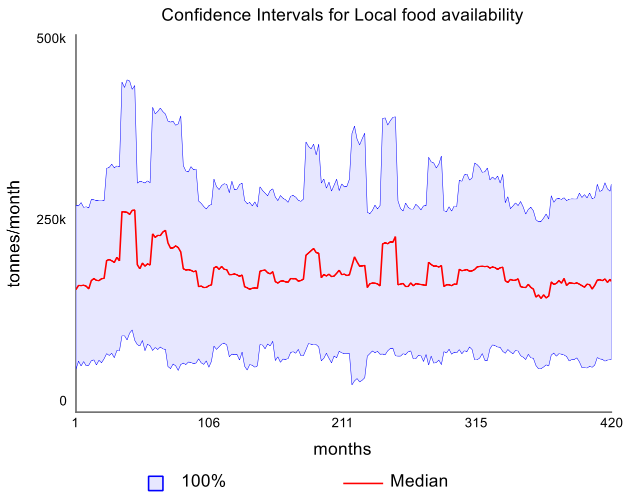


Figure 78. Dynamic confidence interval of local food availability in the Lielupe RB

The considered policies evidence some effect in terms of ecosystems. This is particularly evident regarding Carbon mass in vegetation (Figure 79-a). Increasing the area of grasslands contributes to having a linear increase in carbon stocks over the first half of the simulation. In contrast, proposed policies do not evidence a strong effect in improving biodiversity indicators, for example in terms of bird biodiversity (Figure 79-b). Despite increasing grasslands (by reducing 10% of arable land) showing a slightly positive effect on bird biodiversity, the effect is hindered by highly uncertain bounds inherent in ecological systems.

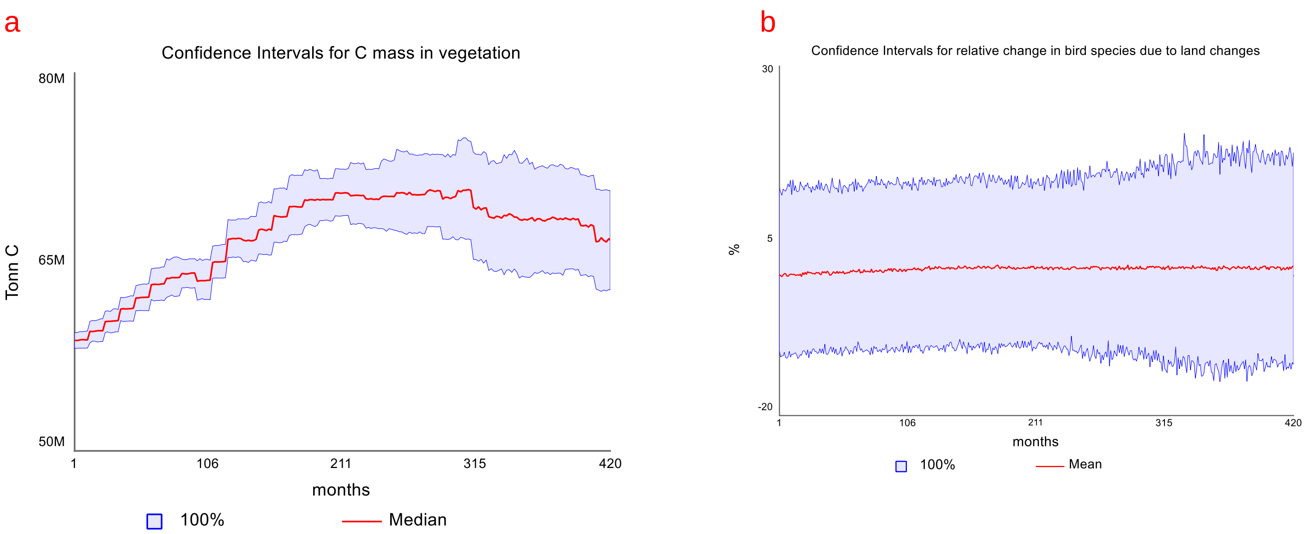


Figure 79. Dynamic confidence interval of a) total carbon mass in vegetation and b) relative change in bird species in the Lielupe RB.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

The considered policy levers show a clear effect in terms of CO2eq land emissions. Figure 80 shows a marked decrease trend in carbon emissions due to the recovery of grasslands. A slower effect continues over the years, likely related to the expected reduction in land emissions in well-drained arable land as part of NBS treatment systems.

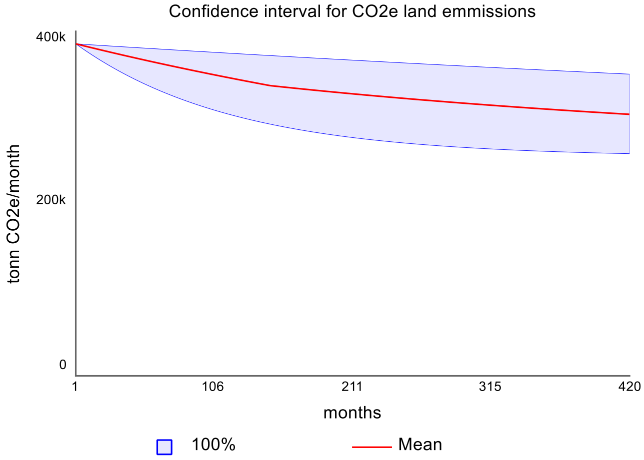


Figure 80. Dynamic confidence interval of CO2eq land emissions in the Lielupe RB

Finally, renewable energy supply shows a linear growth over the simulation (Figure 81). Some effects could be traced to the increase in grasslands and the possibility of using them to develop new renewable energy initiatives. However, other independent trends of renewable installation might be driving the increase in renewable energy production in the basin.

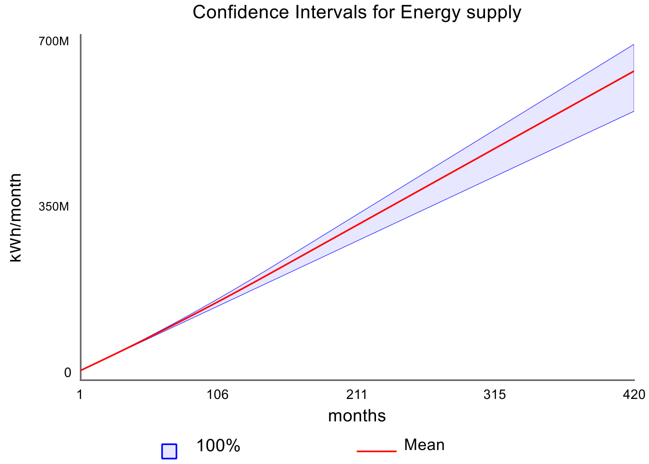


Figure 81 Dynamic confidence interval of CO2eq land emissions in the Lielupe RB

Results show that broad changes across policy levers have various effects across different nexus sectors and key variables. Notably, changes in NBS and extending grasslands will benefit water quality metrics through a long-term reduction of nutrient pollution in the basin. Benefits are also evident in increasing carbon vegetation stock in the basin, land-related CO2eq emissions, and extending renewable energy generation. On the contrary, modelling results do not show significant effects in terms of biodiversity and food production.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES

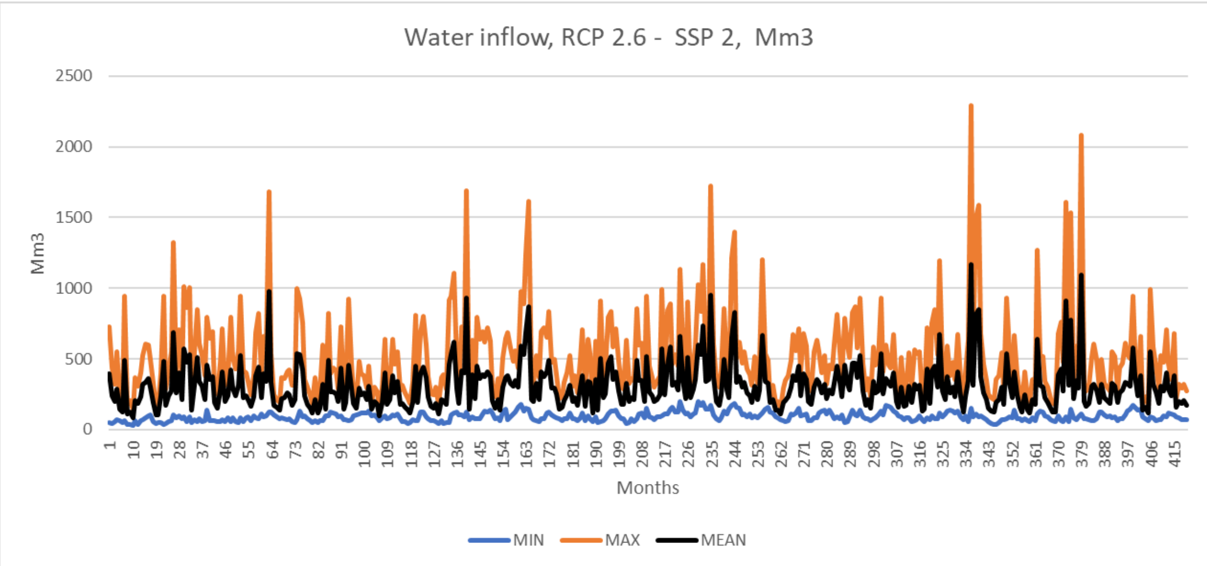
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

4.3 Jiu River Basin

This section shows the parametric and scenario uncertainty of some outputs obtained from the System Dynamic Model (SDM) developed for the Jiu river basin, in Romania. The scenario RCP 2.6 combined with SSP 2 is used to show the parametric uncertainty, while the scenario uncertainty compares results between SSP2 and SSP 4 and RCP 2.6 and RCP 8.5. The uncertainty presented results from 100 SDM runs each from 2015 to 2049, i.e., 420 months.

4.3.1 Parametric uncertainty

The parametric uncertainty for the total water inflow, outflow, and water balance are shown in Figure 82, Figure 83, and Figure 84, respectively. The water balance in the Jiu case study is computed by using input data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) processed through WP2 for both water inflow (availability) and outflow (consumption). The SIMETAW_GIS model was used to compute the irrigated crop water demand for three main crops, such as maize, rapeseed and sunflower. The water inflow in the Jiu case study is obtained considering the surface water and the groundwater (Figure 85). The available water in the basin is used for three main sectors, i.e., domestic, industry, and agriculture. There is large difference between the minimum and the maximum value in the water inflow and this could be explained by the variability in the surface water runoff input data used to populate the SDM. The uncertainty related to the water consumption is shown in Figure 86. The results indicate that the range of uncertainty for this model outcome is lower compared to the water inflow. The main difference between minimum and maximum water outflow is in the period between spring-summer. The water balance in the Jiu river basin is positive, so the water available in the basin can, if managed properly, meet the demand over time. This information could support decision makers in future plans and strategies for sustainable water use in the basin. The balance tends to increase over time; its related uncertainty is shown in Figure 87 and could be explained by the variability coming from the surface water input data.



NEXOGENESIS
STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Figure 82. Uncertainty for the total water inflow for the RCP2.6-SSP2 scenario from 2015 to 2049 in the Jiu river basin.

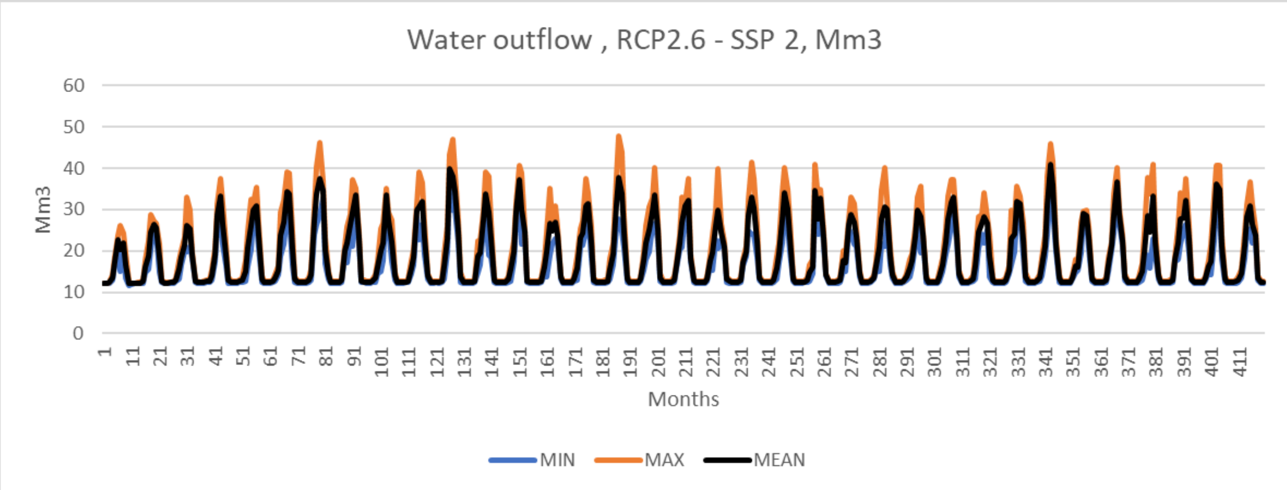


Figure 83. Uncertainty for the total water outflow for the RCP2.6-SSP2 scenario from 2015 to 2049 in the Jiu river basin.

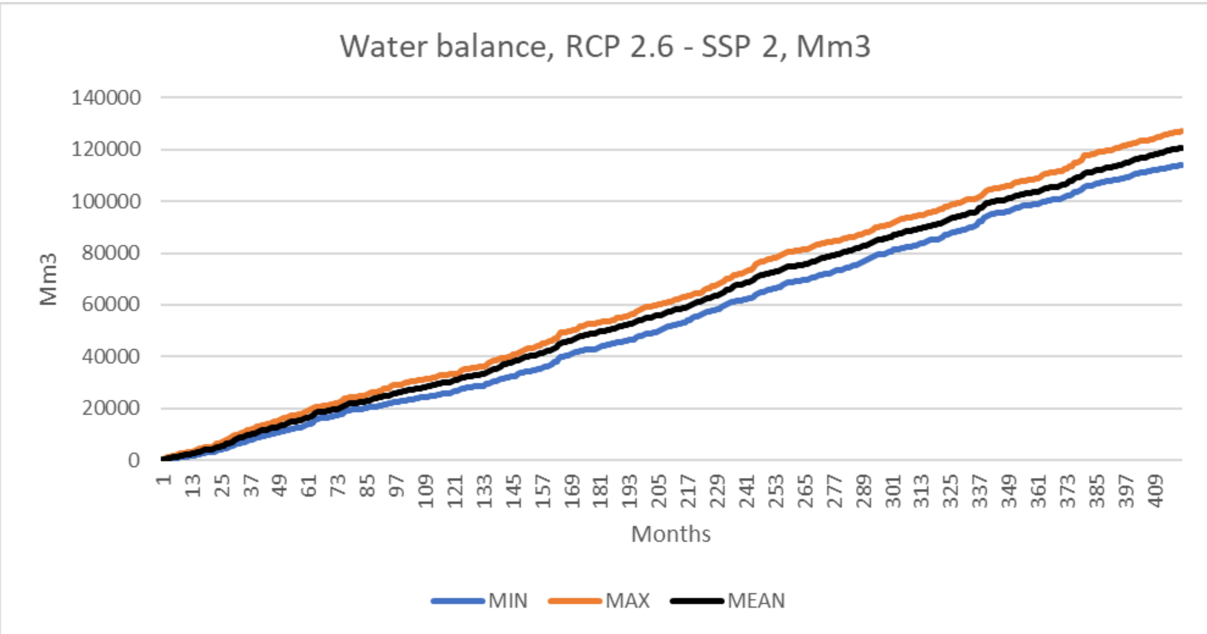


Figure 84. Uncertainty for the water balance for the RCP2.6-SSP2 scenario from 2015 to 2049 in the Jiu river basin.

The Nitrogen load to water bodies was computed in the SDM to estimate water pollution in the Jiu river basin. The source of Nitrogen pollution is from the agricultural sector, with a specific prevalence in the area of maize, sunflower, wheat, and rapeseed cultivated under both irrigated and rainfed conditions. The ISIMIP dataset was used as the source for these input data while the area covered by each crop was collected from local statistics. Future trends of land cover were implemented in the SDM by using input data from the SPAM dataset.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

The uncertainty related to this parameter is shown in Figure 85. In general, the largest range of uncertainty is in spring and summer months when all the crops are on the field and water inflow presents a high variation. A certain range of uncertainty has been found also in winter time and this might be linked to nitrogen leaching from wheat. The uncertainty might come as well from propagation of uncertainties of the models used in ISIMIP.

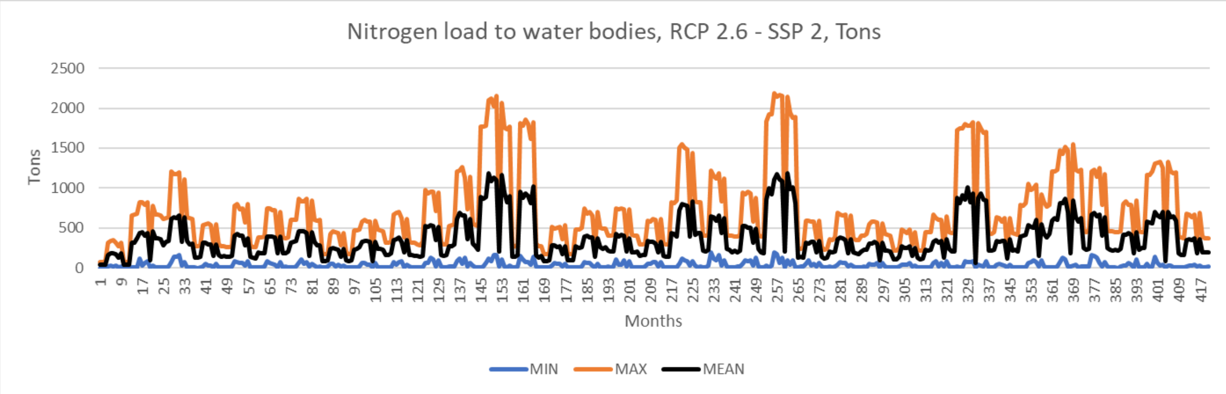


Figure 85. Uncertainty for the Nitrogen leaching to water bodies for the RCP2.6-SSP2 scenario from 2015 to 2049 in the Jiu river basin.

The range of uncertainty for the food sector is shown for the two main SDM outputs, i.e., food production and consumption. Food production is computed by using ISIMIP data for the yield (ton/ha) and the agricultural area covered by the main crops from the local statistical data and, for future trends, from the downscaling in WP2 of GRDM socioeconomic trends through MagnetGRID . Both irrigated and rainfed crops are considered in the computation of food production in the model developed for the case study. The food consumption is obtained by using local statistics and future scenarios under SSP2 from GRDM model. In general, the largest difference between minimum and maximum values of food production is from April to September as shown in Figure 86. The range of uncertainty for food consumption is lower than in food production but also in this case the largest difference between minimum and maximum values in spring and summer (Figure 87). The seasonal trend of food production reflects the growing season of the main crops cultivated in the basin.

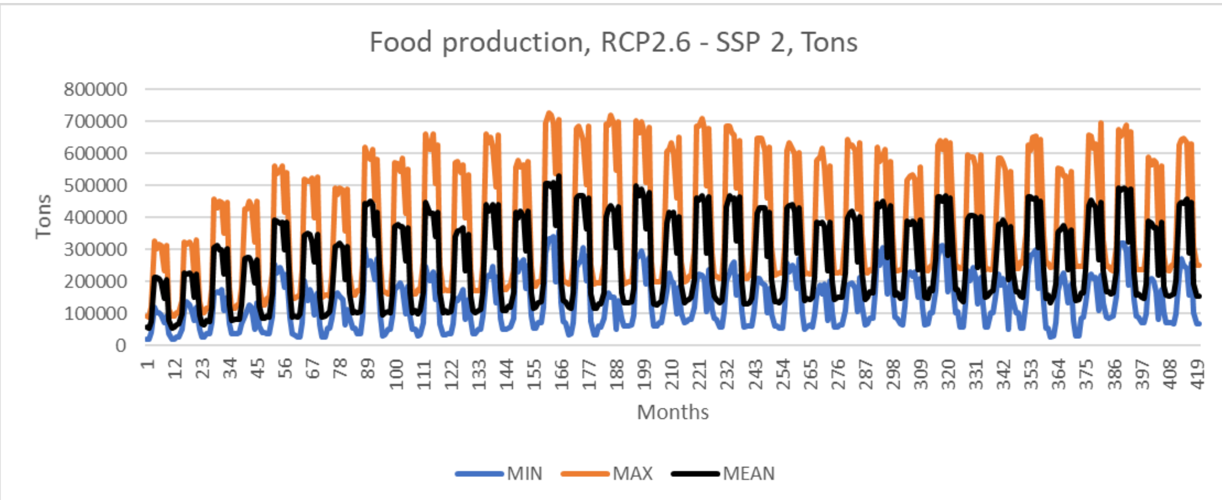


Figure 86. Uncertainty for the food production for the RCP2.6-SSP2 scenario from 2015 to 2049 in the Jiu river basin.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

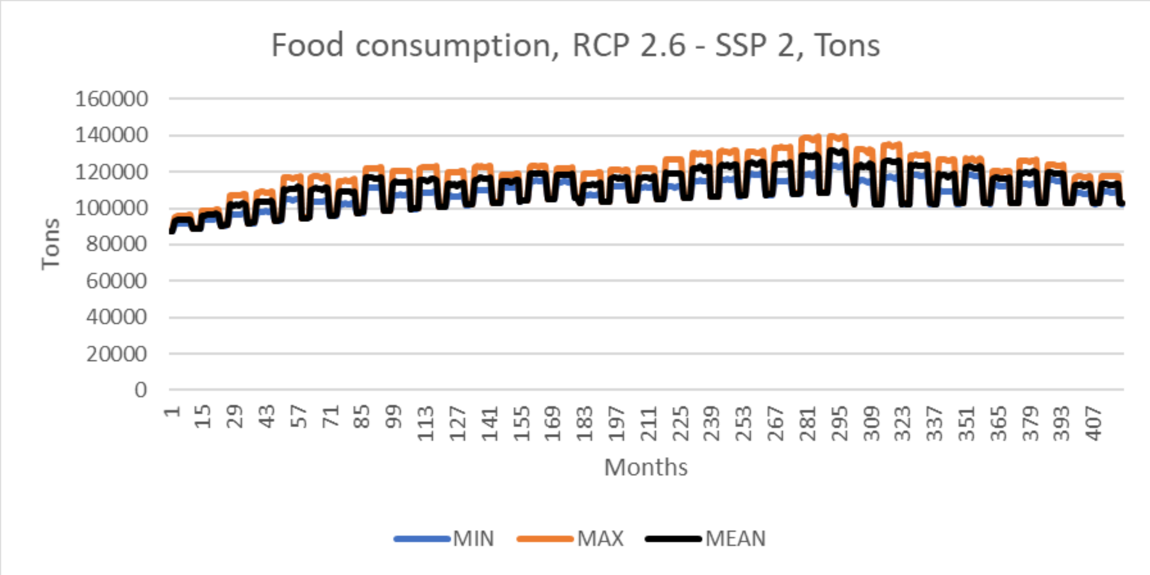


Figure 87. Uncertainty for the food consumption for the RCP2.6-SSP2 scenario from 2015 to 2049 in the Jiu river basin.

In the ecosystem sector, the carbon mass in vegetation is an important parameter for the Jiu river basin and it is estimated by considering the carbon mass in C3 and C4 crops (Figure 88). . The uncertainty related to this parameter might be largely related to the input data collected from the ISIMIP dataset and used for the computation in the SDM.

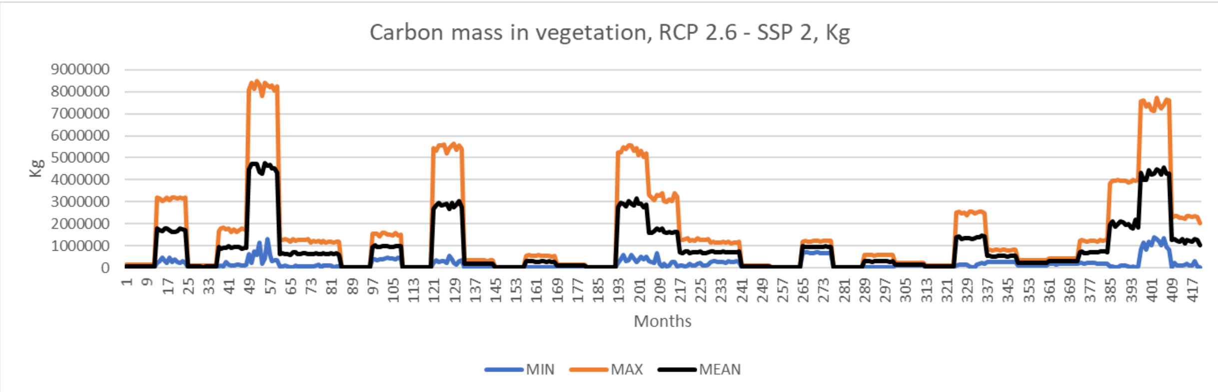


Figure 88. Uncertainty for the carbon mass in vegetation for the RCP2.6-SSP2 scenario from 2015 to 2049 in the Jiu river basin.

The range of uncertainty of the energy availability in the basin (local production and import) is shown in Figure 89. Data on energy availability are collected from local statistics. The future rate of change (%) are from the GRDM model. Only the hydropower production is computed by using ISIMIP input data and local data. Figure 8 shows that there is negligible uncertainty in the energy production parameter in the Jiu river basin model.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

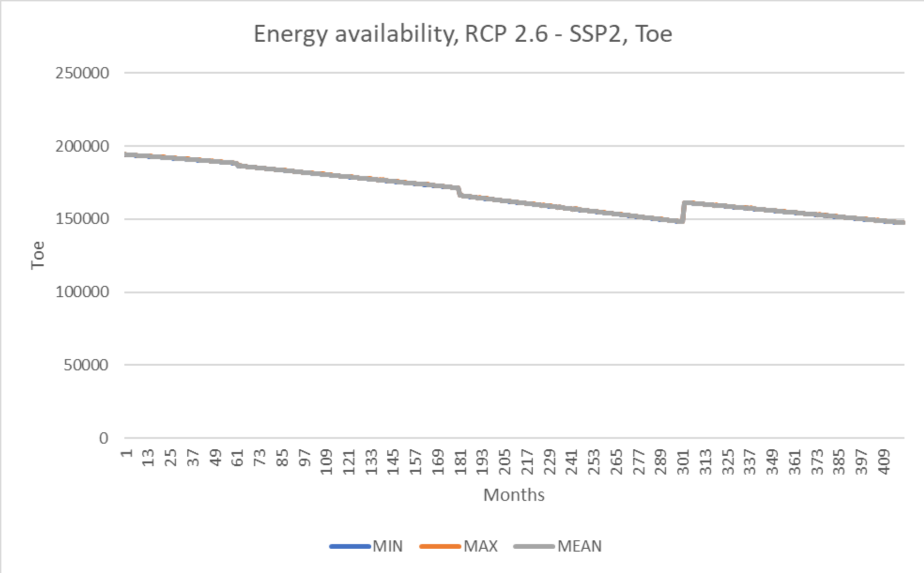


Figure 89. Uncertainty for the energy availability for the RCP2.6-SSP2 scenario from 2015 to 2049 in the Jiu river basin.

4.3.2 Scenario uncertainty

In this section, the mean values for some parameters of the SDM developed for the Jiu case study are reported to show the range of uncertainty between RCPs 2.6 and RCP 8.5 and between SSP 2 and SSP 4 scenarios.

The input data used for the water sector for both water quality and quantity in the SDM are all, except from land cover, under climate scenarios (i.e., RCPs). Thus the comparison in Figure 90, 91, 92, and 93 is between the SDM results obtained by using input data under RCP 2.6 and RCP 8.5. The water inflow in the Jiu river basin is composed of total surface water and groundwater, whose computation in the SDM was done by using ISIMIP data from 2015 to 2049. Comparison between water inflow under RCP 2.6 and RCP 8.5 is shown in Figure 90. The difference between RCPs is higher when considering the water inflow results in comparison with the water consumption (outflow). The water consumption results obtained by running the SDM with the two scenarios are similar. In general, the results under RCP 8.5 are slightly higher than the ones under RCP 2.6 (Figure 91). The highest peaks (> 9 Mm3) when water outflow under RCP 2.6 is higher than RCP 8.5 are mostly in summer months. The main difference between RCPs in the water balance, computed by considering the total water inflow and outflow, is estimated between 2021 and 2042, while decreasing afterwards (Figure 92).

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

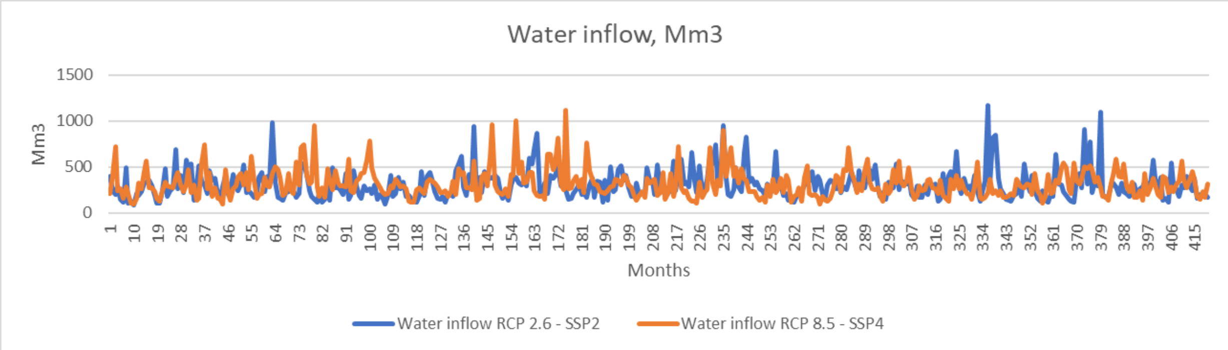


Figure 90. Water inflow between RCP 2.6 and RCP 8.5 in the Jiu case study.

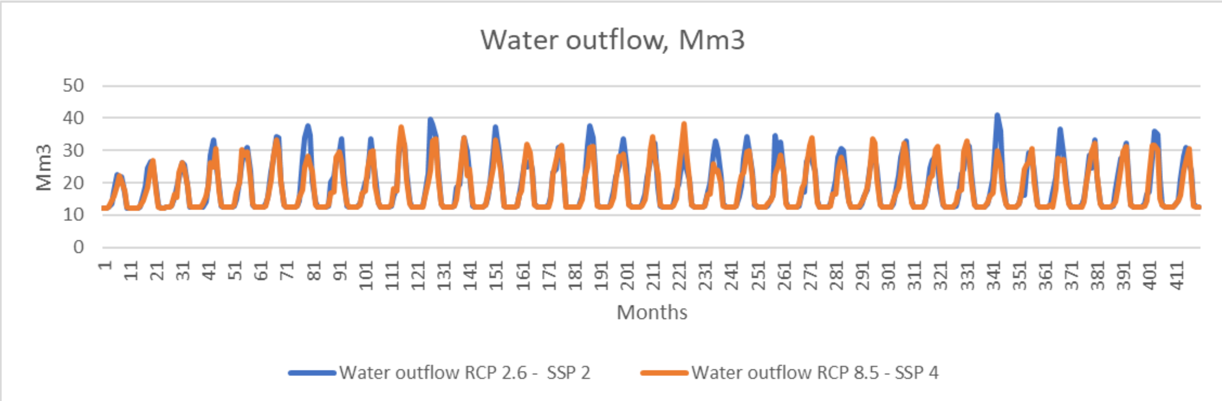


Figure 91. Water outflow between RCP 2.6 and RCP 8.5 in the Jiu case study.

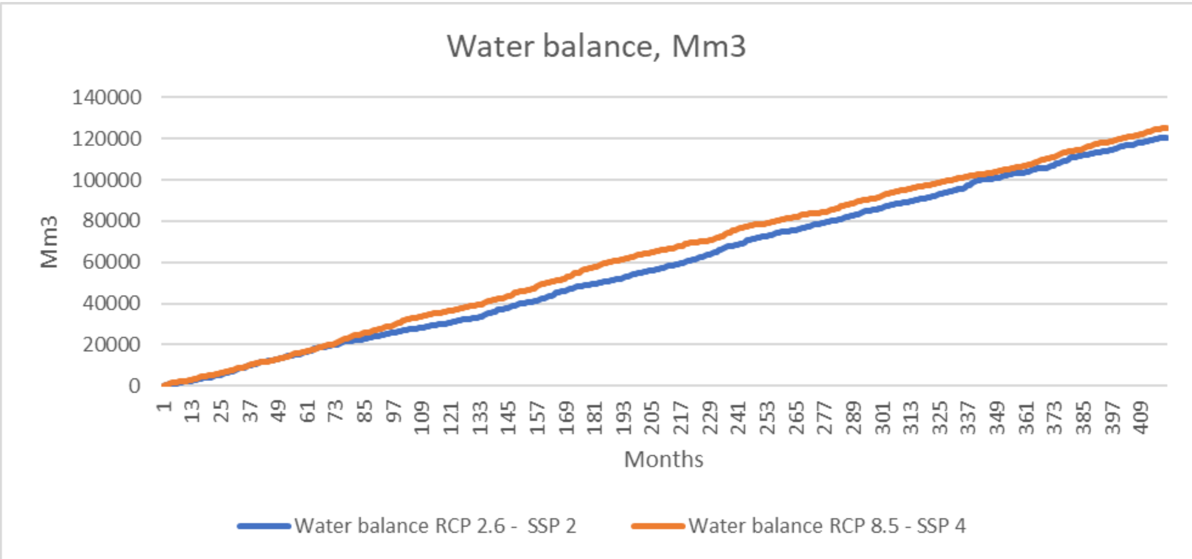


Figure 92. Difference in water balance between RCP 2.6 and RCP 8.5 in the Jiu case study.

Results under RCP 2.6 and RCP 8.5 are also compared to show the main differences in nitrogen leaching to water bodies. The nitrogen leaching is computed in the SDM by using input data from the ISIMIP dataset for the fertiliser applications. The quantitative information for land cover is collected from the SPAM datasets and local statistics. The nitrogen is applied during the growing season of the four main crops in the case study, i.e., maize, wheat, sunflower, and rapeseed. The differences between the nitrogen leaching results computed by

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

using input data under the two different climatic scenarios for both application and land cover is shown in Figure 93. In specific years the difference between the two RCPs can be 1000 tons higher under RCP 8.5 compared to RCP 2.6 scenario.

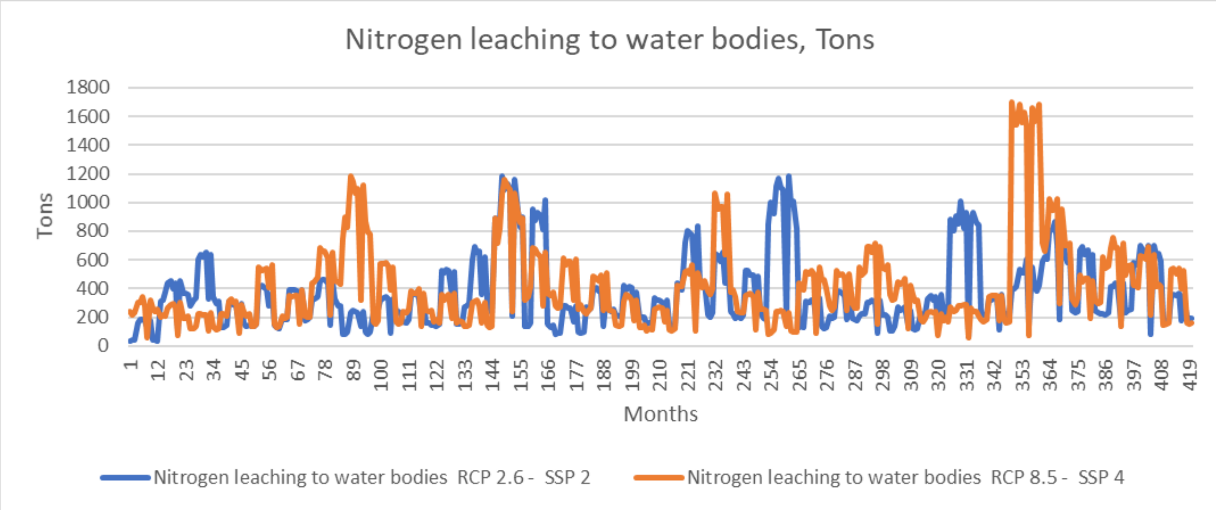


Figure 93. Difference in nitrogen leaching to water bodies between RCP 2.6 and RCP 8.5 in the Jiu case study.

In the food sector of the Jiu case study, the balance is composed of food production, consumption, import and export. In this section, the differences between scenarios are presented for production and consumption. The food production is estimated by using ISIMIP data for crop productivity and the SPAM database for crop extent. Food consumption data from local statistics are used in combination with future trends from GRDM. The difference between the two RCPs is shown in Figure 94 for food production while the difference between the two SSPs is reported in Figure 95 for food consumption. Both figures show similar trajectories between scenarios. The food consumption estimated under SSP2 is expected to be higher than results estimated under RCP 8.5, especially towards the end of the time series.

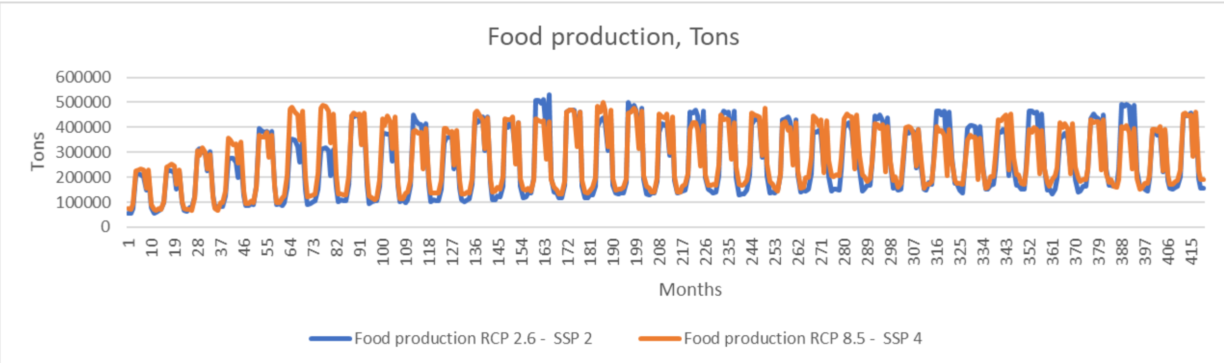


Figure 94. Difference in food production between RCP 2.6 and RCP 8.5 in the Jiu case study.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

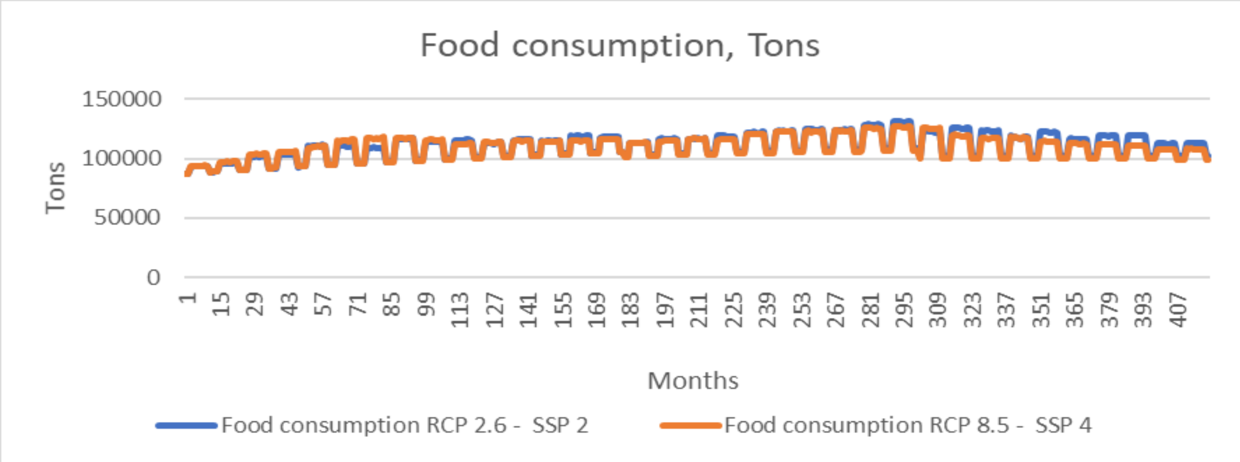


Figure 65. Difference in food consumption between SSP2 and SSP4 in the Jiu case study.

The carbon mass in vegetation is estimated by using the input data from the ISIMIP dataset, thus the comparison for this model parameter is between RCP 2.6 and RCP 8.5. The difference between the two climatic scenarios is shown in Figure 96. The highest peak is estimated in 2033 when results under RCP 8.5 are much higher than the ones obtained under RCP 2.6.

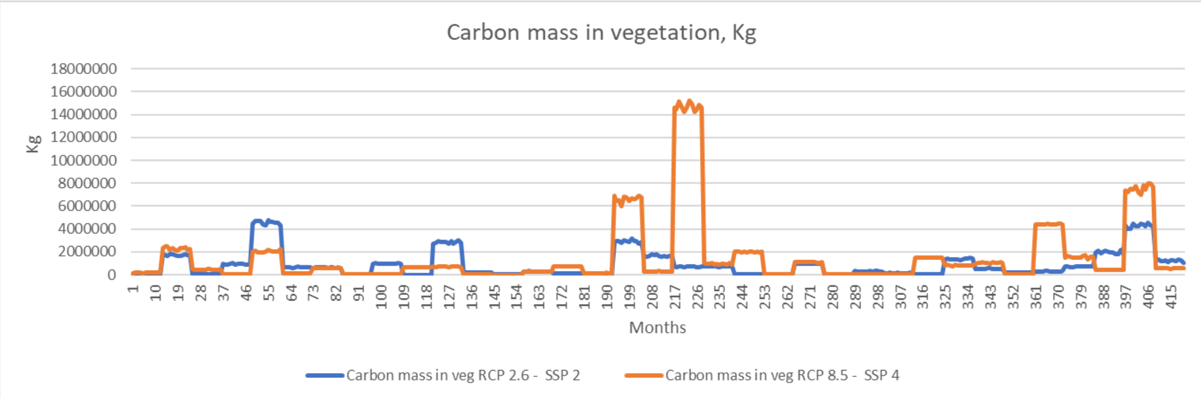


Figure 96. Difference in carbon mass in vegetation between SSP2 and SSP4 in the Jiu case study.

The energy production for the Jiu case study is estimated by considering import and export of coal, gas, and oil. The import of petroleum is considered as well. The hydropower production is currently the main source of renewable energy in the basin. The difference between SSP2 and SSP4 is shown in Figure 97. The input data used for estimating energy availability in the basin are from local statistics and GRDM model results. The two scenarios show very similar trajectories that tend to decrease in 2050 compared to 2015.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

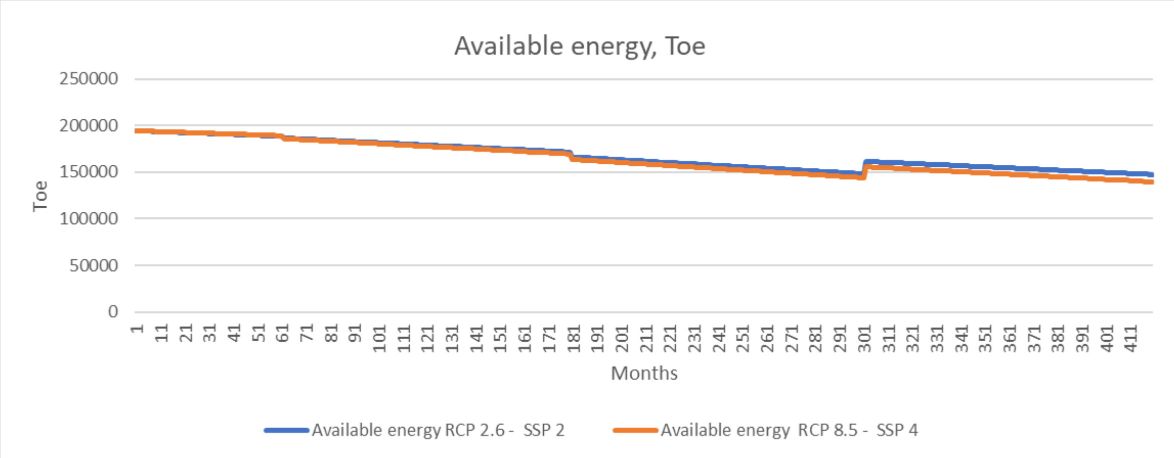


Figure 97. Difference in energy production between SSP2 and SSP4 in the Jiu case study.

4.3.3 What-if and stress tests

To assess the behaviour of the Jiu River basin under stress conditions, targeted variables have been doubled and/or halved. Variables relevant to the case study were chosen to run the what if/stress test, i.e., population, total cultivated area, irrigated land, water inflow, and energy consumption. In line with the parametric uncertainty, the applied test shows changes in the Jiu river basin system under RCP2.6-SSP2. The action of doubling and/or halving the selected variables is to show results in extreme conditions that will unlikely occur in reality in the case study. Results obtained when doubling and/or halving relevant variables in the system are shown in this section where reference values (i.e., when no stressing conditions and/or policies are implemented) are also shown.

One of the key variables in the system is the irrigated area covered by maize, wheat, sunflower, and rapeseed. Currently, the irrigated area is much less extended than the rainfed area. One of the scenarios highlighted in the Jiu River basin strategy is the equipment of the rainfed area with irrigation systems. Doubling the area under irrigation will increase the total water outflow (Figure 98). In the case of both, halving or doubling the irrigated area, the values of total water outflow (i.e., sum of agriculture, domestic, industrial and energy water use) are higher in spring/summer; the seasonal trend of water outflow reflects the crop growing season of the most relevant crops in the basin.

These results are relevant to support decision-makers in water management plans in the case study.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

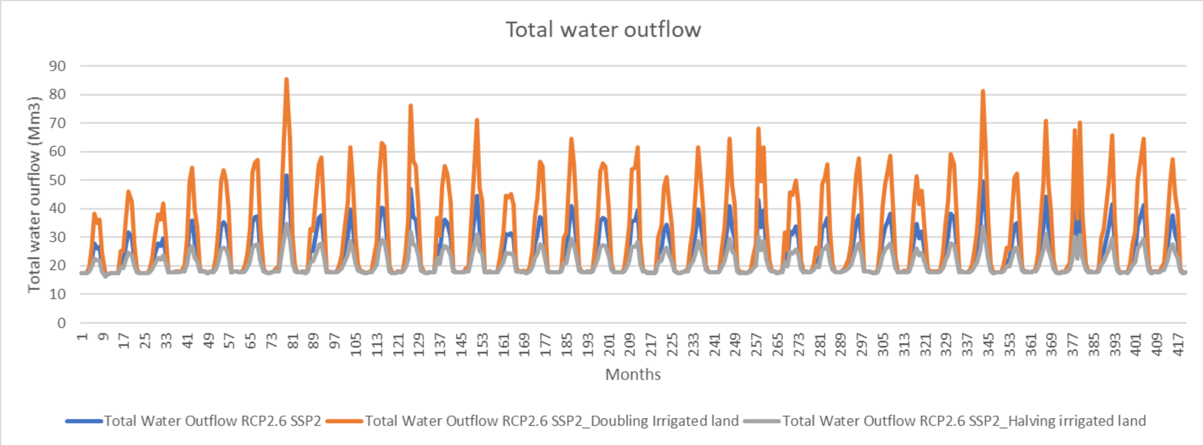


Figure 98: Total water outflow under the RCP2.6-SSP2 scenario (blue line) and when the irrigated land is halved (grey) and doubled (orange).

The nitrogen leaching to water bodies is relatively unaffected when doubling or halving the irrigated area with potentially no significant impact on the ecosystem (Figure 99).

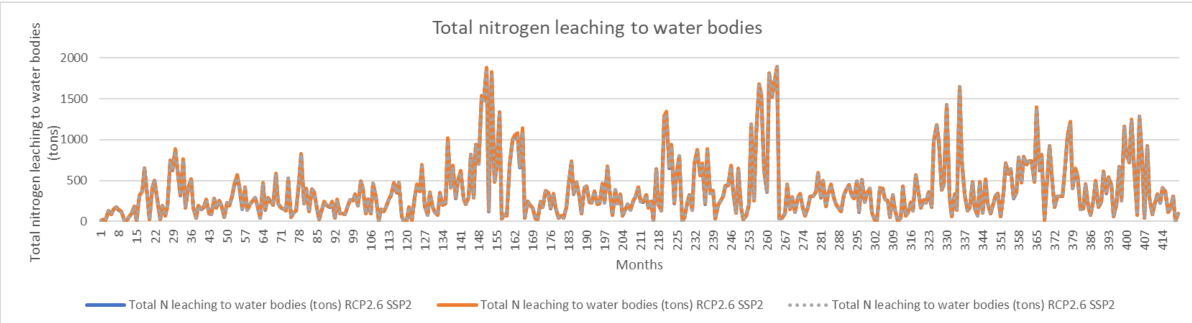


Figure 99: Total nitrogen leaching to water bodies under the RCP2.6-SSP2 scenario (blue line) and when the irrigated land is halved (grey) and doubled (orange).

The total (rainfed plus irrigated) area covered by the main crops is expected to have an impact on the total CO2eq emissions in the atmosphere. The results obtained from doubling and halving the cultivated area to the emissions are shown in Figure 100. The sensitivity of emissions from the agricultural sector to changes in cultivated area is quite high.

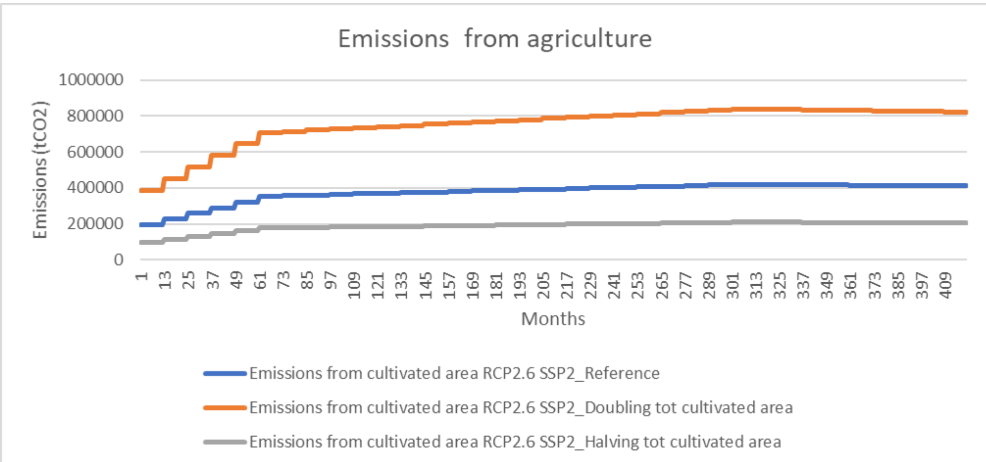


Figure 100: CO2eq emissions from the agricultural sector under the RCP2.6-SSP2 scenario (blue line) and when the total cultivated land is halved (grey) and doubled (orange).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

The extreme conditions created for stressing the Jiu River basin system are expected to also have an impact on the total energy consumption. Figure 101 shows the results obtained when halving and doubling the cultivated area compared to the reference values. As shown in Figure 101, the changes in the total energy consumed by all the main sectors in the basin (i.e., agriculture, domestic, industry, and transport) due to agricultural land changes are minor compared to the reference scenario. The sensitivity is higher when considering only the impact on the energy consumed in the agricultural sector (Figure 102).

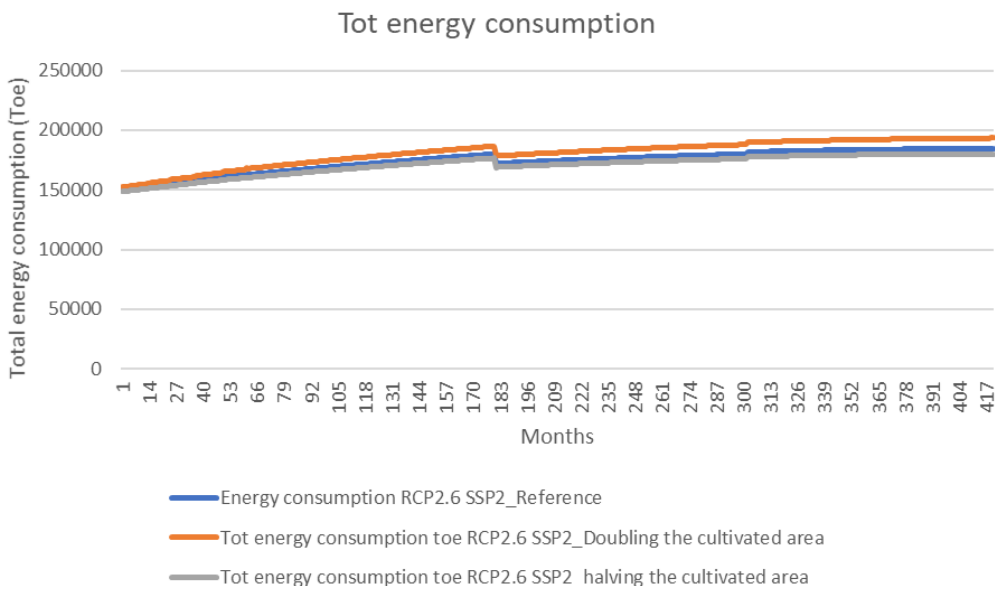


Figure 101: Total energy consumption under the RCP2.6-SSP2 scenario (blue line) and when the total cultivated land is halved (grey) and doubled (orange).

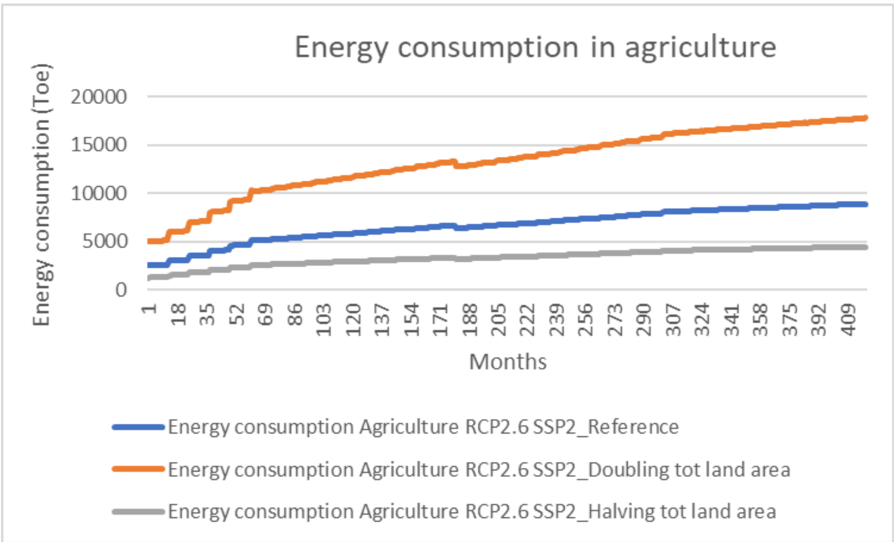


Figure 102: Energy consumption in agriculture under the RCP2.6-SSP2 scenario (blue line) and when the total cultivated land is halved (grey) and doubled (orange).

The population (Figure 103) in the basin plays a key role in water and crop consumption. Figures 104 and 015 show the sensitivity of domestic water use and maize and wheat

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

consumption when the population is doubled and halved (Figure 106). Both variables are quite sensitive to changes in population. Although the extreme scenarios tested, these results might be useful to inform policymakers in terms of food and water security in the case study.

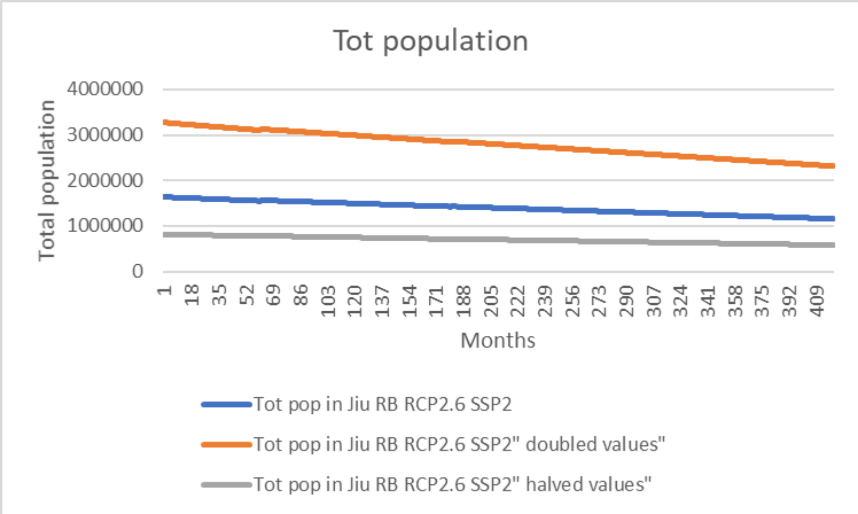


Figure 103: Total population under the RCP2.6-SSP2 scenario (blue line) and when the population is halved (grey) and doubled (orange).

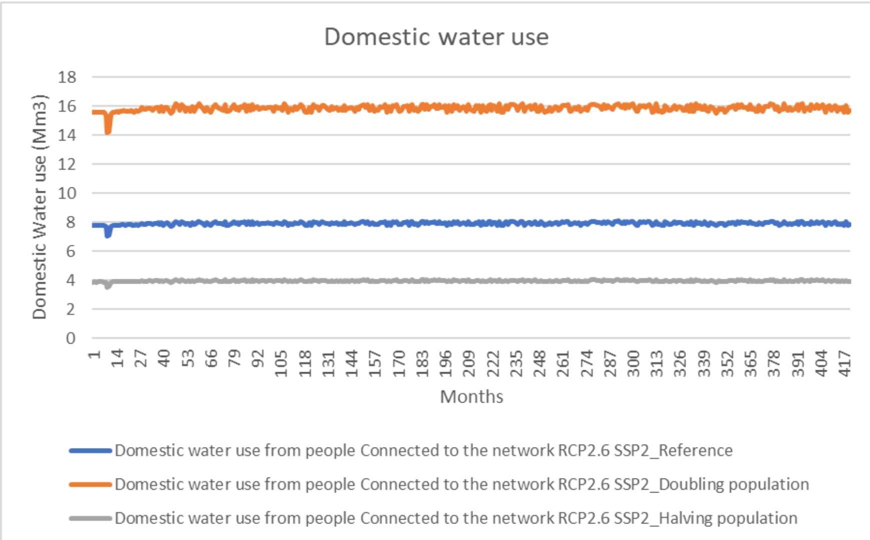


Figure 104: Total domestic water use under the RCP2.6-SSP2 scenario (blue line) and when the population is halved (grey) and doubled (orange).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

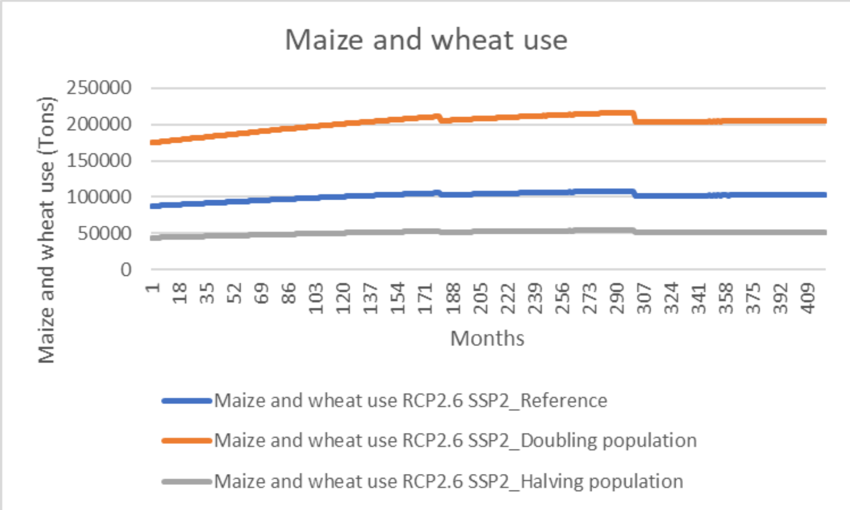


Figure 105: Maize and wheat use under the RCP2.6-SSP2 scenario (blue line) and when the population is halved (grey) and doubled (orange).

Doubling the surface water inflow (Figure 106) in the basin leads to an improvement in the water balance that can be beneficial for supporting water demand in the main sectors (i.e., agriculture, domestic, industry, and energy) in the Jiu River basin. Although lower than the reference values, the balance is still positive in the case of halving the total surface inflow. The results might be of interest to water managers in the development of measures and/or plans aimed at ensuring water security in the basin and supporting the needed amount of water in the main sectors (Figure 107).

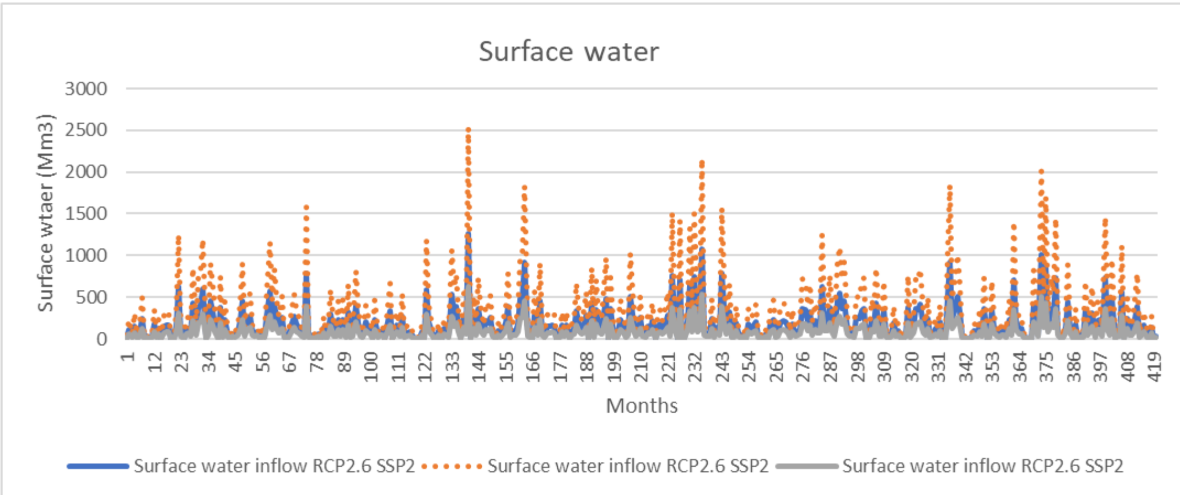


Figure 106: Surface water inflow under the RCP2.6-SSP2 scenario (blue line) and when it is halved (grey) and doubled (orange).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

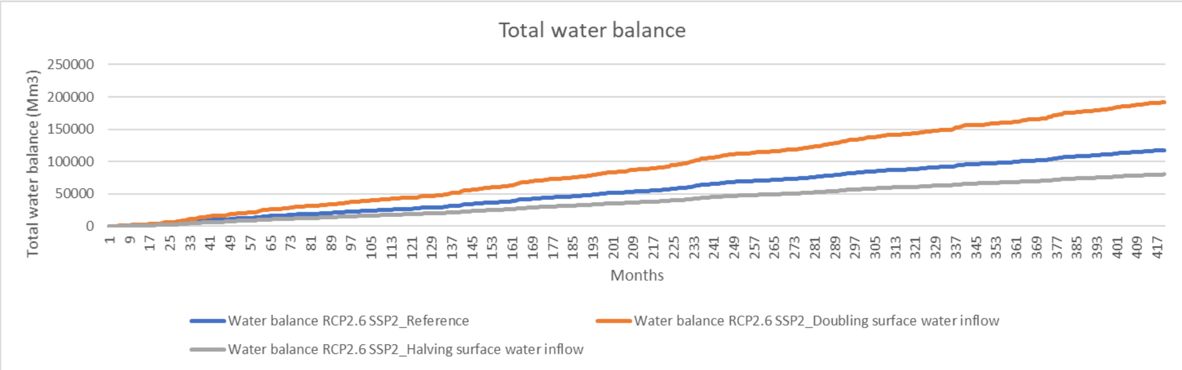


Figure 107: Total water balance under the RCP2.6-SSP2 scenario (blue line) and when the surface water inflow is halved (grey) and doubled (orange).

The energy balance is fairly sensitive to energy consumption changes. Results compared to the reference scenario are shown in Figure 108. Doubling the total energy consumed in the main sectors identified in the basin (i.e., from industry, domestic, agriculture, and transport) negatively impacts the balance with consequent influence on energy security (Figure 109). On the other hand, the balance would largely benefit from measures aimed at reducing, in this case halving, the energy consumption in the basin (Figure 109).

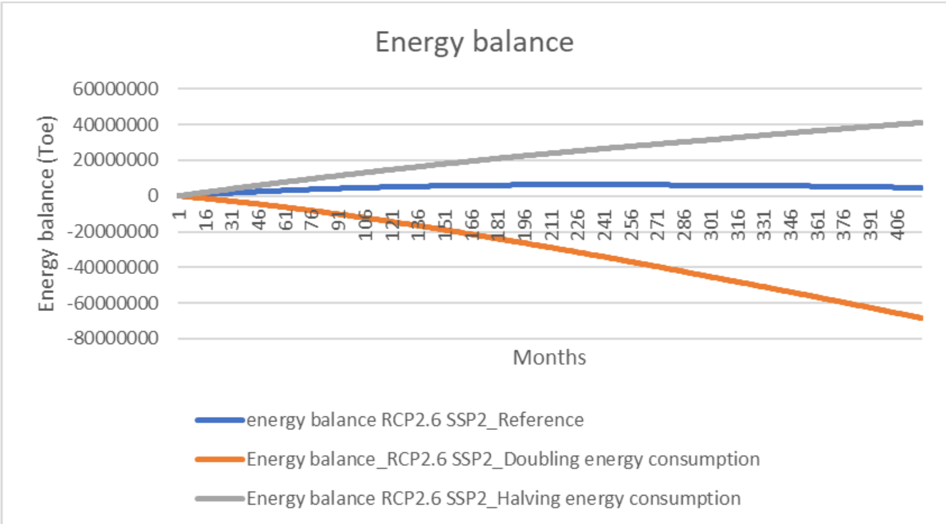


Figure 108: Energy balance under the RCP2.6-SSP2 scenario (blue line) and when the energy consumption is halved (grey) and doubled (orange).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

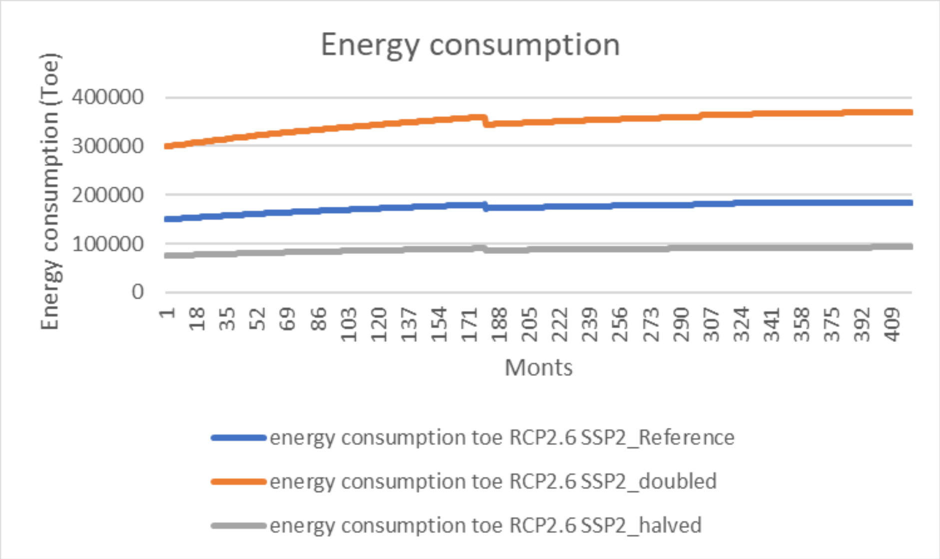


Figure 109: Energy consumed from the main sectors under the RCP2.6-SSP2 scenario (blue line) and when the energy consumption is halved (grey) and doubled (orange).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

4.4 Adige River Basin

The Adige case study is considering uncertainty analysis both for input model parameters as well as integrating future models' conditions. In this section, we report analysis and simulations for only some parts of the different used models.

Moreover, in this CS, a subset of the overall parameters have been selected and tested :

- Surface water runoff
- Precipitation
- Temperature
- Population
- Agricultural water demand

These were chosen as they reflect parameters of interest for the CS, and cover critical nexus sectors for the Adige River Basin.

4.4.1 Parametric uncertainty

In the water security sector, three different hydrological model parameters, namely the precipitation correction factor, the rain melt factor and the combined melt factor, were randomly varied to generate 20 sets of model parameters inputs and capture their effect on the runoff output (Figure 110).

The mean areal precipitation estimate is adjusted using a Precipitation Correction Factor (PCF) to address the spatial representativeness issues of the rain gauges. The PCF, a dimensionless parameter ranging between 1 and 1.5, acted as a multiplicative factor on the mean sub-catchment precipitation.

For rain-on-snow conditions, the melting process is determined by both air temperature and the energy imparted by rain. This melting rate, represented by RMF (Rain melt factor) ($mm\ h^{-1}\ {}^{\circ}C^{-1}$) influences rain-on-snowmelt dynamics. Moreover, the snowmelt routine's primary sensitivity lies in the combined melt factor (CMF), a significant calibration parameter ($mm \cdot m^{2} \cdot {}^{\circ}C^{-1} \cdot MJ^{-1}$), which accounts for both thermal and radiative effects.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

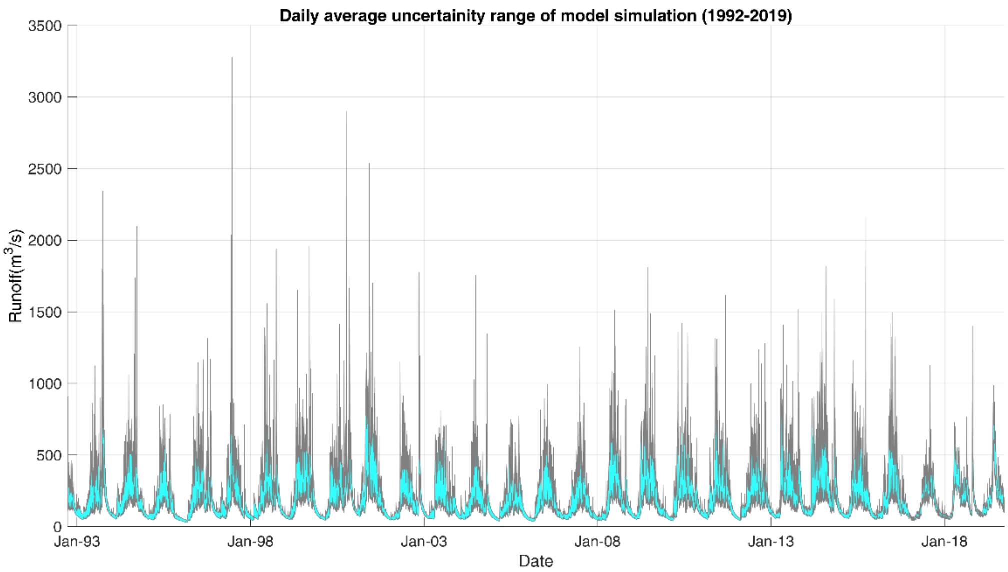


Figure 110 – Uncertainty analysis for runoff values for the 1993-2018 period.

Focusing on a shorter period of simulation (i.e., Oct 2000- Sept 2001; Figure 111) it is possible to capture the range of uncertainty associated with each time step of runoff simulation.

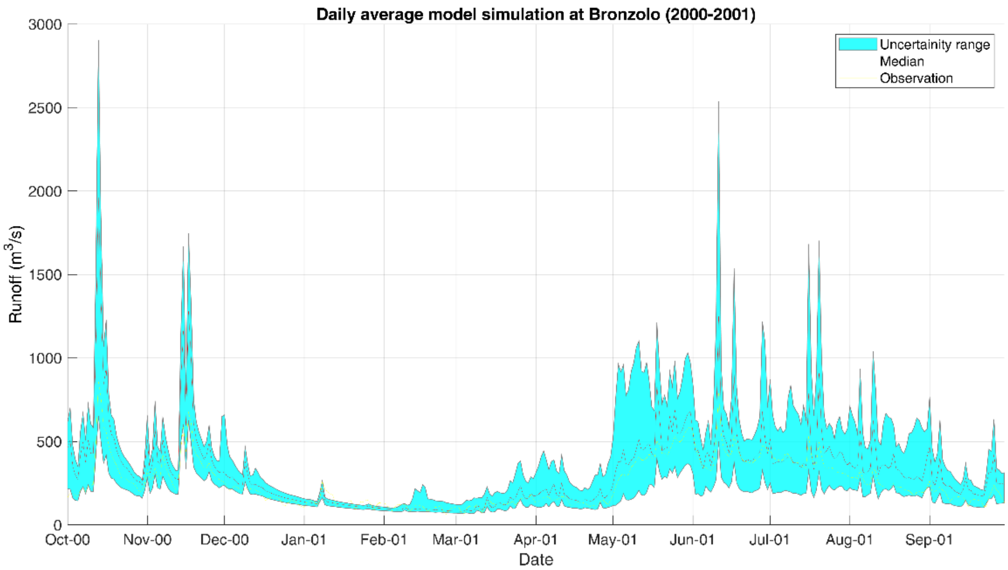


Figure 111 – Runoff values with 0-100 uncertainty bands for one hydrological year from October 2000 to September 2001

In the food security sector, the uncertainty analysis considers changes in (i) the irrigation method and hence in their related water use efficiency, (ii) irrigated areas extension and finally (iii) changes in crop types and their effect on the final water net application.

4.4.2 Scenario uncertainty

In the case of scenario analysis, the RCP2.6 and RCP8.5 were here considered and integrated in the different models.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

For the water security sector, the use of a hydrological model allowed us to investigate in details climate conditions and their effects on the simulated runoff. In particular, the analysis of climate scenarios highlighted a "wet bias" for low precipitation values (Figures 112-113). Such condition might be due to the orographic terrain in the mountainous part of the Adige River basin, which needs to be acknowledged when considering precipitation values as an input for other modelling chains.

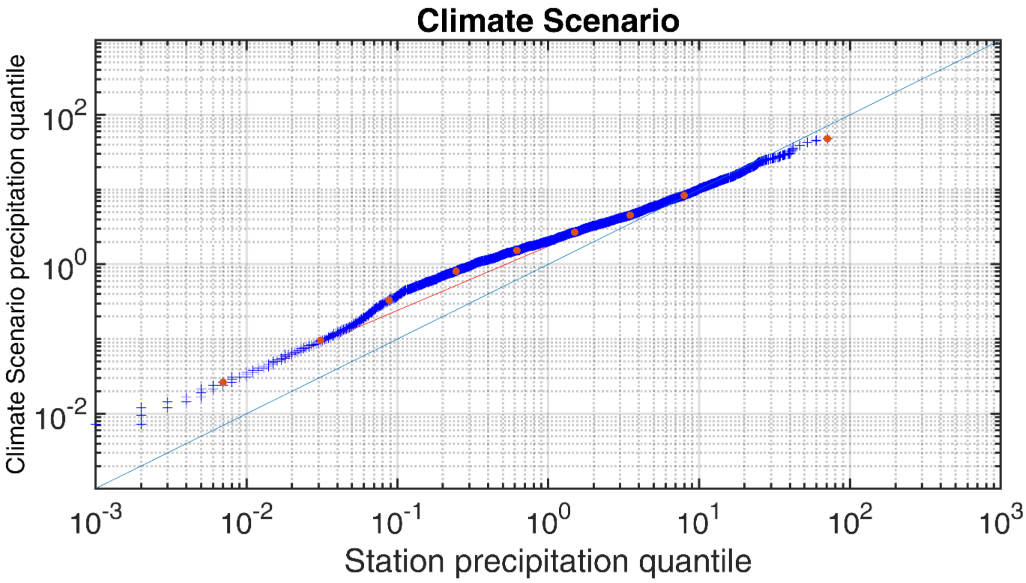


Figure 112 – Precipitation values for the climate model ssp585 vs observed precipitation values for the 2000-2014 period.

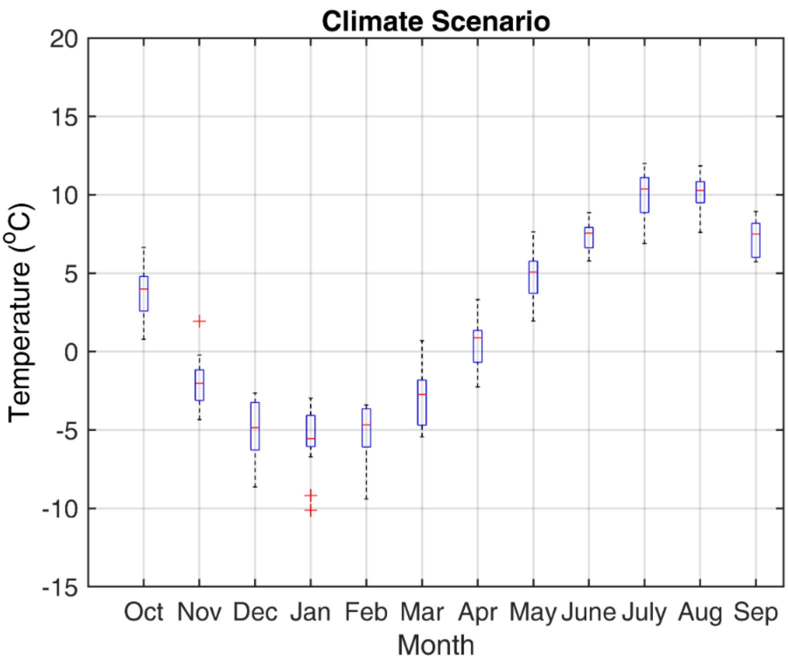


Figure 113 – Temperature values for the climate model ssp585 vs observed precipitation values for the 2000-2014 period

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Similarly, also for the case of temperature the ssp585 climate model shows a cold bias especially during the January month (Figure 114). The condition can lead to a greater accumulation of snow in the high elevation areas and hence needs to be further investigated.

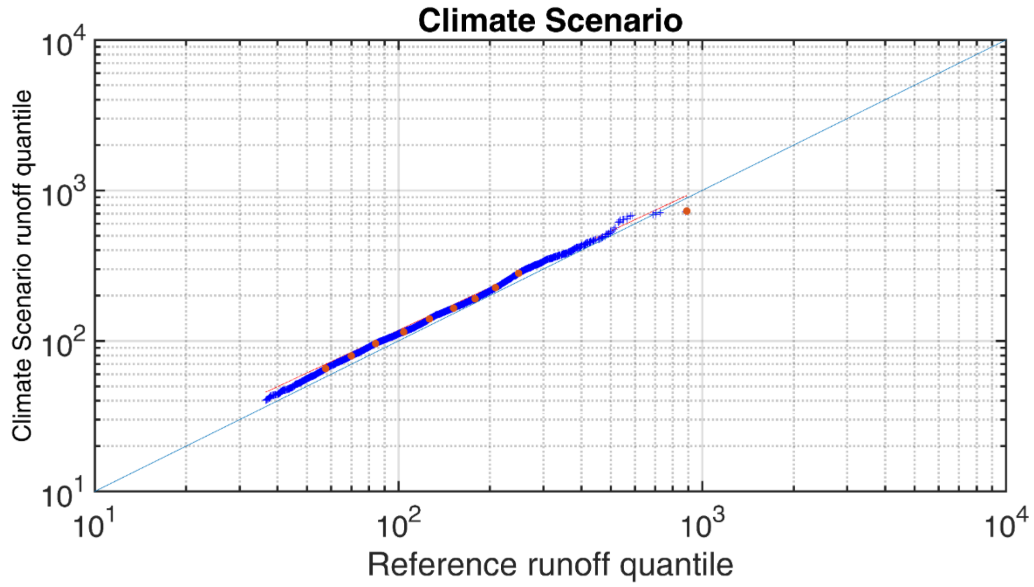


Figure 114 – Runoff performance for the climate scenario ssp585 vs reference period (2000-2014)

Despite the cold and wet bias, the runoff values well simulate all quantiles and exceedance probabilities.

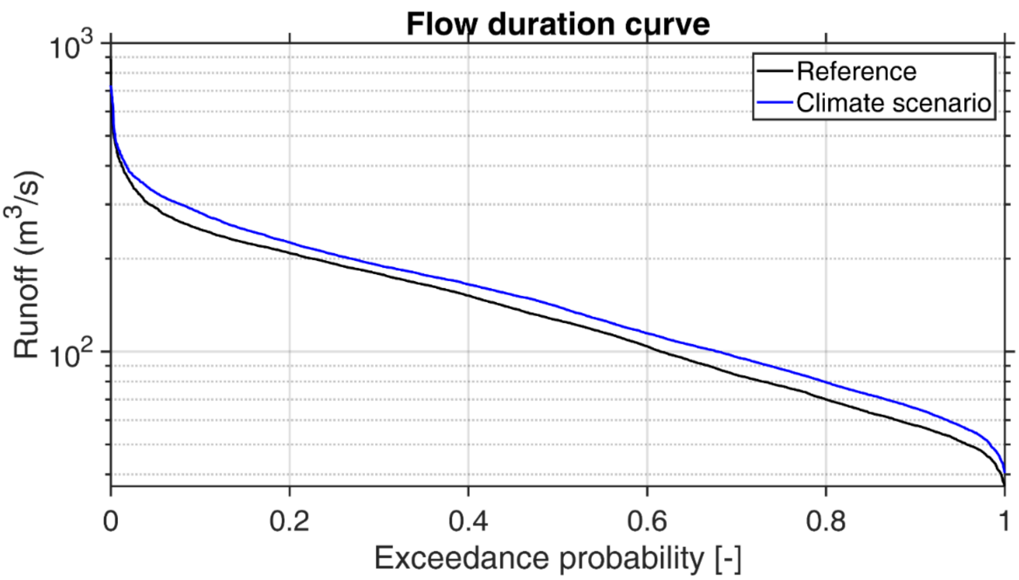


Figure 115 – Flow duration curve for the climate scenario ssp585 vs reference period (2000-2014)

Moreover, boxplots were developed in order to highlight the differences among the climate projections for each of the three climate models (namely, GFDL, IPSL and MPI) for each month of a hydrological year going from October to September (Figures 116-117-118). In particular, the RCP2.6 scenario shows greater variability and greater mean values compared to the

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

reference period for all the months with many more outliers especially for the maximum values. Differently RCP8.5 depicts higher mean values during winter pointing to the effect of temperature increase on snow and glacier melt.

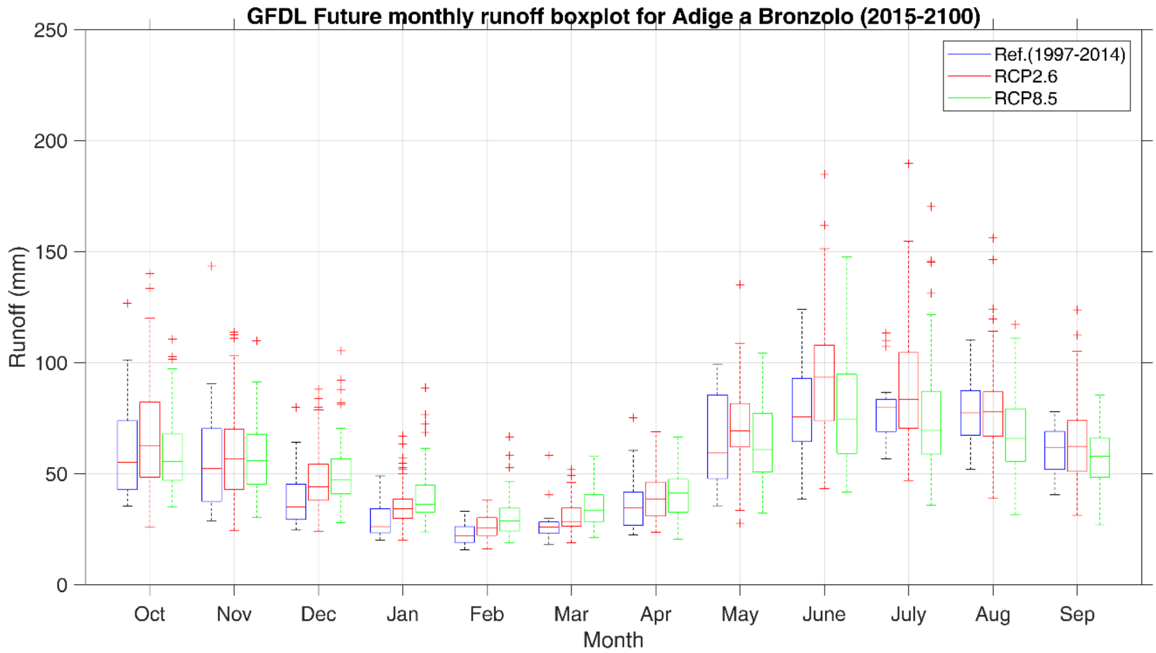


Figure 116 – Boxplots of runoff values for the reference period and for the GFDL climate scenario for RCP2.6 and 8.5

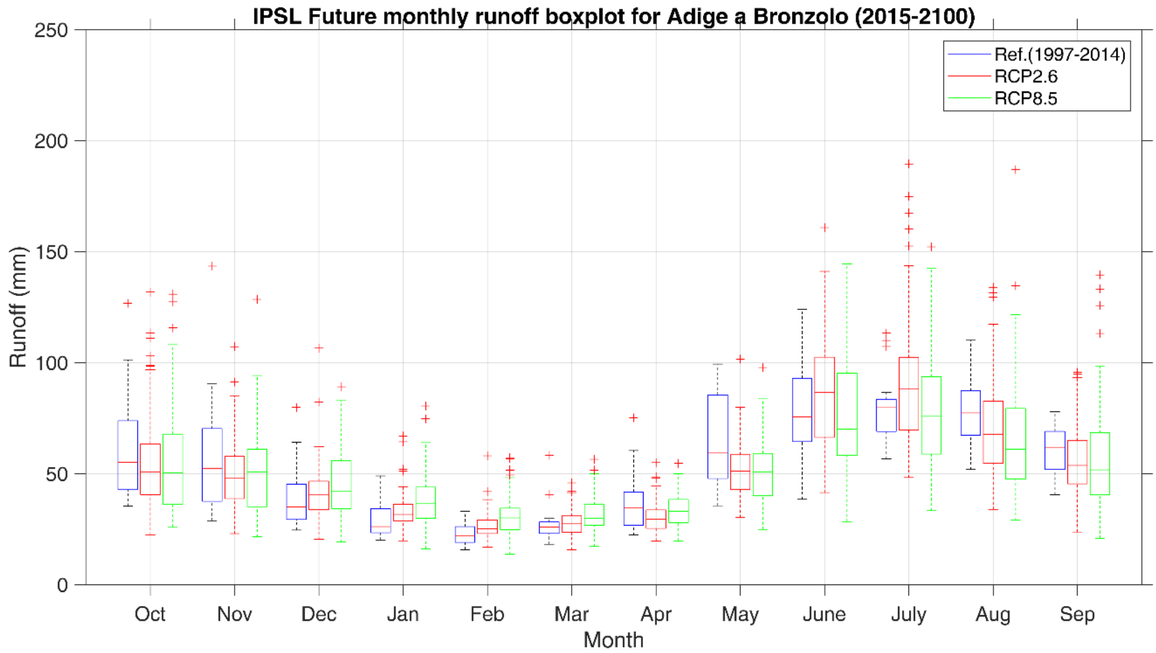


Figure 117 – Boxplots of runoff values for the reference period and for the IPSL climate scenario for RCP2.6 and 8.5

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

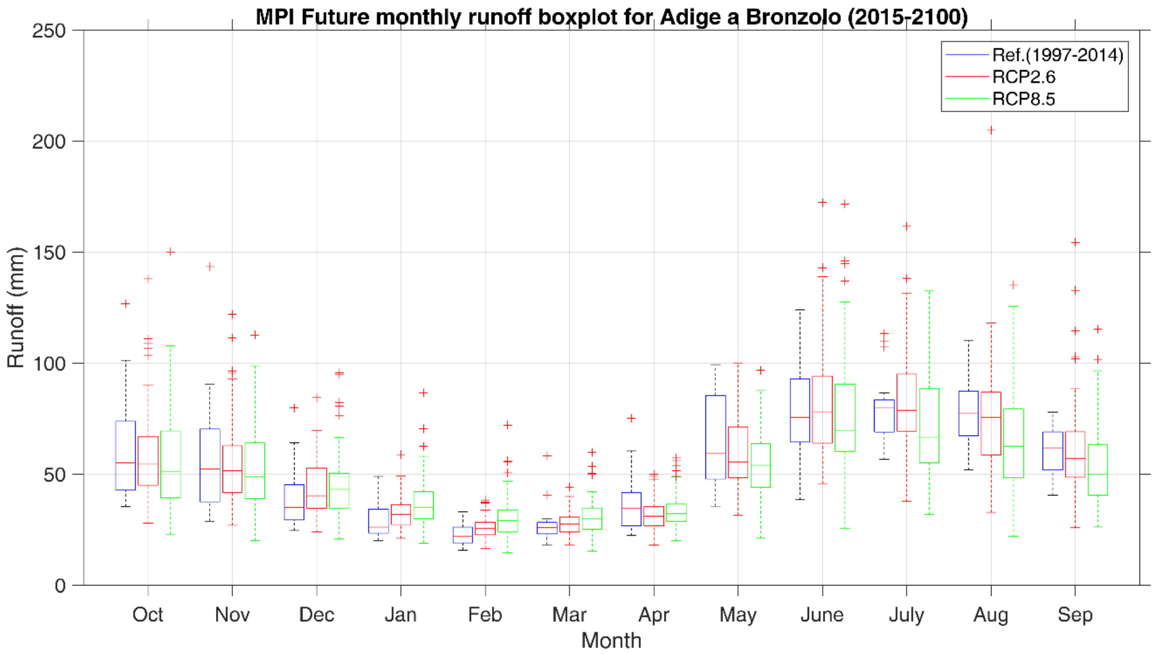


Figure 118 – Boxplots of runoff values for the reference period and for the MPI climate scenario for RCP2.6 and 8.5

For the population sector, future scenarios of growth rate for inhabitants (Figure 119) represent conditions of increasing number of people living in the Adige River basin especially for SSP4 compared to SSP2 with a clearly visible diverging trend especially from 2030 onwards.

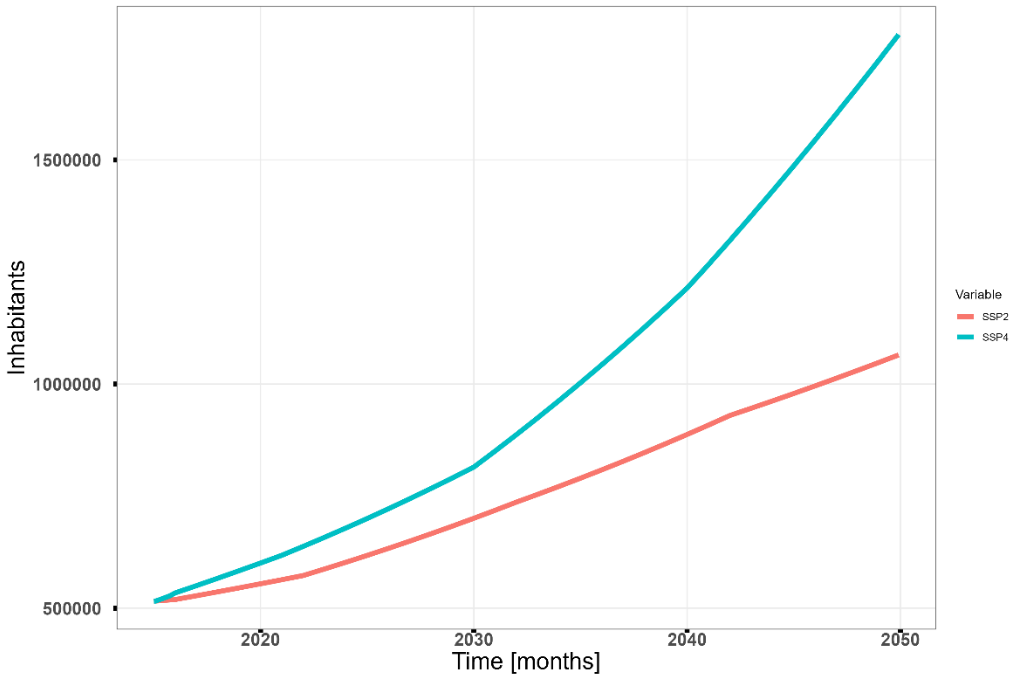


Figure 119 – Future population (inhabitants) for two SSP future scenarios

For the food security sector, the two climate scenarios here considered led to an increase of irrigation required for sustaining the optimal growth of the selected crop types (Apple, Maize and Vineyards). This condition points to an increase for all crop type, driven by the increase of temperature and hence of evapotranspiration during the growing seasons. Moreover, the

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

boxplot representation allows to capture the variability associated with the future net water applications within the Adige River basin.

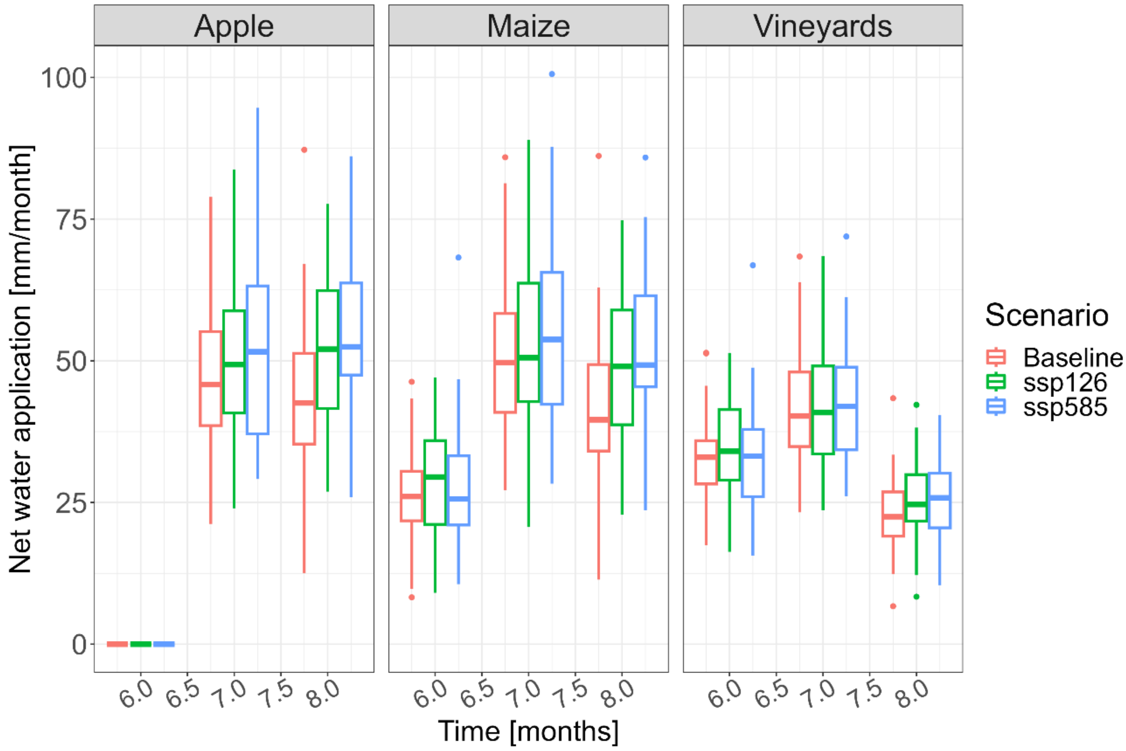


Figure 120 – Boxplots of net water application (mm/month*ha) for the reference period and for the RCP2.6 and 8.5 climate scenarios

4.4.3 What-if and stress tests

In the Adige case study, we implemented different what-if / stress tests on the developed models. In particular, we doubled and halved:

- for the water sector:
  - the population growth (to assess the implications on water demand, energy demand, food demand, and greenhouse gas emissions);
  - domestic water withdrawals
- for the agricultural sector:
  - changes in agricultural land (irrigated vineyards, orchards, maize and pasturelands)
- for the energy sector:
  - domestic energy demands

These tests were chosen due to their relevance for the Adige River Basin acting as stress tests on the selected part of the system. It is noted that the tests conducted here are only some of all the possible tests that can be developed and simulate extreme/not deemed realistic conditions. Nevertheless, the simulation usefully show the impacts of significant what-if changes upon the system on key output results. As with the parametric uncertainty, this section compares the tests against the RCP26-SSP2 scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Doubling and halving both the domestic per capita water demand and the number of residents. If the value of water demand doubles and the population is halved then there is a higher decrease in the total amount of domestic water withdrawals (dotted purple line) compared to the case of doubling the population and halving the per capita water demand.

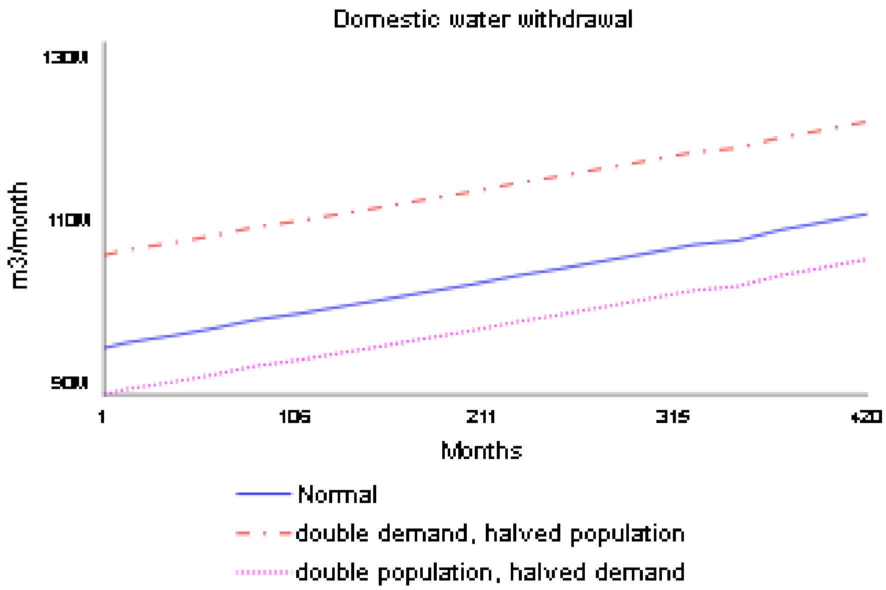


Figure 121: temporal pattern of the domestic water withdrawals in the Adige River Basin, showing RCP26-SSP2 simulation mean (blue full line) and the trends under doubling per capita water demand + halving resident population (purple dotted line) and doubling population and halving per capita water demand (dashed orange line).

For agricultural water withdrawals, tests were implemented on the extension of different irrigated land cover types, specifically on vineyards and orchards extensions without changes to the maize and pasture extensions. Conditions of doubled vineyards and orchards were implemented in order to evaluate their effects on the overall agricultural water withdrawals being the most water demanding and extended land cover types (red dashed line). Moreover, conditions of halved extensions for vineyards and orchards were implemented, without further changes to the other land cover types (purple dotted line).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

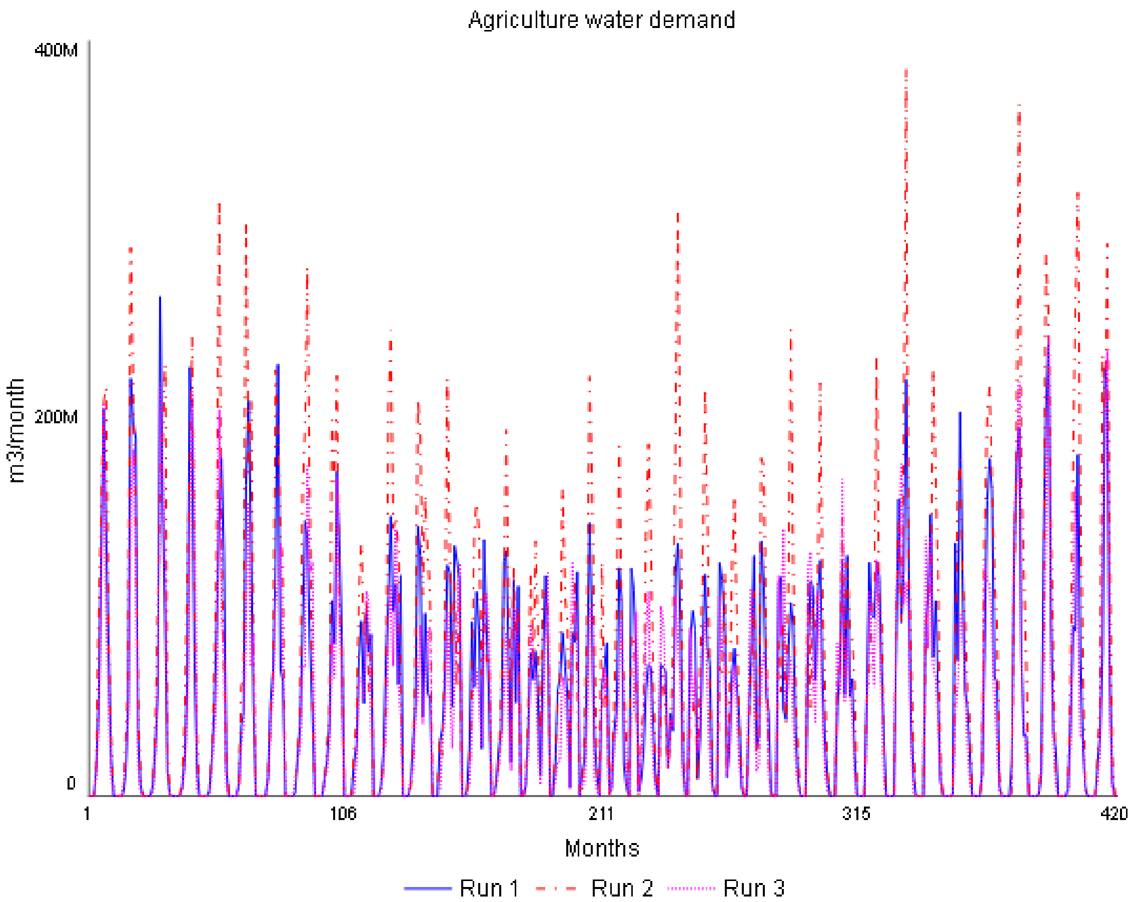


Figure 122: temporal pattern of the agricultural water withdrawals in the Adige River Basin, showing RCP26-SSP2 simulation mean (blue full line) and trends under doubling (red dashed line) and halving (purple dotted line) of vineyards and orchards land cover extension.

For the case of energy demand 6 conditions were tested doubling or halving the energy demand for either residents, tourists or both. Figure 123 shows run1 as the mean condition, run2 with halving of residents energy demand only and run 3 halving tourists energy demand only. It is clear that tourists play a major role affecting the overall energy demand in the Adige River Basin as compared to that one required by the residents. Moreover, this is strengthen by the runs4 (doubling of residents energy demand only), run5 (doubling of the tourists energy demand only) and run6 (doubling both).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

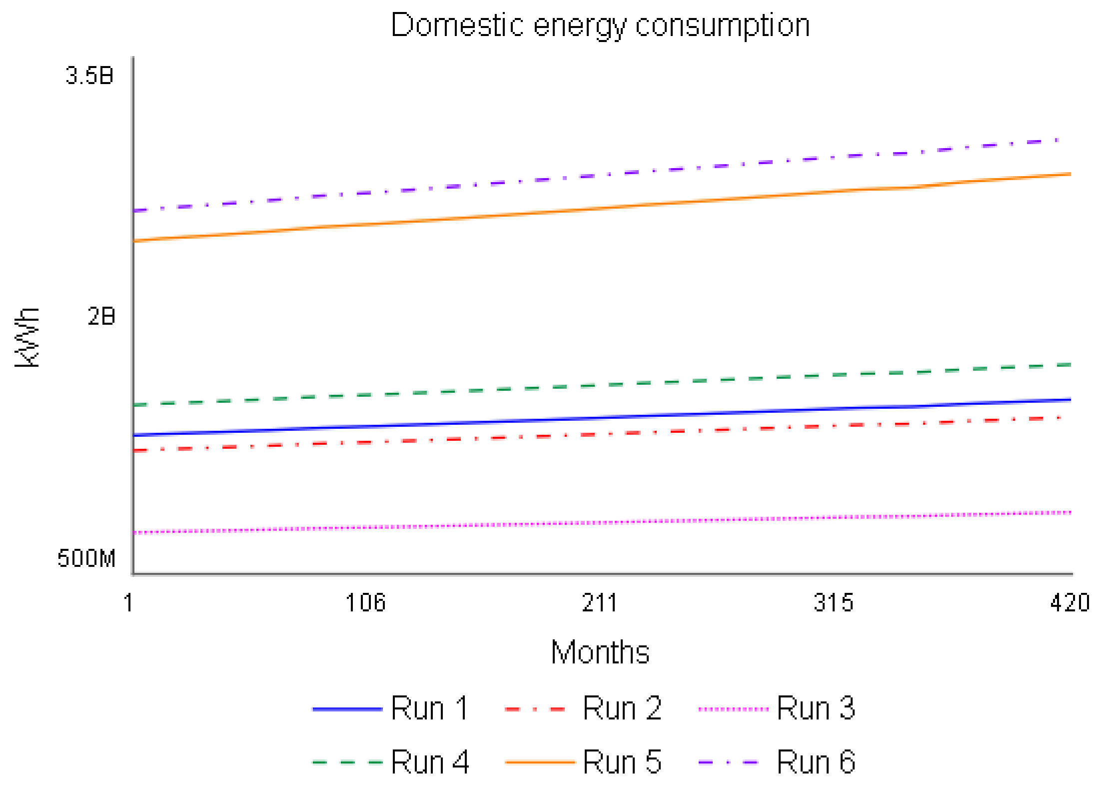


Figure 123: temporal pattern of the energy demand in the Adige River Basin a a sum of residents and tourists.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

4.5 Inkomati-Usuthu

In this section, a sample of uncertainty results will be presented to illustrate the outputs from the system dynamics model that is developed. For parametric uncertainty, the scenario RCP26-SSP2 will be used to demonstrate the uncertainty associated with model input and output parameters. Scenario uncertainty will compare results between the RCPs (26 and 85), and the SSPs (2 and 4).

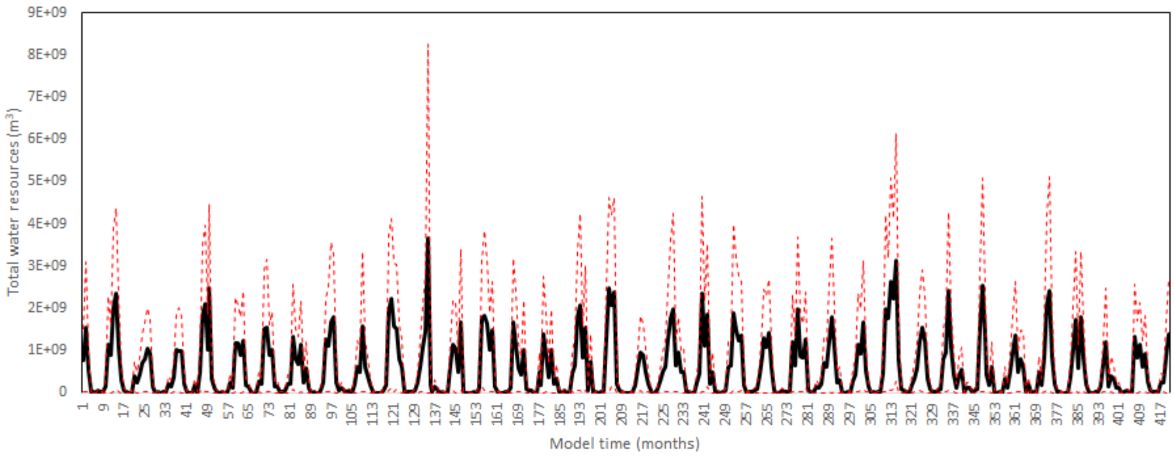
In this CS, the parameters tested are:

- Water resources
- Surface water runoff
- Total water withdrawals
- Water balance
- Total crop production
- Irrigated crop production
- Nitrogen leaching form agricultural lands
- Energy demand
- Energy balance
- Carbon mass in vegetation
- Carbon sequestration
- Above ground biomass
- Emissions from local fossil fuel consumption
- Emissions from renewable energy consumption
- Total local energy consumption
- Carbon sequestration

These were chosen as they reflect parameters of interest for the CS, and cover all nexus sectors.

4.5.1 Parametric uncertainty

In the water sector, Figures 124-127 show parametric uncertainty results for total water resources, surface water runoff, total water withdrawals, and the water balance respectively.



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Figure 124: uncertainty for the total water resources parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

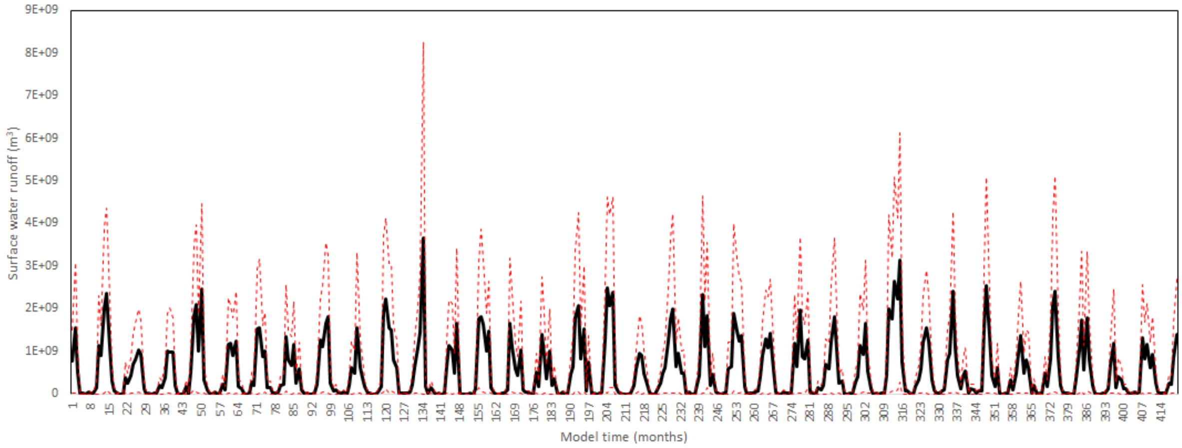


Figure 125: uncertainty for the surface water runoff parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

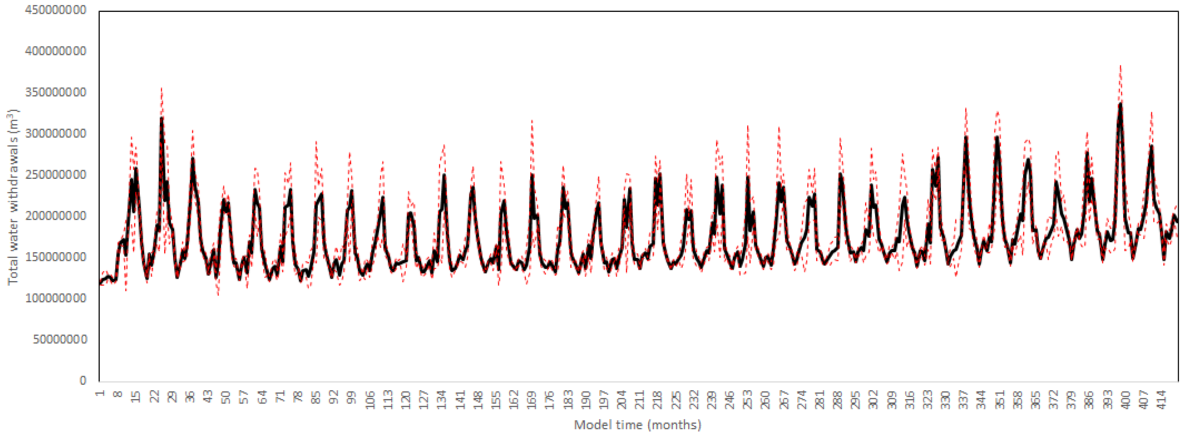


Figure 126: uncertainty for the total water withdrawals parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

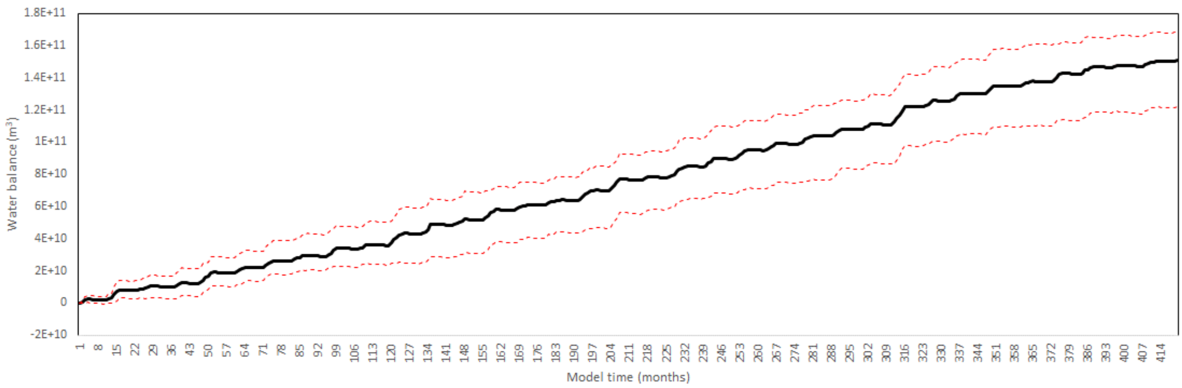


Figure 127: uncertainty for the water balance parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

For total water resources (Figure 125), there is considerable uncertainty between the parameter values, with large differences between minimum and maximum values across the simulation time horizon. The seasonality of resources is captured by all the input models however, with wet and dry periods being consistent in this respect. The main source of uncertainty therefore is the degree of water resources available at different times through the year. Much of this uncertainty comes from the uncertainty related to the surface water runoff (Figure 125), plus a smaller contribution from dam outflow.

Water withdrawals (Figure 126) results show a lower range of uncertainty compared with water resources. This is perhaps a little surprising as the water withdrawals are estimated from a number of different parameters, some of which themselves are subject to uncertainty. Water withdrawals comprises of industrial demand, domestic demand, livestock water demand, agricultural water demand, transboundary obligations, and water exported from the region. Of these, domestic, livestock, and agricultural water demands are all subject to uncertainty. The implication is that the combined uncertainty in each of these parameters is still lower than that for water resources.

Finally in the water sector, figure 127 shows the uncertainty associated with the water balance parameter in the model. Much of this variation in results is as a consequence in the uncertainty associated in the water resources parameter. When resources are lower, the balance will track towards the lower end of the envelope in Figure 135, and vice-versa. Acknowledging this variation will clearly aid planners when considering optimistic and pessimistic scenarios for water resources management. In any case, what is promising, is that, according to model simulations, the water resources over time in the Inkomati are positive, implying that if managed carefully, there should be enough to meet demand into the future. The probability distribution for the water balance at different time intervals in shown in Figure 128.

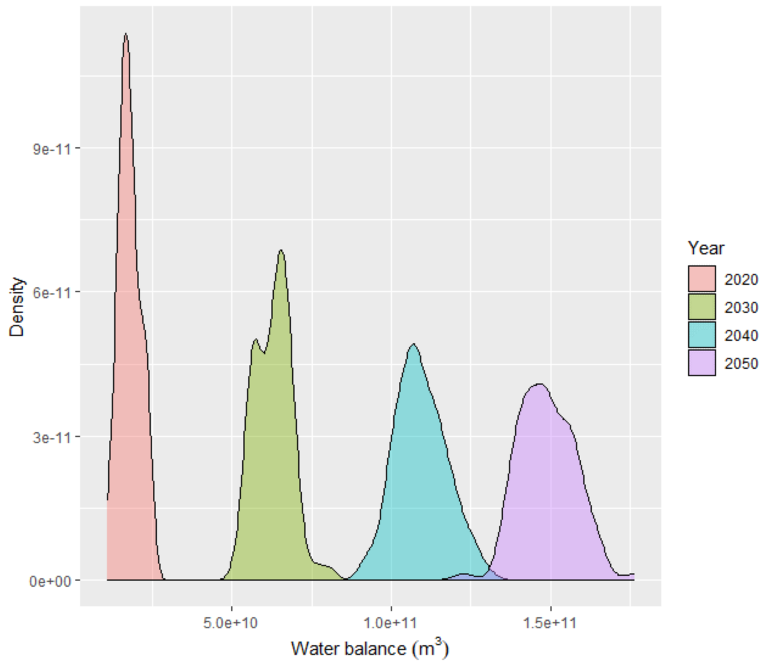


Figure 128 probability distributions for water balance at different time intervals.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

In the food sector, Figures 129-131 show the results for total local crop production, irrigated crop production, and the total nitrogen (N) leaching from agricultural land respectively.

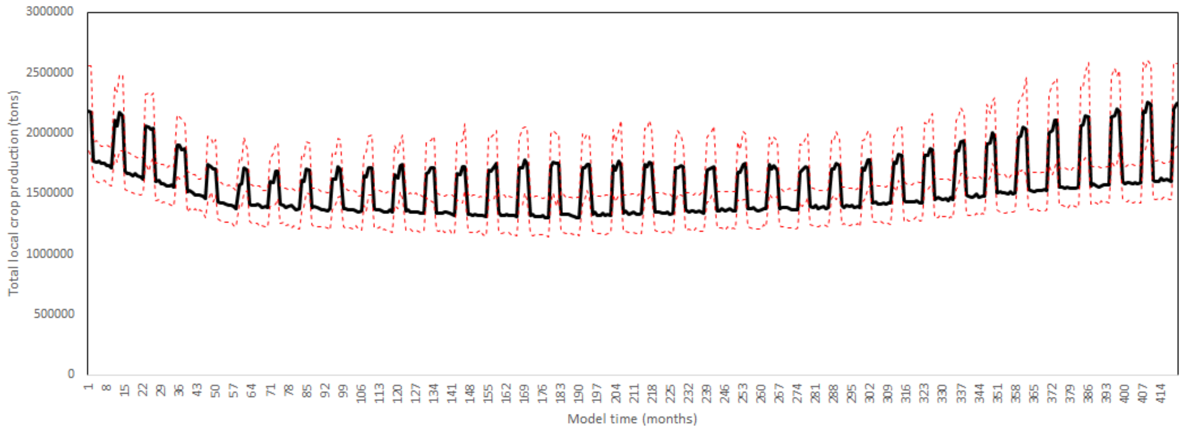


Figure 129: uncertainty for the total local crop production parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

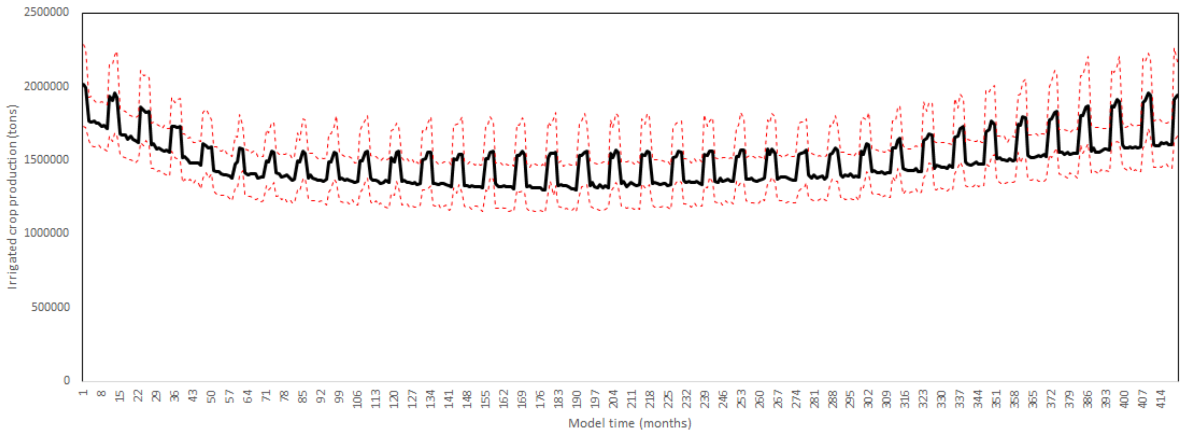


Figure 130: uncertainty for the total local irrigated production parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

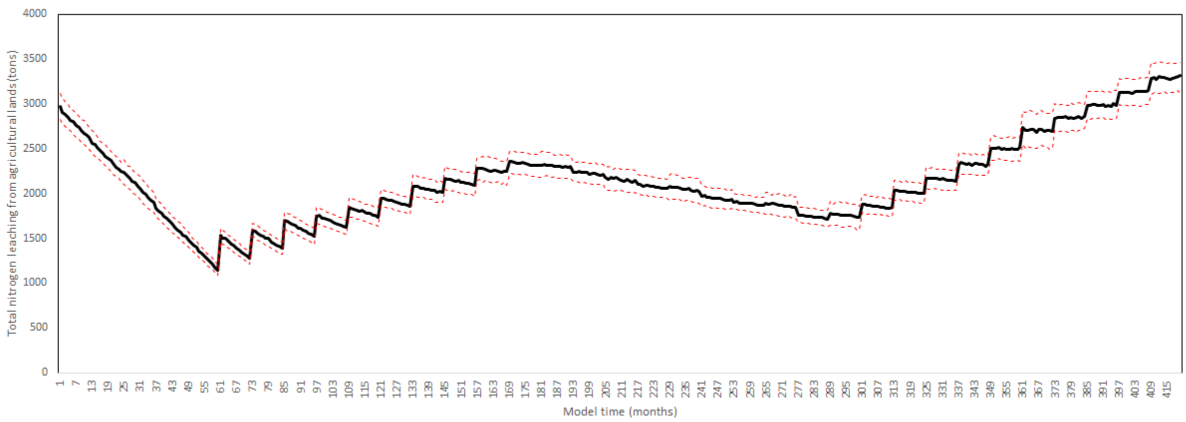


Figure 131: uncertainty for the nitrogen leaching from agricultural land parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Results show similar levels of uncertainty in both total and irrigated crop production (Figures 129 and 130), suggesting that most of the uncertainty in crop production comes from uncertainty in irrigated crop production models. The seasonal trend on crop production is obvious, reflecting the main growing season in South Africa. Uncertainty is somewhat lower for total nitrogen leaching (Figure 131). The reduction in the first third of the simulation is related to land use trends, which show a modelling reduction in agricultural land use area, demonstrating a clear link between land use, food production, nitrogen leaching, and water requirements in agriculture. The probability distribution for the nitrogen leaching at different time intervals in shown in Figure 132.

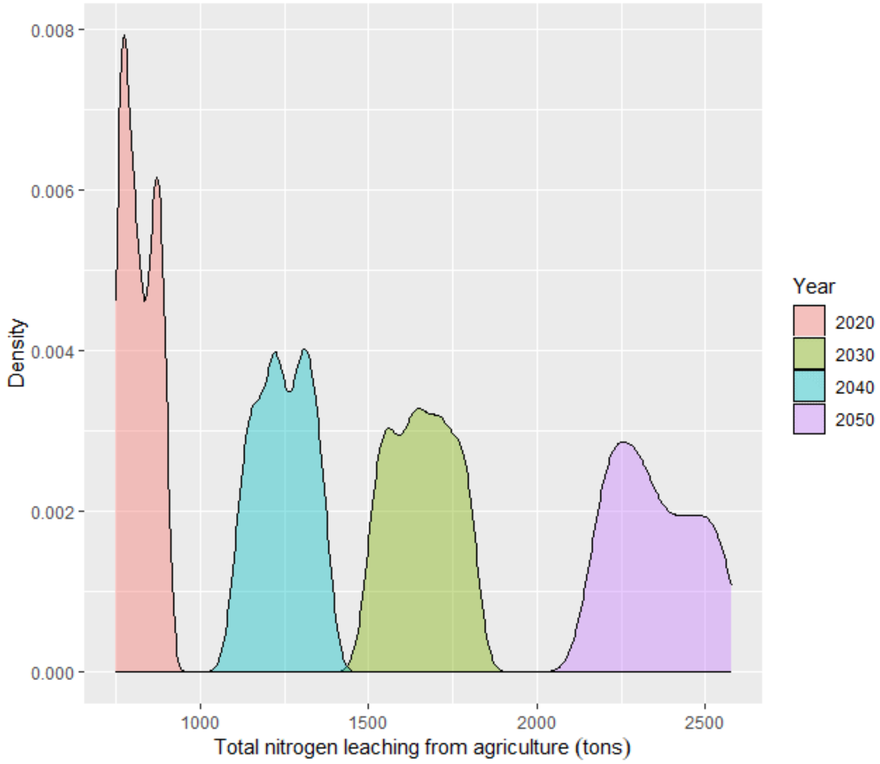


Figure 132: probability distributions for nitrogen leaching at different time intervals.

In the Inkomati energy sector, figures 133-134 show the results of parametric uncertainty. Energy supply is not subject to parametric uncertainty, therefore no results are shown for this part of the model. Figure 133 shows the output for uncertainty in the energy demand for water supply parameter. As can be seen, there is a considerable degree of uncertainty in this parameter, which itself is modulated entirely by i) the total water withdrawal parameter in the water sector, and ii) by uncertainty in the energy demand per m^3 of water delivered. The combination of these two sources of uncertainty give rise to the large degree of total uncertainty in the parameter. On the other hand, there is negligible uncertainty in the total energy balance (Figure 134). Even though the energy for water is highly uncertain, this corresponds to a minor impact on the energy balance of the case study.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

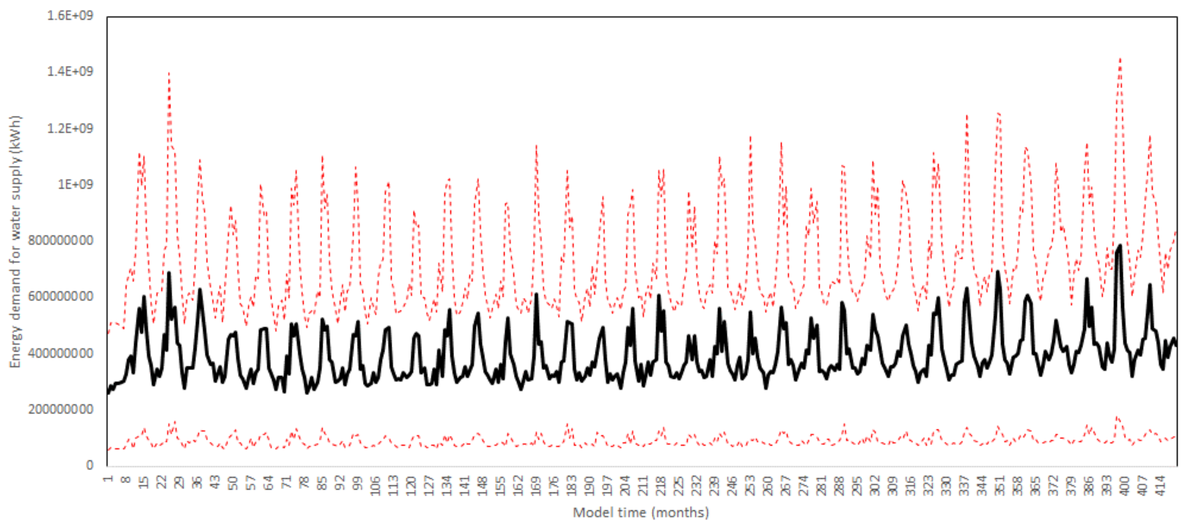


Figure 133: uncertainty for the energy demand from water supply parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

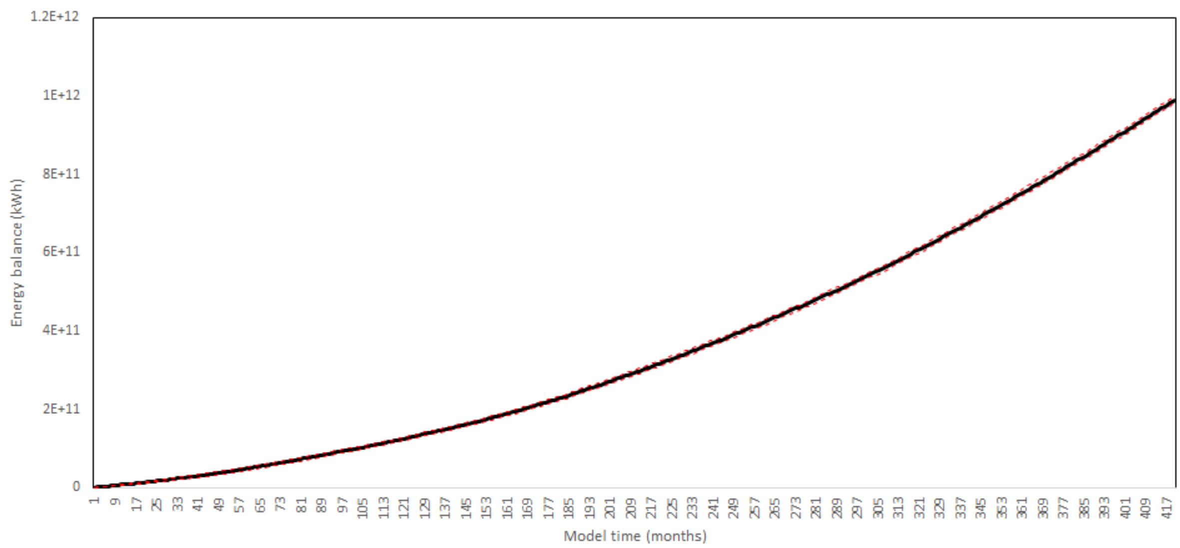


Figure 134: uncertainty for the energy balance parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

In the Ecosystems models, Figures 135-137 show the uncertainty results for the Inkomati. Figure 135 shows the uncertainty associated with carbon mass stored in vegetation. As shown, the uncertainty in this parameter, largely coming from uncertainty in the input datasets, is not too large, though it does increase towards the end of the simulation. Likewise, uncertainty in carbon sequestration (Figure 136) is not too high, again being associated mostly with uncertainty in input models from WP2. However, the uncertainty in above ground biomass is considerable (Figure 137). The uncertainty here derives from both uncertainty in external model input data, and variations in the land coverage of crops for which this parameter is estimated. Interestingly, it is important to note that the seasonality of both above ground biomass and carbon sequestration are clearly visible in model output, reflecting the growing season in South Africa.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

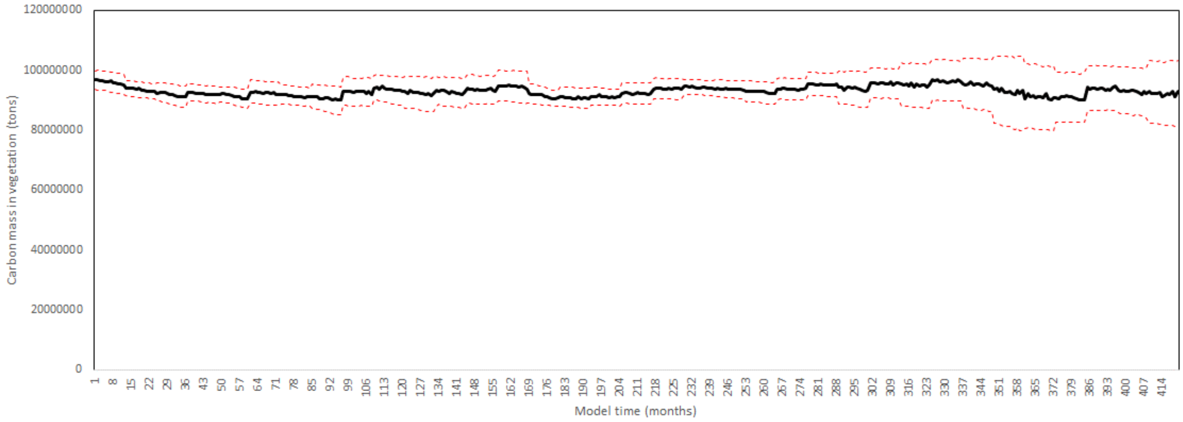


Figure 135: uncertainty for the carbon mass in vegetation parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

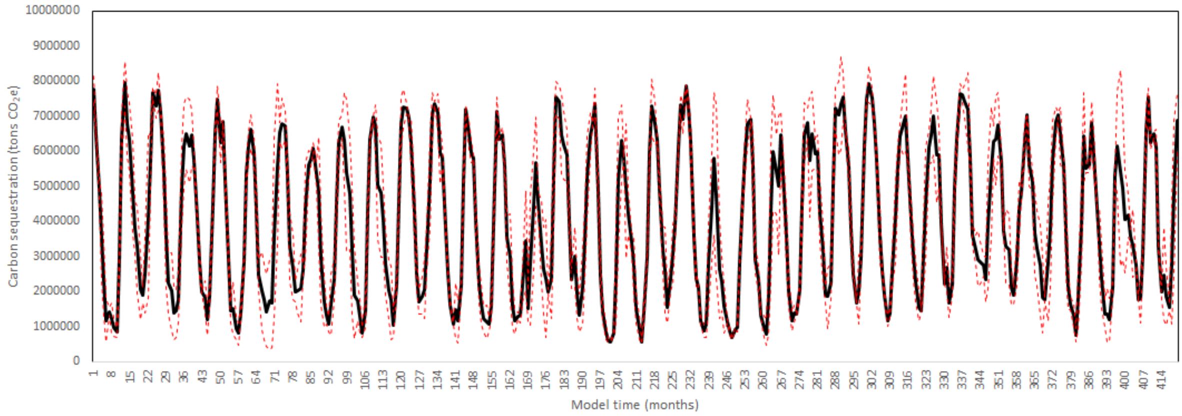


Figure 136: uncertainty for the carbon sequestration parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

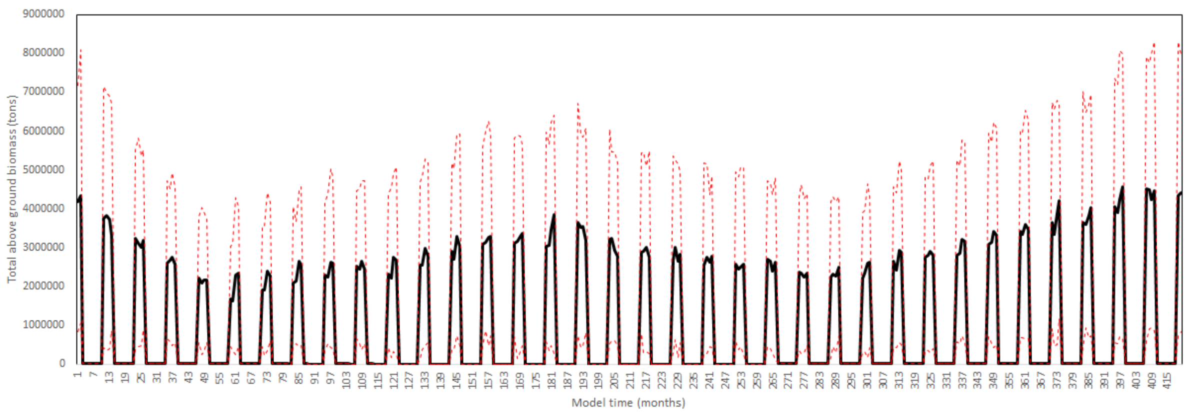


Figure 137: uncertainty for the total above ground biomass parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

Finally, in the climate sector, Figures 138-140 show the uncertainty in emissions for local fossil fuel consumption, local renewable energy consumption, total local energy consumption, and carbon sequestration respectively. There is somewhat considerable uncertainty in both the emissions from local fossil fuels and renewable energy consumption (Figures 138 and 139), which in turn feeds through to the emissions from total local energy consumption (Figure 140).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

This uncertainty is due to uncertainty in the amount of energy consumed in the study area in different sectors of the economy (e.g. for domestic consumption, in irrigated agriculture, in energy required for water supply, etc.). As the emissions factors are fixed values, it is the uncertainty in the consumption of energy that drives the uncertainty in emissions estimation. Uncertainty in carbon sequestration is considerably lower, and has already been discussed above. In sum, it is worth noting that sequestration is greater than emissions in this model. This is very likely due to the fact that not all emissions are attributed. For example, emissions due to the transport sector are unaccounted for in the model, resulting in an underestimation in carbon emissions. This is important to stress in future communication and dissemination activities. The probability distribution for the greenhouse gas emissions at different time intervals in shown in Figure 141.

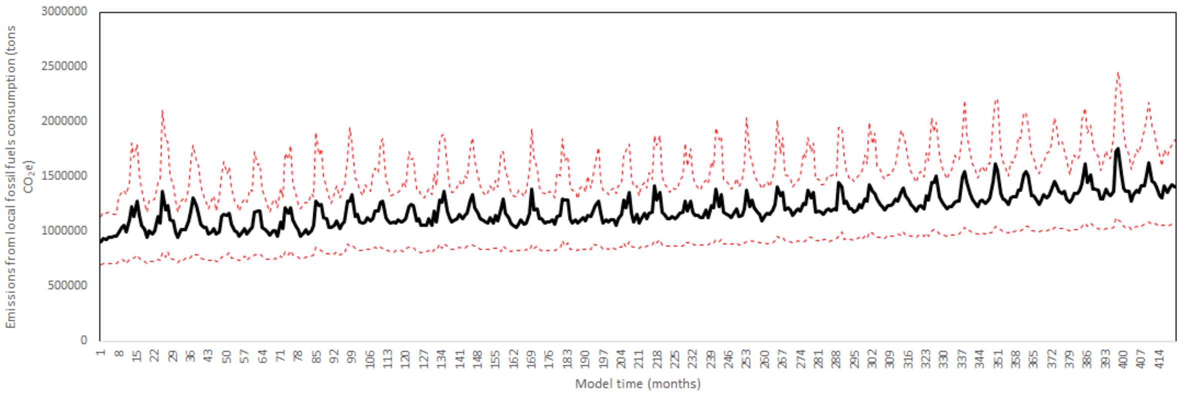


Figure 138: uncertainty for the emissions from local fossil fuels consumption parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

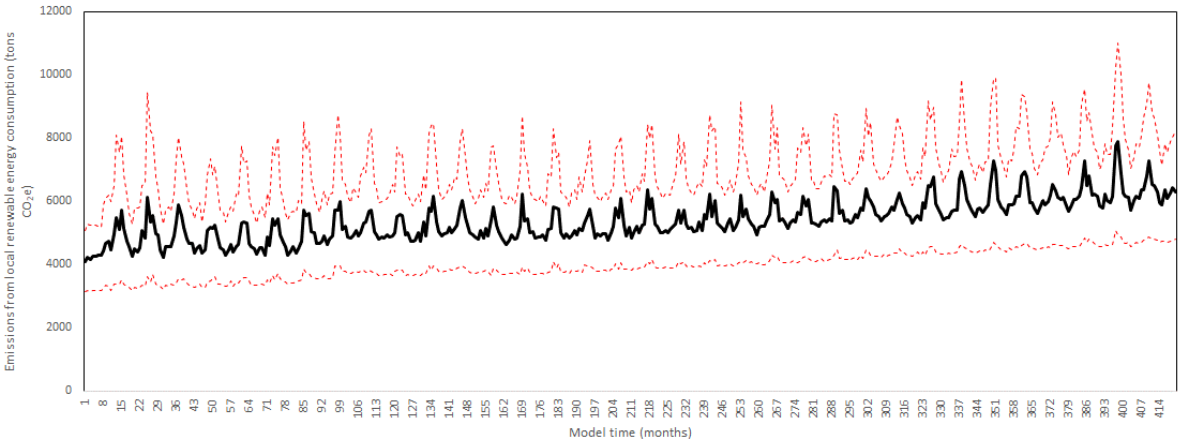


Figure 139: uncertainty for the emissions from local renewable energy consumption parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

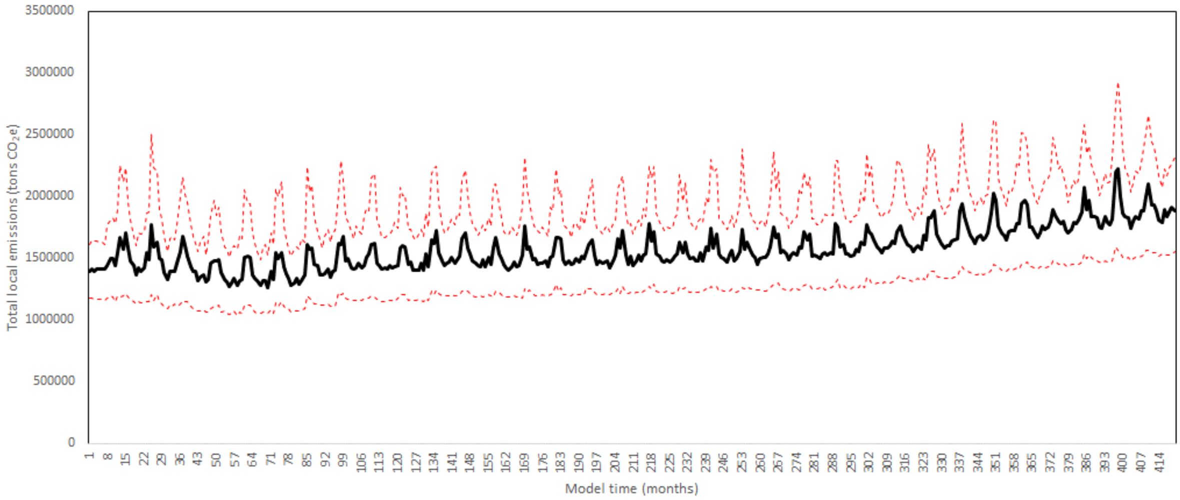


Figure 140: uncertainty for the emissions from total local energy consumption parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

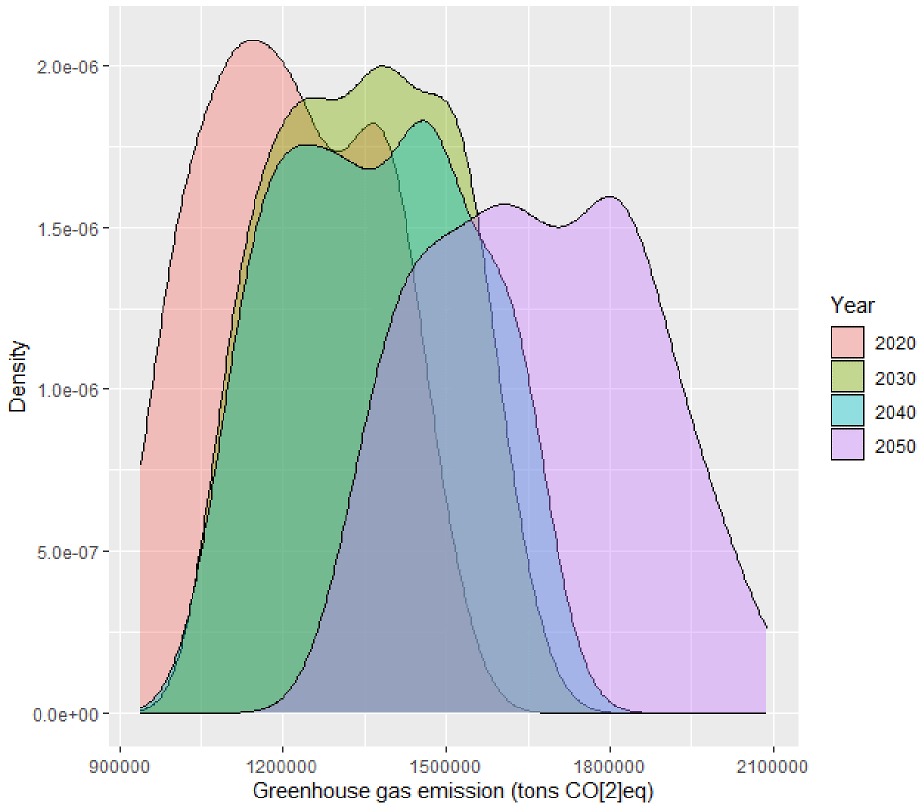


Figure 141: probability distributions for greenhouse gas emissions at different time intervals.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

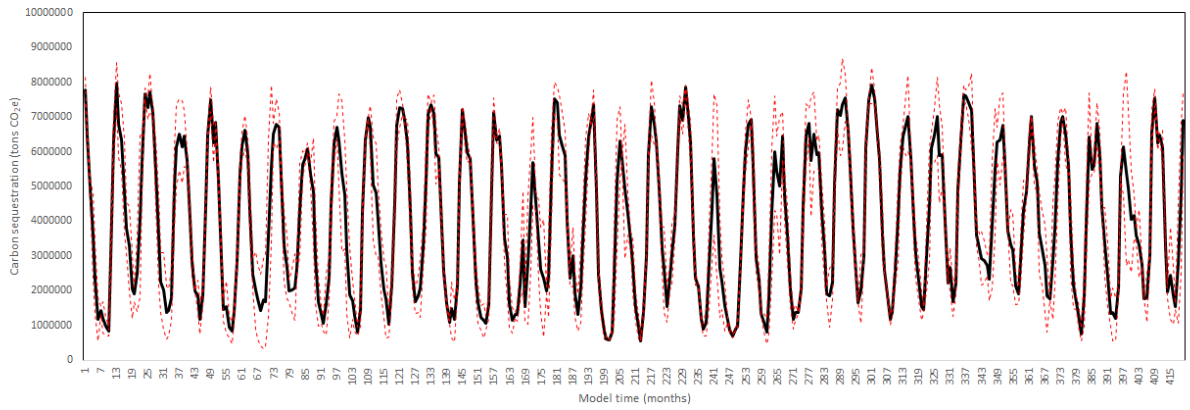


Figure 142: uncertainty for the emissions from the carbon sequestration parameter for the RCP26-SSP2 scenario in the Inkomati-Usuthu case study.

4.5.2 Scenario uncertainty

This section presents some key results demonstrating the uncertainty between results for the same parameter between the RCP climate scenarios (i.e. RCPs 2.6 and 8.5), and the SSP socio-economic scenarios (i.e. SSP2 and 4).

Figure 143 shows the differences in population projections coming from the two SSPs. The main difference is a divergence between the two trends, with SSP2 projecting a small population growth, while SSP4 projects a small population decline by 2050 (the end of the simulation).

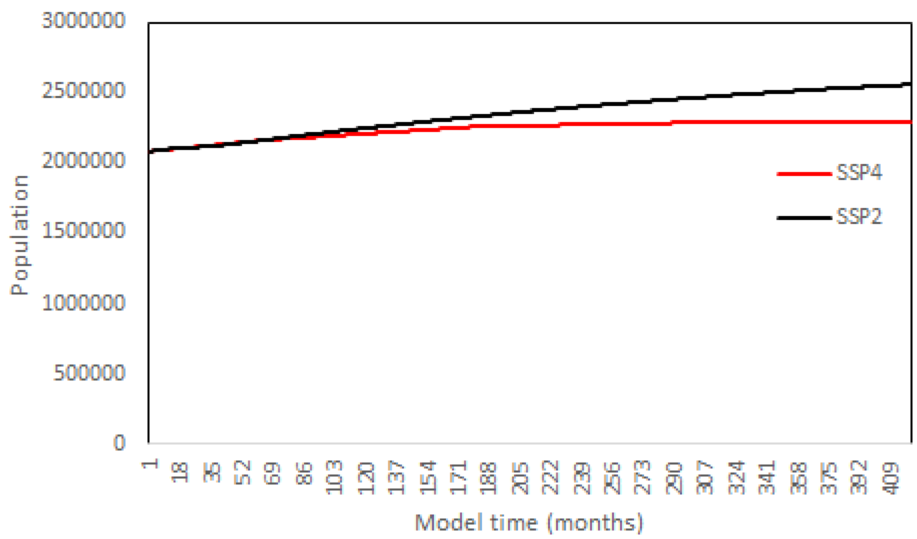


Figure 143: difference in population between SSPs 2 and 4 in the Inkomati-Usuthu case study.

In the water sector, the parameters 'Domestic Water Withdrawals', 'Total Water Withdrawals', and 'Water Balance' are affected by the SSPs (Figures 144-148), while 'Water Resources' and the 'Water Balance' are affected by the RCPs (Figures 149-150). The domestic water demand shows significant divergence towards the end of the simulation (Figure 151), driven by the differences in population projections between the SSPs. This translates however to a negligible

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

difference in total water withdrawals (Figure 152) as domestic water withdrawals are minor compared with other water demanding sectors, especially agriculture. Similarly, the difference in water balance between the SSPs due to differences in the demand side (the supply side is affected only by RCP input data) are negligible (Figure 153). Concerning uncertainty due to the RCPs, Figure 152 shows the variation in water supply, with the main differences appearing as the magnitude of peak flows in the wet season, with RCP2.6 suggesting that under these climate conditions, peak flows would, most of the time, be higher than under RCP8.5 conditions. The impact on the total water balance is relatively minor (Figure 153) with both RCP scenarios showing very similar trajectories over time, and neither suggesting a shortfall in water availability.

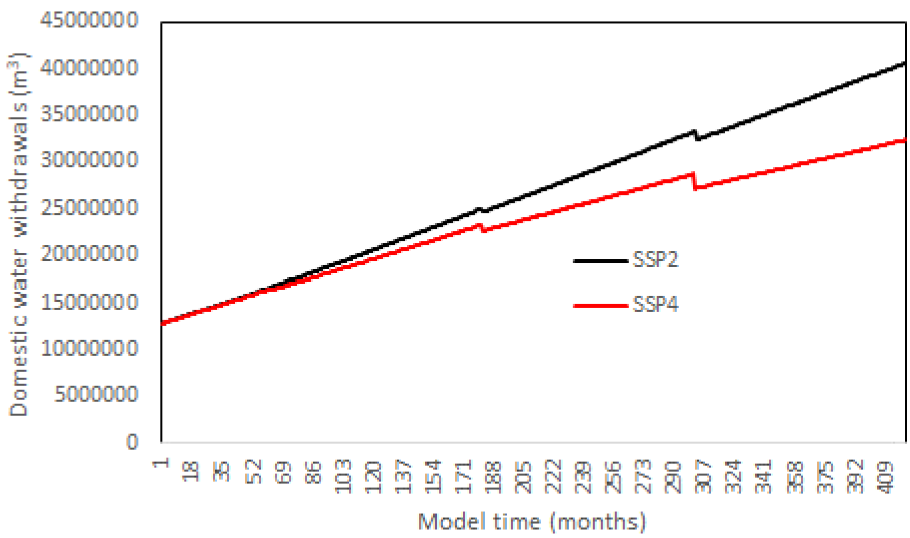


Figure 144 difference in mean domestic water withdrawals between SSPs 2 and 4 in the Inkomati-Usuthu case study.

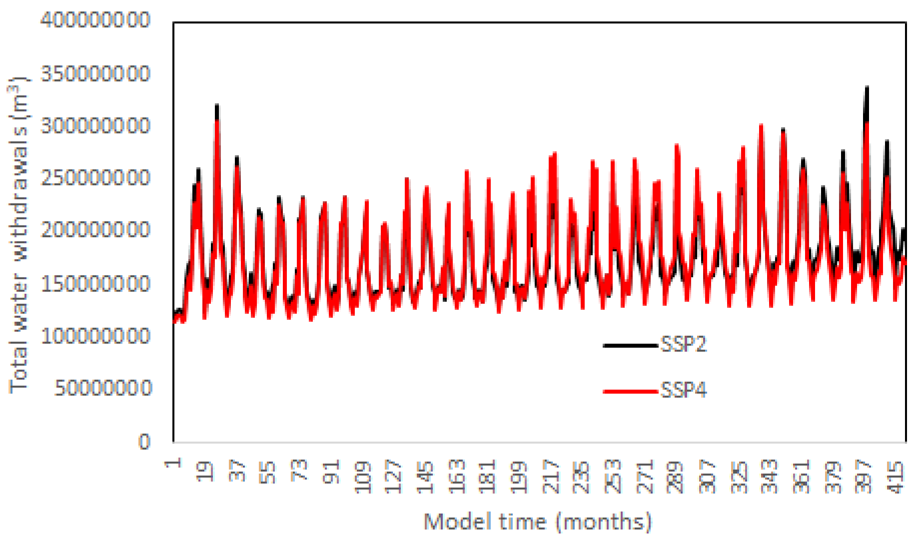


Figure 145: difference in mean total water withdrawals between SSPs 2 and 4 in the Inkomati-Usuthu case study.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

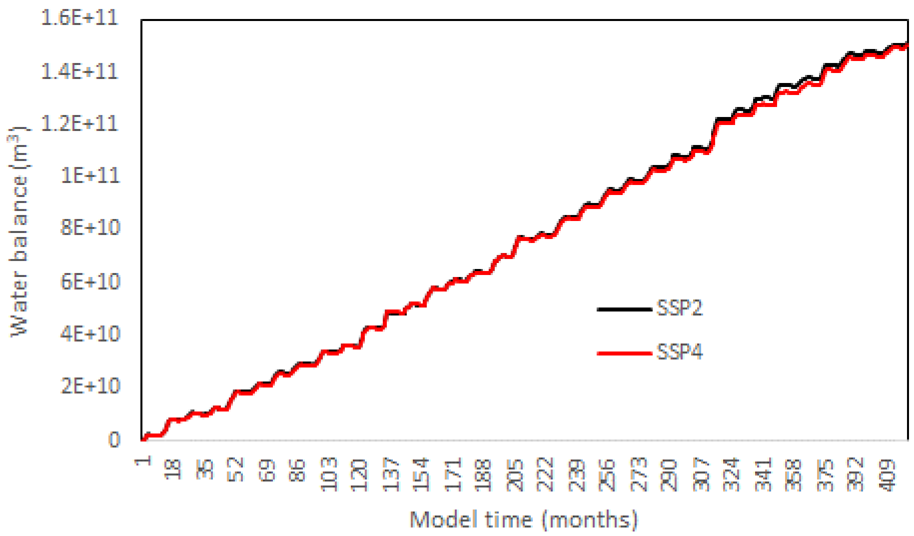


Figure 146: difference in mean water balance between SSPs 2 and 4 in the Inkomati-Usuthu case study.

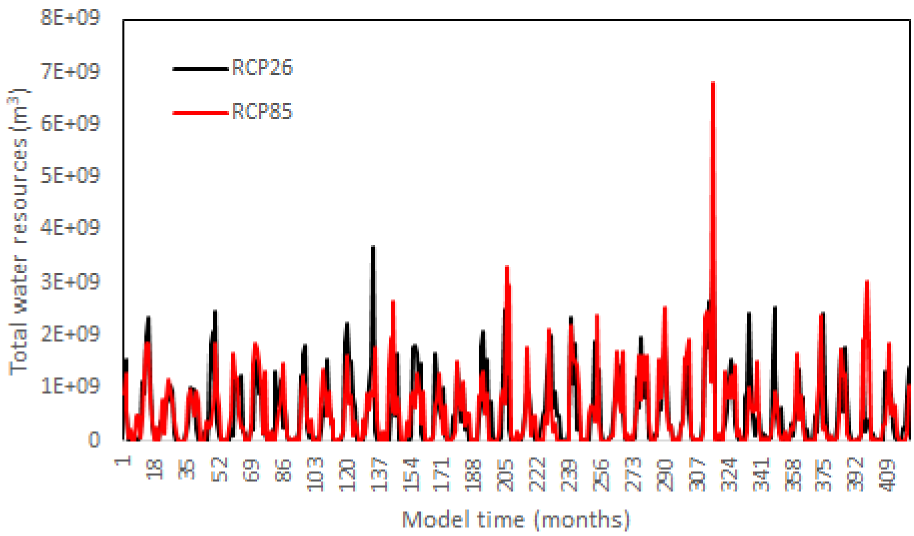


Figure 147: difference in mean water resources between RCPs 2.6 and 8.5 in the Inkomati-Usuthu case study.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

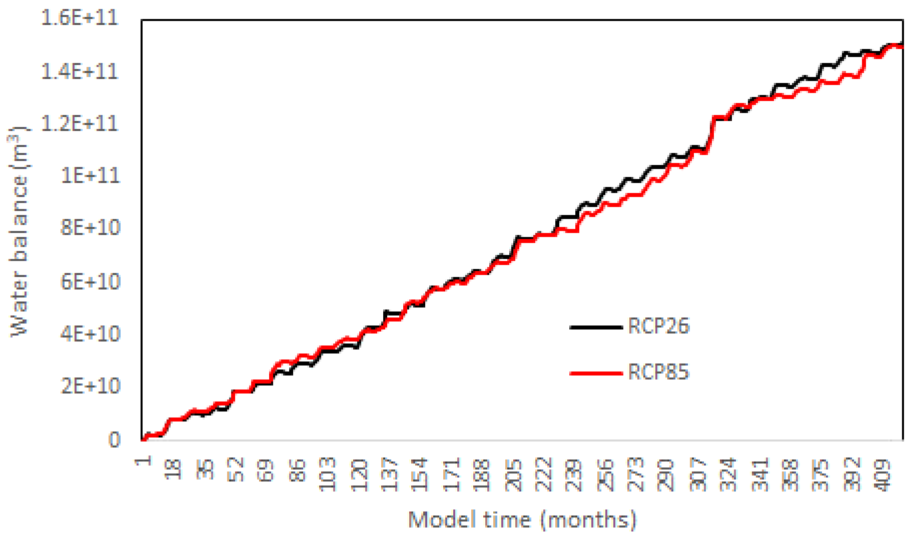


Figure 148: difference in mean water balance between RCPs 2.6 and 8.5 in the Inkomati-Usuthu case study.

In the food sector, the total and irrigated crop productivity, and the nitrogen leaching are affected by RCP variables (Figures 149-150), while the local food demand is impacts by the SSP scenarios (Figure 151). Results for the total and irrigated crop production (Figures 154 and 152) show considerable differences between the two RCPs, with RCP85 suggesting much higher levels of production than RCP26. Upon further investigation, this is due to the input model data from WP2 giving much higher crop yields (kg ha^{-1}) then for the same crops in RCP26, especially for irrigated crops. Subsequent checks must be made to see if these yields make sense, or indeed are plausible.

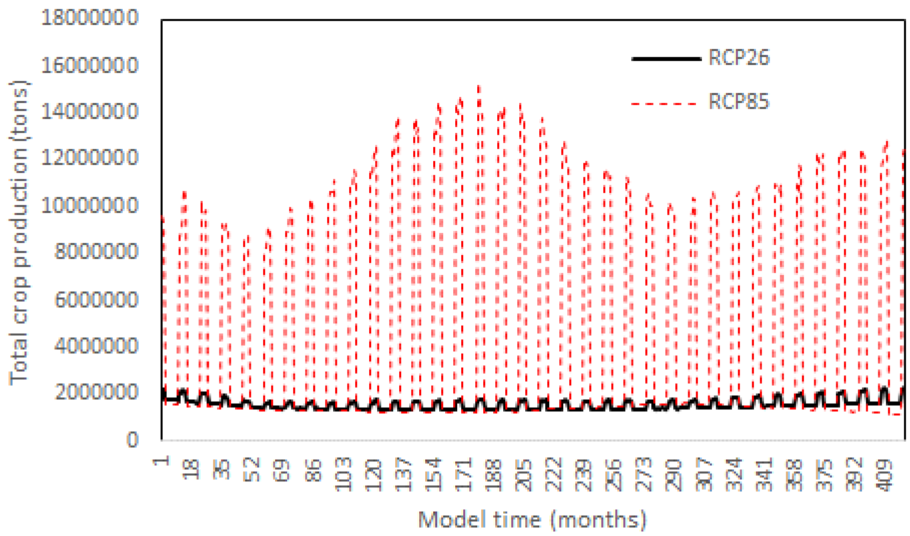


Figure 149: difference in total crop production between RCPs 2.6 and 8.5 in the Inkomati-Usuthu case study.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

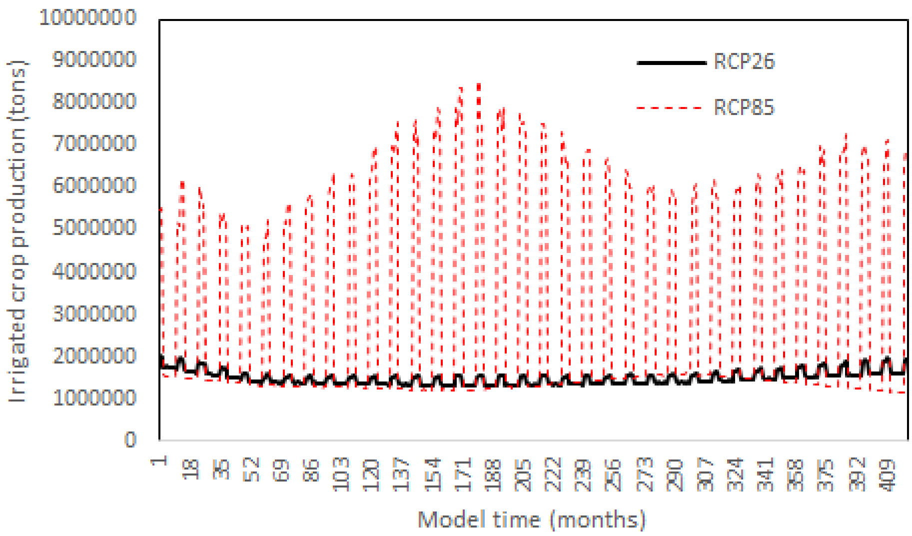


Figure 150: difference in irrigated crop production between RCPs 2.6 and 8.5 in the Inkomati-Usuthu case study.

Total nitrogen leaching (Figure 151) likewise shows quite a significant difference between RCP2.6 and 8.5. One reason is down to differences in the WP2 input model data, while a second reason is that the areas of planted crops changes differently under SSP2 and SSP4, hence the change not just in values, but also in trajectories. In total, RCP8.5 suggests a lower nitrogen leaching total throughout the simulation compared with RCP2.6, a combination of both lower leaching rates, and reduced planted area.

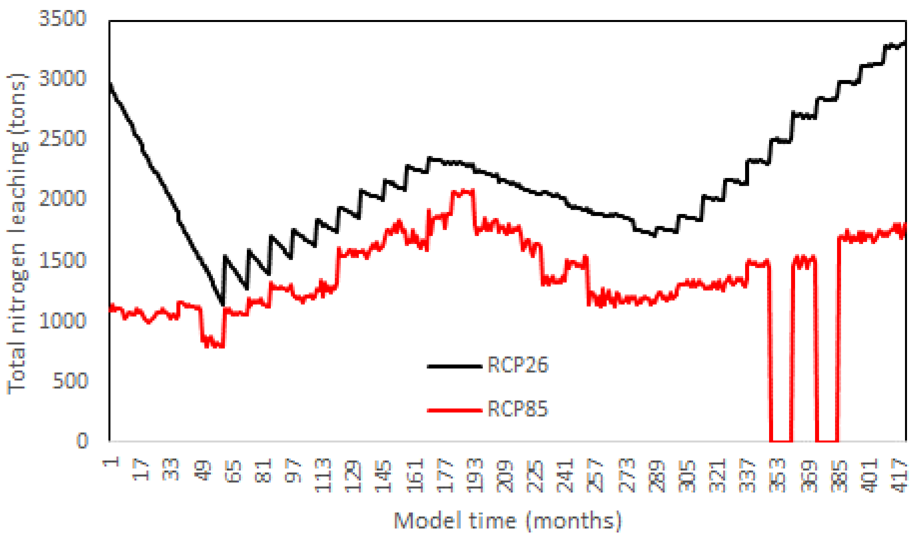


Figure 151: difference in total nitrogen leaching between RCPs 2.6 and 8.5 in the Inkomati-Usuthu case study.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

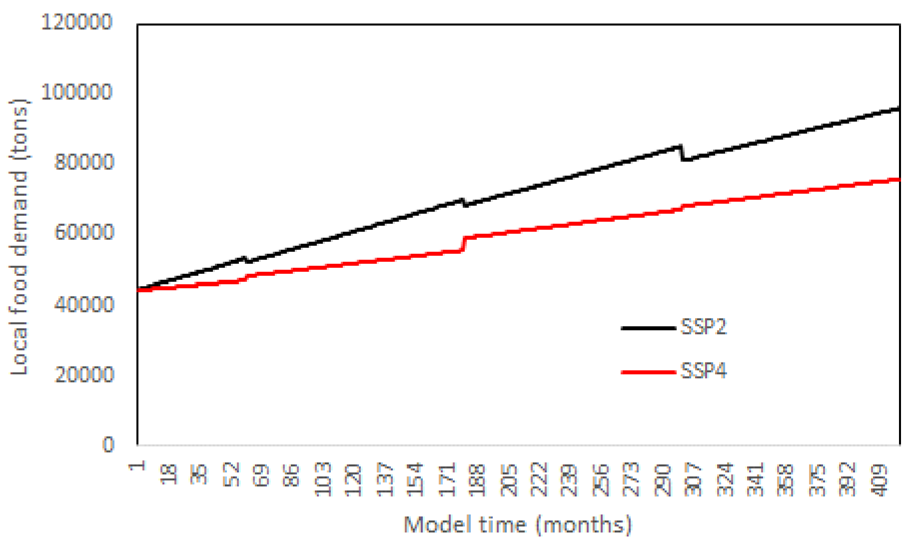


Figure 152: difference in total food demand between SSPs 2 and 4 in the Inkomati-Usuthu case study.

In terms of food demand, this is driven by differences in population projections between SS2 and SSP4 (Figure 152). The differences in the population projections have clear differences in the total food demand for the Inkomati case study, with a significant divergence by the end of the simulation. Therefore, planning food production appropriately will depend to a large extent on the population trajectory, which is a key metric for local planners and policy makers to track.

In the energy sector, the total energy supply, the energy for water distribution, and the energy balance are impacted by SSP scenarios (Figures 153-155). The RCPs do not play a role in this sector. The energy supply curves (Figure 153) do show some divergence, with a lower level of supply expected under SSP4. This may be important for policy makers and resources planners to take note of to ensure energy supply is sufficient in the region and beyond.

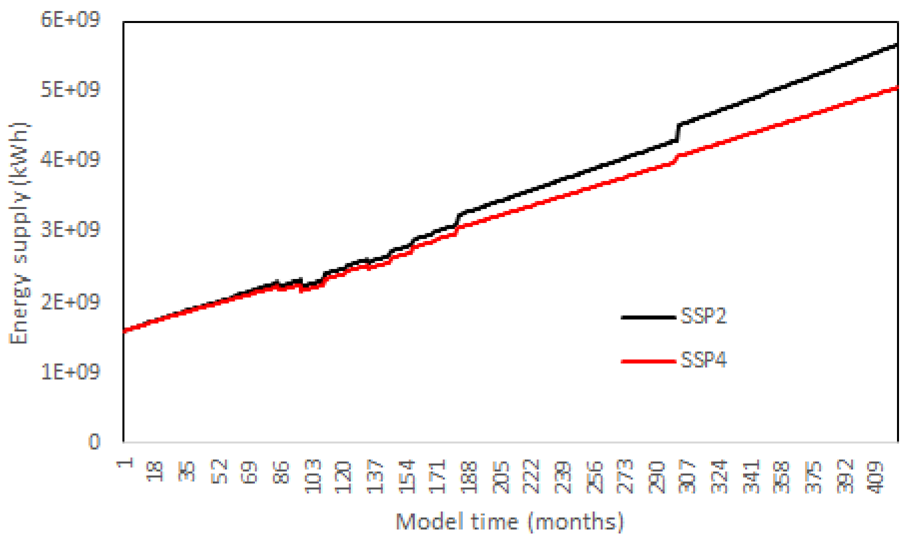


Figure 153: difference in total energy supply between SSPs 2 and 4 in the Inkomati-Usuthu case study.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

The energy demand for water supply (Figure 159) is very similar between the two SSPs (Figure 159), although SSP4 suggests a slightly lower demand towards the very end of simulation results.

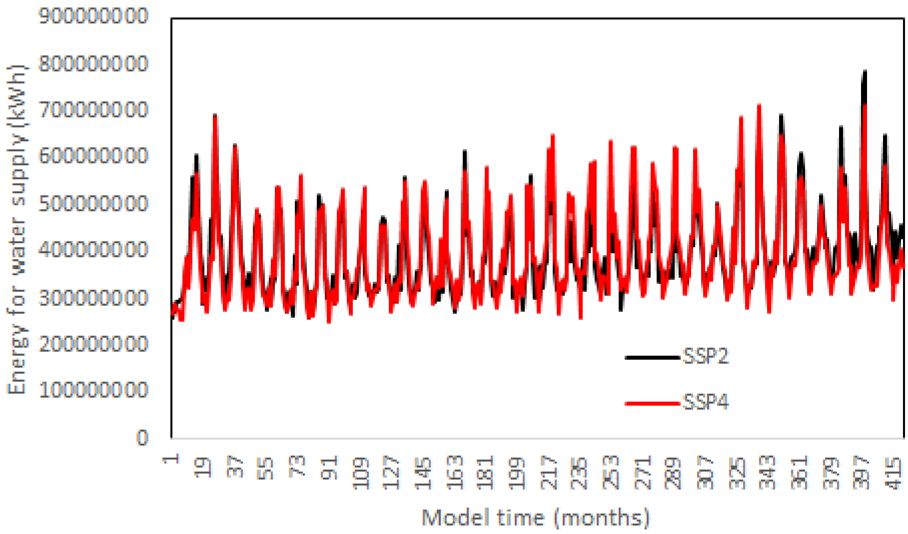


Figure 154: difference in energy demand for water supply between SSPs 2 and 4 in the Inkomati-Usuthu case study.

The total energy balance, although being lower under SSP4 than SSP2 (Figure 155) is still very positive under both scenarios, with no cause for concern noted regarding energy security for the region.

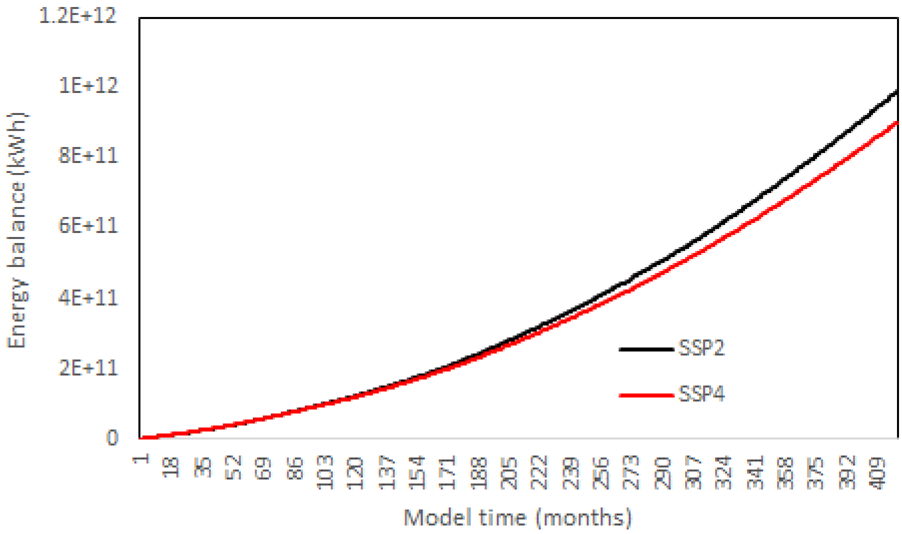


Figure 155: difference in the energy balance between SSPs 2 and 4 in the Inkomati-Usuthu case study.

In the ecosystems sector, all parameters are impacted by the RCPs and none by the SSPs. The carbon mass in vegetation, carbon sequestration, and above ground biomass results are shown in Figures 156-158. The carbon mass in vegetation (Figure 156) is shown to be lower

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

under RCP8.5 than in RCP2.6. The difference is quite large at the start of the simulation, but narrows towards the end. This parameter is impacted both by the area of different land uses, and by changes in the carbon mass input model data from WP2. Overall however, as less carbon is expected to be stored in vegetation under RCP8.5, this could have implications for reaching climate-related goals and targets.

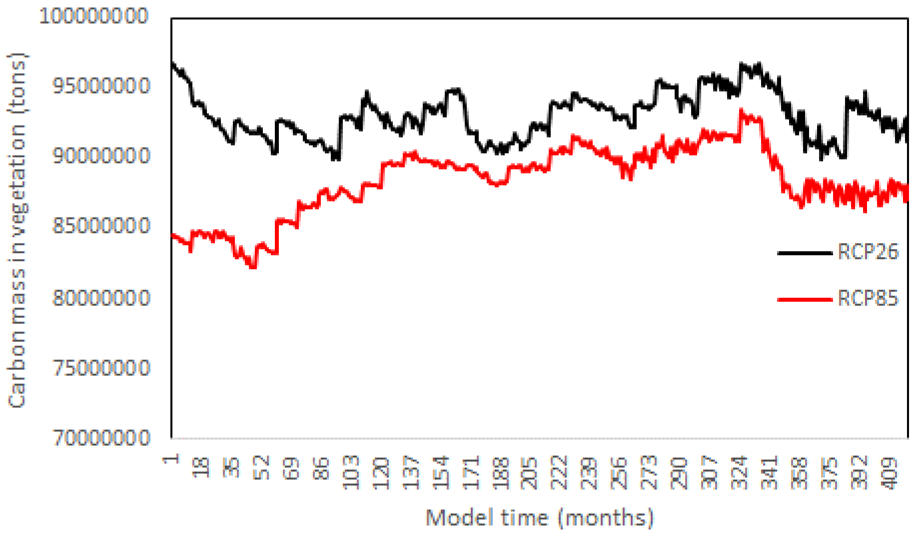


Figure 156: difference in the carbon mass in vegetation parameter between RCPs 2.6 and 8.5 in the Inkomati-Usuthu case study.

The differences in carbon sequestration between the RCPs is relatively minor (Figure 157 with no significant difference in either the magnitude or trend of the SDM output.

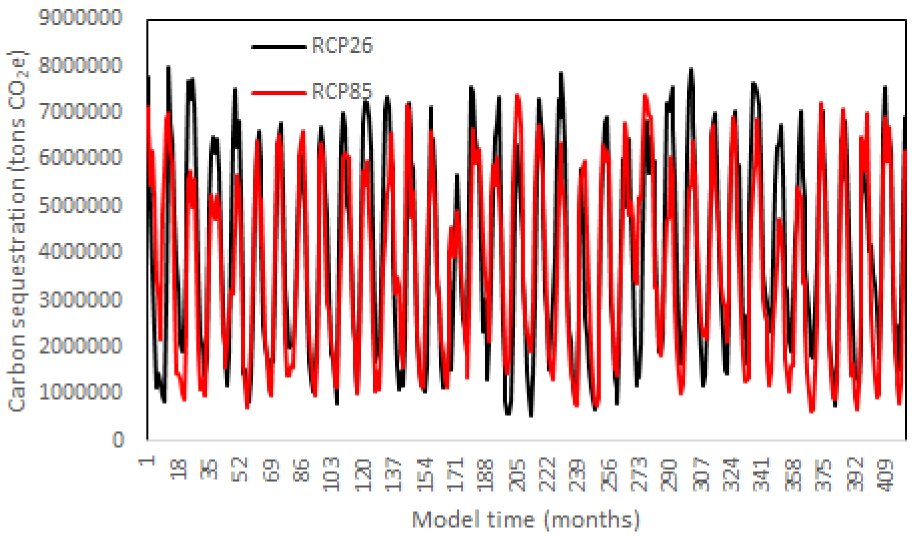


Figure 157: difference in the carbon sequestration parameter between RCPs 2.6 and 8.5 in the Inkomati-Usuthu case study.

There are significant differences between the RCPs in terms of the above ground biomass parameter (Figure 163). This is affected by land use areas and by external model input data from WP2. While the timing of the biomass curves are identical suggesting that the two

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

RCPs are capturing seasonality equally, RCP2.6 shows much higher biomass values in the peak growing season than RCP8.5. This could have significant consequences for carbon sequestration, soil conservation, and food production. At the same time, this trend is opposite to that for crop production, which is much higher under RCP8.5 than for RCP2.6. These two results seem incongruous and need further investigation.

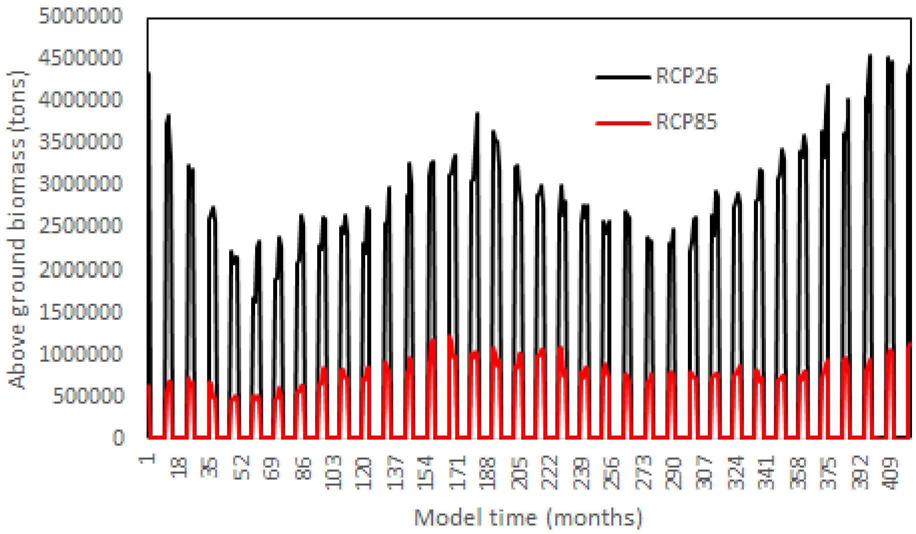
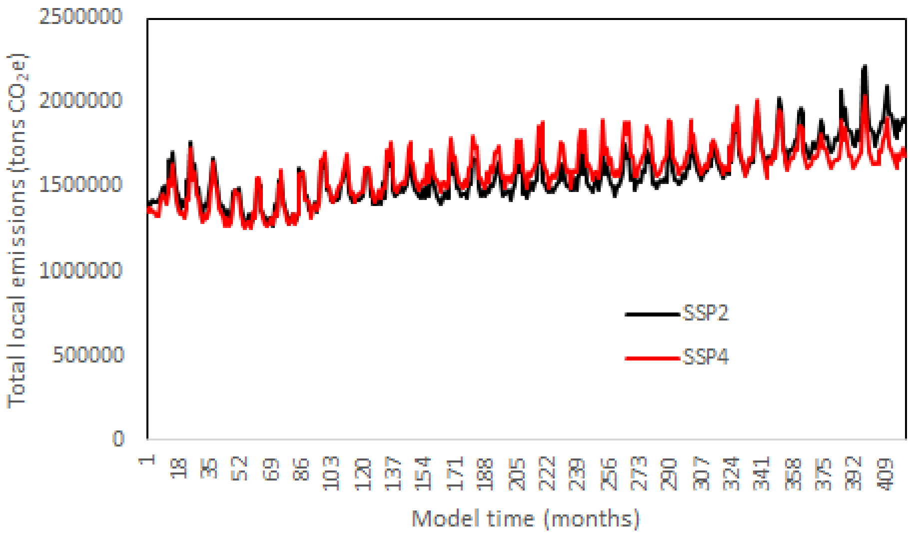


Figure 158: difference in the above ground biomass parameter between RCPs 2.6 and 8.5 in the Inkomati-Usuthu case study.

In the climate sector, the total local emissions are guided by the SSPs (carbon sequestration is dealt within the ecosystems sector). Figure 159 shows that both SSPs have similar trajectories, however while SSP4 is slightly higher in the middle of the simulation, by the end, SSP2 suggests the highest CO_2e emissions. The differences are relatively small however, suggesting that, for the parameters considered in the model, the SSPs have relatively little impact on emissions. It is again important to note however that emissions from many sectors of the economy are missing from this analysis, especially emissions from local transport.



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Figure 159: difference in the total local emissions between SSPs 2 and 4 in the Inkomati-Usuthu case study.

4.5.3 What-if and stress tests

In the Inkomati case study, the following what-if / stress tests are conducted. Doubling and halving population growth (to assess the implications on water demand, energy demand, food demand, and greenhouse gas emissions); doubling and halving water supply; doubling of energy demand; drastic reductions in agricultural land in order to assess the impact on food production, nitrogen leaching, and carbon sequestration). These were chosen as being especially pertinent for the CS. They ask the question of what if extreme, but very unlikely, changes occur in the system. At the same time, these analyses act as stress tests, stress the system in terms of supply and demand. It is noted that the tests conducted here are not deemed realistic, but serve to show the impacts of significant what-if changes upon the system on key output results. As with the parametric uncertainty, this section compares the tests against the RCP26-SSP2 scenario.

The what-if / stress tests showing the results of doubling and halving the water resources are shown in Figures 160-161. Doubling the supply clearly has very beneficial impacts on the total water demand, while halving the supply has significantly detrimental impacts to the water balance in the basin. Although overall the water balance in the long run is still positive if water supply is halved, there could be seasonal or annual negative instances where demand exceeds supply, leading to water shortage situations and water stress. Thus, a halving of water supply would be a situation to be carefully monitored by local resources planners.

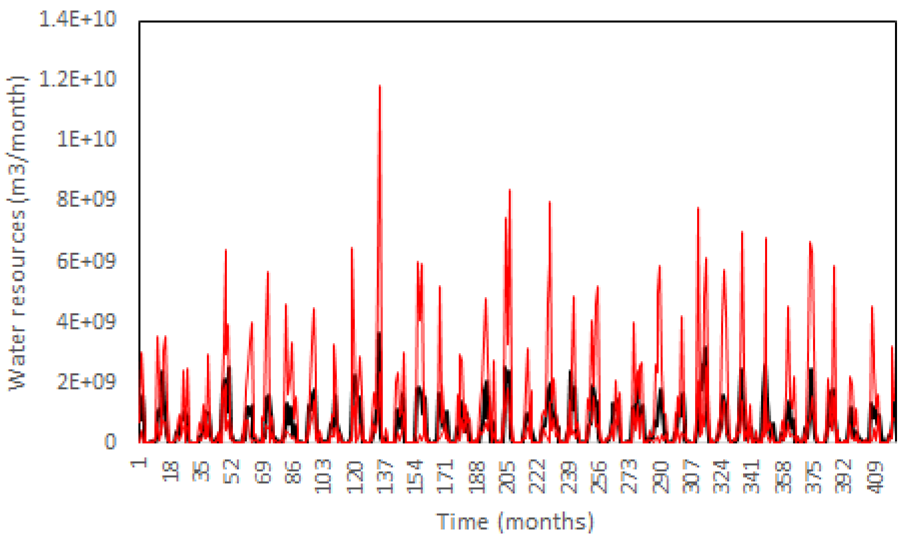


Figure 160: temporal pattern of water supply, showing RCP26-SSP2 simulation mean (black) and the trends under doubling and halving the water supply (red).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

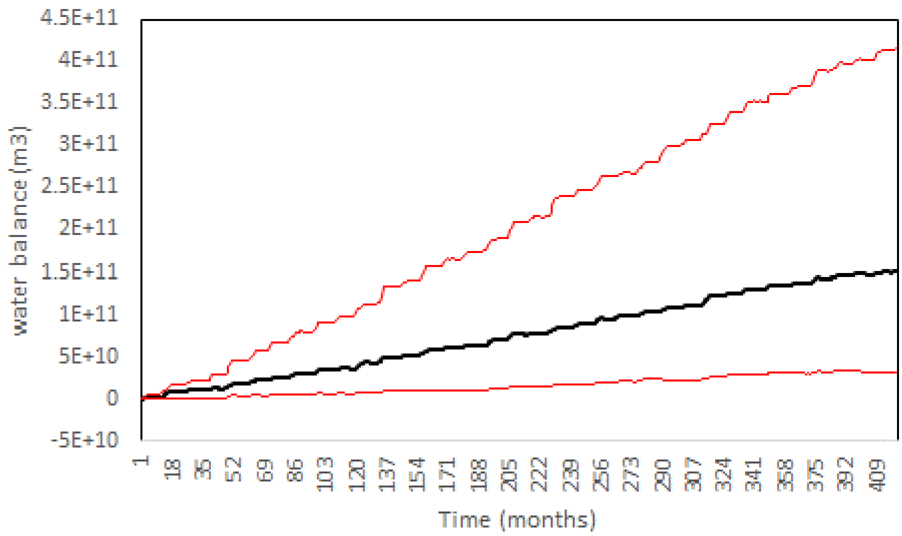


Figure 161: temporal pattern of water balance, showing RCP26-SSP2 simulation mean (black) and the trends under doubling and halving the water supply (red).

When the energy supply is doubled, again not thought realistic, the energy balance in the region improves significantly over the standard RCP26-SSP2 simulation (Figure 162).

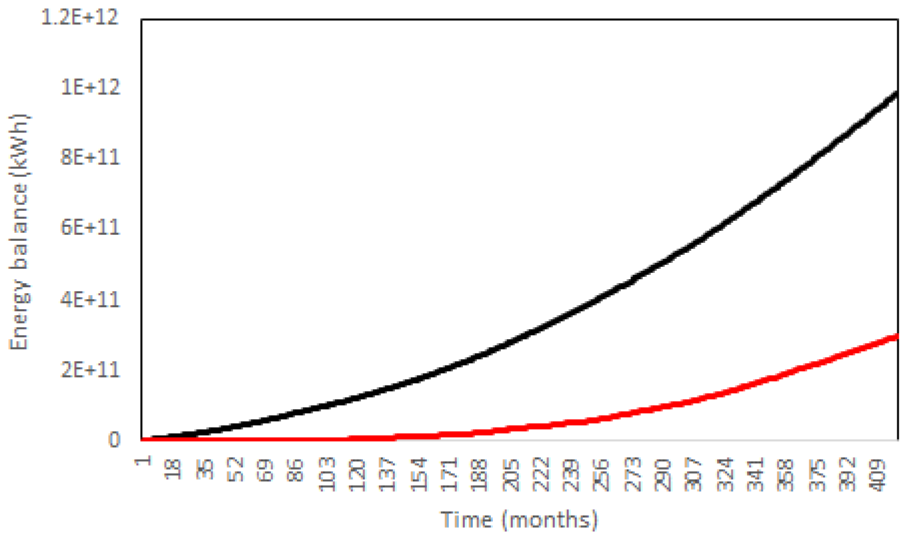


Figure 162: energy balance under the base scenario (red) and when energy supply is doubled (black).

In the very unlikely situation that the area of all agricultural lands are halved in area (i.e. both rainfed and irrigated), the impacts on food production, carbon sequestration, and nitrogen leaching were assessed (Figures 163-165). Food production is very negatively impacted, which would impact on local food security and likely on human health, a situation that local planners must keep under consideration. Carbon sequestration is far less sensitive to changes in agricultural land area (Figure 163). Although a reduction compared to the base RCP26-SSP2 simulation is observed, the change is relatively minor. Nitrogen leaching on the other hand drops substantially when agricultural land is reduced, a potentially beneficial impact for ecosystems health.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

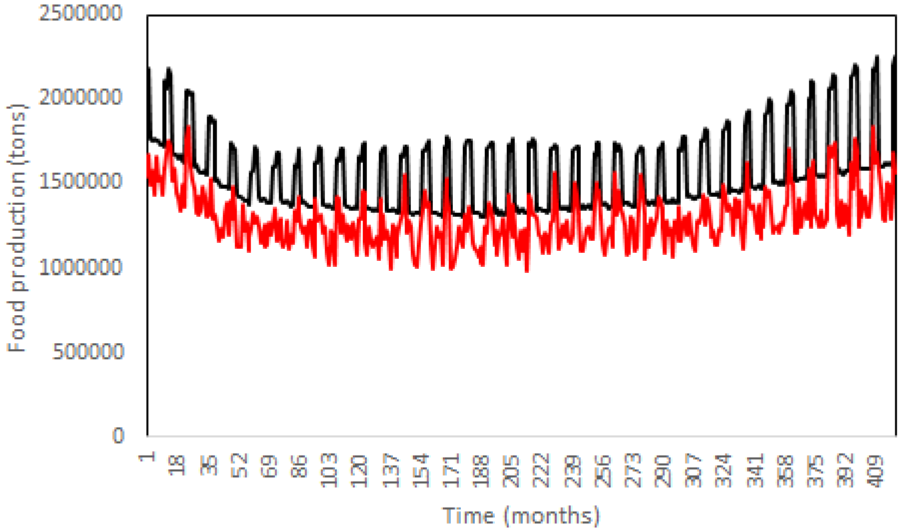


Figure 163: food production under the RCP26-SSP2 scenario (black) and when agricultural lands are halved in area (red).

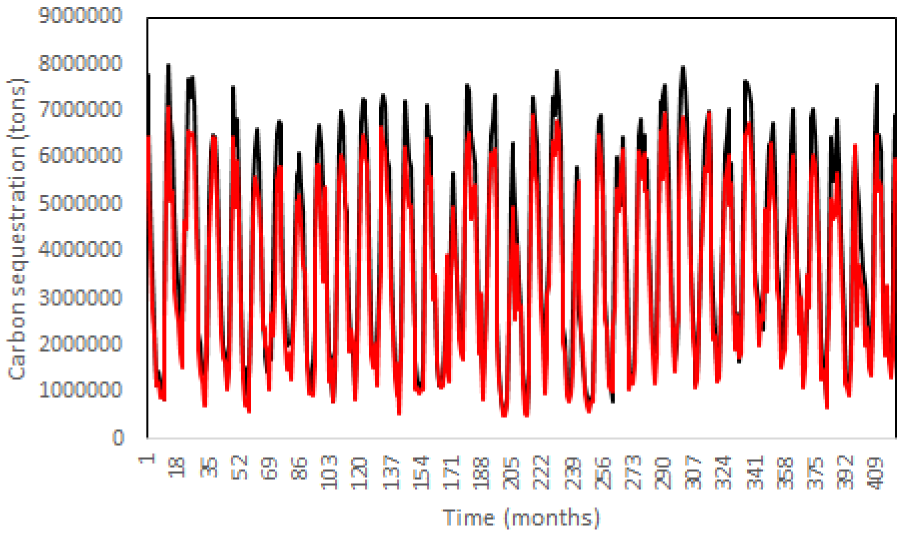


Figure 164: carbon sequestration under the RCP26-SSP2 scenario (black) and when agricultural lands are halved in area (red).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

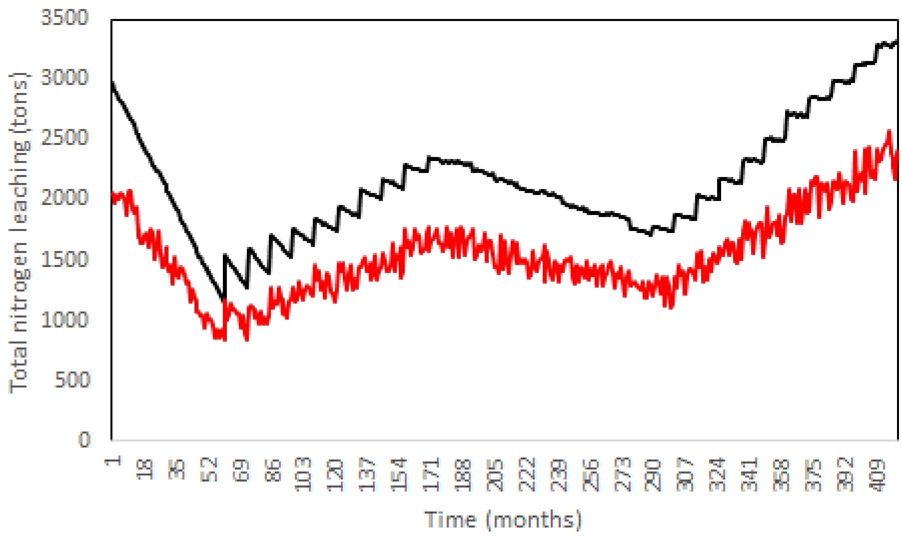


Figure 165: Nitrogen leaching under the RCP26-SSP2 scenario (black) and when agricultural lands are halved in area (red).

The final what-if / stress test considers a halving and doubling of population change compared with the base RCP26-SSP2 scenario, assessing the impacts on domestic water demand, food demand, the energy demand for water supply, and greenhouse gas emissions (Figures 166-168). Domestic water demand shows considerable sensitivity to changes in population (Figure 166), though the impact to the overall water balance is minor. Food demand likewise is highly sensitive to changes in population, yet like with water, the over food balance in the region is relatively unaffected. The changes to energy demand for water supply resulting from population changes are minor, showing low sensitivity and therefore are unlikely to stress either water or energy networks. Finally, greenhouse gas emissions are fairly sensitive to population changes because changes in population impact on multiple parameters that affect greenhouse gas emissions in the study area, especially in the energy demand sector.

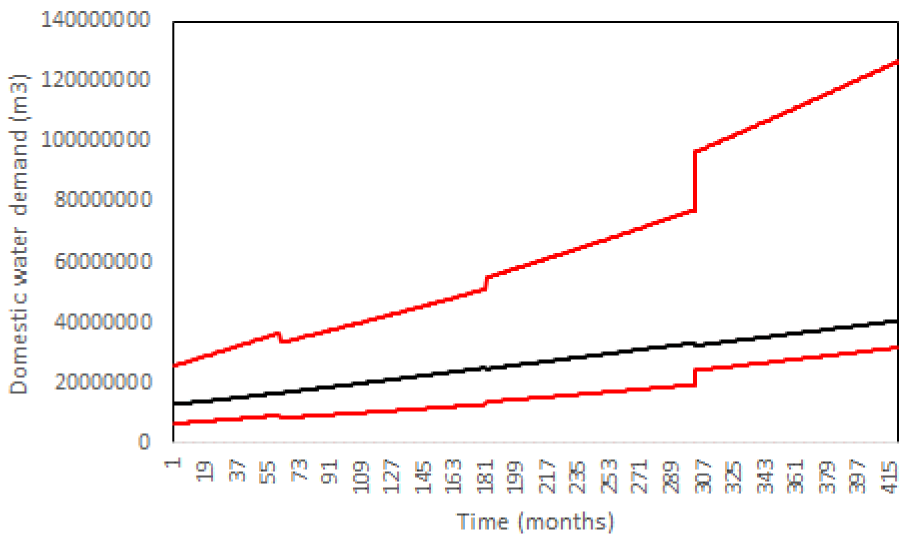


Figure 166: domestic water demand under the RCP26-SSP2 scenario (black) and when population is halved and doubled (red).

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

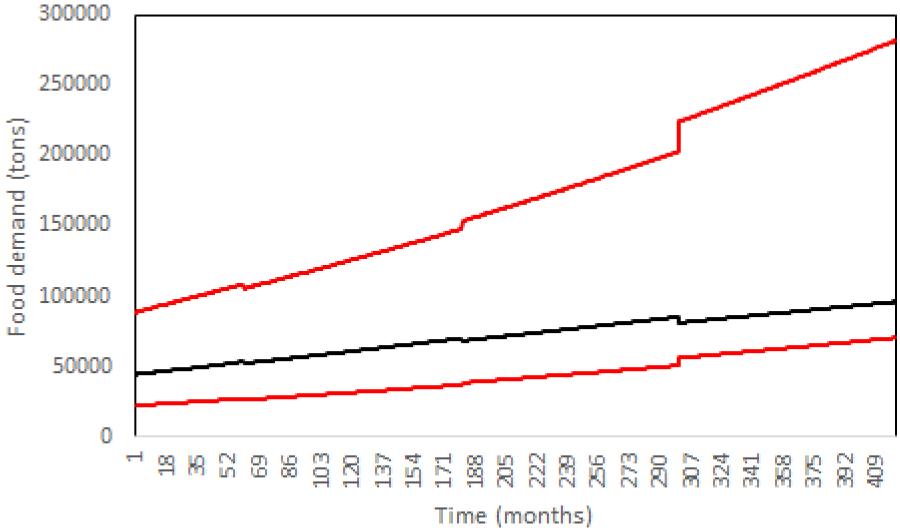


Figure 166: food demand under the RCP26-SSP2 scenario (black) and when population is halved and doubled (red).

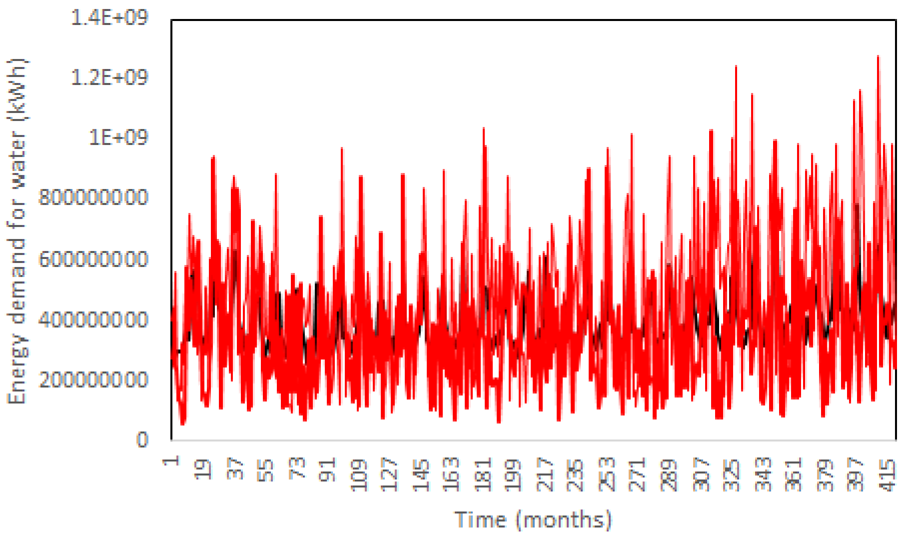


Figure 167: energy needed for water supply under the RCP26-SSP2 scenario (black) and when population is halved and doubled (red).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

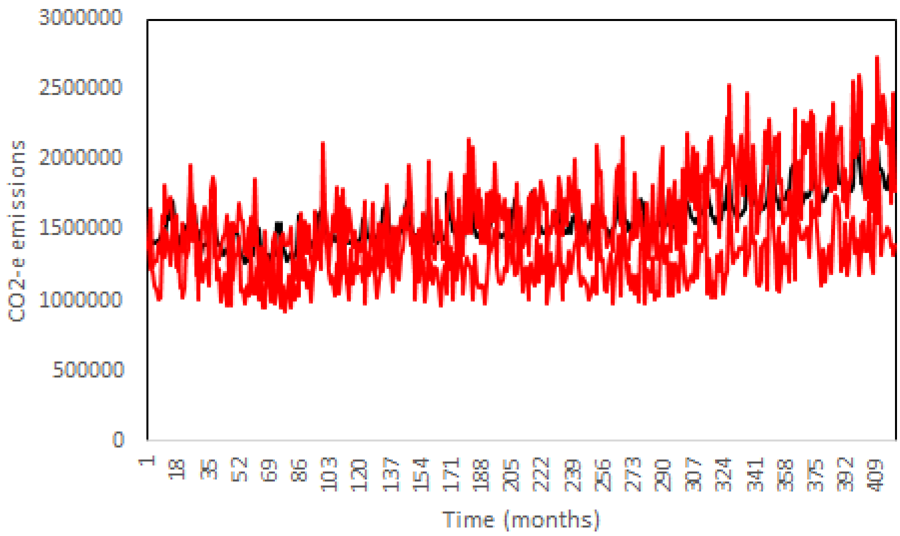


Figure 168: greenhouse gas emissions under the RCP26-SSP2 scenario (black) and when population is halved and doubled (red).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

5. The utility of the uncertainty results

The primary utility of the results presented here is to demonstrate that ‘the future’ is not known with certainty (scenario uncertainty), and that model projections of potential futures are themselves subject to uncertainty (parametric uncertainty). By explicitly showing the range of uncertainties to stakeholders, they are equipped with more information. This information can be used to make better resources planning and management decisions. If a singular deterministic projection was used as planning, the ‘bandwidth’ of potential uncertainty would be missed, with only the single future being considered. This means that circumstances might be missed, for example higher or lower water availability, higher or lower crop water demands. By seeing and considering the range of uncertainty, the full range can be taken into account when planning for different futures. This means that policy, development, and strategies are likely to be more flexible and adaptive to a wider range of conditions that may be faced. Figure 165 attempts to sum up this idea. From this example, one could think of streamflow as an example. Under a deterministic set of results, one could easily be drawn into designing policy or development plans considering only one streamflow future. With a bandwidth of possible streamflows, the policy maker is more likely to consider a wider range of possibilities, perhaps leading to policy design that is more flexible, accounting not just for the ‘average’ streamflow, but also for lower probability extreme events such as floods and droughts (red circles, Figure 169).

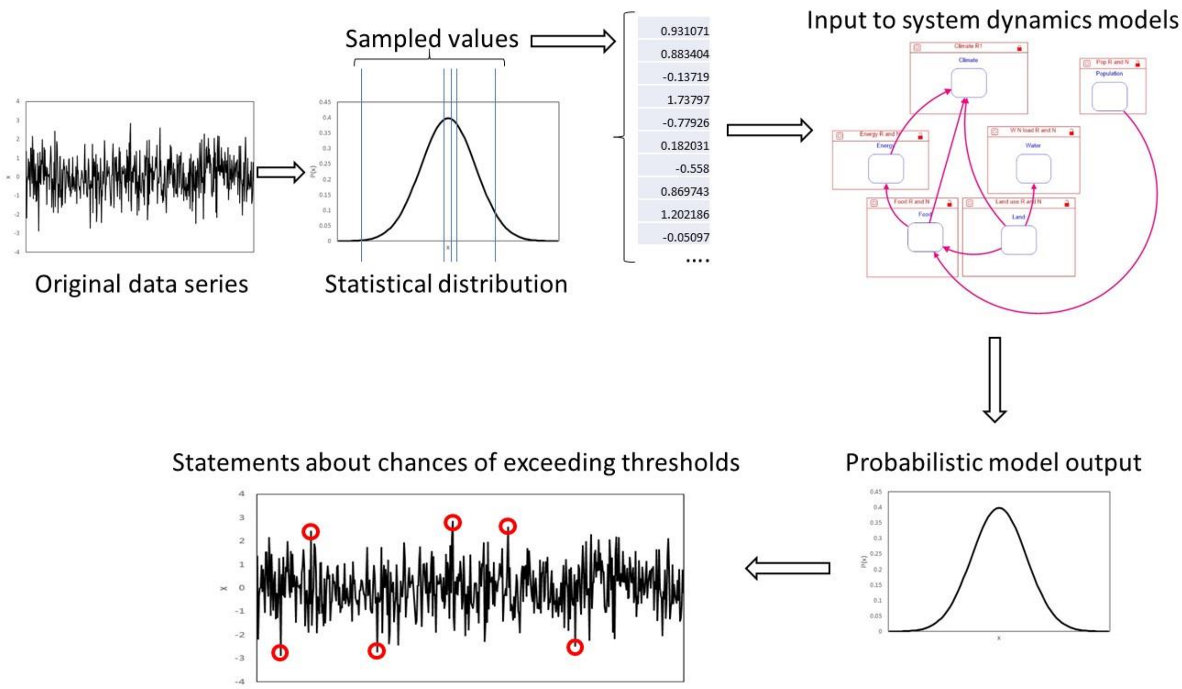


Figure 169: by assessing uncertainty, stakeholder have more information about the ‘bandwidth’ of potential futures, potentially leading to more robust policy and decision making.

A similar idea applies to scenario uncertainty, which explores system trajectories when forced under different climate and socio-economic development futures, which are of course, not known a-priori. By assessing the four scenarios in NEXOGENESIS, policy makers, decision makers, and natural resources planners are better equipped to understand the potentially different system trajectories, and subsequently to plan accounting for these various potential

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101003881

futures. This idea can apply to, for example, resources supply and how to manage and allocated resources to different users, and resources demand accounting for potential differences in per-capita resources demand patterns, or changes in the demand for water of different crops. The supply and demand change under the different RCPs and SSPs. Therefore, testing a range of scenarios are presenting the uncertainty of these results to stakeholders may lead to people thinking in more depth about how to better plan and manage natural resources to cover a wider possibility of futures.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

6. Further work and use in NEXOGENESIS

Within the frame of NEXOGENESIS, the uncertainty results will be extensively used through the remainder of the project.

1) Use in the NEPAT tool. Being developed as part of the NEPAT tool is the option for users to view and interrogate uncertainty in mode output should they wish. Clearly, as the NEPAT is built in part on the SDMs for the five case studies, the integration of the uncertainty characterisation is essential. As such, ensuring uncertainty is captured and reported in the SDMs is critical. This Deliverable demonstrates that the NEXOGENESIS SD models do indeed simulate uncertainty throughout the WEFE nexus, and as such this will be carried through into WP4 where NEPAT tool development is taking place. WP3 members are in close collaboration with WP4 members to ensure this process goes well. Part of the collaboration is discussing ideas for visualisation, including the uncertainty. This is important as uncertainty can be a ‘foreign’ concept for non-specialists, and therefore communicating the range of uncertainty in model output, and the implication for policy and decision making is critical. At the time of writing, this process of uncertainty integration into the NEPAT and the visualisation is ongoing.
2) For stakeholder communication of model uncertainty. This relates very closely with (1) above. As alluded to above in (1) and in Section 5, it is important to characterise and communicate the model uncertainty to stakeholders and users of NEXOGENESIS output. As stated, by realising that there can be considerable uncertainty in model results, this might lead to policy makers, decision makers, and other stakeholders to potentially reconsider how policies, decisions, and strategies are designed with regard to natural resources management and development. This, coupled with the policy space exploration potential offered by the NEPAT, may lead to more holistic, robust, and adaptable policies and decisions in the face of an uncertain future.
3) The development of scientific papers and publications. The analysis being carried out and analysed in the case study SD models is largely novel in the WEFE nexus context. Therefore, much of the work used to produce this Deliverable will be used in the context of academic publications, thus demonstrating the power and utility of incorporating uncertainty into system dynamics model assessments of the WEFE nexus. This will raise the profile of the project and team members in academic circles.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101003881

7. Conclusions

This Deliverable presents the results of the uncertainty analyses implemented in the system dynamics model for each case study in NEXOGENESIS. Data provided from WP2 (see Deliverable 2.2-2.4) are inherently uncertain, with large variability in multi-model outputs. The NEXOGENESIS assess this model input uncertainty on key model outputs in each of the NEXOGENESIS case studies. These output variables include for example, water balances, food production, greenhouse gas emissions, nitrogen leakage to water bodies, and impacts to above ground biomass. The Deliverable also shows the implications of testing different future scenarios on these same variables. The scenarios are driven by four combinations of biophysical (represented by the RCPs) and socio-economic (represented by the SSPs) pathways. In this way, the impacts on resources supply, demand, and ecological functions can be assessed under an inherently uncertain future. The uncertainty implementation in the SDMs is taken up in WP4, and explained for example in D4.3. In terms of project Tasks, this work relates directly to Task 3.4 by implementing the uncertainty analysis in all NEXOGENESIS case studies. It also indirectly links to Tasks 4.3 and 4.5, which relate to the development of the online decision support tool.

NEXOGENESIS STREAMLINING WATER RELATED POLICIES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

8. References

Bakhshianlamouki E., Masia S., Karimi P., van der Zaag P., Sušnik J. 2020. A system dynamics model to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia Lake Basin, Iran. Science of the Total Environment. 708: 134874. DOI: 10.1016/j.scitotenv.2019.134874.

Borga, M., 2002: Accuracy of radar rainfall estimates for streamflow simulation. Journal of Hydrology, 267, 26-39.

Borga, M., S. Degli Esposti and D. Norbiato, 2006: Influence of errors in radar rainfall estimates on hydrological modelling prediction uncertainty. Water Resources Research, 42, W08409, doi:10.1029/2005WR004559.

Castellano, M. J., Archontoulis, S. V., Helmers, M. J., Poffenbarger, H. J., & Six, J. (2019). Sustainable intensification of agricultural drainage. Nature Sustainability, 2(10), 914-921. doi:10.1038/s41893-019-0393-0.

Ford A. 2009. Modeling the Environment (2nd Edition). 488pp. Island Press, Washington DC, USA. ISBN: 9781597264730.

Freebairn, L., Atkinson, J. A., Osgood, N. D., Kelly, P. M., McDonnell, G., & Rychetnik, L. (2019). Turning conceptual systems maps into dynamic simulation models: An Australian case study for diabetes in pregnancy. PLoS One, 14(6), e0218875. doi:10.1371/journal.pone.0218875.

Limburg, K. E., Breitburg, D., Swaney, D. P., & Jacinto, G. (2020). Ocean Deoxygenation: A Primer. One Earth, 2(1), 24-29. doi:10.1016/j.oneear.2020.01.001

Mancosu, N., Spano, D., Orang, M., Sarreshteh, S., Snyder, R.L., 2016. SIMETAW# - A model for agricultural water demand planning. Water Resour. Manag. 30, 541–557. https://doi.org/10.1007/s11269-015-1176-7.

Masia, S., Trabucco, A., Spano, D., Snyder, R.L., Sušnik, J., Marras, S., 2021. A modelling platform for climate change impact on local and regional crop water requirements. Agric. Water Manag. 255, 107005. https://doi.org/10.1016/j.agwat.2021.107005.

Mereu S., Sušnik J., Trabucco A., Daccache A., Vamvakeridou-Lyroudia L.S., Renoldi S., Virdis A., Savić D.A., Assimacopoulos D. 2016. Operational resilience of reservoirs to climate change, agricultural demand, and tourism: a case study from Sardinia. Science of the Total Environment. 543: 1028-1038. DOI: 10.1016/j.scitotenv.2015.04.066.

Laspidou C, Ziliaskopoulos K. Using System Dynamics Modelling to visualize the effects of resource management and policy interventions on biodiversity at a regional scale. Ecological Indicators. 2022 Dec 1;145:109630.

Purwanto A., Sušnik J., Suryadi F.X., de Fraiture C. 2021. Quantitative simulation of the water-energy-food (WEF) security nexus in a local planning context in Indonesia. Sustainable Production and Consumption. 25: 198-216. DOI: 10.1016/j.spc.2020.08.009.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881

Sterman, J. (2000). Business Dynamics: Systems Thinking and Modeling for a Complex World: McGraw-Hill.

Sušnik J. 2018. Data-driven quantification of the global water-energy-food system. Resources, Conservation, and Recycling. 133: 179-190. DOI: 10.1016/j.resconrec.2018.02.023.

Sušnik J., Vamvakeridou-Lyroudia L.S., Savić D.A., Kapelan Z. 2013. Integrated modelling of a coupled water-agricultural system using system dynamics. Journal of Water and Climate Change. 4(3): 209-231. DOI: 10.2166/wcc.2013.069.

Terzi, S., Sušnik, J., Schneiderbauer, S., Torresan, S., Critto, A., 2021. Stochastic system dynamics modelling for climate change water scarcity assessment of a reservoir in the Italian Alps. Nat. Hazards Earth Syst. Sci. 21, 3519–3537. https://doi.org/10.5194/nhess-21-3519-2021.

Thomopoulos NT. 2013. Essentials of Monte Carlo Simulation. Statistical Methods for Building Simulation Models. 174pp. Springer, New York. DOI: 10.1007/978-1-4614-6022-0.

Wang X., Dong Z., Sušnik J. 2023. System dynamics modelling to simulate regional water-energy-food nexus combined with the society-economy-environment system in Hunan Province, China. Science of the Total Environment. 863: 160993. DOI: 10.1016/j.scitotenv.2022.160993.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003881