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Deliverable 3.4

Complexity science models implemented for all the Case Studies: Prototypes and explanatory report/manual for each CS methodology

Lead: UTH
Date: July 2023

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
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Public	**Report**

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NEXOGENESIS
STREAMLINING WATER RELATED POLICIES

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Abstract

This Deliverable presents the first preliminary version of the NEXOGENESIS case study system dynamics models as well as a preliminary set of results from these draft models. The Deliverable demonstrates that models are setup, contain data, and produce nexus-wide results. It describes the model structures, emphasising places where the WEFE sectors interact with each other. At the time of writing, the models are prototypes only, and therefore the results are not finalised, with further development ongoing through 2023. There is therefore much further work to be done before the models can be considered as final. This work includes:

- Finalising data availability (with WP2 input), for example to account for all climate and socio-economic scenarios, to disaggregate crop and land use types, to account for case-study specific requirements such as transboundary water obligations, and to cover the ecosystems sector in an adequate way. These discussions are ongoing within the project;
- Incorporation of the climate and socio-economic scenarios;
- Define and incorporate calculation of the WEFE Nexus Footprint for all case studies;
- Data analysis to prepare for uncertainty and sensitivity analyses, neither of which are incorporated in these early prototypes;
- Inclusion of validated policy packages (with WP1 and 5 input). The policies to be modelled and assessed are not yet finalised for all case studies, and therefore are not at this stage included in the models;
- To account for the above point, refine model structures to account for data availability, uncertainty testing, scenario analysis, and policy impact assessment.

This Deliverable shows that work is well on track regarding the complexity science modelling, and that towards the end of 2023, models should be nearing their final state. At the same time, collaboration with WP4 will significantly increase as the machine learning and artificial intelligence tools will be implemented for the model prototypes and further iterations as complexity science models develop.

The models and results as presented in this Deliverable are prototypes that were still under development at the time of writing. The models, data, and results are all subject to change. **All results in this Deliverable are representative only** to demonstrate that models contain data and produce output as at the time of writing. **No results herein are to be used for scientific or policy advice.** Future steps in NEXOGENESIS will refine model development, finalise data inputs, and have model outputs validated in stakeholder workshop settings, all of which are activities to take place in later stages of the project.

Keywords: interlinkages, models, WEFE nexus, data, sector, crops, emissions.

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List of abbreviations

CS – Case Study

D - Deliverable

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

RCP – Representative Concentration Pathway

SDM – System Dynamics Modelling

SH - stakeholder

SLNAE – Self Learning Nexus Assessment Engine

SSP – Shared Socio-economic Pathway

WEFE – Water-Energy-Food-Ecosystems

WS - workshop

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Disclaimer

Deliverable D3.4 is structured in accordance with the Grant Agreement and aligns with its title, which explicitly requires the submission of Case Studies - Prototypes, rather than the final System Dynamics Models (SDMs). At the time of submission, only the SDM prototypes had been developed and were presented accordingly. The models and results as presented in this Deliverable are prototypes that were still under development at the time of writing. The models, data, and results are all subject to change as the project process. All results in this Deliverable are representative only to demonstrate that models contain data and produce output as at the time of writing. No results herein are to be used for scientific or policy advice.

The conceptual maps were initially co-developed with stakeholders and later refined and validated by them during the 1st and 2nd workshops, respectively. These activities have been documented in Deliverables D3.1, D3.4, and Milestone MS23. This validation process ensured that the foundational concepts were robust and accurately reflected the needs and perspectives of the stakeholders involved, providing a solid basis for the subsequent development of the SDMs.

From the time of submission of the present deliverable, the SDMs have since been continually refined, and the final versions are now fully developed, incorporating policies and WEFE indices. The final SDMs have been integrated into the NEPAT tool and were or will (it depends on the CS) validated by stakeholders during Workshop 5, held on different dates for each case study. During WS5, is planned to a) make a brief presentation of the SDM b) NEPAT demonstration 4) validate the policies included in the NEPAT 5) introduce the Governance Roadmap and results chains - Towards the final agreement on policy implementation 6) assessment of the SHE process and outcomes. Specifically, in Romania case study WS 5 was conducted in September 2024. In Latvia and South Africa WS5 took place in October 2024. In Nestos/Mesta CS WS5 took place at 21-22 of November 2024, while the workshop for the Italian CS is planned for the spring of 2025. Nevertheless, it is important to emphasize that the entire process is occurring **within the RP3** period and **will be thoroughly documented in the corresponding deliverables and RP3 report.**

When the deliverable was submitted in August 2023, the final SDMs were not yet complete, and as such, only prototypes were included. It should be noted that neither the Grant Agreement nor the title of D3.4 stipulates the submission of final SDMs. The final versions of the SDMs have been delivered via the NEPAT tool. SDMs serve as the backbone of the NEPAT, while the later constitutes and facilitating simulation – user interface.

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1. Introduction, purpose of the Deliverable

Deliverable 3.4 introduces the current state of the art regarding the development of the NEXOGENESIS complexity science models for each case study (CS). Under each CS, the conceptual maps (reported in full in Deliverable 3.1) are summarised for completeness of information. The system dynamics model (SDM) structures are then introduced and described in detail, focussing on the links between the WEFE nexus sectors, showing how changes in one sector may have ripple effects throughout the nexus. Data collection and incorporation into the SDMs is then described, showing the close link with WP2 data provision. A first set of preliminary results for each CS is then shown, demonstrating for each that the models run and output results, and showing that there is a solid body of work to take forward in further model development through to the end of 2023 and into early 2024, by which time, most models should be at a final state. Finally, a brief summary of further work for each CS is provided.

The rest of this Deliverable describes in detail each of these methods to be used (scenario analysis, sensitivity analysis, what-if tests, uncertainty analyses), explains how the data from WP2 will be leveraged in this regard, and explains how future work in the project, predominantly in WP4, will make use of the analyses described here and largely implemented in WP3.

The preliminary models described here will continue to be refined and developed in 2023 and early 2024 until they are in a final state. This will require a variety of further work, including:

- Finalising data availability (with WP2 input), for example to account for all climate and socio-economic scenarios, to disaggregate crop and land use types, to account for case-study specific requirements such as transboundary water obligations, and to cover the ecosystems sector in an adequate way. These discussions are ongoing within the project;
- Incorporating climate and socio-economic scenario data;
- Define and incorporate calculation of the WEFE Nexus Footprint for all case studies;
- Data analysis to prepare for uncertainty and sensitivity analyses, neither of which are incorporated in these early prototypes;
- Inclusion of validated policy packages (with WP1 and 5 input). The policies to be modelled and assessed are not yet finalised for all case studies, and therefore are not at this stage included in the models;

To account for the above points, refine model structures to account for data availability, uncertainty testing, scenario analysis, and policy impact assessment, will be formulated, with results being updated as a result. The models form a central element in NEXOGENESIS. They quantify the WEFE nexus. They account for climate and socio-economic scenarios to 2050. They also assess the nexus wide impacts of policy implementation. It is this last point that ultimately will lead to suggestions on how to streamline water-related policies into the WEFE nexus. The models will also define and track the WEFE Nexus Footprint for all the case studies. The models will feed the machine learning and artificial intelligence tool developed in WP4, which will suggest optimal policy combinations with respect to the achievement of various policy targets and goals from the potentially millions of climate, socio-economic, and policy

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combinations. Therefore, robust model development and validation forms a key block of work in NEXOGENESIS in 2023 and early 2024, being critical for project success and impact.

~~Disclaimer~~

~~The models and results as presented in this Deliverable are prototypes that were still under development at the time of writing. The models, data, and results are all subject to change.~~ **~~All results in this Deliverable are representative only~~** ~~to demonstrate that models contain data and produce output as at the time of writing.~~ **~~No results herein are to be used for scientific or policy advice.~~** ~~Future steps in NEXOGENESIS will refine model development, finalise data inputs, and have model outputs validated in stakeholder workshop settings, all of which are activities to take place in later stages of the project.~~

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2. System dynamics model prototypes for each case study

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.

2.1 Case Study #1: Nestos-Mesta River Basin (Bulgaria-Greece)

2.1.1 Conceptual model recap

The Nestos/Mesta conceptual map was co-created by the scientific team of CS#1 and the relative stakeholders at the 1st workshop that took place on 4th of March 2022. At the 2nd workshop that took place on 18th of November 2022 the conceptual map was validated through participatory actions and possible conflicts among the synergies were explored by the stakeholders. Both workshops took place at Chrysoupoli, Kavala, Greece. In addition, stakeholders contributed by sharing their knowledge and expertise on the water resources management, critical hot-spots, proactive actions, management of flood and drought risks, ecosystems maintenance, hydropower generation, agricultural practices, land uses, etc.

The Nestos/Mesta case study conceptual model depicts a representative graphic that captures the interlinkages between water, energy, food, ecosystems, and climate components. The conceptual maps are separated into two sub-models, one for the upstream Mesta river basin, and one for the downstream Nestos river basin, where the water flows across the border between the two nations. The conceptual model presented in figure 1, is a high-level map that illustrates the nexus components and their interconnections and is described in deliverable D3.1 in detail. For each of the water, energy, food, ecosystems, and climate component a detailed conceptual map has been constructed, presented in deliverable D3.1. Indicatively, in this deliverable the water and ecosystems conceptual maps are presented in figures 2 and 3. All the components have been presented thoroughly at the deliverable D3.1.

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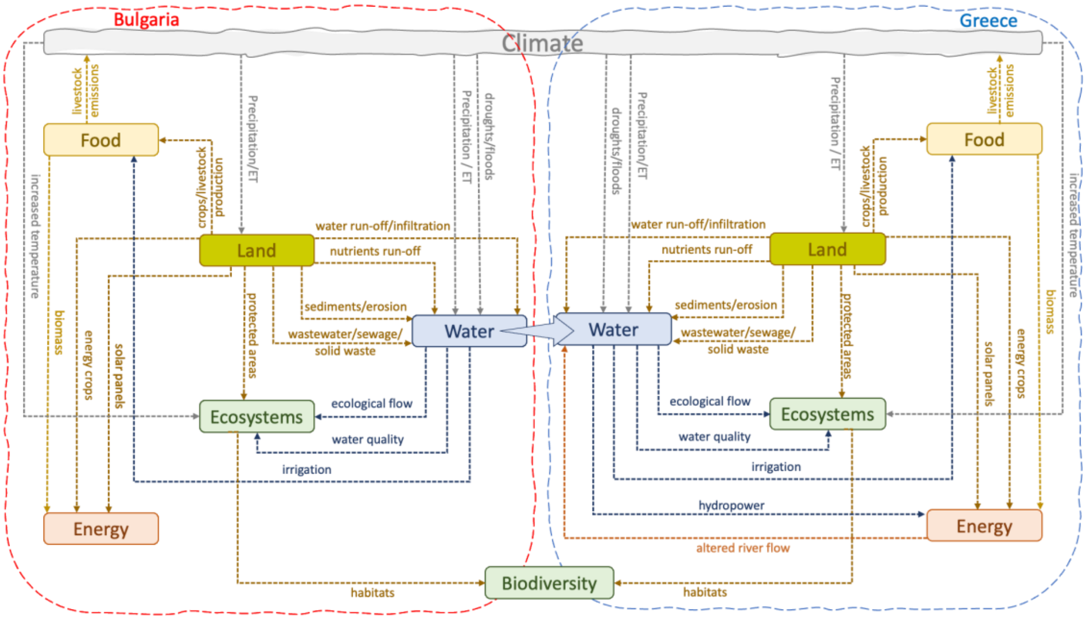

Figure 1: High-level conceptual map depicting the nexus interlinkages for the Nestos/Mesta River Basin.

Water component links the two conceptual models in national level, shown in a dashed line (red for Bulgaria and blue for Greece) considering water quality (nutrients, pesticides, sediments, organics and plastics) and quantity (hydropower, altered river flow, ecological flow, irrigation demand, and precipitation/ET) (Figure 2).

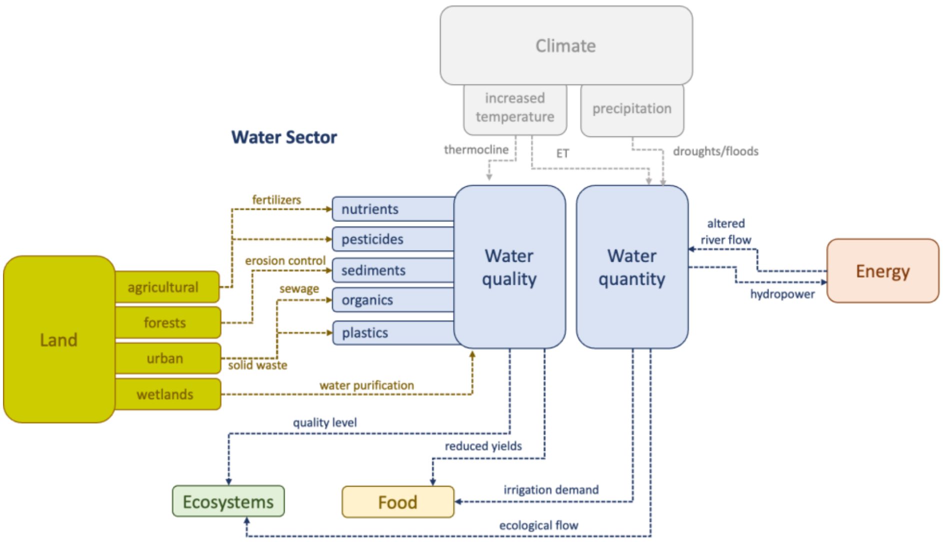

Figure 2: Water sector conceptual map for the Nestos/Mesta River Basin.

The ecosystem component described through the ecosystem services which are provisioning, cultural, regulating and supporting. Provisioning ecosystem services encompass food production, wood and fiber in forests and for all these goods consumed by humans. Wetlands provide regulating ecosystem services such as regulating flows, pollutants, carbon, etc also acting as purifiers for water and air. Supporting ecosystem services are strongly linked to terrestrial and freshwater biodiversity while cultural services is of high importance for the urban activities (Figure 3).

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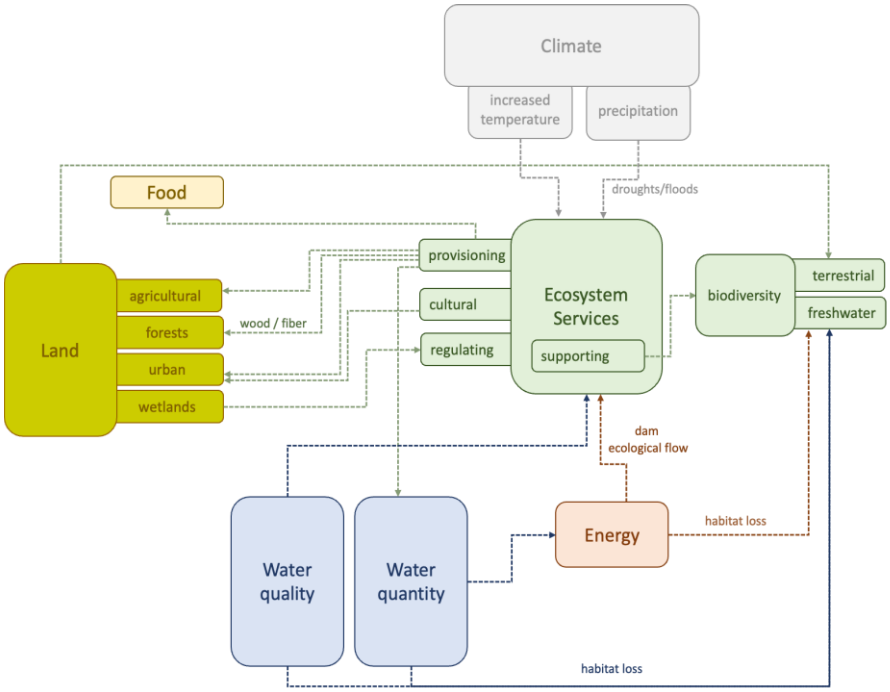

Figure 3: The Ecosystem sector conceptual map for the Nestos/Mesta River Basin.

2.1.2 System Dynamics Model description

The Nestos/Mesta case study consists of 12 sub-basins, 7 of which belong to the Bulgarian side and 5 to the Greek one. The river rises in the Rila mountains in southern Bulgaria and flows some 230 km through Bulgarian and Greek territory before emptying into the North Aegean Sea. About 126 km of the river flow through Bulgaria and about 130 km through Greece. The flow of the Nestos/Mesta River is used by both countries for irrigation, municipal water supply and hydroelectric power production. In Figure 4, the Bulgarian sub-basins are illustrated with beige colour while the Greek ones with grey. Additionally, the Nestos/Mesta River and its tributaries are depicted with blue colour. As one can observe, the two tributaries originating from the sub-basins W730 and W830 join in the sub-basin W880 where the Nestos/Mesta River begins. The river continues to sub-basin W430 where it receives water from the sub-basins W680 and W330. Then the river passes into the Greek territory and into sub-basin W930 and receives water from the tributary that passes through sub-basins W580 and W520 of the Bulgarian territory. Subsequently, the river passes from the sub-basins W1080, W1030 and W970 and ends up to the North Aegean Sea. The Nestos/Mesta SDM is the only one in NEXOGENESIS that splits the basin into sub-regions.

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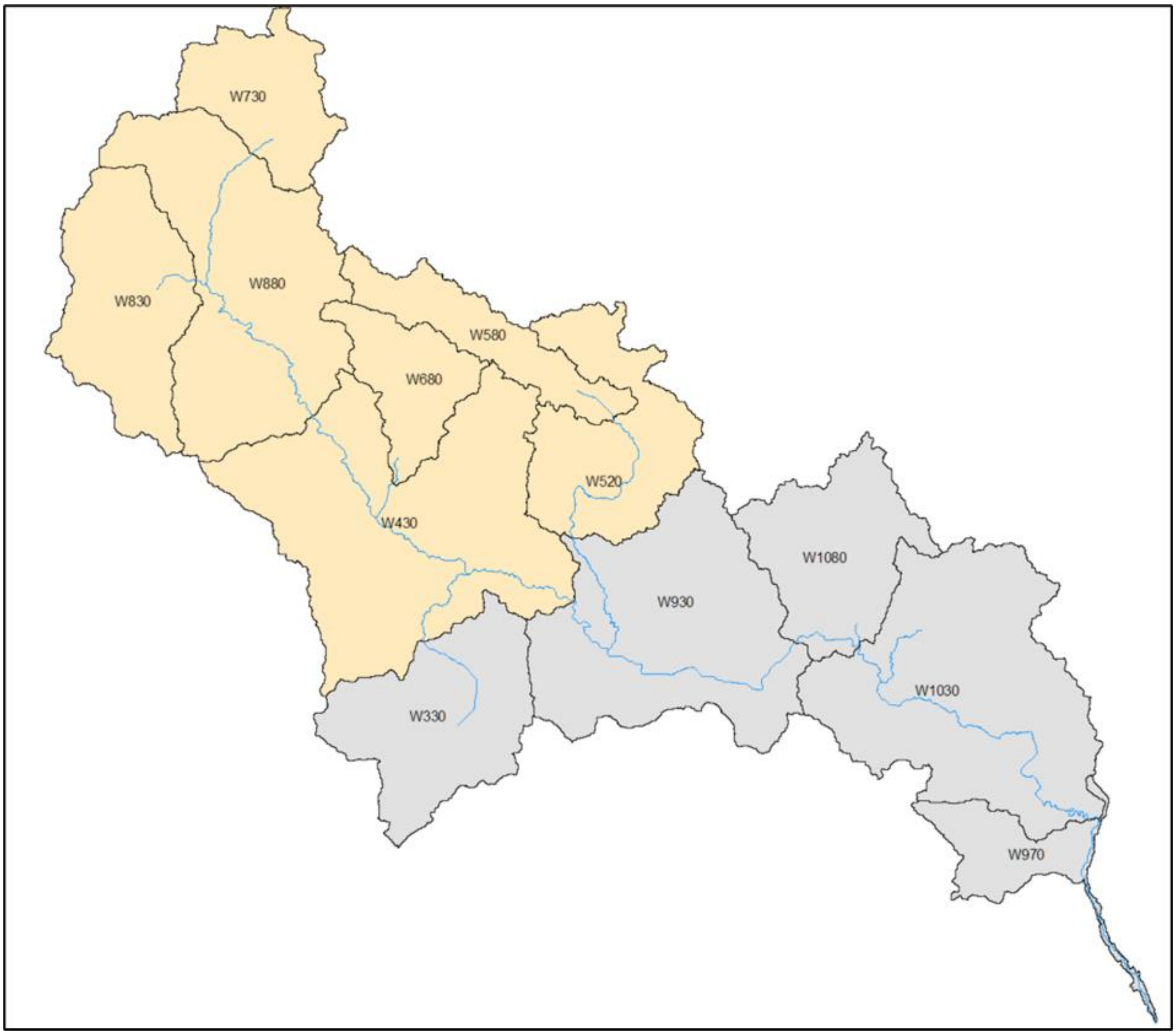

Figure 4: The Nestos/Mesta River basin; the Bulgarian sub-basins are colored with beige and the Greek ones with grey. The river and its tributaries are depicted with blue colour. Each sub-basin has a unique code name, which is also illustrated.

At this stage, the SDM for the Nestos-Mesta case study is under development and further progress regarding the several components and the relevant data time-series of the system is going to be made during the next months. Till its final version is possible more variables to be added in the SDM across the sectors. The current draft or prototype SDM includes all the information and input gathered from stakeholders during the workshops conducted in the wider area of interest.

Due to the great variety of the sub-basins that feed the river with water and the fact that each sub-basin is in essence an autonomous entity that both adds and abstracts water from the river through anthropogenic pressures, the SDM follows the same structure as the physical one. In figure 5, the 1st level overview of the SDM is illustrated where the different modules depict the sub-basins of the river, and the arrows indicate the river flows from one sub-basin to the other. The final arrow (bottom right) represents the river flow to the Aegean Sea. Overall, the SDM maps the physical topography of the sub-basins which feed with water the river throughout its route till the final outflow to the Aegean Sea.

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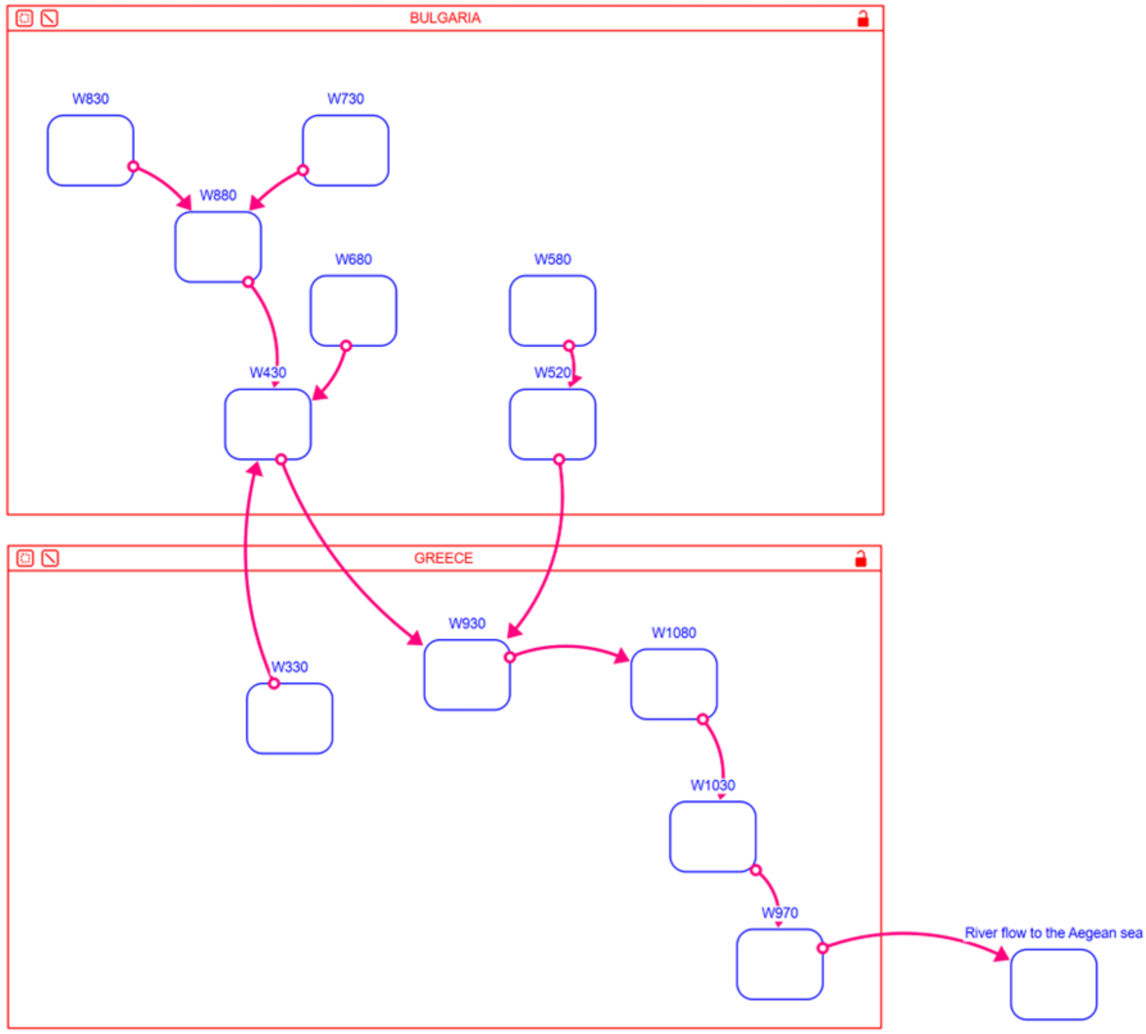

Figure 5: The 1st level overview of the Nestos/Mesta SDM; The red frames depict the two countries' boundaries while the modules with the code names represent the different sub-basins belonging to each country. The red arrows are showing the river flows from one sub-basin to the other and the red arrow on the bottom right illustrates the Nestos/Mesta River outflow to the Aegean Sea.

Diving into each module that represents one of the 12 sub-basins of the Nestos/Mesta case study, 6 components of the nexus have been identified, namely water, energy, food, land use, ecosystem, and climate (2nd level overview). In figure 6, the W330 sub-basin nexus components are illustrated among with the population, tourists, and governance submodules, which play role in different parts of the nexus components. All the sub-basins of the case study follow the same structure and are fed with datasets according to availability and the specific extent of activities taking place in each one.

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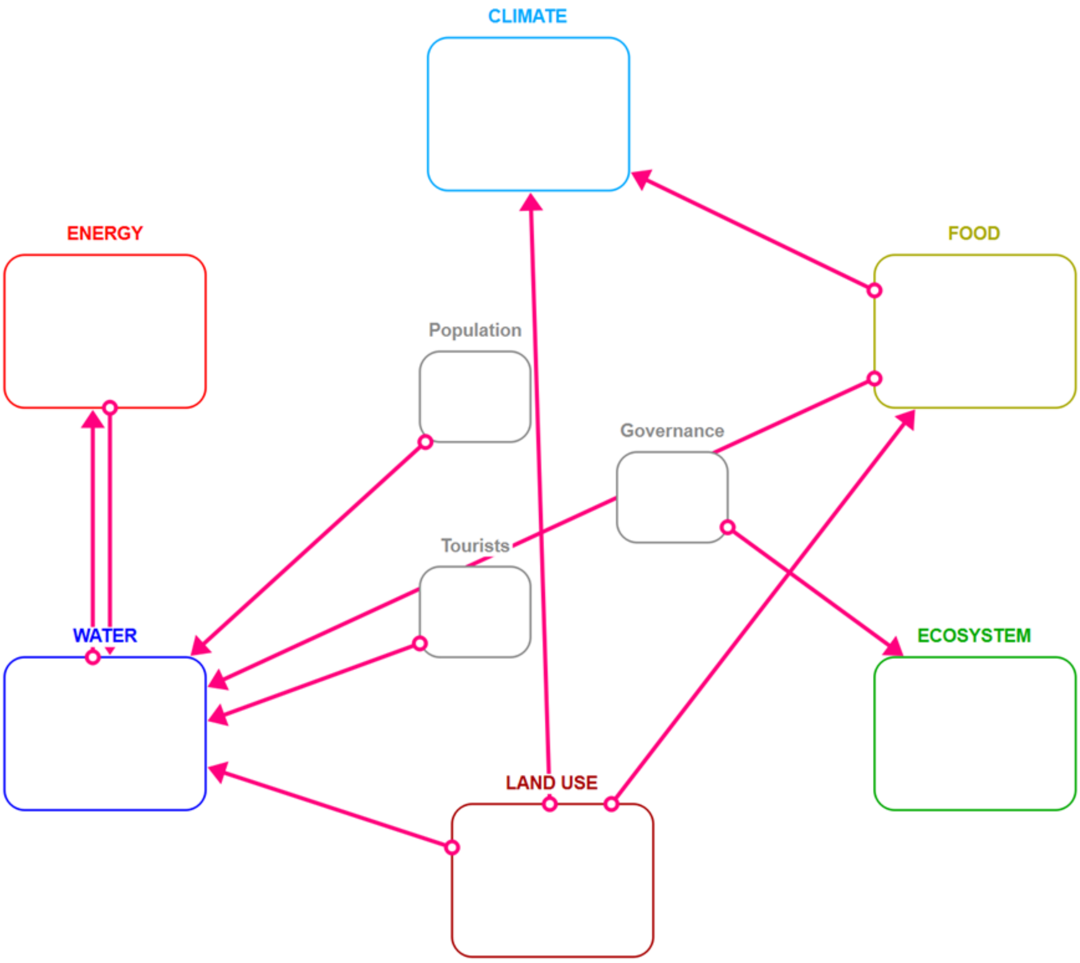

Figure 6: The 2nd level overview of the W330 sub-basin; It includes the modules of water, energy, food, land use, ecosystem, and climate components as well as the subcomponents of population, tourists, and governance. Some relevant interlinkages between the nexus components have already been identified as indicated by the red arrows.

In the following paragraphs, each component of the nexus is briefly described:

Water: This sector is divided into River flow and River quality subsectors. River flow represents the monthly water volume of the river in cubic meters as a result of the river basin runoff minus the agricultural, livestock, domestic, and industrial demand. Depending on this equation and on a monthly basis, the remaining water is transferred to the next sub-basin and so on. Thus, we calculate the available water that is transferred from sub-basin to sub-basin till water reaches its final destination which is the Aegean Sea. Agricultural water demand is calculated by multiplying the crop types areas by the crop types-specific monthly water needs. Domestic water demand is calculated by multiplying per capita population and tourists' water demand by the monthly distribution of each component.

Regarding River quality, we estimate the Total Phosphorus and Total Nitrogen concentrations of the river as a result of fertilizers' application in agriculture and the leaching extent to the river. The computational procedure relies on the mass of fertilizers used per unit area of the

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cultivated extent, multiplied by a leaching factor which mostly depends on plant and soil absorbency and the distance from the river.

In figure 7, the W330 sub-basin 3rd level overview of the water component is illustrated.

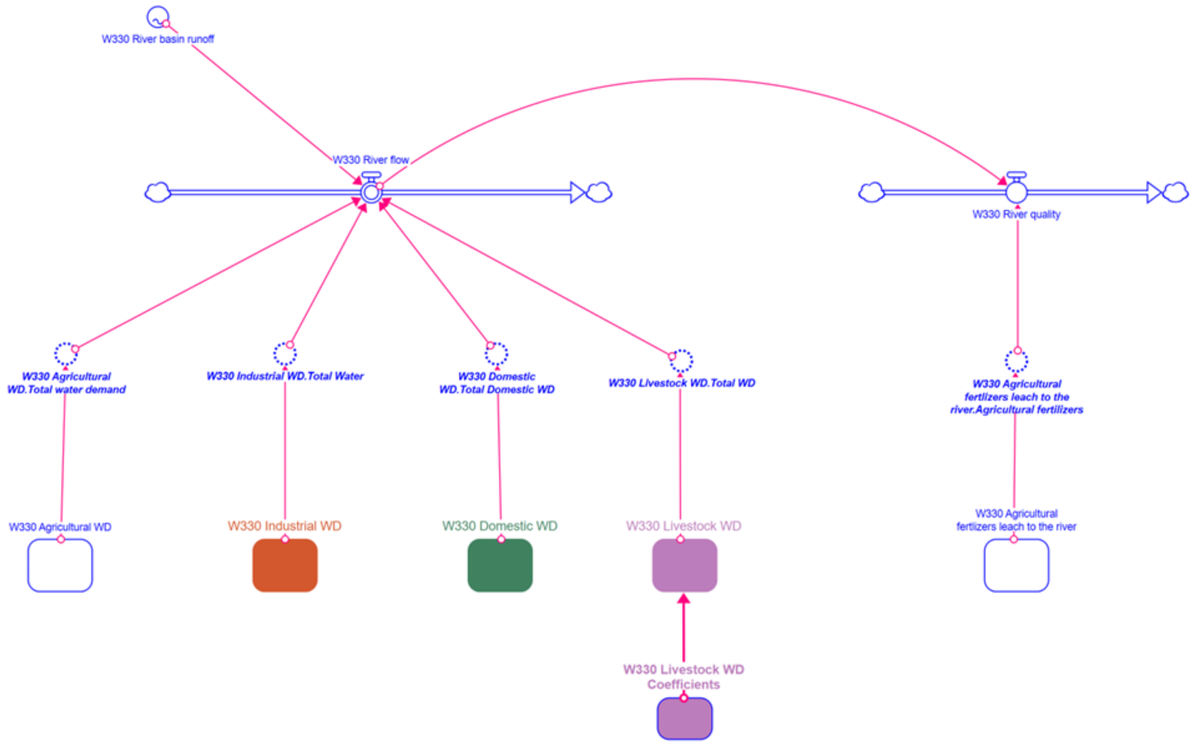

Figure 7: The W330 sub-basin water module.

The **agricultural sector** contains 9 different crop categories, namely cereals for grain, edible pulse, fodder pulses, industrial plants, fodder plants for hey, fodder plants for grass and rootstocks, fodder plants for grazing, melons, watermelons and potatoes, and vegetables. The total number of all crop types belonging to the aforementioned categories is 87. Most of the cultivated crops are irrigated while others are rainfed, so one can understand that they pose a great water stress on the river water balance, since the river is the main direct irrigation provider.

In the following figures (Figure 8 & 9), the different crop categories as well as the different crop types belonging to the category “vegetables”, are illustrated. It is obvious that especially for the Greek side which is the most cultivated in comparison to the Bulgarian one, agricultural activities highly influence the river regime.

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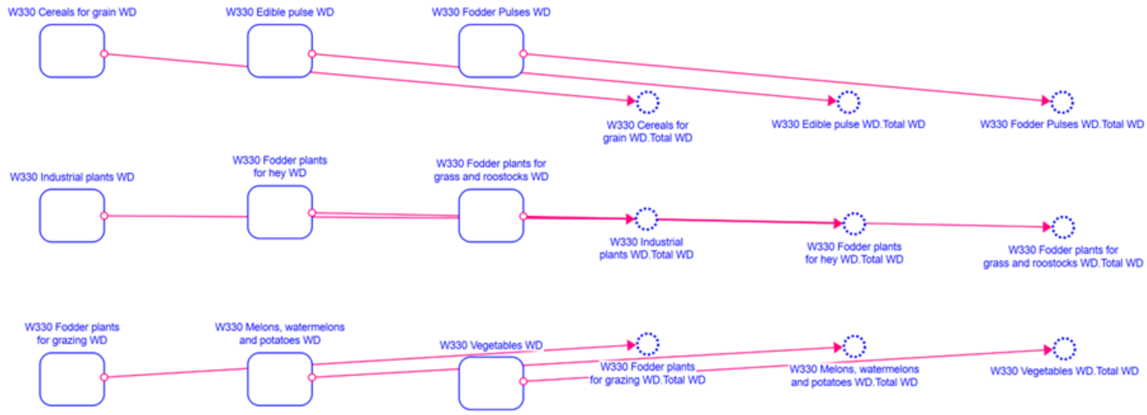

Figure 8: The 9 different crop categories of the agricultural sector.

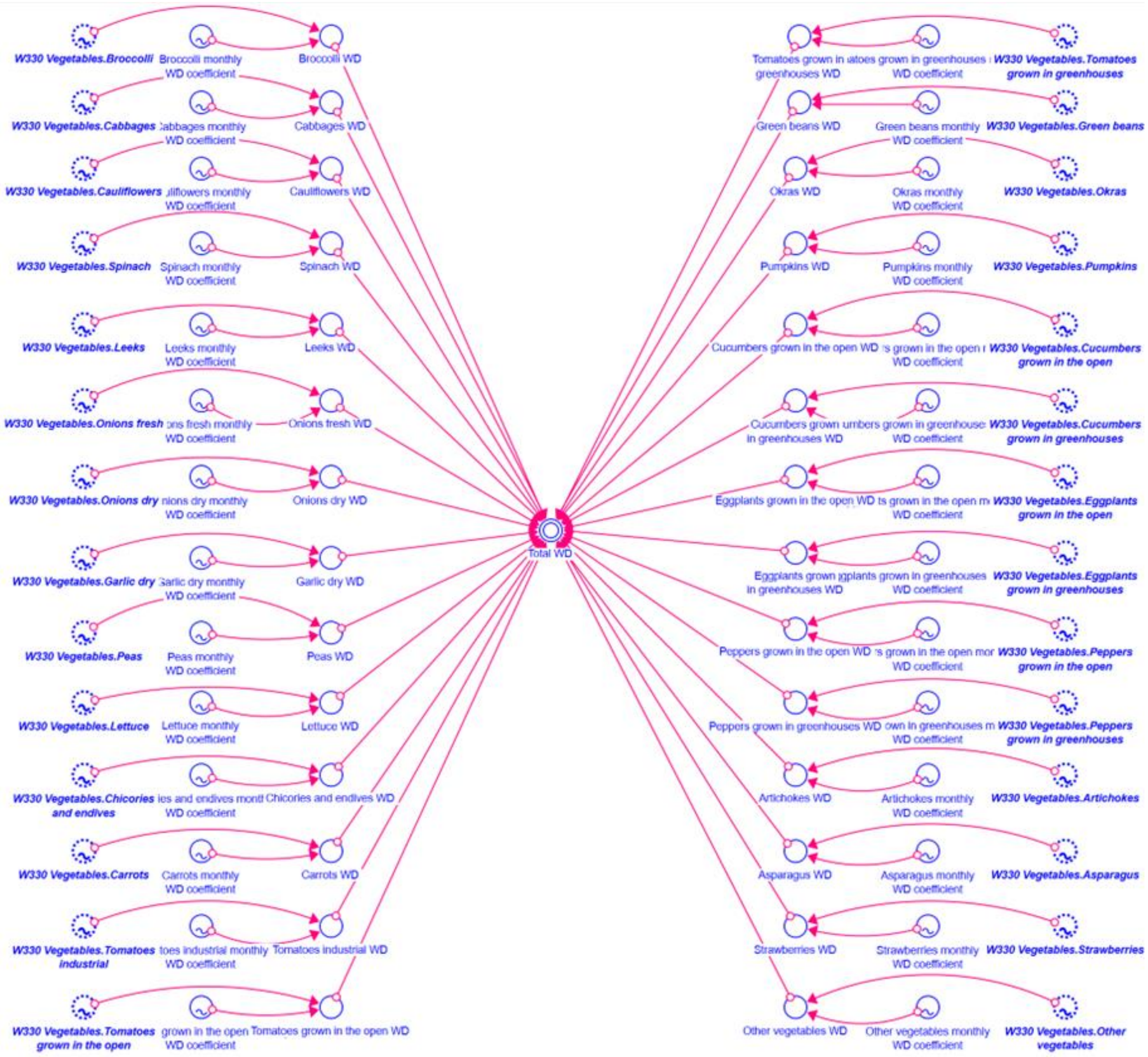

Figure 9: The different crop types belonging to the crop category "vegetables".

Energy: The energy sector includes the hydroelectric energy production which takes place in both countries and in the relevant sub-basins where dams for hydropower exist. The produced

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energy has a considerable contribution to the national energy mix of each country. In figure 10, the procedure of computing the hydroelectric energy production, in the sub-basins where dams exist, is depicted.

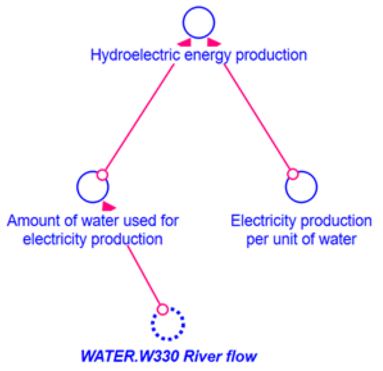

Figure 10: The hydroelectric energy production submodule.

Food: The food sector includes the agricultural and livestock production. In figure 11, we illustrate how we compute the livestock production.

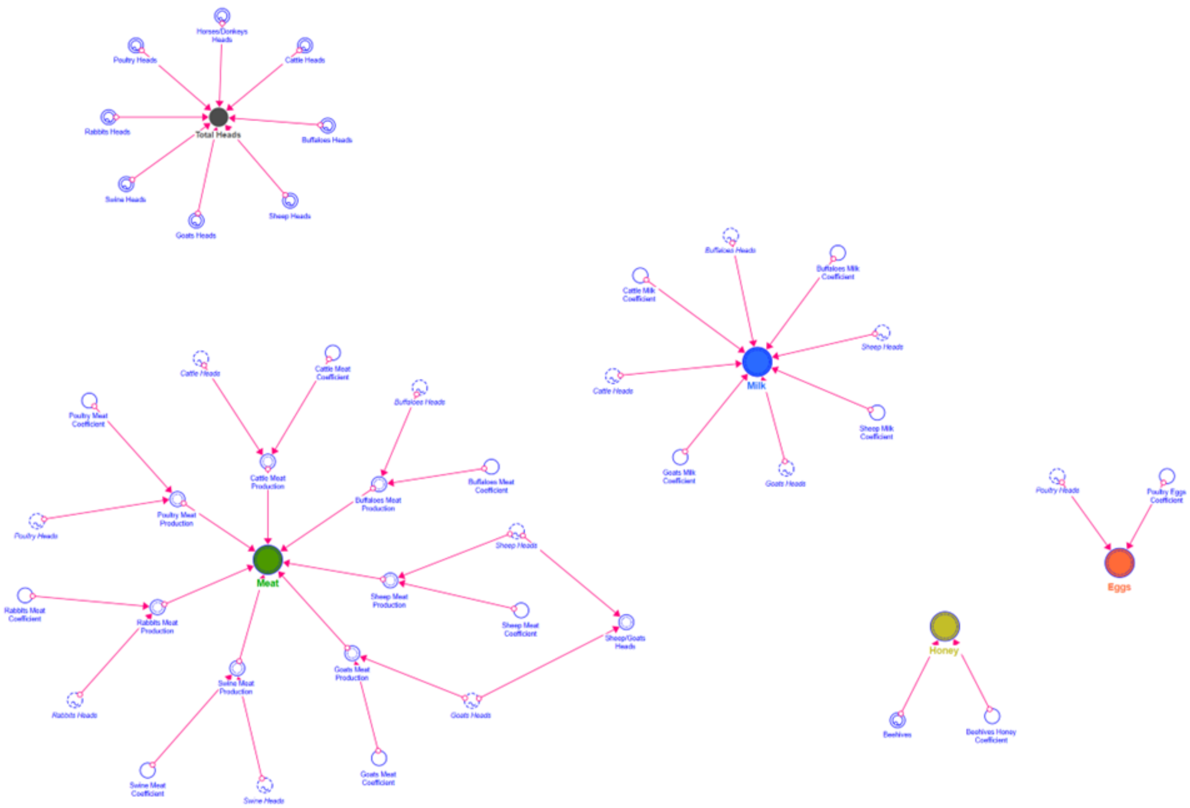

Figure 11: The SDM sub-module where livestock production is computed in terms of meat, milk, eggs, and honey.

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Land use: This sector includes the different types of land use, namely crop areas, livestock areas, forest areas, and wetland areas, as shown in figure 12.

Figure 12: The different land uses incorporated in the SDM.

Ecosystem: A methodology is constructed using published data from the IUCN Red List Index (Laspidou and Ziliaskopoulos 2022) database that can be used for any region/sub-basin to quantify the biodiversity status. The methodology is implemented for the Nestos-Mesta River catchment in Greece and Bulgaria. It is intended to help the authorities run scenarios of different interventions, addressing the specific problems and threats to the local ecosystem that each community might be facing. The methodology enables them to see and quantify biodiversity improvements as a result of these interventions. It compares and contrasts four specific threats to the ecosystem, identified from stakeholder consultation workshops, namely solid waste, agriculture, domestic wastewater and dams and water management/use. In the following figure (figure 13), the Red List Index methodology for quantifying the biodiversity status of the ecosystems component, is presented.

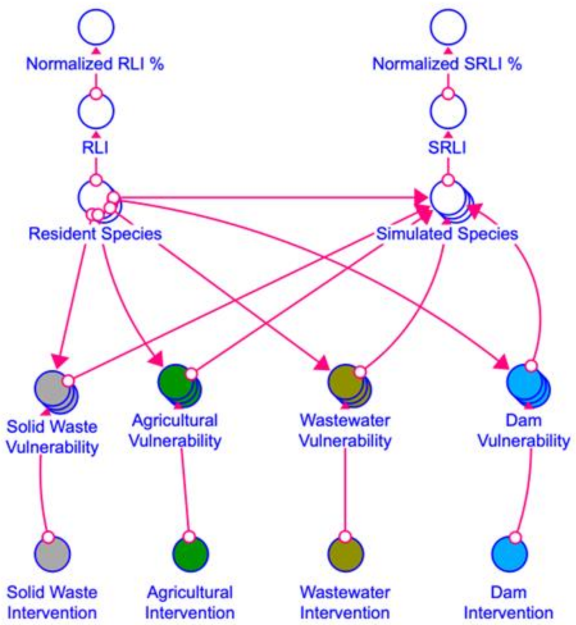

Figure 13: The Red List Index methodology for quantifying the biodiversity status of the ecosystems component.

Climate: The climate sector includes the Greenhouse Gas Emissions (GHGs) produced from the agricultural and livestock domains. A thorough depiction of their calculation methodologies is showcased in Figure 14 and 15.

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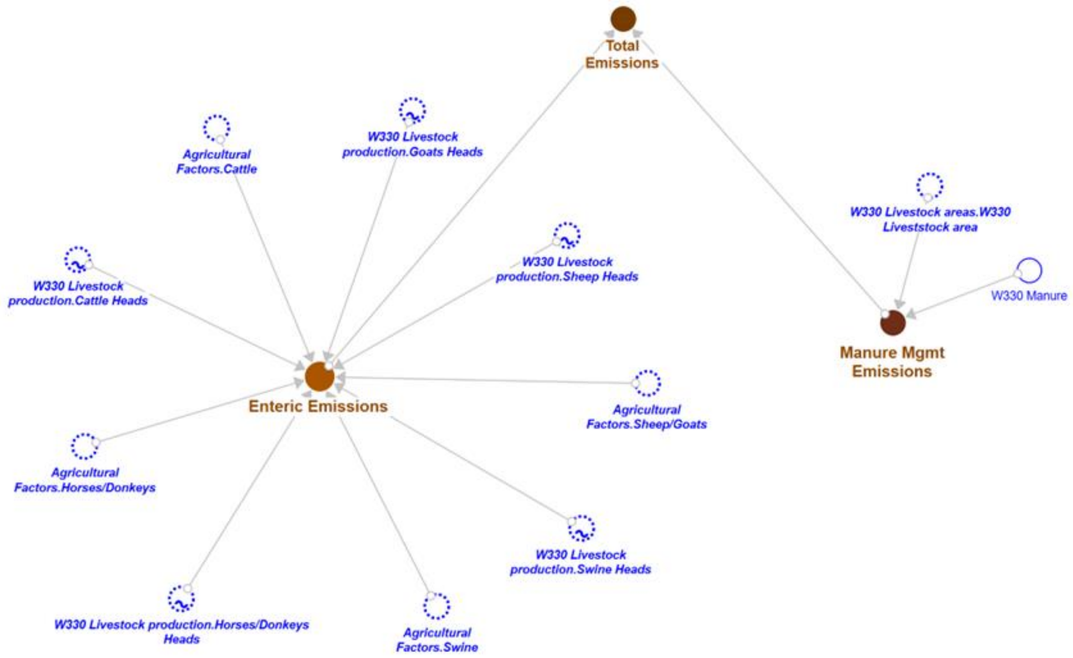

Figure 14: GHG emissions originating from the livestock sector.

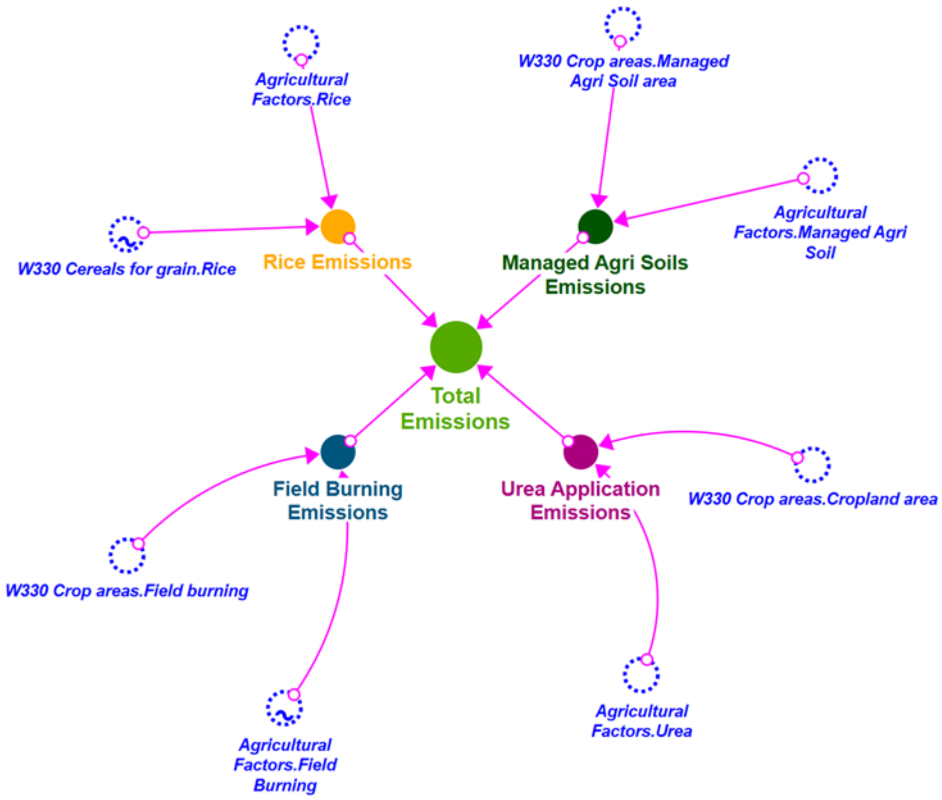

Figure 15: GHG emissions originating from the agricultural sector.

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2.1.3 Data collection and incorporation

Data collection and incorporation is an ongoing procedure that has already been stated in D3.3, where a thorough analysis of the data types and the available resources extending from WP2 results to National Statistical Authorities, etc., has been conducted. Although currently, most of the datasets are available and already incorporated to the SDM, there is still a lot of work to be done especially for the Bulgarian part where data availability is limited. Due to the distinctiveness of the Nestos/Mesta SDM which demands spatial resolution at sub-basin level to represent the river at it's fully extent, more time is needed not only to collect the relevant data but also to incorporate them to the model.

Furthermore, since policy packages are not yet incorporated to the model, additional variables and corresponding datasets' needs may arise under the frame of covering the policy prerequisites towards producing representative and robust nexus outcomes.

2.1.4 Preliminary results

The prototype SDM is currently set-up for the base year of 2015, which is the starting point of the simulation period. This means that most of the available datasets are incorporated to the SDM for the starting year. In the following months, the SDM will be further modified and structured in terms of both data incorporation as well as data projections till 2050, which is the ending year of the simulations. To this end, the preliminary results presented here only depict the current situation in the Nestos/Mesta river basin and can be considered as the basis describing the current regime of the wider area.

Since the Nestos/Mesta SDM is a rather complex system which contains 12 sub-basins and each sub-basin is considered as a separate entity, preliminary results are introduced indicatively for the sub-basin W330.

In the following figure (figure 16), the area distribution among the 6 crop categories is illustrated, showing that cereals for grain and industrial plants occupy the largest areas.

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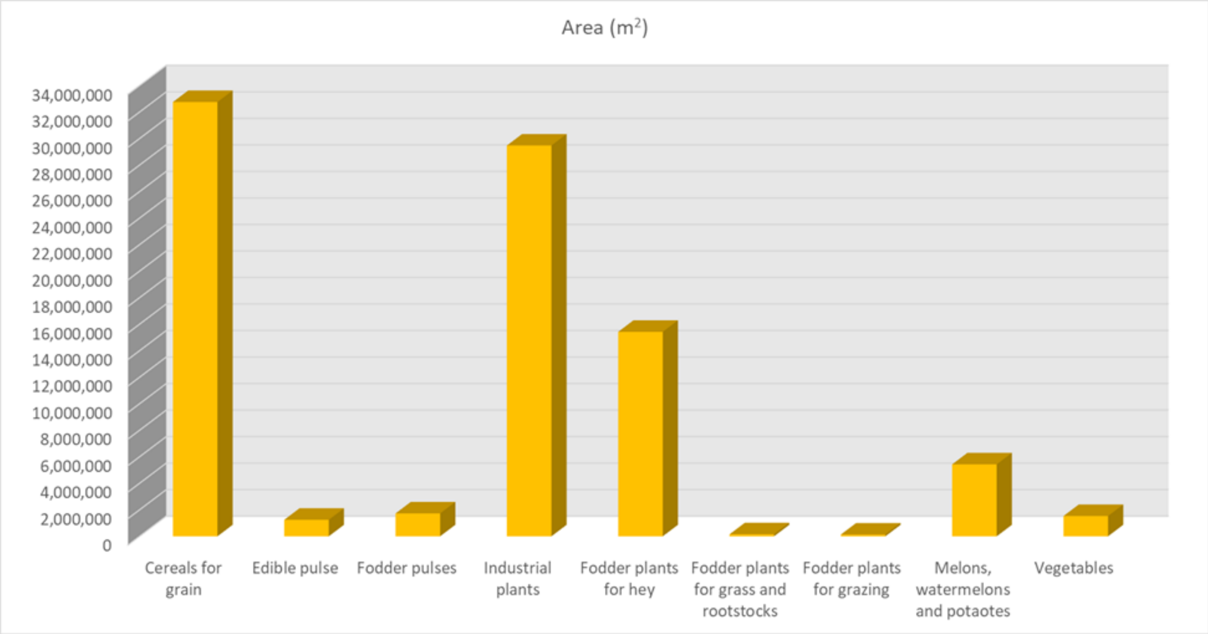

Figure 16: The W330 sub-basin agricultural areas per crop category for the base year of 2015.

In figure 17, we showcase the monthly irrigation water demand per crop category in cubic meters, for the base year of 2015. It is obvious that industrial plants and cereals for grain consume the largest amounts of water, mostly during the dry period. On the other hand, vegetables although they don't consume a lot of water their monthly needs extend throughout the whole year.

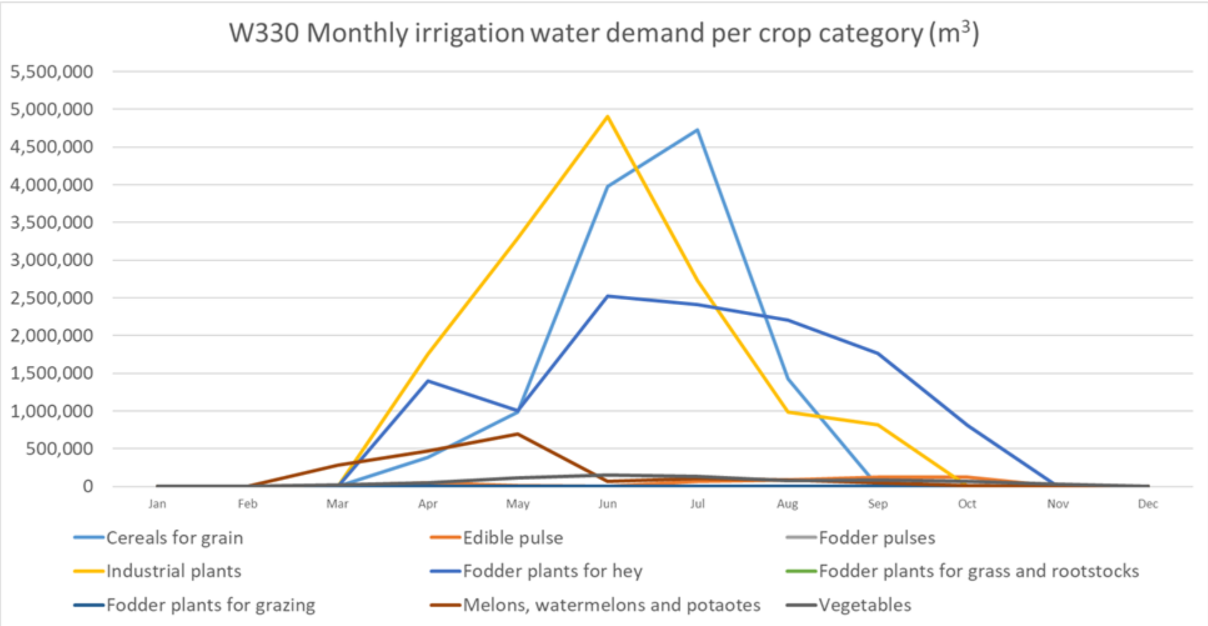

Figure 17: The W330 sub-basin monthly irrigation water demand per crop category for the base year of 2015.

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In figure 18, the W330 sub-basin production per crop category for the base year of 2015, is presented. Cereals for grain and melons, watermelons, and potatoes are the crop categories with the largest production.

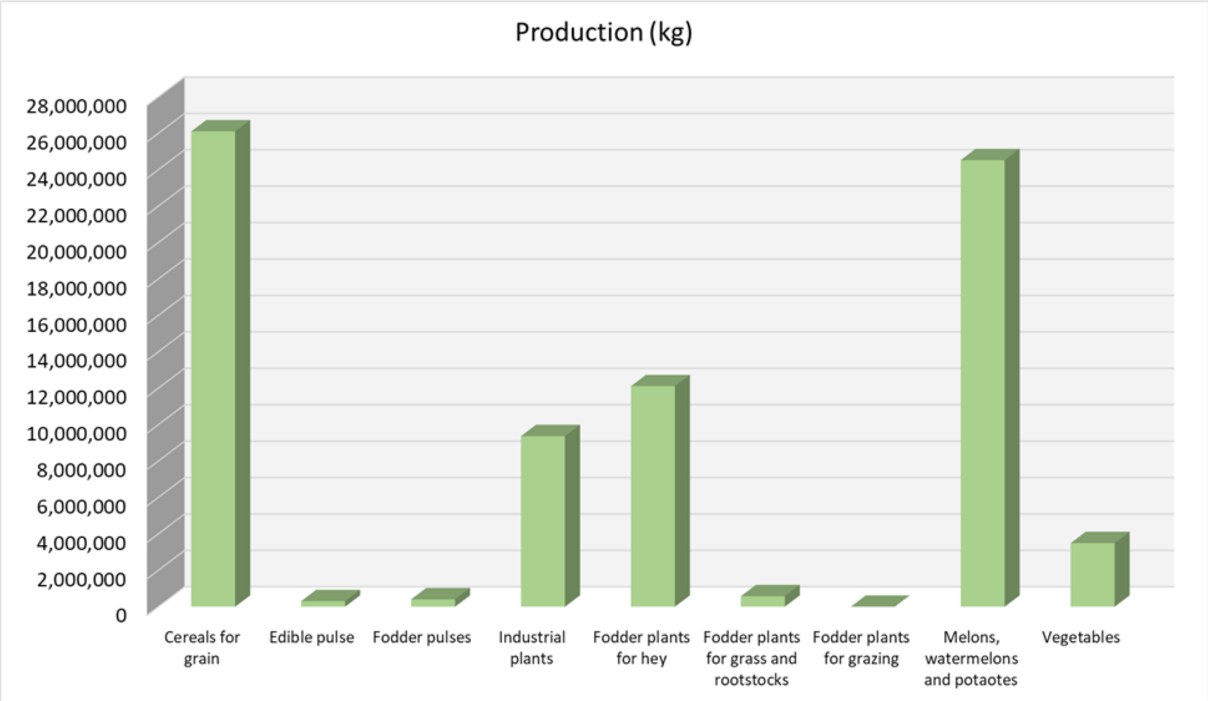

Figure 18: The W330 sub-basin production per crop category for the base year of 2015.

Due to the fact that the Nestos/Mesta SDM has a spatial analysis of sub-basins level, data incorporation is a massive task and during the next months further data incorporation is expected to take place and close the gap of the data availability regime in all nexus sectors. However, the predetermined next steps regarding new data collection, policy scenarios incorporation, and feedback from the upcoming interactions with case study leaders, WP2 data providers and of course relevant stakeholders will shape the ground for improving, updating, and finalizing this prototype/draft SDM.

2.1.5 Next steps and further work

In this deliverable it is presented the Nestos/Mesta system dynamic prototype. The Nestos/Mesta SDM needs further development and interaction with NXG experts and stakeholders to constructively update and shape the whole canvas of the nexus interlinkages, towards producing a robust and representative SDM for the case study. To this end, the next steps and further work for the Nestos/Mesta CS is briefly described, as follows:

- Close the gap in data availability and future data projections by cooperating with WP2 experts and by collecting available data from local resources, where applicable.

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- Finalize the structure of the SDM by expanding the nexus components and interlinkages to include the whole spectrum of relations according to the conceptual map.
- Run the SDM till the ending year of 2050 by incorporating and integrating the policy packages identified.
- Validate the results of the SDM.
- Incorporate all RCPs and SSPs in conjunction with policy scenarios towards conducting uncertainty and sensitivity analyses.
- Disseminate the SDM outputs for the different scenarios to the relevant stakeholders during the next organised workshops and trigger a fruitful discussion to raise the possible concerns and propose meaningful interventions towards retaining a sustainable future of the case study.
- Implement uncertainty analysis
- Incorporate the footprint indicators to the SDM

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2.2 Case Study #2: Lielupe River Basin (Lithuania-Latvia)

2.2.1 Conceptual model recap

A conceptual model of the Lielupe River Basin (LRB) was previously developed and presented in the project Deliverable 3.2. This model was developed in the form of a Causal Loop Diagram (CLD), a qualitative system representation widely used in the field of System Dynamics (SD). The developed CLD represent an effort to extensively map the interlinkages and causal relations among the variables of the nexus system in the basin (Figure 19) presents the WEFE Nexus CLD as a deeply interconnected and complex system. Yet, it was possible to cluster the identified variables into six nexus sectors: Water, energy, food, ecosystems, land and climate.

Establishing a qualitative model like the CLD opens the possibility to develop further quantitative approaches to study the nexus in the LRB (and in fact all NEXOGENESIS case studies). For example, SD approaches usually develop both qualitative and quantitative models to study complex systems (Ford, 2010; Sterman, 2000). Stocks and Flows Diagrams (SFD) represent the SD state of the art approach to model complex problems in a quantitative way. This approach's main aim is to understand the behaviour of a complex issue to further evaluate policy alternatives to intervene it.

The following sub-chapters will focus on presenting an SFD that was developed based on the CLD structure for the LRB WEFE Nexus system. Transitioning from a CLD to SFD is a complex process in itself (Freebairn et al., 2019). As the SFD is a more operative approach, it requires quantifiable variables and defining more clearly a problem to be studied. In order to guide this process, BEF Latvia, the NEXOGENESIS' LRB local partners, engaged stakeholders to identify the most pressing Nexus issues in the transboundary basin. This exercise took place in an international stakeholder workshop held the 15th of June in Vilnius, Lithuania. In this meeting, stakeholders highlighted the urgency and criticality of the issues around river water quality and renewable energy transition in the basin. The SFD prototype presented below aims to operationalise this focus (figure 19).

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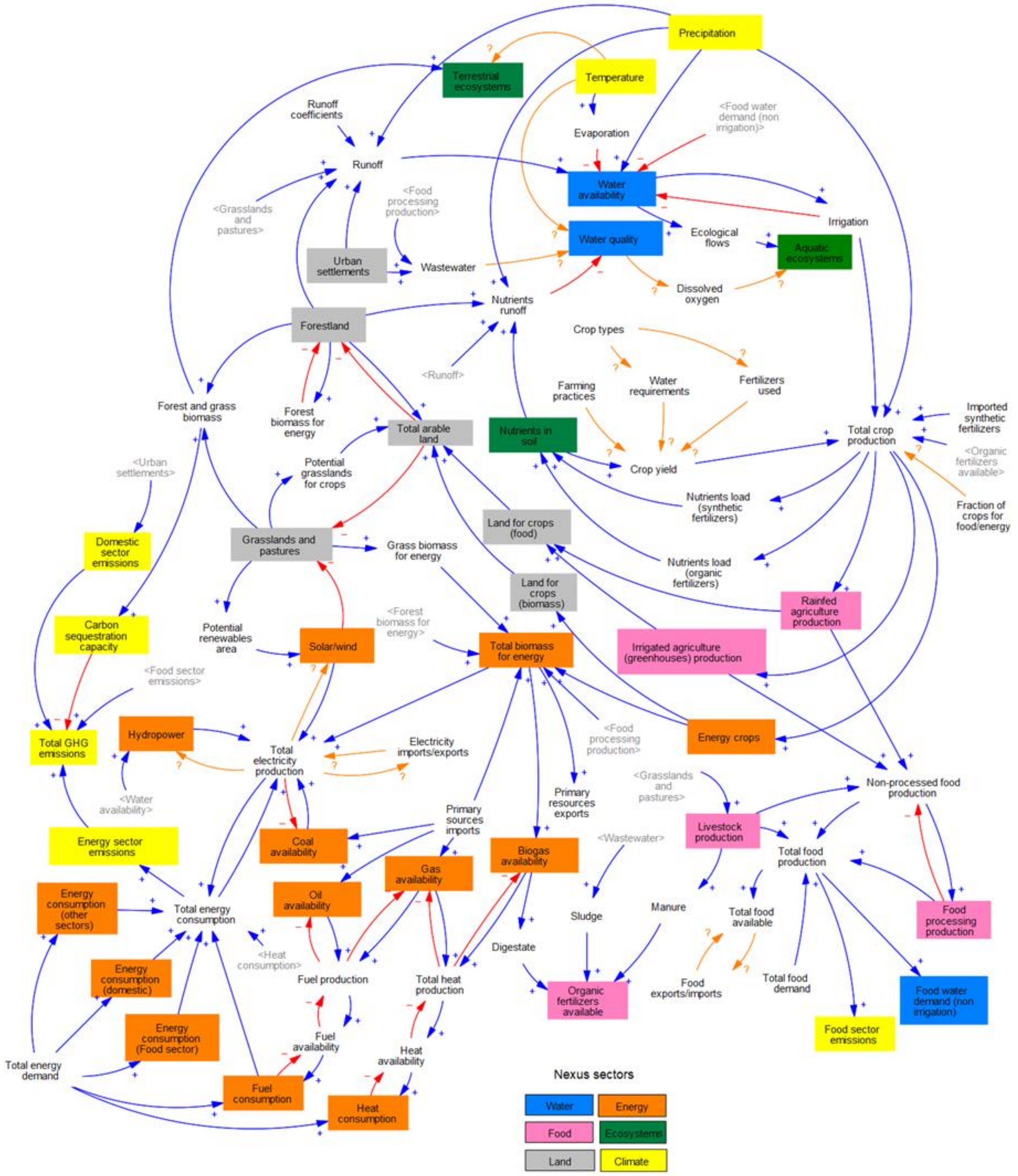

Figure 19: Causal loop diagram for the Lielupe River Basin

2.2.2 System Dynamics Model description

This chapter explains a prototype System Dynamics Model to study issues related with the LRB Nexus system. Building upon the CLD, this new quantitative model aims to represent and assess the interactions of the Nexus sectors in the basin. Figure 20 presents eight nexus clusters that were considered in the SFD. The diagram evidences the deeply intertwined nature of the Nexus system in this case study. At present the model is one single model, with no disaggregation into sub-regions.

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Some changes are highlighted from the previously developed CLD. Two new sectors were added (i.e. Population and Nature based solutions) while one changed focus (i.e. Renewable energy, previously labelled as Energy). The overall changes were processed based on stakeholder feedback. Population is now explicitly considered as a driver of resources demand and pollution pressures. Nature based solutions are considered as a promising focus to control nutrients pollution while helping to restore ecosystems. Finally, Renewable energy aims to show the current and future energy transition initiatives taking place in the basin.

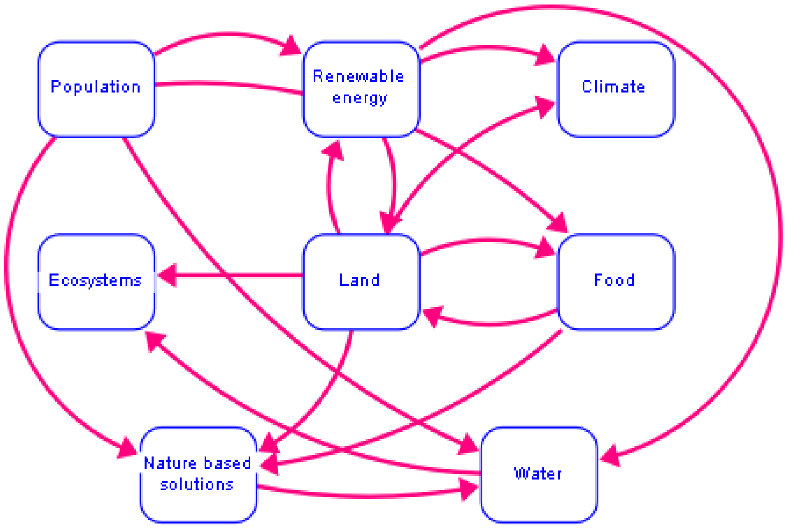

Figure 20: LRB Nexus sector interactions.

A more detailed account of the SD model (i.e. SFD) is shown in Figure 21. Here the operationalization of the nexus sectors is evident in the forms of a network of stocks, flows and variables aiming to capture the basin's structural issues from a Nexus perspective. This modelling effort aims narrow down the system structure as identified in the CLD. That is, it aims to reach a level in which quantification is not only possible but policy relevant in the basin. In this line, we also prioritised the representation of the basin's most critical socio-environmental issues, as identified by stakeholders: water quality and renewable energy transitions. A description of the main sectors' modelling is provided below.

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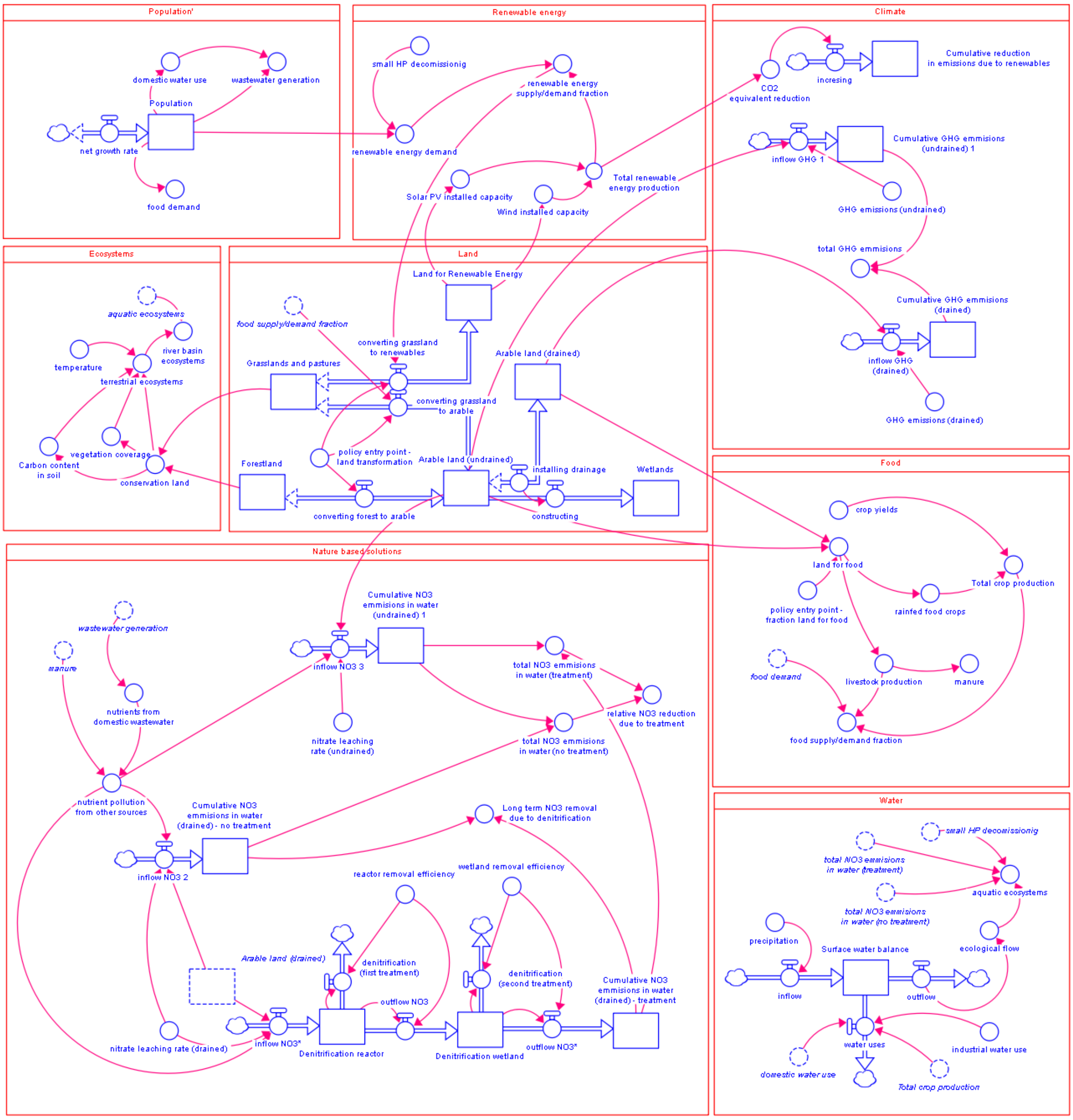

Figure 21: Stock and Flows Diagram (SFD) of the WEFE Nexus in the Lielupe River Basin.

Population is a driver of change for other sectors. More specifically, the population is an important stock that drives resources demand (i.e. water, energy and food). The number of people in the basin also drives important pollution sources like non-removed nutrients coming from domestic wastewater.

The Land sector is at the heart of the SD model. The land use dynamics are recognised as a key nexus driver in the basin. Lands with low human influence (i.e. forest and grasslands) are recognised as carbon sequestration and high vegetation density spots that represent the state of “natural” ecosystems in the basin. Land is also used for installing Renewable energies and very importantly for Food production. In the latter category, a distinction between drained and undrained arable land is made in order to explore the plausible implementation of Nature-based solutions in the basin. Lastly, arable land is accounted as an important contributor to the basin’s GHG emissions.

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The Renewable Energy sector aims to account for the renewable energy expansion in the basin. The expansion is derived from the allocated land both for the installation of photovoltaic panels, as well as wind turbines. As raised by the basin's stakeholders, there is interest in decommissioning small hydropower plants across the Lielupe River. The potential loss in hydropower generation is meant to be compensated by expanding renewable alternatives. Likewise, the overall expansion in renewable energy represents impacts in the Climate sector via emissions savings compared to a basin's business as usual scenario.

The Climate sector aims to account for the basin's GHG emissions and their relative reduction. As aforementioned, emissions are estimated based on arable land use. Similarly, the model aims to estimate CO_2 equivalent emissions' reduction based on renewable energy expansion.

The Water sector is key in this model. A surface water balance aims to capture the dynamics of the Lielupe river. Water inputs are driven by precipitation and also subject to climate change effects. Water uses come from domestic, industrial and agricultural activities. Downstream flow would be linked with ecological flow requirements, which in conjunction with other factors, such as nutrient pollution and wastewater discharge, impact the state of aquatic ecosystems.

The Food sector accounts for agriculture related activities in the basin. It is driven by land use and focuses on rainfed food crop and livestock production. The model aims to capture the effect of the ratio of food supply and demand on the expansion of arable land in the basin. Noteworthy, as shown in the land sector, arable land expansion comes at the expense of a reduction in other land-use types such as pastures and forests.

Lastly, Nature based solutions are considered as a sector aiming to control nutrients pollution in the basin. Nitrogen pollution comes from arable land and other sources like untreated domestic water and manure. This model section aims to capture the effect of implementing a two-treatment denitrification train to reduce nitrogen loads in the river. This will ultimately have a potential positive impact for aquatic ecosystems in the Lielupe and even in the Baltic Sea (Limburg, Breitburg, Swaney, & Jacinto, 2020).

2.2.3 Data collection and incorporation

The data mapping exercise was reported on Deliverable 3.3. Data will come from various sources, including NXG WP2, local available data and literature data. Table 1 shows a summary of the SDF model (Figure 21) required inputs based on their data source. The table shows that the majority of the data is currently available as input for the SDM. Yet roughly a third of these variables still need to be estimated and, therefore, are a priority for the coming months of model building.

Table 1. Summary of the SD model requirement inputs

Model's input variables	WP2	Local	Literature	Available
Arable land (drained)		X		Yes
Arable land (undrained)		X		Yes
Forestland		X		Yes
Grasslands and pastures		X		Yes
Land for Renewable Energy		X		No
Population		X		Yes
Surface water balance	X			Yes
Wetlands		X		Yes
Net growth rate	X			Yes
Carbon content in soil	X			Yes
CO2 equivalent reduction			X	No
Crop yields	X			Yes
domestic water use		X	X	No
ecological flow	X	X		No
food demand	X	X		Yes
GHG emissions (drained)			X	Yes

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GHG emissions (undrained)			X	Yes
industrial water use	X	X		Yes
livestock production	X	X		Yes
manure		X	X	No
nitrate leaching rate (drained)			X	Yes
nitrate leaching rate (undrained)			X	Yes
nutrients from domestic wastewater		X	X	No
policy entry point - fraction land for food		X		Yes
policy entry point - land transformation		X		No
precipitation	X			Yes
renewable energy demand		X	X	No
small HP decommissioning		X		No
Solar PV installed capacity		X		No
temperature	X			Yes
vegetation coverage	X			Yes
wastewater generation		X	X	No
wetland removal efficiency			X	Yes
Wind installed capacity		X		No
Total count	11	21	11	

NXG WP2 plays a very important role in providing downscaled data at river basin level. Table 2~~Table 2~~ presents a summary list of the variables provided by WP2 that will be used during the modelling process. Available data can be used as a variable input, but also can be used for validating or extending the simulation model. The variables that are not currently available are highlighted and will be estimated by WP2 upon request.

Table 2. Summary of relevant available WEFE Nexus variables for the LRB

Sector	Indicators from WP2 (Variable - short name)	Description	Units	Currently available from WP2
Agrticulture	wheat - no irrigated - biom	Biomass yields	Dry matter (t ha-1 per growing season)	Yes
Agrticulture	wheat - no irrigated - yield	Crop yields	dry matter (t ha-1 per growing season)	Yes
Agrticulture	wheat - no irrigated - initr	Nitrogen application rate	g ha-1 per growing season	Yes
Agrticulture	maize - no irrigated - biom	Biomass yields	dry matter (t ha-1 per growing season)	Yes
Agrticulture	maize - no irrigated - yield	Crop yields	dry matter (t ha-1 per growing season)	Yes
Agrticulture	maize - no irrigated - initr	Nitrogen application rate	g ha-1 per growing season	Yes
Agrticulture	rapseed - no irrigated - biom	Biomass yields	Dry matter (t ha-1 per growing season)	Yes
Agrticulture	rapseed - no irrigated - yield	Crop yields	dry matter (t ha-1 per growing season)	Yes
Agrticulture	field peas - no irrigated - biom	Biomass yields	Dry matter (t ha-1 per growing season)	Yes
Agrticulture	field peas - no irrigated - yield	Crop yields	dry matter (t ha-1 per growing season)	Yes
Biomes	MSA_Overall	mean species abundance (MSA) overall	values range from 0 to 1 indicating local biodiversity intactness relative to a pristine reference situation.	No
Biomes	MSA_Plants	mean species abundance (MSA) plants	values range from 0 to 1 indicating local biodiversity intactness relative to a pristine reference situation.	No
Climate	evap	Total Evapotranspiration - Sum of transpiration, evaporation, interception losses, and sublimation.	kg m-2 s-1 or mm s-1	Yes
Climate	pr	Precipitation	kg m-2 s-1 or mm s-1	Yes
Climate	tas	Near-Surface Air Temperature	K	Yes
Climate	adomuse	Actual domestic water consumption	kg m-2 s-1 or mm s-1	Yes
Climate	adomww	Actual manufacturing water withdrawal	kg m-2 s-1 or mm s-1	Yes
Climate	Pr	Precipitation	kg m-2 s-1	Yes
Climate	tas	Near-Surface Air Temperature	K	Yes
Climate	Pr	Precipitation	kg m-2 s-1	Yes
Climate	tas	Near-Surface Air Temperature	K	Yes
Climate	trans	Transpiration	kg m-2 s-1	No
Ecosystems	csoil	Carbon Mass in Soil Pool	kg m-2	Yes
Ecosystems	lai	Leaf Area Index	1	Yes
Ecosystems	cveg	Carbon Mass in Vegetation	kg m-2	No
Ecosystems	cvegag	Carbon Mass in Above Ground Vegetation Biomass	kg m-2	No
Ecosystems	soilc	Total Carbon Mass in Soil Pool	kg m-2	No
Water	ainduse	Actual industrial wáter consumption	kg m-2 s-1 or mm s-1	Yes
Water	aindww	Actual industrial water withdrawal	kg m-2 s-1 or mm s-1	Yes

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Water	airruse	Actual irrigation water consumption	kg m-2 s-1 or mm s-1	Yes
Water	airrusegreen	Actual green water consumption on irrigated cropland	kg m-2 s-1 or mm s-1	Yes
Water	airrww	Actual irrigation water withdrawal	kg m-2 s-1 or mm s-1	Yes
Water	aliveuse	Actual livestock water consumption	kg m-2 s-1 or mm s-1	Yes
Water	aliveww	Actual livestock water withdrawal	kg m-2 s-1 or mm s-1	Yes
Water	arainfusegreen	Actual green water consumption on rainfed cropland	kg m-2 s-1 or mm s-1	Yes
Water	arainfusegreen	Actual green water consumption on rainfed cropland	kg m-2 s-1 or mm s-1	Yes
Water	ptotww	Total (all sectors) water demand (=potential water withdrawal)	kg m-2 s-1 or mm s-1	Yes
Water	qs	Surface runoff	kg m-2 s-1 or mm s-1	Yes
Water	tws	Total water storage	kg m-2 or mm	Yes
Water	qtot	Total Runoff	kg m-2 s-1	No
Water	maxdis	Monthly maximum of daily discharge	m3 s-1	No
Water	mindis	Monthly minimum of daily discharge	m3 s-1	No
Water	evap	Total Evapotranspiration	kg m-2 s-1	Yes
Water	tws	Total water storage	kg m-2	Yes
Water	groundwstor	Groundwater storage	kg m-2	Yes
Water	lakestor	Lake storage	kg m-2	Yes
Water	wetlandstor	Wetland storage	kg m-2	Yes
Water	reservoirstor	Reservoir storage	kg m-2	Yes
Water	riverstor	River storage	kg m-2	Yes
Water	N_concentration	Total Nitrogen concentration in catch-ments	mg/L for reference period % for future periods	No
Water	N_Load	Total Nitrogen load in catchments	kg/year for reference period , kg/month for reference period	No
Water	P_concentration	Total Phosphorus concentration in catchments	mg/L for reference period % for future periods	No
Water	P_Load	Total Phosphorus load in catchments	kg/year for reference period , kg/month for reference period, % for future periods	No
Water	W_Temp	Water temperature in catchments	°C	No

2.2.4 Preliminary results

Stakeholders showed great interest in exploring alternatives to control nutrients water pollution in the basin using nature-based solutions (NBS). Based on their input, Nature based solutions was included in the SD model as a module to explore the impact of NBS pollution control measurements in the agriculture sector (See figure 22). Below there is a brief description of an NBS approach that was operationalized for this case study.

Recent research has shown the synergies of implementing agriculture drainage and NBS. Interestingly, well drained fields that incorporate downstream NBS measures are reported to have lower nitrate emissions in water, less fertilizer requirements and also lower GHG emissions (Castellano, Archontoulis, Helmers, Poffenbarger, & Six, 2019). These authors propose a system were nitrate rich water is collected in field drains that are connected to a two-train NBS treatment that aims to reduce the nitrates concentration before reaching the river (figure 22). The first treatment is a woodchip denitrification reactor installed at field level. Connected to the later, the second treatment is a denitrification wetland that receives the upstream treated water from several fields before being finally disposed in the river.

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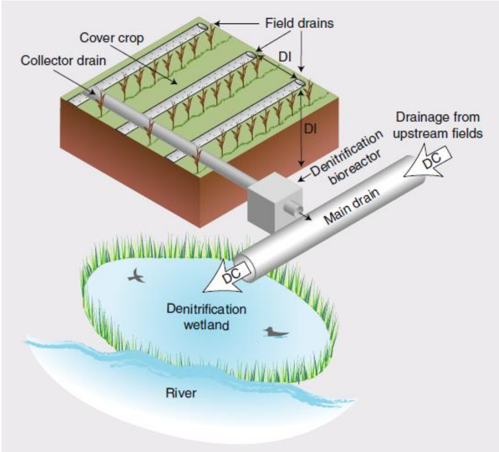

Figure 22: Integrated agriculture drainage and NBS system for nutrient pollution control as proposed by Castellano et al. (2019).

Here we report the potential impact of implementing the aforementioned nutrients treatment system in the LRB. The model parameters were based on the LRB arable land area, as well as the efficiency and emission rates reported in Castellano et al 2019. Similarly, a conservative policy of 5% annual expansion of arable land with nutrients treatment was tested.

The aforementioned conditions made possible to simulate the long-term impacts of a nutrient pollution control policy in the basin. Figure 23 presents a 30-year time series that show the cumulative relative reduction of nitrates, GHG emissions and fertiliser use as a function of the drained land with NBS.

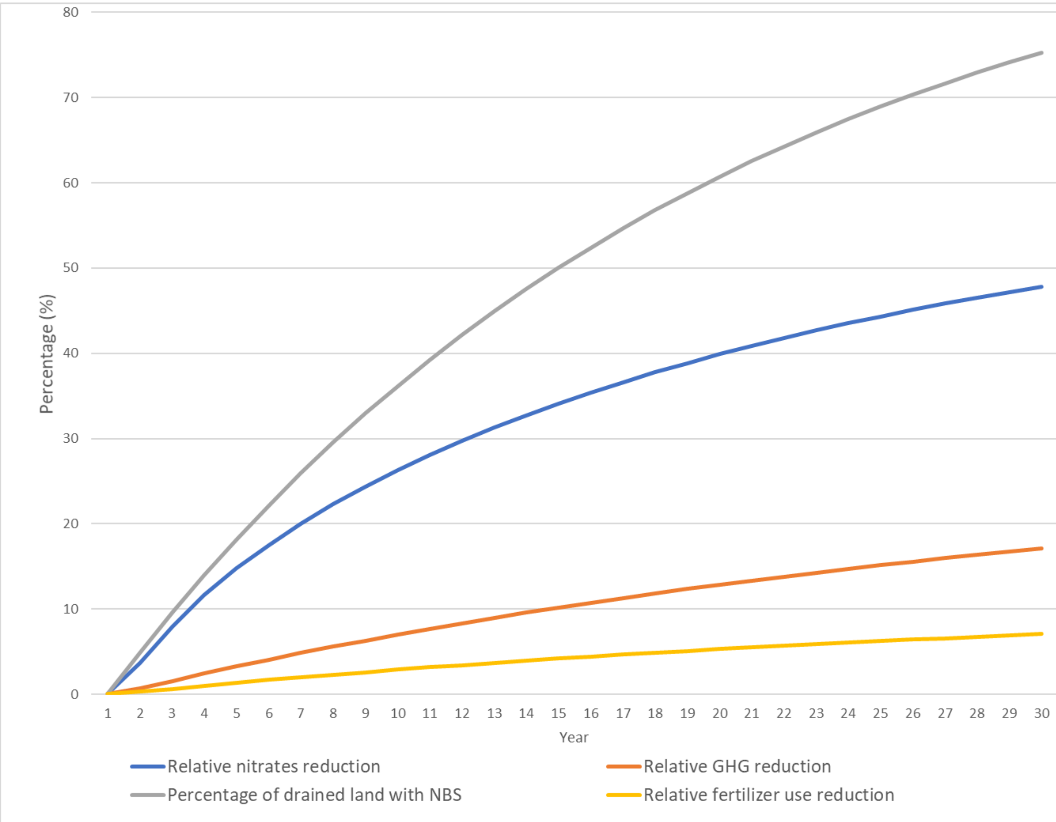

Figure 23: Policy summary results of implementing a 5% annual increase in arable land with nutrients treatment over 30 years.

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A 5% annual treatment expansion rate will imply reaching roughly half of the total arable land in the Lielupe in 15 years. At this stage, the cumulative nutrients loads could be significantly reduced by a third (34%) compared with a business as usual scenario. Likewise, minor co-benefit reductions of 10 and 4% in GHG emissions and fertiliser requirements can be achieved in this period. The results by the year 30 also show promising outputs reaching 75% of drained arable land with nutrients treatment. By this year, it would be possible to have reduced by a half (47%) the total basin nutrients loads compared with a scenario without any treatment. From the co-benefits side, GHG land emissions could also be reduced 17%, while fertiliser requirements around 7%.

The aforementioned results show a remarkable opportunity for reducing nutrients load in the basin. They show that by slowly but consistently increasing the well-drained crop area with NBS nutrient treatment, the cumulative nutrient pollution can be halved in the long-term. Minor but promising co-benefits in reducing GHG emissions and fertiliser use can help to increase the interest in implementing these pollution control alternatives in the agriculture sector.

2.2.5 Next steps and further work

Here we described the structure of a SD model to quantify the WEFE Nexus interactions in the basin. This model consists of eight interlinked sectors (or modules) that aim to account for the main issues in the LRB. Focusing on the stakeholder input, a prototype simulation model was presented to account for the implementation of NBS to control nutrient pollution in the basin.

The work ahead implies to complete the rest of the SFD modules and integrate them in a single simulation model. The outputs of an integrated model, need further stakeholder and expert validation to later be used to start testing relevant policies for the basin. Afterwards, there is good opportunity to explore the impacts of uncertainty on the performance of policy alternatives for the LRB. In addition, further work includes incorporation of the climate (RCP) and socio-economic (SSP) scenarios, as well as integrating locally-relevant policy actions and the WEFE nexus footprint calculation.

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2.3. Case Study #3: Jiu River Basin (Romania)

2.3.1 Conceptual model recap

The interlinkages between water-energy-food-ecosystem (WEFE) in the Jiu river basin were identified and captured by using the conceptual models. The development of these maps was the results of a very close collaboration between case study leaders and modellers. The maps were refined with inputs from stakeholders and local experts. The final version of the conceptual maps is representative of the case study and includes the main sectors (e.g., water, energy, etc), sub-sectors (e.g., water quantity, energy consumption, food production, etc), drivers (e.g., climate change, land use change, etc), and WEFE issues that characterise the Jiu river basin (figure 24). The maps were developed in two parts; “high-level” conceptual map and “extended” conceptual map. The high-level conceptual map for the Jiu case study includes all the main sectors and interlinkages between them, but no details are shown. The details are included in the “extended” version where each sector is analysed into detail in terms of its subsectors and interlinkages between them and all the other sectors of the nexus.

In the Jiu case study, the high-level map shows land use change and climate change as the main drivers impacting available water in the basin. The quantity and the quality of water in the system is essential to ensure drinking water to the basin’s population. Both water quality and quantity are projected to increase and improve in the future thanks to the expansion and upgrading of the water network system with a consequent impact on water security and human health. Agriculture is an important sector in the basin and together with the energy and industrial sectors, is one of the main water consumers. The agricultural sector is currently also one of the main responsible for water pollution due to due to the large amount of fertilisers used to boost crop yield. Flood protection plans and measures and well as floodplain restoration are essential to ensure the good status of the ecosystems. The good health of the aquatic ecosystem is ensured by the ecological flow.

Further details of the high-level conceptual map for the Jiu river basin are shown in figure 24 and reported in NEXOGENESIS Deliverable 3.1. The final version of the extended conceptual map for the Jiu river basin and the related details can be found in Deliverable 3.1

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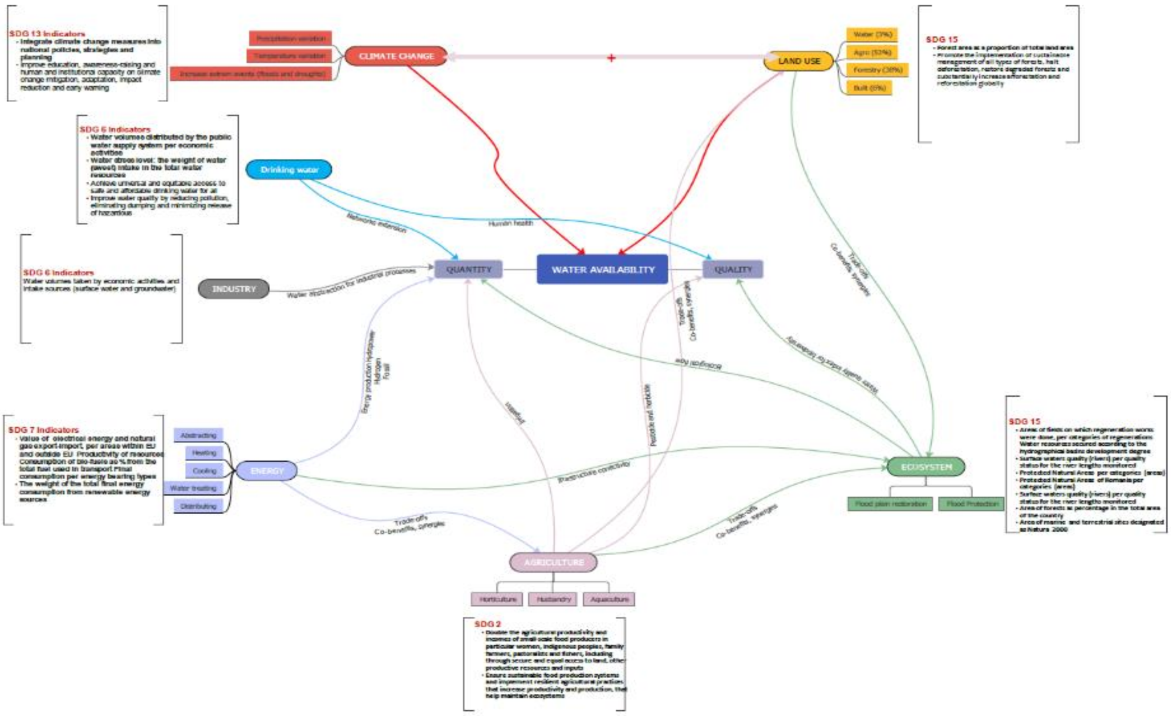

Figure 24: high-level conceptual map of the Jiu River Basin. From Deliverable 3.1.

2.3.2 System Dynamics Model description

The SDM for the Jiu case study is currently under development and the results shown in D3.4 are preliminary. The development of the model prototype is the result of a close interactions and collaboration with case study leaders, data providers (WP2, CMCC, CAF, and WR), and SDM modellers (IHE Delft). The current structure and content of the model includes all the information, input, feedback collected from stakeholders during the workshops.

In the Jiu case study, seven sectors have been identified, i.e., climate, water, land, food, energy, ecosystem, and the socio-economic sector. The sectors are currently reflected as "modules" in the SDM and some relevant interlinkages between them has been already identified (figure 25). Figure 25 shows the high-level of the Jiu river basin SDM and the intersectoral interlinkages.

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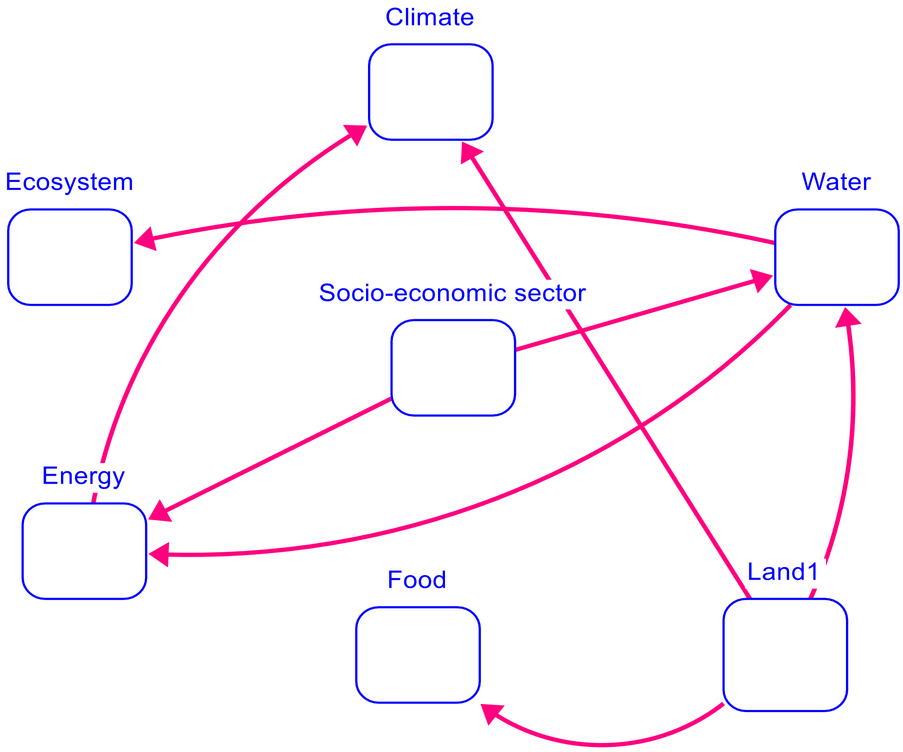

Figure 25: high level SDM representation of the Jiu River Basin.

The water sector is composed of two sub-sectors, i.e., water quantity and water quality. The water availability in the basin is computed as the balance between water supply and water consumption in the different sectors. The main sources of water supply in the basin are surface water and groundwater (Tot water inflow, figure 26), while the water is used mostly in agriculture, domestic, and industrial purposes.

Being captured as an important aspect to explore in the basin, the model reflects the domestic water consumed by people currently connected and not connected to the water network. Three of the four main crops (maize, rapeseed, and sunflower) cultivated in the basin are influencing the water balance and their water requirement is computed as an outflow to the available water (figure 26). Currently in Romania it is estimated up to 75% of wheat production is rainfed, but due the increasing frequency and intensity of the drought events, the irrigation of this crop is expected to increase by 2050. In view of this, wheat irrigation will be implemented in the next version of the SDM and its impact on the whole system will be tested.

The quality of water is computed considering the total nitrogen (N) load into the river. This is computed considering both the nitrogen applied to the hectares cultivated with the four most cultivated crops. The water sector is connected to the ecosystem in terms of water pollution and potential impact on aquatic ecosystem as well as maintenance of low flows in dry periods. The population in the basin, currently included in the socio-economic sector, is the main driver of water use. Land use is also driving the changes in the total amount of water needed for crop production. The land sector includes the hectares covered by the four most relevant crops and the forested area. The cultivated hectares are driving the local food production (figure 26 and figure 27).

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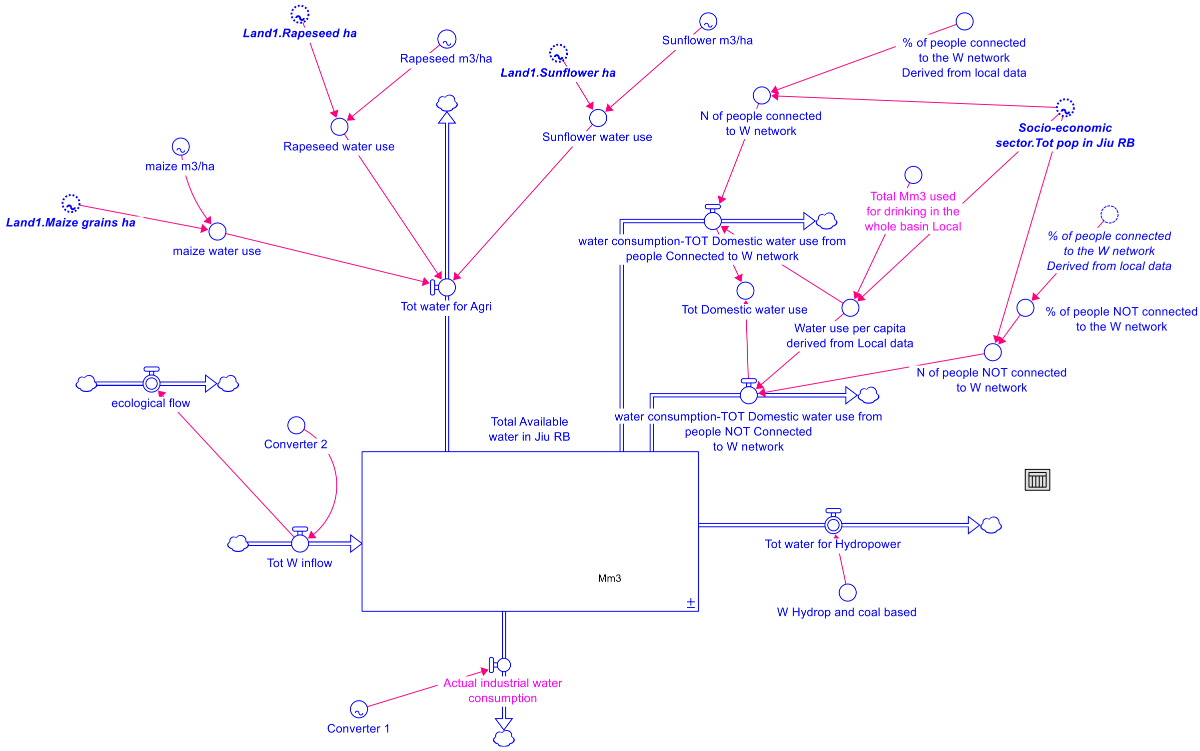

Figure 26:The Jiu River Basin water SDM sub-module.

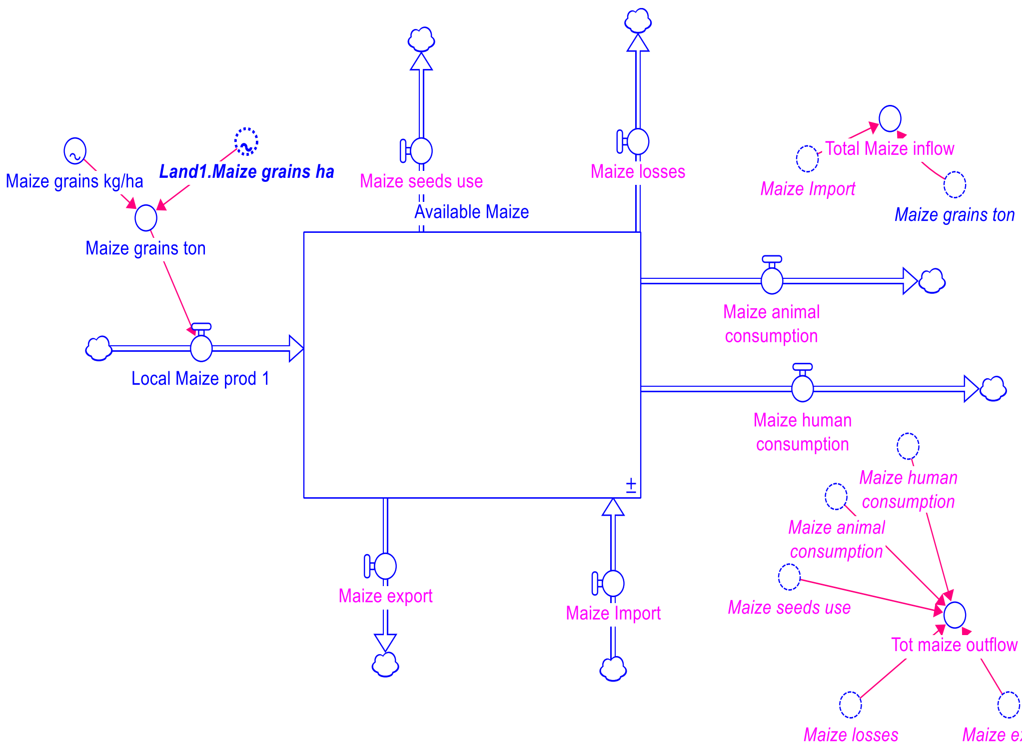

Figure 27: detail from the food sector – maize balance.

The food security in the basin is assessed considering the balance between food inflow and food outflow. The representative crops above-mentioned are at the core of this sector where their availability is estimated considering the inflow "to" and the outflow "from" the system. The supply is computed as the sum of local crop production and import to the basin. The outflow is influenced by human and animal consumption, crop losses, seeds use, and the export of the crop outside the basin.

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The energy sector includes the energy balance given by energy supply and the energy use. Renewable energy sources such as hydropower, solar, wind and fossil fuel such as gas, coal, coke, oil, and petroleum products are the main energy sources used for energy production in the basin. The energy produced in the basin has a major contribution to the national energy mix. Domestic, industry, and agriculture are the major energy consumers in the basin. The domestic energy use is driven by the population change. Both energy and land sector are influencing the climate sector where the balance between GHGs emissions and sequestration is computed. The climate sector includes emissions from the energy consumption and the cultivated land and the sequestration from the area covered by forest.

Being a work in progress, the current structure of the SDM might change in the coming months to reflects the main issues of the case study, the key indicators needed to assess the status of the nexus system in the Jiu river basin, the availability of data, and any other relevant information useful to make the model to as much representative of the case study as possible.

2.3.3 Data collection and incorporation

The conceptual model co-developed and co-validated with case study leaders and stakeholders were essential to build the current structure of the SDM and to start collecting the data needed for populating it. The extended conceptual map of each sector (D3.1, and section 2.3.1) were used to explore the data needed in each sub-sector (e.g., food supply, water availability, energy sources, etc). The data needed to make representative the case study and make possible to explore the key synergies and trade-offs in the Jiu river basin were mapped in very collaboration with case study leaders. In order to allow for data coherence across project case study, the Jiu river basin SDM, as well as the other SDMs developed within NEXOGENESIS, will be populated by using data coming from WP2 (CMCC, CAF, WR) when available. WP2 data are available from 2015 to 2050. Local data will be used to populate the model with data where WP2 data are not available. The biophysical and socio-economic data used to populate the Jiu river basin SDM are provided by the WP2 and by the case study leaders. The case study leaders provided large set of local data that currently covers most of the variables that characterise the prototype of the SDM structure and the sectors identified as relevant for the basin. The local data are at yearly scale, available from 2014 to 2021, and collected from statistics, reports, literature, experts, etc. The local data will be used to validate the biophysical data (e.g., surface water, crop yield, crop water requirements, etc) provided by CMCC (WP2). In addition, the local data will be used as starting value to CAF/WR (WP2) future socio-economic trends.

The data needs and the model structure were refined during rounds of interaction with case study leaders, WP2 leaders, and SDM modellers. The biophysical data provided by CMCC and local data are currently used in the model. The SDM prototype does not include yet socio-economic trends because the discussion related to the best data fit for case study representation is ongoing.

Water, energy, food, ecosystems, land, population, and socio-economic system are the most important sector in the basin. To allow the quantification of the main variables and interlinkages, data from the above-mentioned sources were used. The model is currently running from 2015 to 2050 at monthly scale, under RCP2.6.

Water sector. Input data for water quality (nitrogen application) are provided by the CMCC. Input data for water use in the main sectors is provided by both CMCC (water use in industry

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and agriculture) and by local sources (drinking water and water used for hydropower and coal based) while data for supply water is provided by local data. The climate driver for data used in the water sector except for domestic water use is hadgem2-es. Local data will be replaced in the next SDM version with data from CMCC. The local values will be used to validate the CMCC input data.

Ecosystem. Forest area and water quality are currently the key issues explored in this sector. CMCC data are recalled from the water sector (e.g., pollution due to agricultural sector) and CAF/WR data from the land sector (e.g., land use change). For the time being the data used to estimate the forested area are from local sources.

Land. The local land use input data for maize, wheat, rapeseed, sunflower, and forest have been used to run the current structure of the SDM. These data will be replaced in the future version of the model with data from WP2 (Magnet model) and the local data will at the base for estimating future trends and for WP2 data validation.

Food. All the data used in the SDM prototype are from local sources except for crop yield that is from CMCC. As for the land sector, the different use of food (section 2.3.2) will be used, in the next version of the model, as initial values for food socio-economic trends provided by GRDEM model (CAF).

Energy. Except for the domestic energy use all the input data for the current version of this sector are from local sources. WP2-GRDEM model data will be used to compute future socio-economic trends for the data that characterise this sector (see details in section 2.3.2). Local values will be used initial value and for validation.

Climate. The climate data (e.g., CO_2/ha, CO_2eq/KWh) needed to compute the GHGs balance are all from local sources. Data from WP2 are used as well but they are recalled from other sectors (e.g., from the land sector, the cultivated forest hectares will be used; from the energy sector, the emissions from energy consumptions will be used).

Population. Population is one of the main drivers in the system and its data are delivered by WP2 (GRDEM model). The local data will be used as starting value to which the growth change will be applied in the final version of the model.

Further details about the collected data per each sector and sub-sectors can be found in Deliverable 3.3 “Final report on the application of biophysical models and stakeholder recommendations”.

2.3.4 Preliminary results

The Jiu river basin SDM is currently running as a prototype. The data used to populate the current structure of the model will be updated in the coming months in view of the refinement of the data collection and stakeholders’ involvement in the process. As a consequence of data availability, local expert information, and feedback, the structure of the model might change as well.

Some preliminary results obtained by running the prototype have been collected, discussed with the case study leaders, and reported in this Deliverable. The model was run for 420 months under RCP 2.6.

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Both local data and trends indicated by WP2 GRDEM model estimate a decrease in the basin's population (-303091 people in 2022 compared to 2015 according to local statistics). No changes in population growth have been implemented in the model yet, because discussions about the most representative values for the basin are currently ongoing.

In the water sector, the water balance is estimated by considering the total water inflow and outflow in the basin. Results show a sufficient water inflow to meet water consumption needs in the different sectors (figure 28). The highest values of water outflow are estimated during late spring and summer months and might be explained by the interlinkage between the land and the water sector. Being the water and the land sector closely linked, this might be explained by the production of the most relevant crops, such as maize, rapeseed, and sunflower which is concentrated especially in the above-mentioned months.

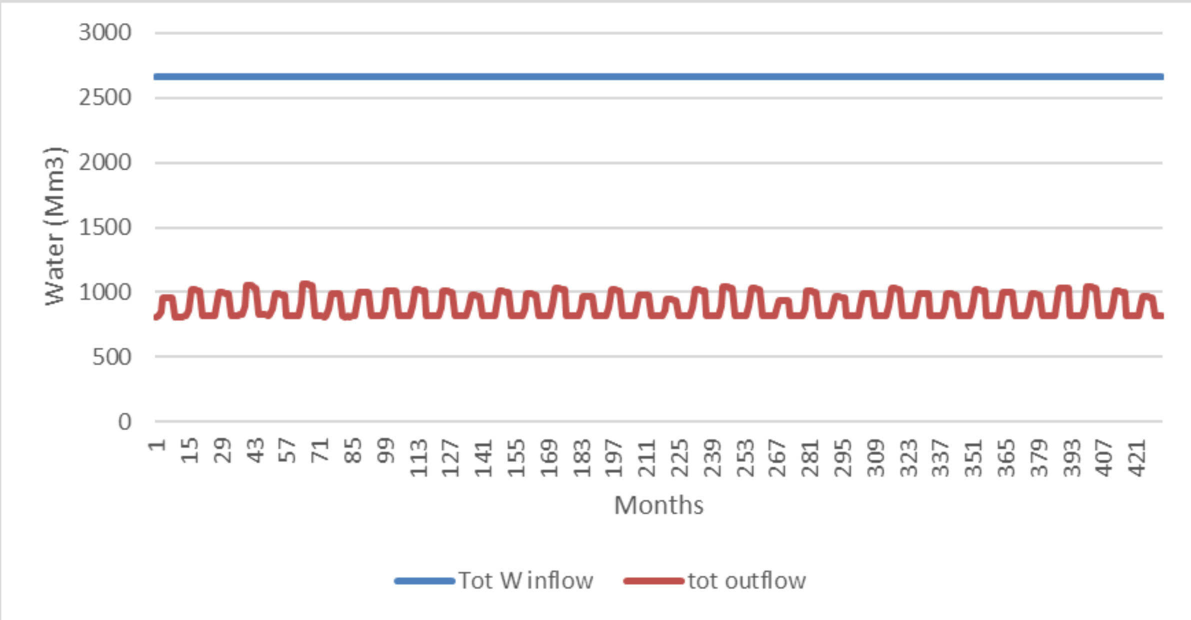

Figure 28: Preliminary water inflow and outflows in the Jiu River Basin.

Most of the available water in the basin is used for industrial sector (figure 29). The second largest water consumer is the agricultural (crop production) sector. The crop water consumption is particularly high especially in late spring and summer months (figure 29) when water is used to irrigate especially maize, sunflower, and in part also rapeseed. Wheat water demand is not computed in the total crop water use because its production is considered in rainfed in the SDM prototype. Given the increasing irrigation needs due to climate change impact on the basin, the next version of the SDM will incorporate wheat irrigation.

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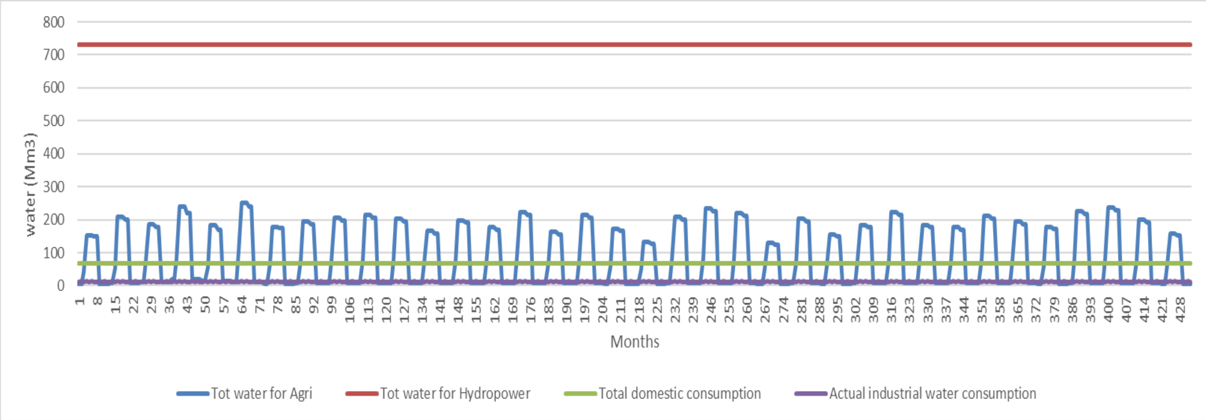

Figure 29: Preliminary water consumption by sector in the Jiu River Basin.

Local data are currently used as input to the land sector (details in section 2.3.2 and 2.2.3).

Wheat and maize are the largest crops produced in the basin in the period 2015-2021 (figure 30).

The land sector is closely linked to the water sector in terms of both water quantity (water used for irrigating the cultivated areas) and water quality (fertilisers used in the cultivated area).

The land sector (ha) and the food sector (kg) being closely linked, the cultivated area for each relevant crop becomes the main driver for ensuring local food production in the basin and this is computed considering both the cultivated area (ha) and the crop yield (kg/ha).

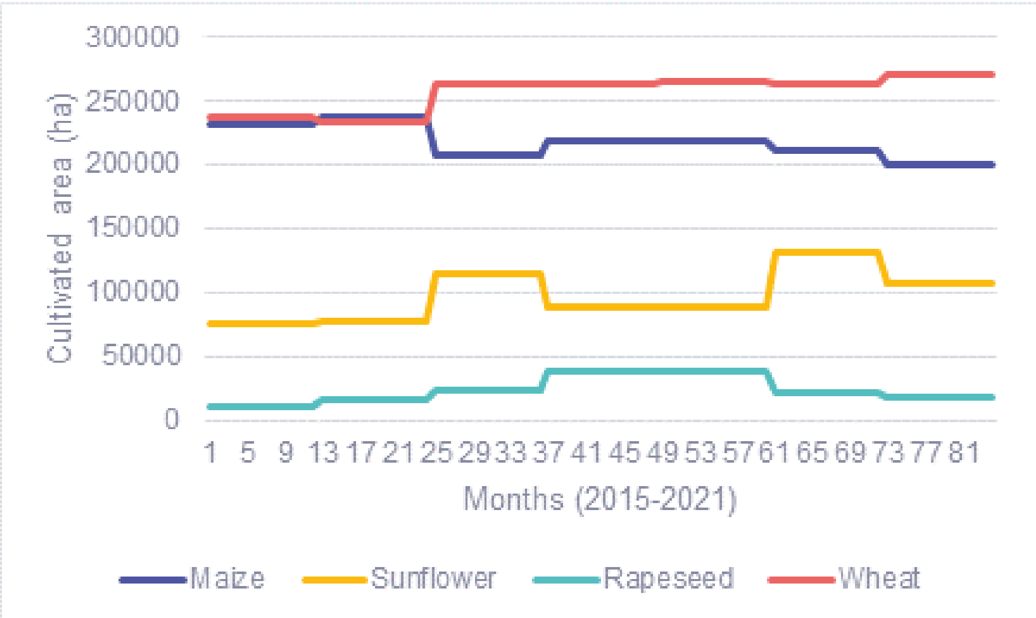

Figure 30: Preliminary cultivated area of different crops in the Jiu River Basin.

In the current structure of the SDM the total fertilisers used to produce maize and wheat is estimated by considering the kilogram of Nitrogen applied per cultivated hectare during the crop growing season in the basin. Figure 31 shows that despite the largest area is cultivated with wheat (Figure 31), the highest amount of nitrogen (total) is applied for growing maize. This is due to the higher amount of nitrogen per hectare (kg/ha) used to grow maize rather the one used to grow wheat.

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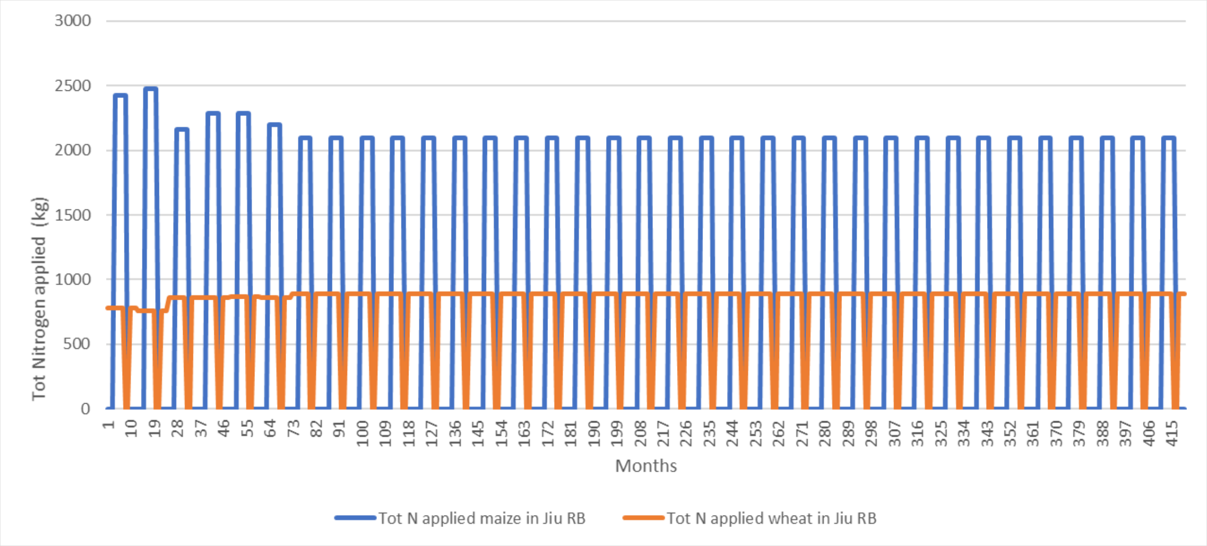

Figure 31: Preliminary total nitrogen applied for wheat and maize production in the Jiu River Basin.

The local data for energy production and consumption in the basin are essential to be able to estimate future socio-economic trends. Figure 32 shows the inflow (energy production) and the outflow (energy used in the basin and energy exported out of the basin) obtained by using the local data sources. Results show that for 2015 (initial local value to estimate trends by using CAF WP2 future rate of changes) the energy available in the basin is sufficient to meet energy demand in the industry, agriculture, and domestic sectors.

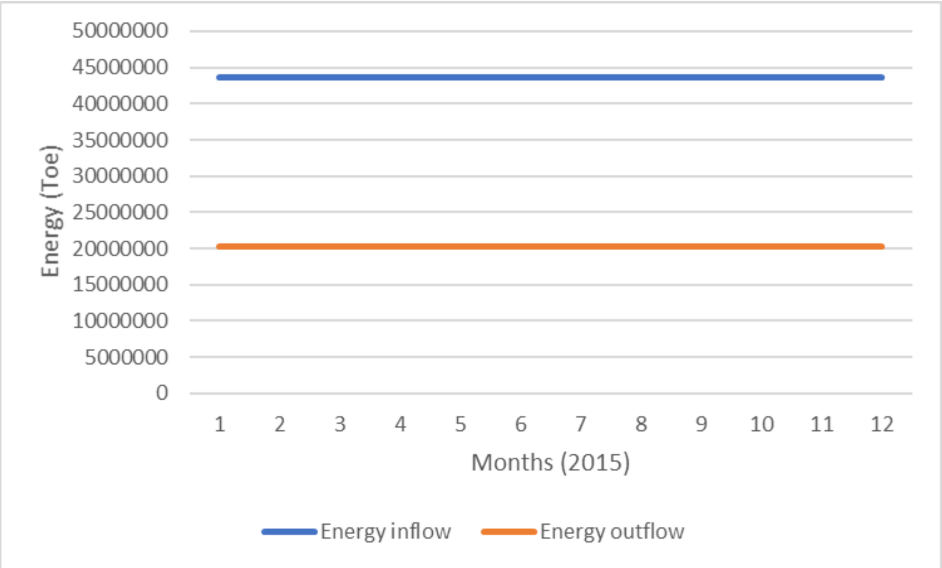

Figure 32: Preliminary energy inflows and outflows in the Jiu River Basin.

Local statistics indicate that for the same year (2015) oil, followed by gas, coal and coke are the most prominent energy sources in the basin with a total availability of about 426960000 tons of oil equivalent (toe) in 2015. The imported petroleum products were equal to about 35952000 toe. In the same year, the renewable energy, (i.e., hydropower, wind, solar, and nuclear) accounted for about 5096000 toe.

The total energy exported from the basin is relevant and future data trend will be tested in the final SDM version by using trends provided by CAF WP2.

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The preliminary results obtained by running the SDM prototype might change according to the new data, scenarios, information, and feedback that will be collected in the coming round of interactions with case study leaders, WP2 data providers, SDM modellers, stakeholders and local experts.

2.3.5 Next steps and further work

The development of the system dynamic model for the Jiu case study is still ongoing and further interaction with case study leaders, WP2 data providers, SDM modellers, stakeholders and local expert will be needed to revise the current prototype and co-develop, co-refine, and co-validate a robust base that will be used to implement policies. Indeed, in NXG project, each SDM will be run first without and then with policies. The model will be run with the policies only after the validation of outcomes obtained running the model without policies. Simulated model outputs will be validated against observed data and stakeholder's feedback. The policies that will be implemented in the SDM are the ones selected in consultation with WP1, case study leaders, and stakeholders. In addition, further work includes incorporation of the climate (RCP) and socio-economic (SSP) scenarios, as well as integrating locally-relevant policy actions and the WEFE nexus footprint calculation.

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2.4 Case Study #4: Adige River Basin (Italy)

2.4.1 Conceptual model recap

The first understanding of the WEFE nexus within the Adige River Basin started integrating information coming from experts' knowledge, literature review and opinions of different stakeholders into conceptual models. They were developed to identify variables and their linkages across the WEFE sectors and later translated into a comprehensive causal loop diagram (figure 33). More information on the development of the preliminary conceptual models and the causal loop diagram is reported in Deliverable 3.1 "Conceptual models completed for all case studies".

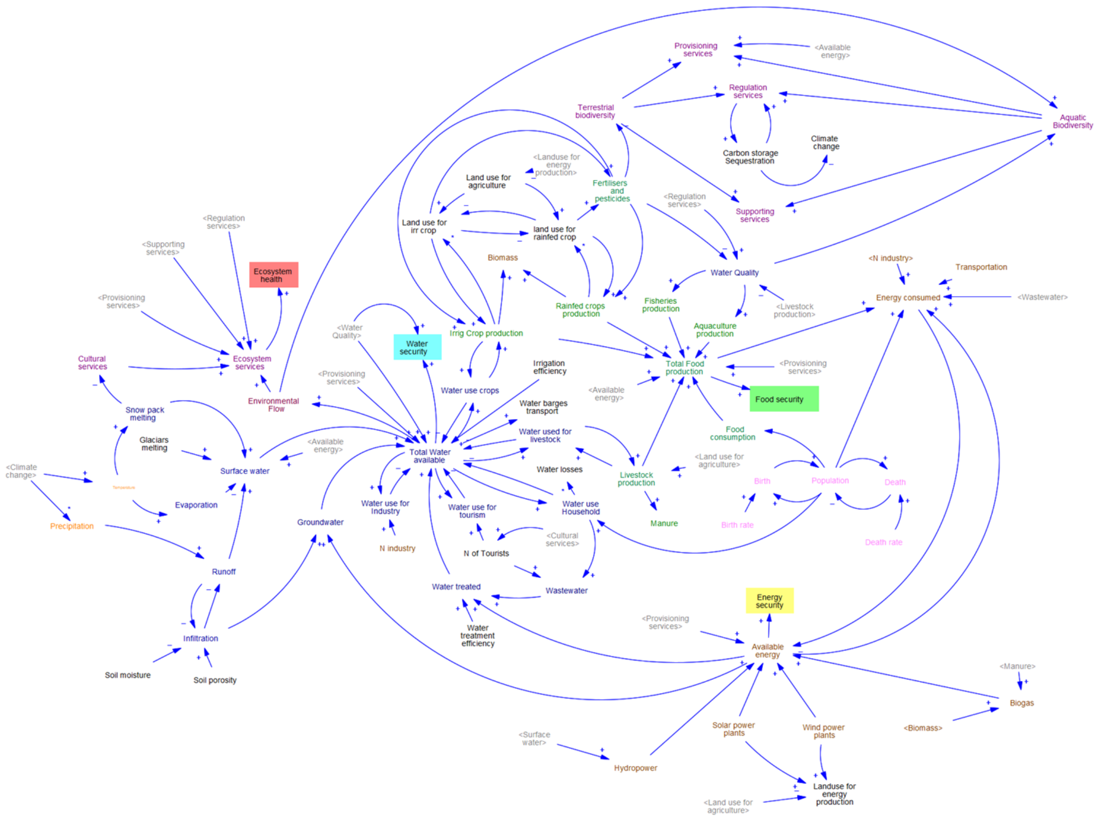

Figure 33: Causal Loop Diagram of the WEFE sectors for the Adige River Basin.

2.4.2 System Dynamics Model description

Overview

The SDM prototype for the Adige River Basin was developed as a direct consequence of the CLD and in accordance with the characteristics and an initial evaluation of the available datasets (figure 34). Five WEFE sectors, namely water security, food security, energy security, population and ecosystem health, were identified in the CLD and represented as dedicated modules in the SDM (red boxes in figure 34) connected by flows of material from the different stocks in each module (blue arrows) as well as by information exchanges from parameters and stocks to modulate the material flows (red arrows). At present the model is one single model, with no disaggregation into sub-regions.

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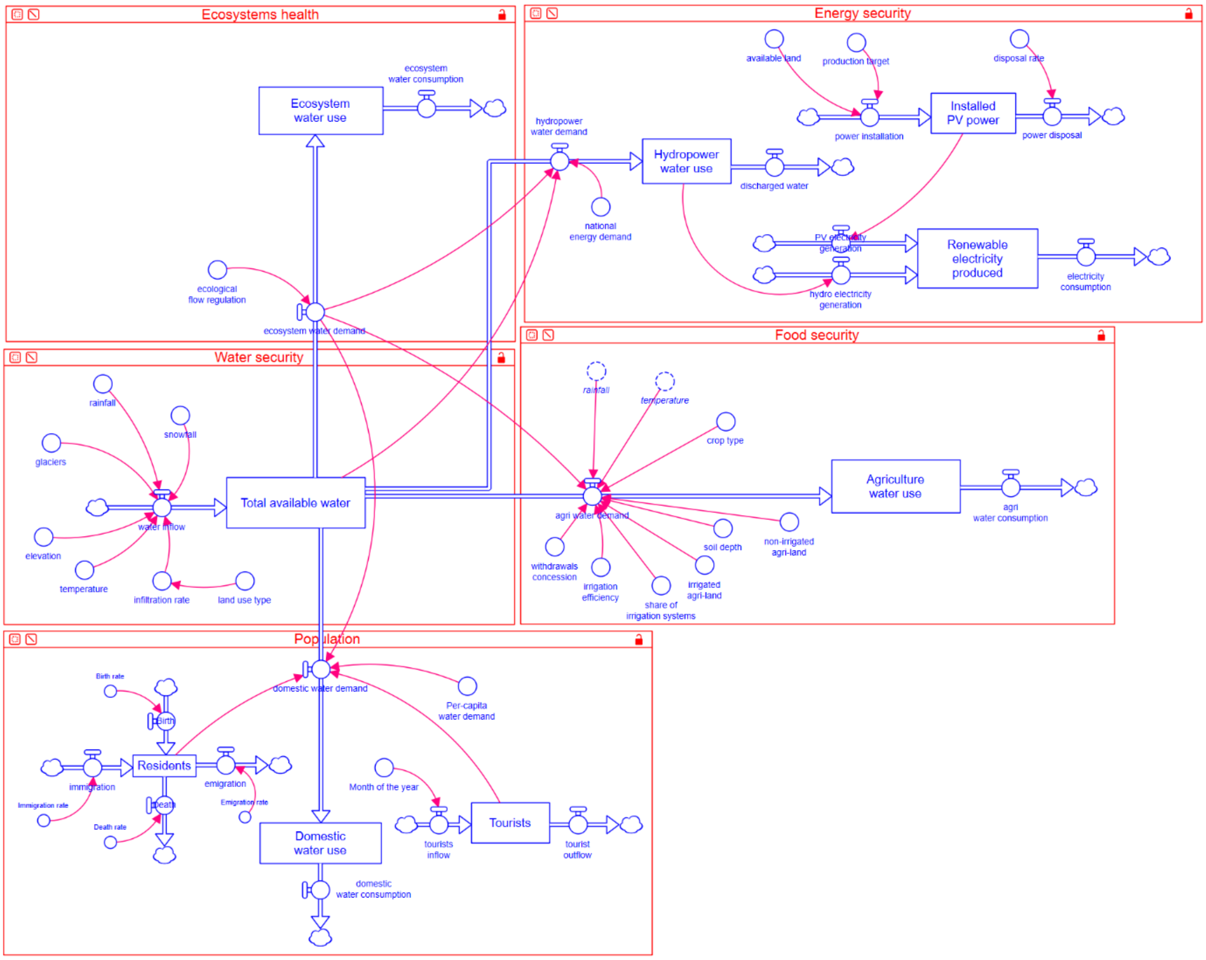

Figure 34: Overview of the System Dynamics prototype for the WEFE Nexus in the Adige River Basin.

For some of the selected sectors, dedicated physically-based models have been and will be applied to represent complex conditions of water availability or sectorial water demand. This is particularly important given the high landscape heterogeneity in the Adige case study and the complex physical processes regulating water availability from upstream to downstream as well as water demands from different sectors. To do this, SDM is here considered as a wrapper combining multiple outputs ranging from physically-based models to statistical regressions.

Water security

The water sector considers and simulates water quantity conditions in the whole Adige River basin. Given the high complexity of water-related physical processes, such as glaciers and snow dynamics in mountains, and the high interest of some crucial stakeholders in using the existing resources, the ICHYMOD semi-distributed hydrological model has been here considered and applied (Borga et al., 2002, 2006). In particular, ICHYMOD simulates conditions of snow, soil moisture and streamflow at an hourly time scale for different sub-basins of the whole Adige River basin. Moreover, within ICHYMOD the largest dam reservoirs and their operating rules are implemented in order to account for their water releases in the main river network which greatly influence streamflow values. A simplified representation of the input variables into ICHYMOD is reported in figure 35.

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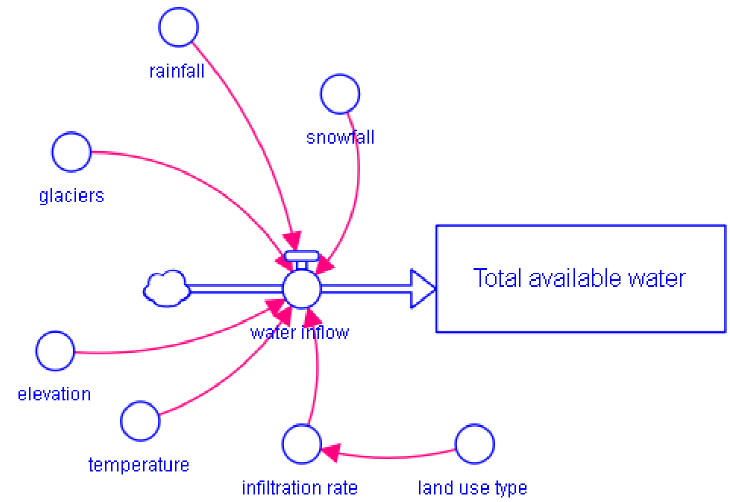

Figure 35: Stock and Flow representation of the total available water from the ICHYMOD hydrological model with the input parameters.

Food security

The food sector focuses on the main crop types distributed within the Adige river Basin accounting for the largest share of water demand in agriculture. Grapes and apple orchards in the upstream part of the basin, maize and rice in the downstream part. Moreover, water demand in agriculture is strongly modulated by the presence and type of irrigation system in place being drip or sprinkler irrigation systems as well as its timing and duration. Moreover, the withdrawals of water for agricultural purposes is theoretically limited by the water concession provided to the irrigation consortia. Although flow measurements in agriculture are sparse, the concession value affects the amount of water actually used in agriculture for irrigation purposes. Given the high number of variable and complexity, the module on agriculture considers and applies the SIMETAW# model (Mancosu et al., 2016, Masia et al., 2021) which provides information on the Net Water Application at a monthly time step with a gridded outputs covering the whole Adige River Basin.

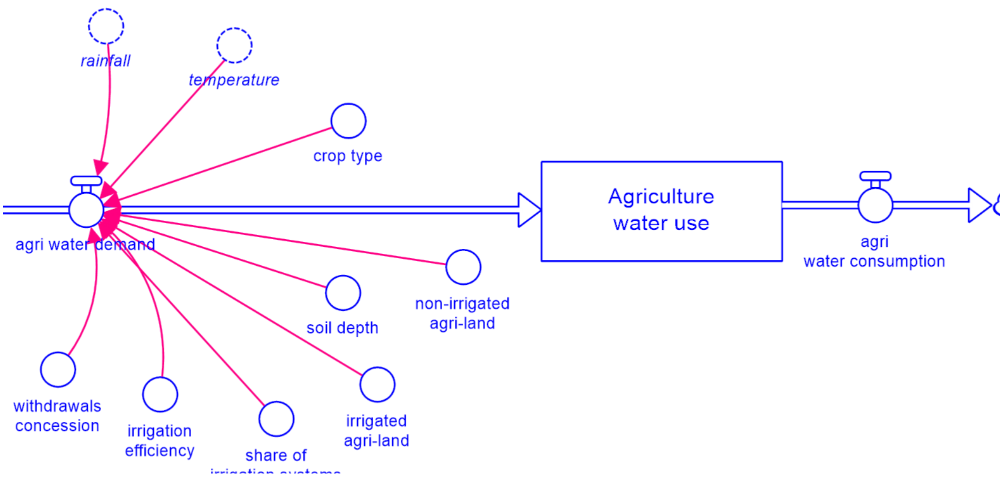

Figure 36: Stock and Flow representation of the water use in agriculture and its underlying parameters.

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Ecosystem Health

The ecosystem health module aims to track a number of relevant ecosystem services (ES) indicators in the Adige case study. Based on literature reviews and the involvement of stakeholders through interviews and dedicated workshops, we developed conceptual models covering specific ES for the case study area. Moreover, the analysis of ES is ongoing and further analysis will be conducted in order to better identify the dynamics among the different ESs. Research activities are undergoing and evaluating the role of land cover in the ESs characterization together with the available data. The carbon storage sequestration can be considered implementing the carbon storage model (Rueschc Gibbs 2008) through the ARIES (ARtificial Intelligence for Environment & Sustainability) platform, for which the organic carbon mass stored (t/ha) is the output indicator which is computed by considering both the vegetation (strongly connected with land use) and soil carbon storage. To analyse the biodiversity losses, the Habitat Quality model (InVest) is under discussion, since it uses habitat quality and rarity as proxies (0-1) to represent the biodiversity of a landscape, estimating the extent of habitat and vegetation types across a landscape, land cover, and their state of degradation (Bhagabati et al., 2014; Terrado et al., 2016). The sediment retention model can be applied to obtain two outputs indicator related to the potential soil removed mass and the soil retained by vegetation computed by calculating the RUSLE equation. Crop yield residuals contribute in the potential of having biomass; the bioenergy potential provides indications on the provisioning of energy, and this is often based on dedicated energy crops which compete with food provision for the use of agricultural land (Mattias et al., 2021); the energy potentially obtainable from crop residues is being considered to determine areas more suitable for sustaining the residues-based supply chains. Further discussion is ongoing and modifications to the SDM might happen to align the ecosystem services with the data availability within the SDM.

Energy security

The energy modules mainly consider the electricity production coming from hydropower plants as in figure 37. This is due to their very large share within the overall production of energy in the Adige River Basin (above 90%). Part of the flow of water simulated through the hydrological model is used for the hydropower water demand and affected by the national energy demand which is here considered as an external parameter.

Besides hydropower, photovoltaic (PV) plants also contribute to the overall production of electricity and are modulated by the amount of available land for installation as well as the production targets, mostly coming from national, regional and provincial policy goals. The sum of the hydropower and PV constitute the renewable electricity production within the Adige River Basin as in figure 37.

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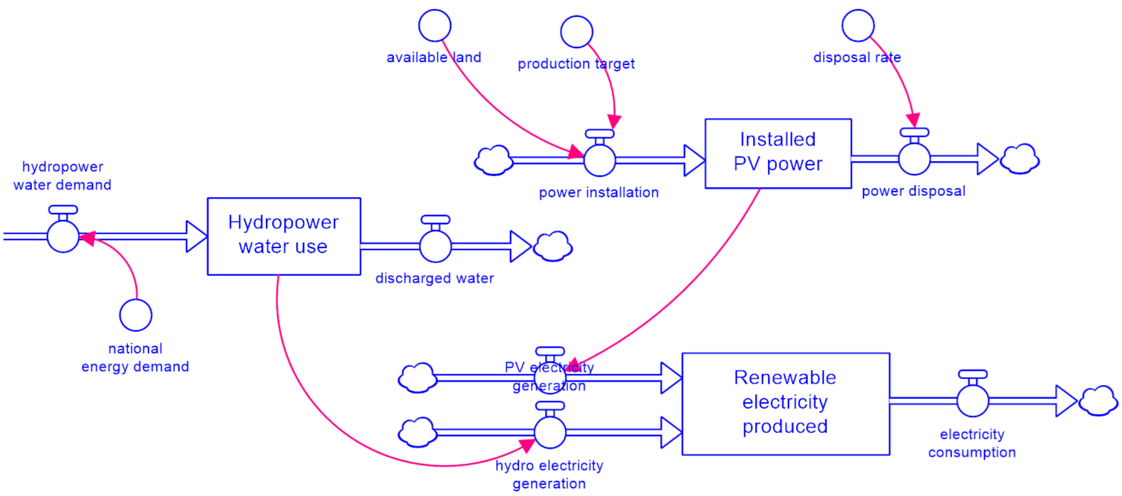

Figure 37: Stock and Flow representation of the energy security sector with hydropower and photovoltaic (PV) power production and underlying parameters.

Population

The population module in the Adige River basin considers both permanent residents and flows of seasonal tourists due to their high number and impact in terms of water demand. Residents are modulated by the rates of births and death as well as the immigration and emigration rates and are evaluated by the change over time using percentage variations. Seasonal tourists play an important role and are modulated by the month of the year as predictor in multi-linear statistical regressions.

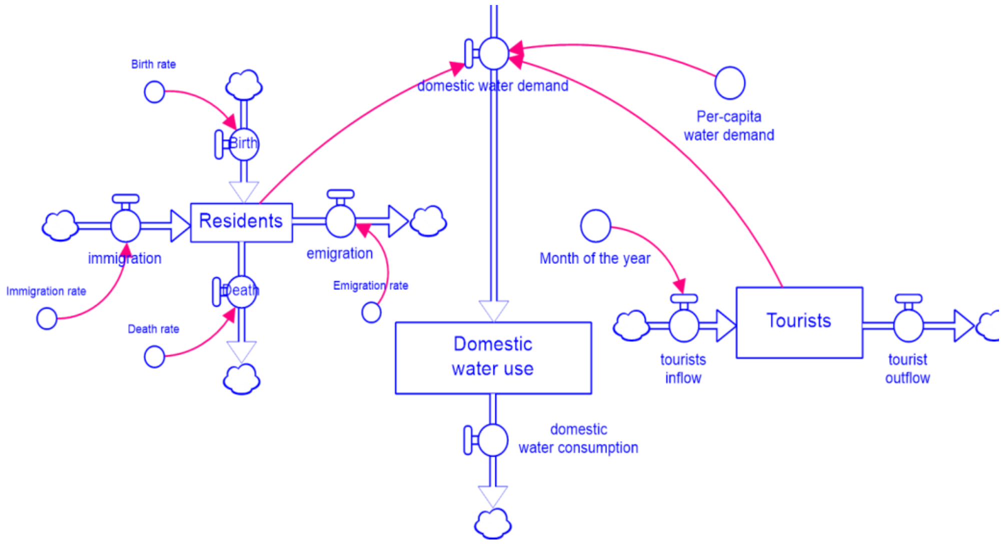

Figure 38: Stock and Flow representation of the population module considering residents and tourists and the underlying parameters.

2.4.3 Data collection and incorporation

A comprehensive description of the data collection process can be found in Deliverable 3.3 “Final report on the application of biophysical models and stakeholder recommendations”.

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The considered datasets belong to those coming from those retrieved and made available in WP2 or have been identified and filtered from local open repositories and provincial portals. In particular, given the spatially explicit nature of some models (for water security and food) the spatial outputs are made available to represent conditions in the different parts of the Adige River Basin represented by in dedicated SDMs and incorporated as time-series to represent dynamic changes. In the presented prototype not all the variables and their analysis are completed and changes might be further implemented. This is particularly relevant due to the ongoing discussions on policy packages and the identified measures by the local stakeholder that will be implemented for creating different scenarios and that can lead to slight modifications to the SDM structure in accordance with the available data.

2.4.4 Preliminary results

Water security

The ICHYMOD model has been already applied to simulate streamflow conditions in different parts of the whole river basin. In particular, two of the three outlet locations of Bronzolo, Trento were considered for calibration and validation of the model outputs as reported in figure 39.

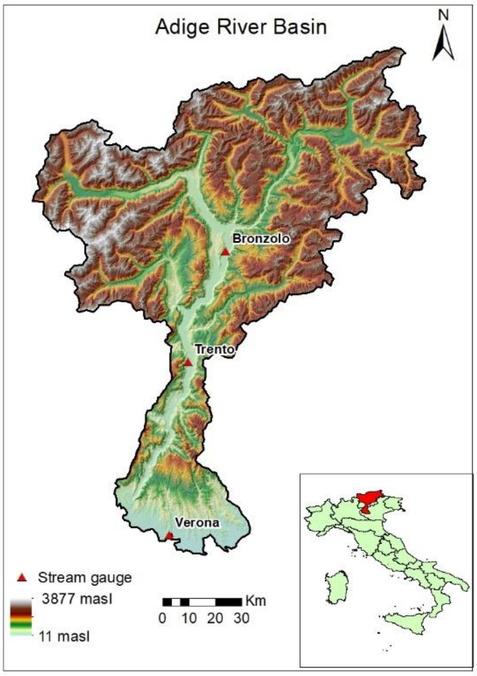

Figure 39: Overview map of the Adige River Basin and the three outlet locations considered for he calibration and validation of the hydrological model

Streamflow simulations in Bronzolo provided a good performance replicating measured values of streamflow in the river as reported in figure 40.

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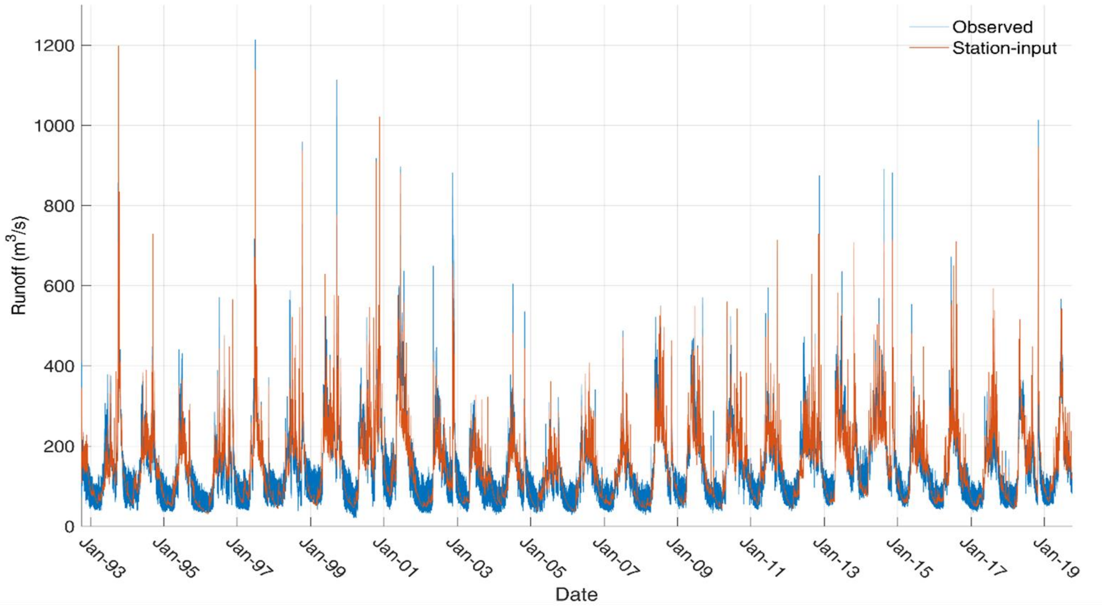

Figure 40: Time series at an hourly time scale of the river discharge (runoff) at the Bronzolo outlet with observed (blue line) and modelled (red line) values. Calibration 2003-2019 and validation 1992-2003, squared-R of 0.82 (calibration and validation) and Kling–Gupta efficiency of 0.89 (calibration) and 0.85 (validation).

Moreover, similar performance was obtained for the Trento outlet, showing promising results for the final evaluation of the total water availability in different parts of the Adige river basin as well as the amount of hydropower from the main dam reservoirs.

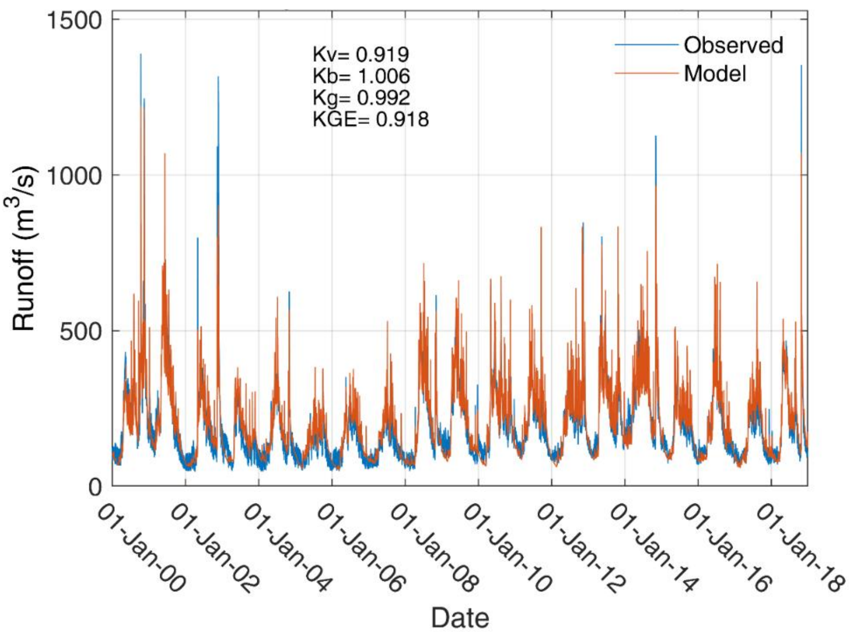

Figure 41:Time series at an hourly time scale of the river discharge (runoff) at the Trento outlet with observed (blue line) and modelled (red line) values.

2.4.5 Next steps and further work

The next steps for the Adige River Basin are here reported:

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1) Reiterating the structuring of the SDM based on data availability and the incorporation of policy packages;
2) Expanding the hydrological model to cover:
   a. Calibration and validation for downstream parts of the catchment
   b. Glacier melt contributions on base streamflow and especially during low flow conditions
   c. Exploring changes in the initial set up to integrate policy package scenarios
3) Simulations and validation of the water consumption in agriculture with SIMETAW#;
4) Advancing the representation of ecosystem services and the application of dedicated models;
5) Finalise data requirements and its collection both from WP2 and from local data sources and following up with local stakeholders.

Further work is expected to advance in the next months by the end of 2023-early 2024. In addition, further work includes incorporation of the climate (RCP) and socio-economic (SSP) scenarios, as well as integrating locally-relevant policy actions and the WEFE nexus footprint calculation.

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2.5 Case Study #5: Inkomati-Usuthu (South Africa)

2.5.1 Conceptual model recap

The conceptual map developed for this CS was reported in detail in Deliverable 3.1 “Conceptual models completed for all the case studies”. This section presents a brief recap of the conceptual map rather than a repeat of the information in D3.1. The ‘top-level’ conceptual map, showing the main connections between the WEFE sectors is shown again here in figure 42. Further from this, detailed conceptual maps for each WEFE sectors have been developed and reported in D3.1. Here, just the example from the water sector is shown in figure 42 as an illustration of the level of detail included. To view the conceptual maps for each WEFE sector, see Deliverable 3.1, Section 4.5.2. All conceptual maps have been discussed with and validated by stakeholder during case study stakeholder workshops.

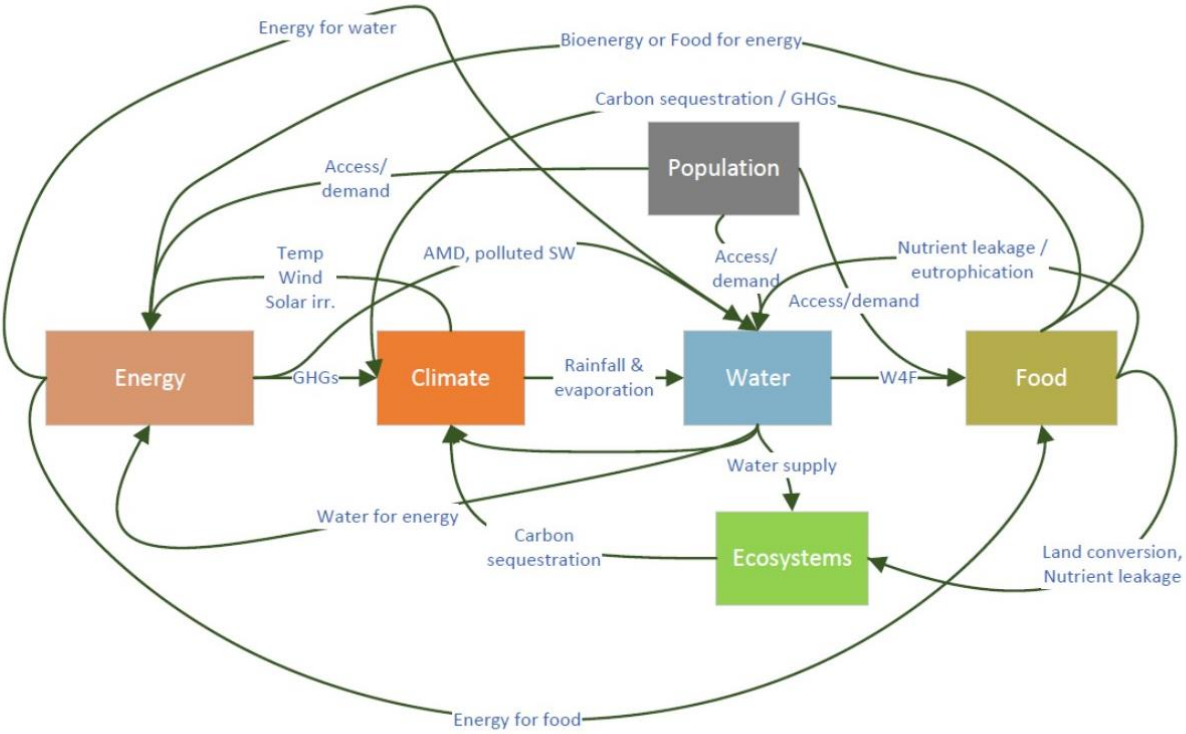

Figure 42: Top-level conceptual map for the Inkomati-Usuthu case study.

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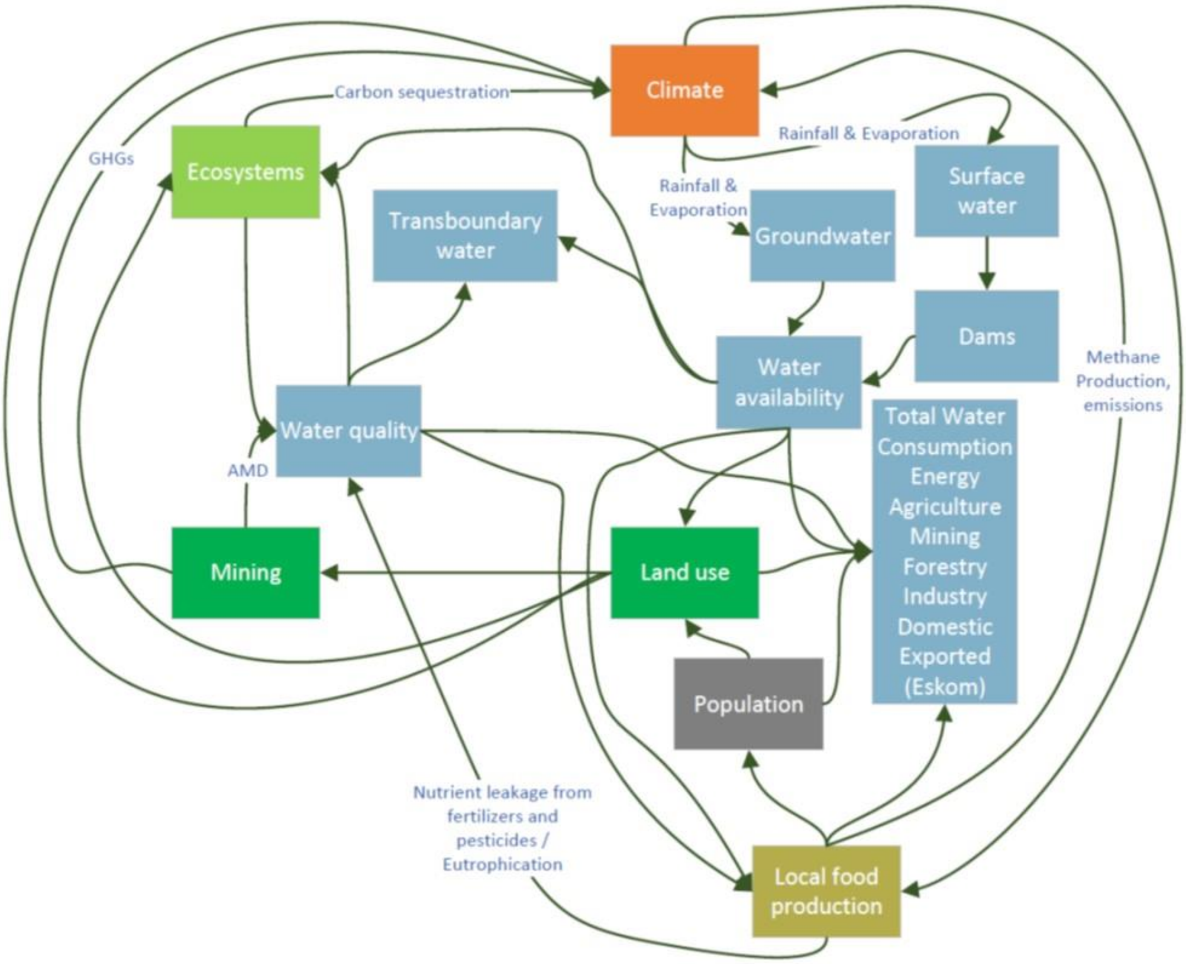

Figure 43: Detailed water sector conceptual map for the Inkomati-Usuthu case study.

2.5.2 System Dynamics Model description

This section describes the Inkomati-Usuthu SDM as currently developed. It is a reflection of the details captured in the conceptual model for the case study (D3.1). This draft model structure will be refined over the latter half of 2023 to account for final selection and availability, for the opportunity to carry out uncertainty and sensitivity tests, and for the inclusion of identified policies and policy packages as well as the WEFE nexus footprint. The model is a single model covering the entire study area (i.e. it is not split into sub-basins).

2.5.2.1 Top level model

The top-level of the Inkomati-Usuthu SDM is shown in figure 44. This is equivalent to the top-level conceptual map (figure 42), and simply shows the connections between the various nexus sectors. As shown, the population influences water, food, and energy sectors. Water is connected to the ecosystems sector. Energy is connected to the climate sector. Food is connected to the energy, ecosystems, and climate sectors. Land use is connected to the water, food, ecosystems, and climate sectors. The ecosystems sector is connected to the climate sector, and the climate sector connects to the water sector. The top-level model indicates a complex system with many connections. Each rounded blue box in figure 44 contains a detailed sectoral sub-model, described in the following sections.

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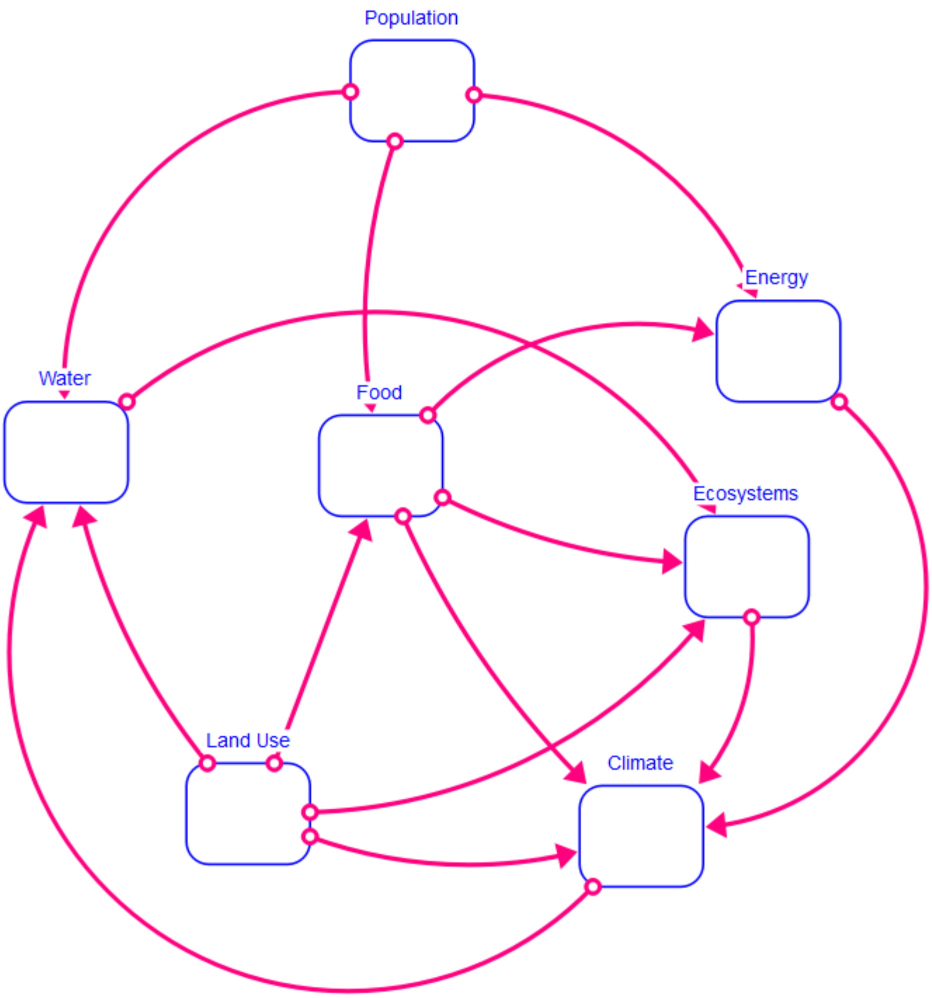

Figure 44: Top-level Inkomati-Usuthu SDM.

2.5.2.2 Population sector

The population sector (figure 45) simply tracks population change over time and will be forced by percentage changes given under the different SSPs deriving from WP2 data (D3.3). Because population change will take 2015 as a base year and then be changed over time using percentage variations, a structural change to the model is required compared to that shown in figure 45, however this structural change has no significant impact on the model results. In figure 45, the population stock (square box) is added to by births and immigration, and depleted by deaths and emigration. In future iterations, a baseline population stock will simply be changed by percentage variations given by WP2 data.

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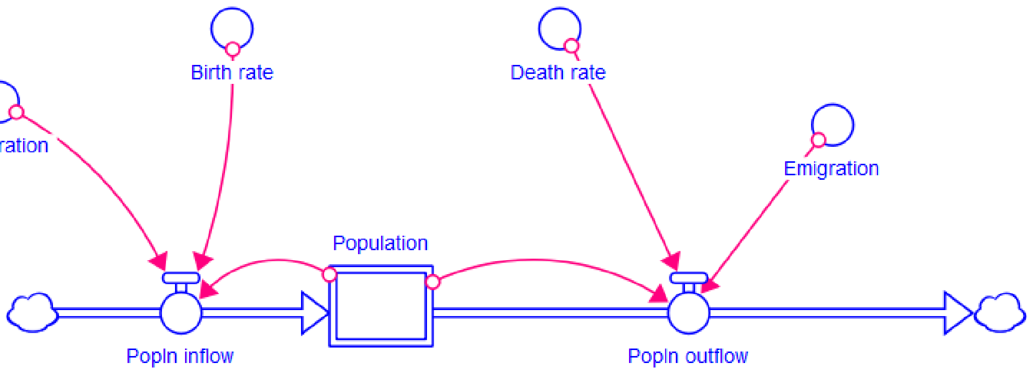

Figure 45: The population module of the Inkomati-Usuthu SDM. Note that this structure will change to accommodate the type of data coming from WP2 sources.

2.5.2.3 Water sector

The water sector (Figures 46 and 47) consists of two blocks, one for quantity, and another for quality. For water quantity, the trend of water balance (relatively from a 'zero' initial value) will be tracked over time. Water supply consists of surface and ground water (both modulated by the climate system, e.g. the RCPs), dams (reservoir storage), and any transboundary obligations. Water demand is controlled by industrial demand, domestic demand (which is modulated by the population), water exported outside of the basin, forestry water demand (influenced by the land use sector), mining water demand, and agricultural water demand, controlled by the irrigated land use area.

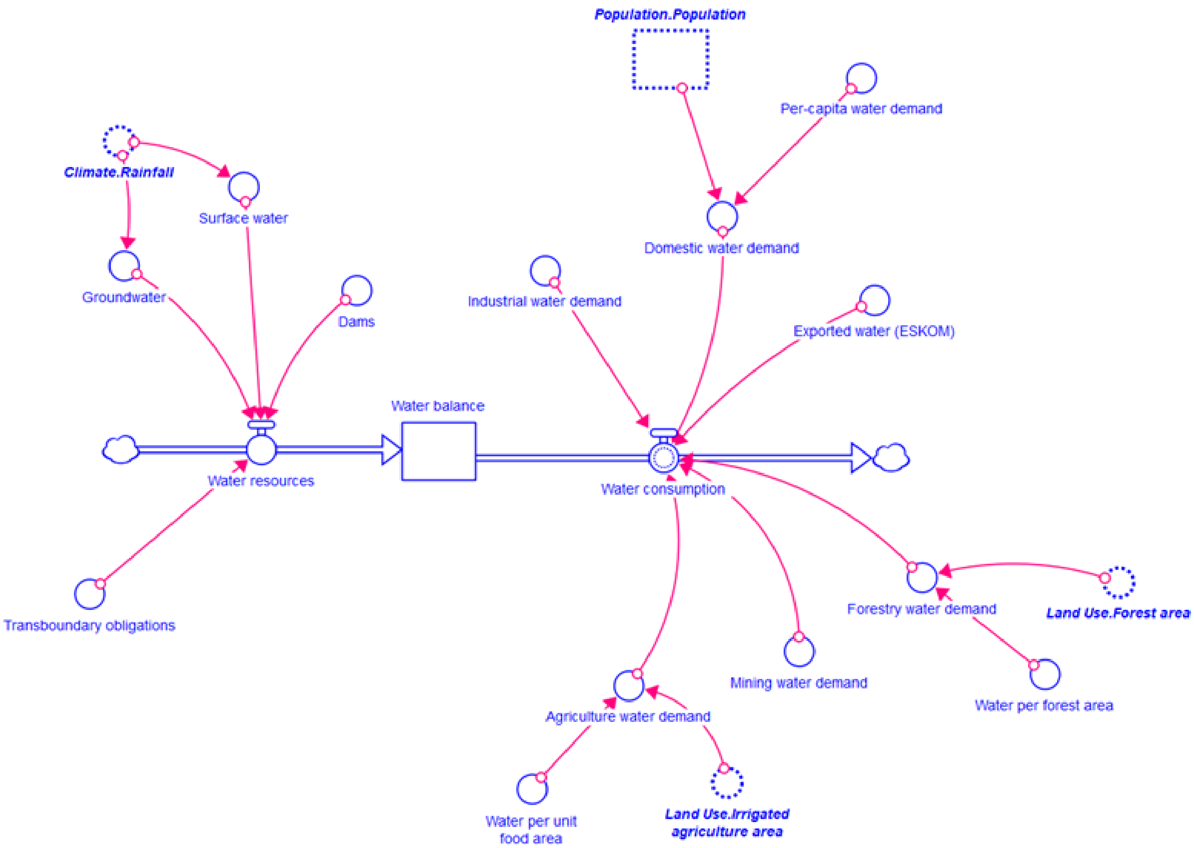

Figure 46: The water sector quantity part of the Inkomati-Usuthu SDM.

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The water quality block (figure 47) consists of aggregating the nitrogen (N) runoff from a number of sources. These sources include N runoff from rainfed agriculture, irrigated agriculture, mining land, and forestry. From N runoff from each of these class is modulated by the land use of each class (in the Land module) and a N runoff per-area coefficient.

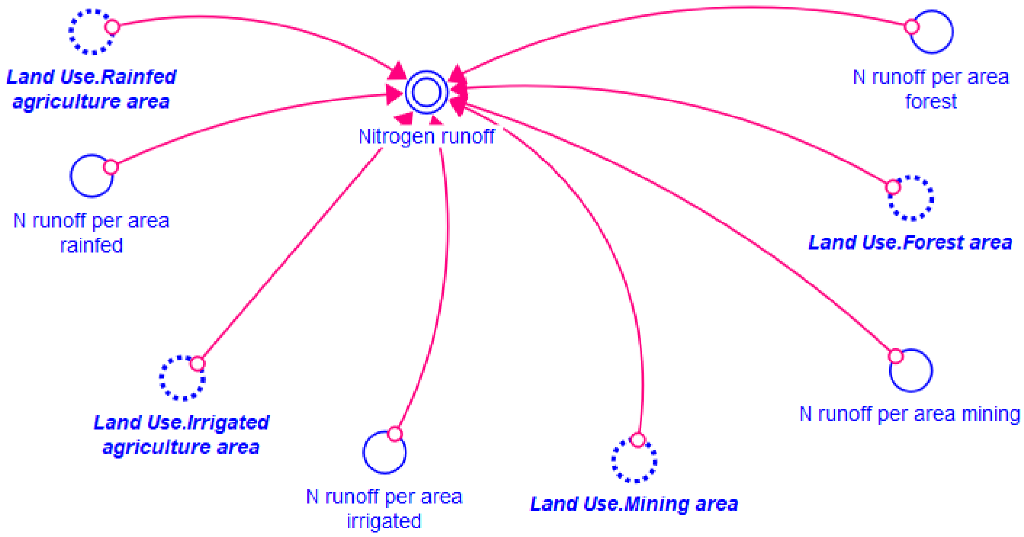

Figure 47: The water sector quality part of the Inkomati-Usuthu SDM.

2.5.2.4 Energy sector

The energy sector module (figure 48) represents an energy balance (solid square box) between energy supply and demand. Energy supply is split between fossil fuels supply coming entirely from outside the study area, and renewable energy supply generated within the case study. Energy consumption is from the agricultural sector, modulated by food production, mining energy use, industrial energy use, energy used in the forestry sector, and domestic energy use, itself controlled by the population and per-capita energy use data. In addition, and energy security metric hopes to be defined using information of the ratio between supply and demand, and the access to electricity in the study area.

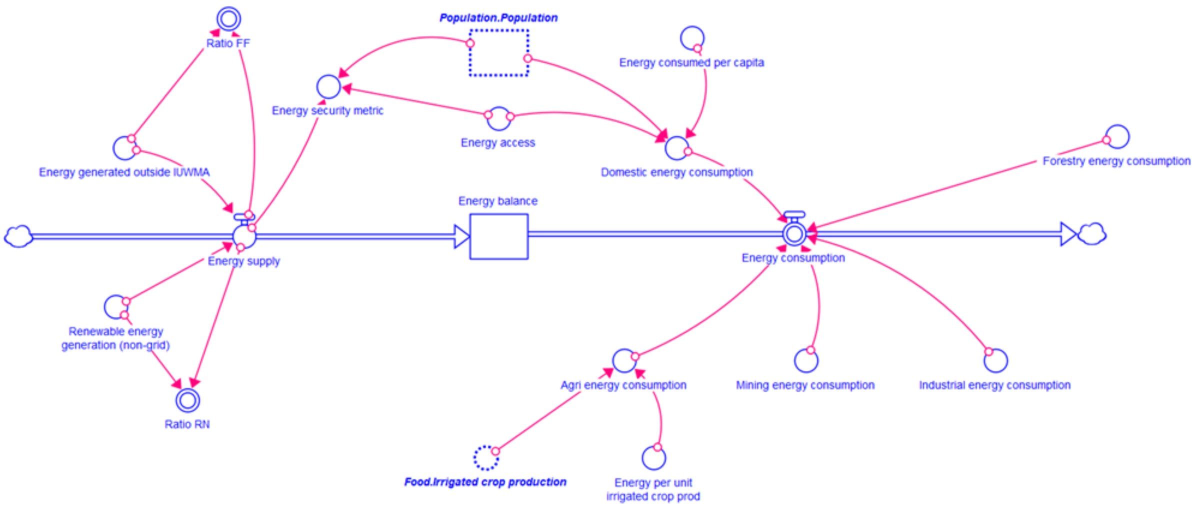

Figure 48: The energy sector module for the Inkomati-Usuthu SDM.

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2.5.2.5 Food sector

The food sector module (figure 49) considers food production and consumption. Food production is split into rainfed and irrigated production. A number of crops under rainfed and irrigated production will be considered, but at the time of writing, these are not yet finalised. Production will be calculated as the product of the area under cultivation per-crop type (split by rainfed and irrigated) and the yield per-area of that crop type. In addition, the N and pesticide application rates will be estimated for crops under rainfed and irrigated production separately. Therefore, there are links to the land sector, and to the water sector (for the N runoff which impacts on water quality). In addition, livestock production may also be considered as well as crops, as long as appropriate data can be sourced. Food imports to region and exports from the region may be accounted for if data are available. On the food consumption side, the population modulates this, together with statistics on per-capita food consumption. The balance is simply the difference between supply and demand.

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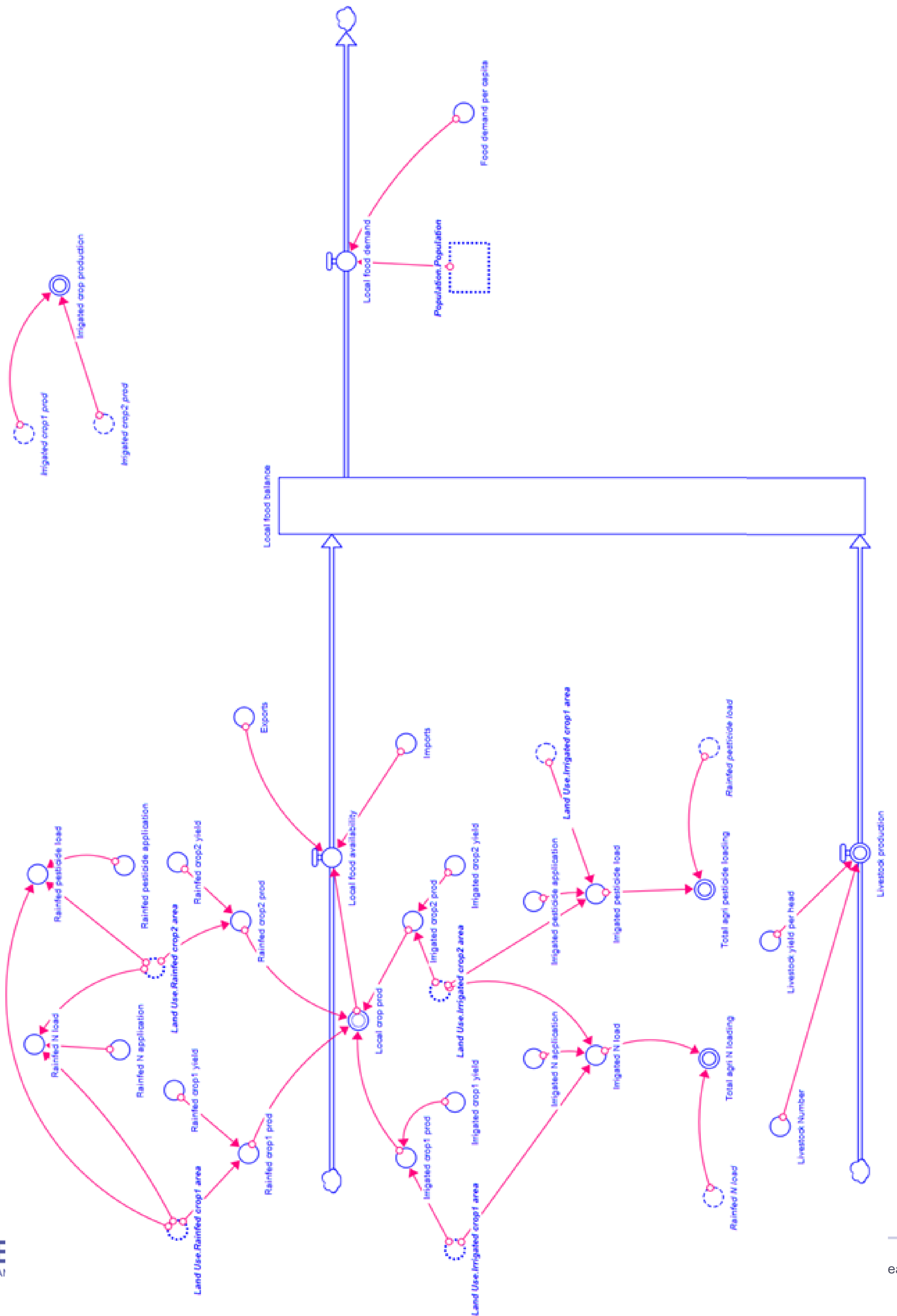
Local food balance
Local food demand
Food demand per capita
Population.Population
Irrigated crop production
Irrigated crop1 prod
Irrigated crop2 prod
Exports
Imports
Local food availability
Local crop prod
Rainfed pesticide load
Rainfed pesticide application
Rainfed crop2 yield
Rainfed crop2 prod
Land Use.Rainfed crop2 area
Rainfed N load
Rainfed N application
Rainfed crop1 yield
Rainfed crop1 prod
Land Use.Rainfed crop1 area
Irrigated crop2 prod
Irrigated crop2 yield
Land Use.Irrigated crop2 area
Irrigated crop1 prod
Irrigated crop1 yield
Land Use.Irrigated crop1 area
Land Use.Irrigated crop1 area
Irrigated pesticide application
Irrigated pesticide load
Total agri pesticide loading
Rainfed pesticide load
Irrigated N application
Irrigated N load
Total agri N loading
Rainfed N load
Livestock yield per head
Livestock Number
Livestock production

Figure 49: *Food module in the Inkomati-Usuthu SDM.*

2.5.2.6 Land use sector

The land use module (figure 50) will track the area of land covered by different land use classes. In the current model development, rainfed and irrigated lands are individually tracked, these being broken down by the specific crop types, forming a link to food production. The area under mining, forests, and wetland areas are also to be tracked. New area types may be added depending on data availability. This module will allow the tracking of the implications on other sectors (e.g. food production, water quality impacts) of changes to land use coverage in the Inkomati-Usuthu case study.

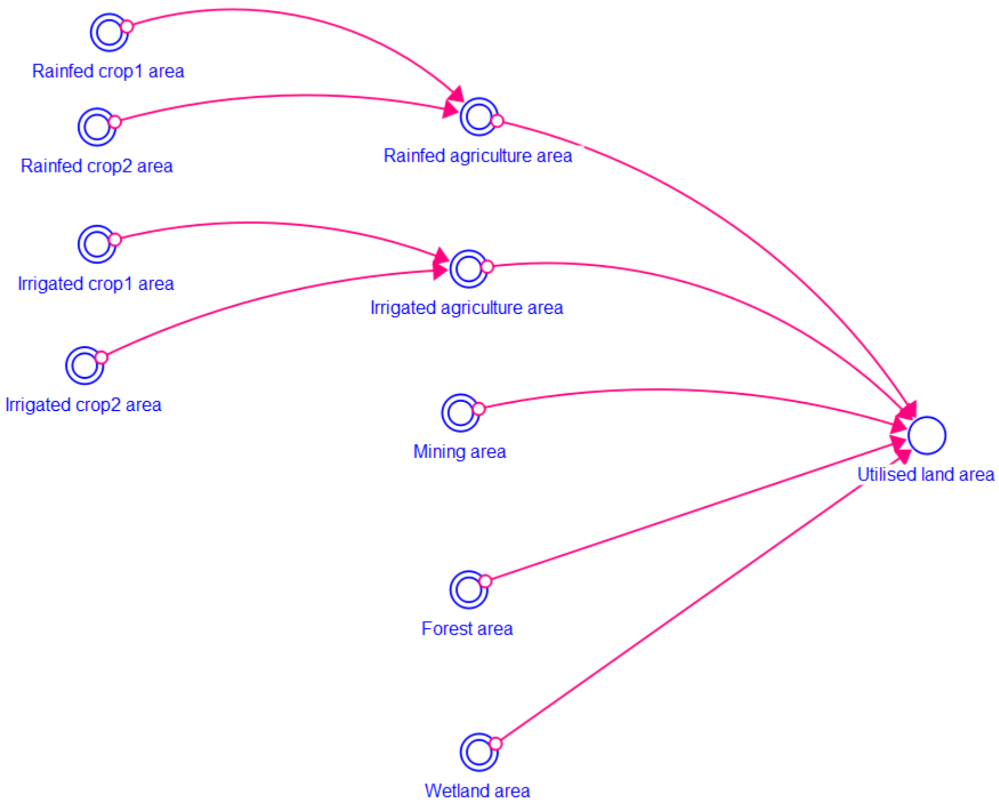

Figure 50: Land use module in the Inkomati-Usuthu SDM.

2.5.2.7 Ecosystems sector

The ecosystems module (figure 51) aims to track a number of relevant ecosystem parameters in the Inkomati-Usuthu case study. The vegetated area is composed of land covered by rainfed and irrigated agriculture, wetlands, and forests. This area then contributes to estimating the carbon (C) mass stored in vegetation as an ecosystem function. The mean species abundance of birds and mammals will be tracked, as will the water stored in wetlands. The total above ground biomass hopes to be estimated, and is made up from the biomass on agricultural and forestry lands. There is clearly a link between ecosystems and the land use module. The water quality, N runoff, and pesticide application mass contribute to degrading ecosystems. The above-ground biomass and C stored in vegetation contribute to C sequestration, a climate-related service.

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It is still unclear how to track the 'ecosystems metric', and its composite parts, but one idea is to renormalize the data so that in the base year (2015), the metric is equal to 1. Then changes over time will be tracked relative to this 1, with increases representing 'improvement', and decreases representing 'degradation'. Because the base value is known along with the fractional change over time, absolute values can be recovered if desired. This renormalisation procedure also allows for the relative comparison of ecosystems performance over time between all five case studies. This is very difficult based on absolute values because the very meaning of an ecosystem is so diverse between the NEXOGENESIS case studies, so comparing absolute numbers would be misleading and probably unfair. Track relative trends however can give an indication of relative ecosystems response, and point out potentially troubling issues in the future, or highlight positive ecosystems trends under different policies.

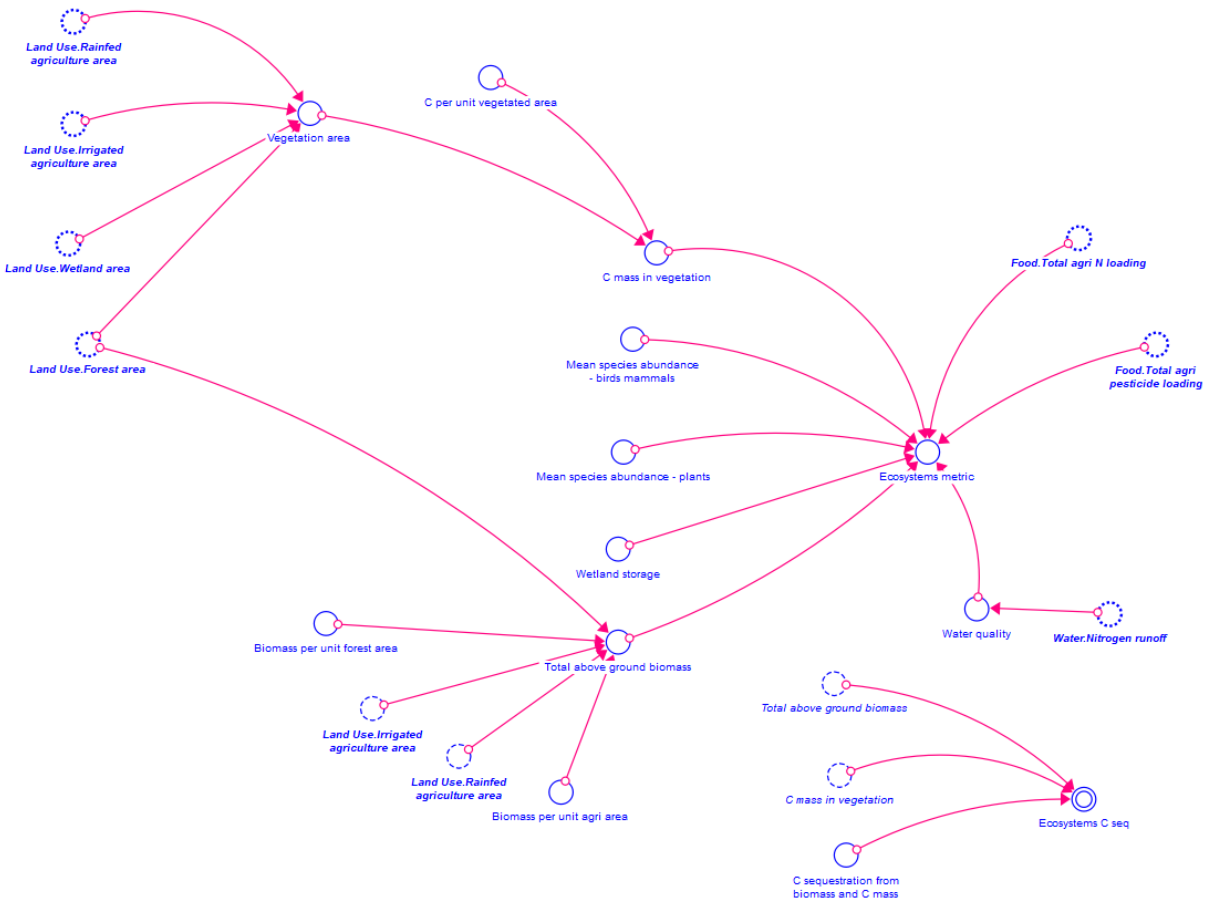

Figure 51: *The ecosystems module in the Inkomati-Usuthu SDM.*

2.5.2.8 Climate sector

In the climate sector, the SDM (figure 52) aims to consider primarily GHG emissions. Sequestration may be considered, but past experience shows that this tends to be vastly underestimated, so this may be neglected to reduce uncertainty in the output. For GHG emissions, a number of metrics are tracked. The emissions from livestock production will be tracked, forming a link to the food sector. Emissions from mining in the region will also be estimated. Emissions from agricultural production, separate to livestock production, will be tracked and split by rainfed and irrigated agriculture. The emissions from renewable energy consumption and fossil fuel-based energy consumption in the case study area will be estimated.

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It is noted that a decision has been made not to estimate the GHG emissions from energy production as most of the energy produced in all NEXOGENESIS case studies is produced outside the study basins, and therefore a GHG attribution to this production is extremely challenging and introduces large uncertainty. Instead, GHG emissions will be attributed to local (i.e. within case study basin) energy consumption, which can be more reliably assessed. When combined with knowledge of the energy mix, more reliable estimates of consumption-based GHG emissions can be derived. This also allows assessment of the impact of energy policies, for example to replace fossil fuel sources with renewables.

All emissions will be expressed in units of CO2-equivilent (CO2-e), in units of tons (of multiples thereof) using well established emissions factors related to different sectors of the economy (e.g. emissions factors for agricultural production, or fossil fuel-based energy consumption under different activities in different regions).

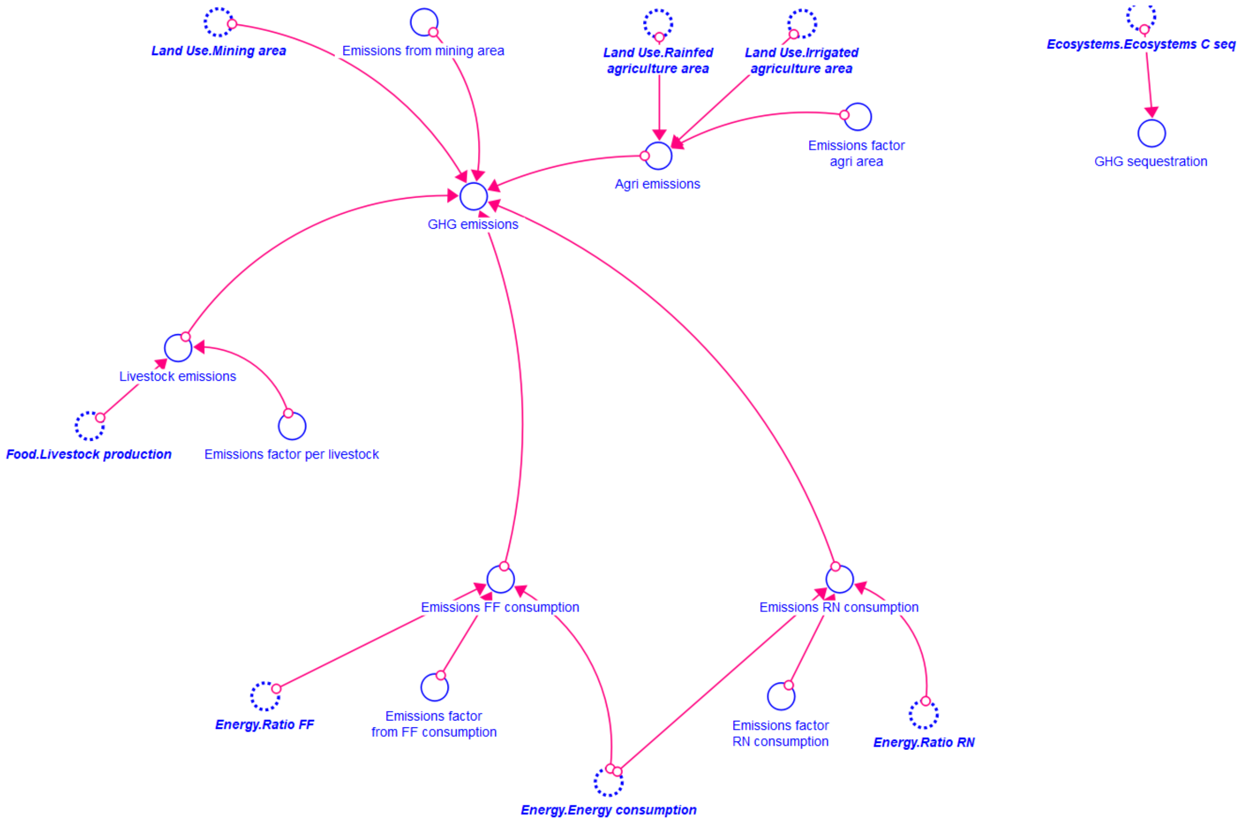

Figure 52: The climate module for the Inkomati-Usuthu case study SDM.

2.5.3 Data collection and incorporation

In a similar way to the conceptual maps, the data identification and description for all NEXOGENESIS case studies is reported fully in Deliverable 3.3 “Final report on the application of biophysical models and stakeholder recommendations”. Here, in Section 3.5.2, the data identified for the Inkomati-Usuthu case study has been described in detail, both from WP2 sources, and from local sources where necessary (e.g. related to detailed mining activities not covered in WP2). These data sets, either existing as constants (i.e. unchanging over time) or as time-series (e.g. surface water runoff, percent changes in population over time), are incorporated where possible into the SDM as currently developed (Section 2.5.2). At the time of writing, where data are not available, these parameters have been given the value ‘0’ (zero),

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and can either be updated with data as they become available, or deleted if data are not available. In this prototype draft, not all data analysis is complete at the time of writing. Therefore, some variables which may be subject to future uncertainty analysis are here reported simply as deterministic timeseries'. This is an avenue for further work in NEXOGENESIS (see Section 2.5.5). In addition, new variables may be added to allow for the incorporation of identified policies and policy packages and to explore their nexus wide impacts. This is also a work in progress, with research possibly leading to slight modifications to the SDM structure, as well as to changes in data needs.

As the model structure is not finalised at the time of writing, the data inputs are also not finalised. In addition, the policy packages are not fully incorporated into the current model version. Finally, uncertainty and sensitivity analysis is not yet possible as the data analysis work is not yet complete. This implies that all results in the next section are strictly preliminary, subject to change, and are not to be used for scientific or policy comment.

2.5.4 Preliminary results

This section presents the preliminary results of the Inkomati case study SDM as of July 2023. As mentioned above, and below in Section 2.5.5, this is a draft, and future modifications will be made to data, the model structure, and therefore the results as work develops throughout 2023. As made explicit in the disclaimer, the results presented here are preliminary only and for illustration, and are not to be used for scientific statements or policy advice.

2.5.4.1 Population

The Inkomati population starts at 2081589, and ends in 2050 at 2556949 (figure 53). The growth rate is forced by WP2 socio-economic data for the SSP2 scenario.

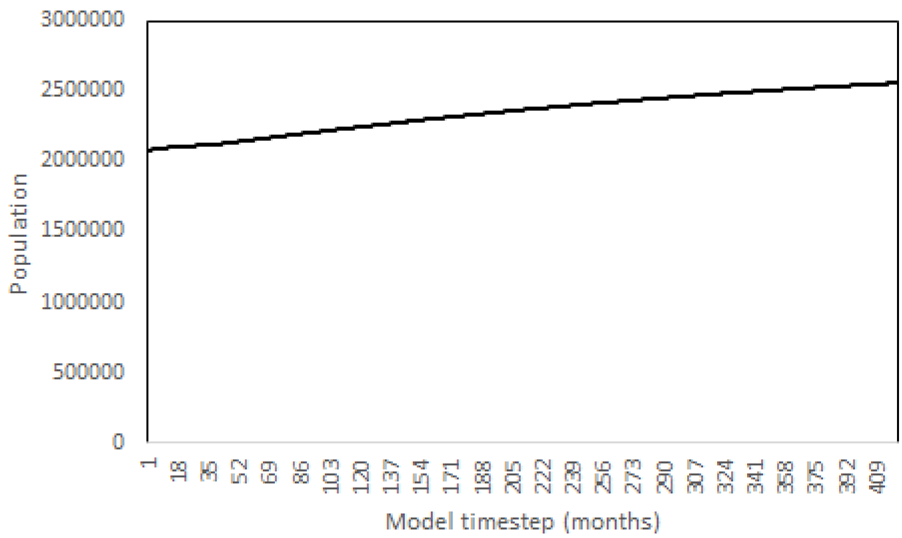

Figure 53: Preliminary population results in the Inkomati case study.

2.5.4.2 Water

In the water sector, results (figure 54) show a significant mismatch between supply (blue line) and total demand (black line). This is likely due to missing data, and is a situation that will be

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looked into and rectified moving forwards. Supply at the moment is largely driven by surface water and dams, while demand is dominated by the domestic sector (orange line) and agricultural sector (green line). Mining, industrial, and forestry water demand figures need updating in the model. Domestic demand is modulated by the population, while forestry demand is controlled by the forest area. Groundwater supply and transboundary obligations also need improved model representation.

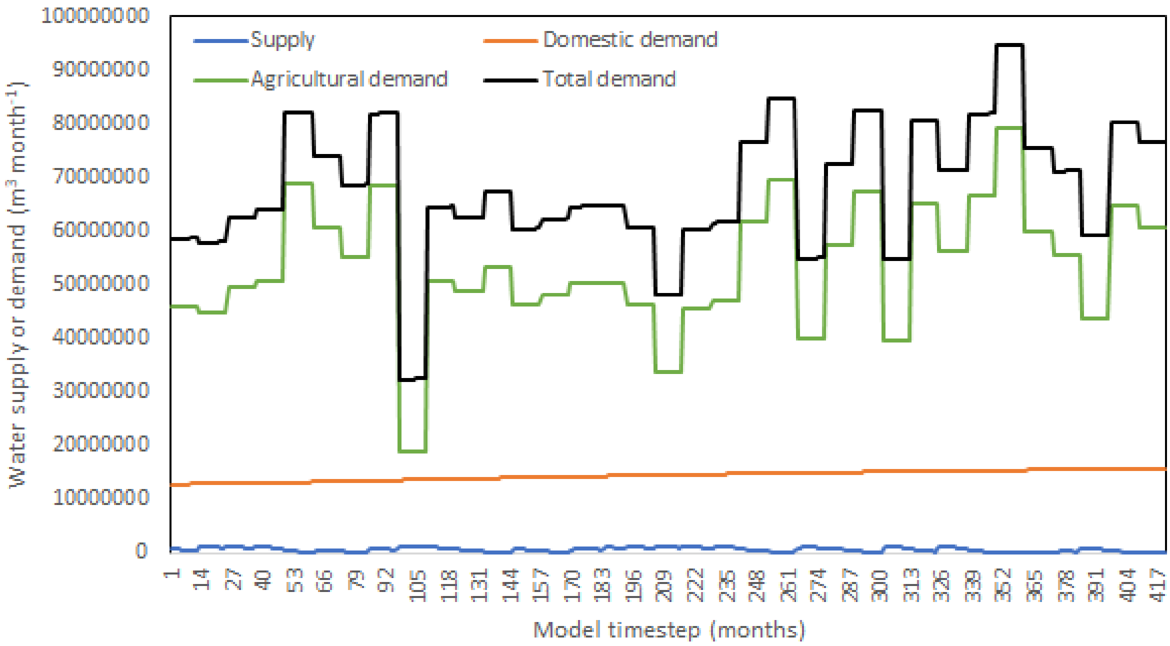

Figure 54: Preliminary results in the water sector for the Inkomati case study.

2.5.4.3 Energy

Energy results (figure 55) show that current energy supply (at the moment entirely from energy supplied from outside the study area (black line); local renewable supply is not yet represented), is sufficient to meet presently modelled demand. Energy demand appears to be dominated by the domestic sector, controlled by the population and the percent access to electricity in the study area. Industrial energy consumption is next in importance, followed by agricultural energy demand (modulated by food production amounts and changes in food production). Mining energy use is the lowest energy consumer in the study area. Forestry energy use is not yet represented, and improvement is also needed to represent local renewable energy sources.

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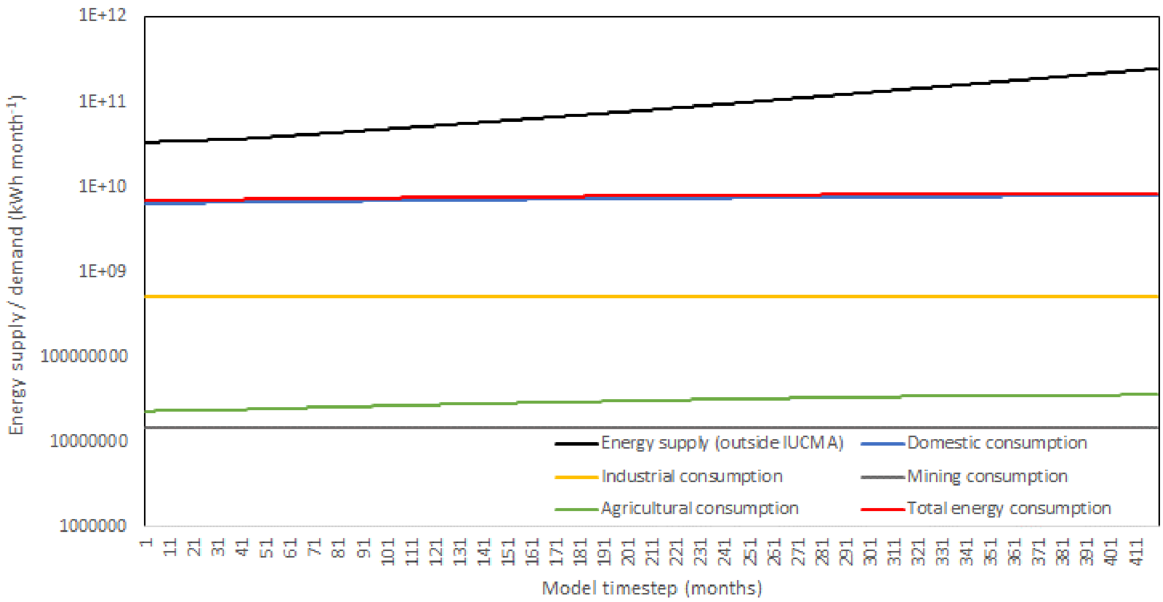

Figure 55: Preliminary energy results for the Inkomati case study.

2.5.4.3 Food

In terms of the food sector, results (figure 56), in the preliminary results, demand outstrips supply. However, not all supply sources have available data yet, and are thus represented. In addition, import and export statistics are not yet in the model. Therefore, the food supply sector does need additional information to better represent food availability. Food supply is modulated by the land area covered by different crops, which may change in the scenarios. Livestock production is also unaccounted for in this model version. In terms of food demand, the population largely controls the total case study food demand. However, a food demand growth factor from WP2 data also regulates the temporal change in demand pattern.

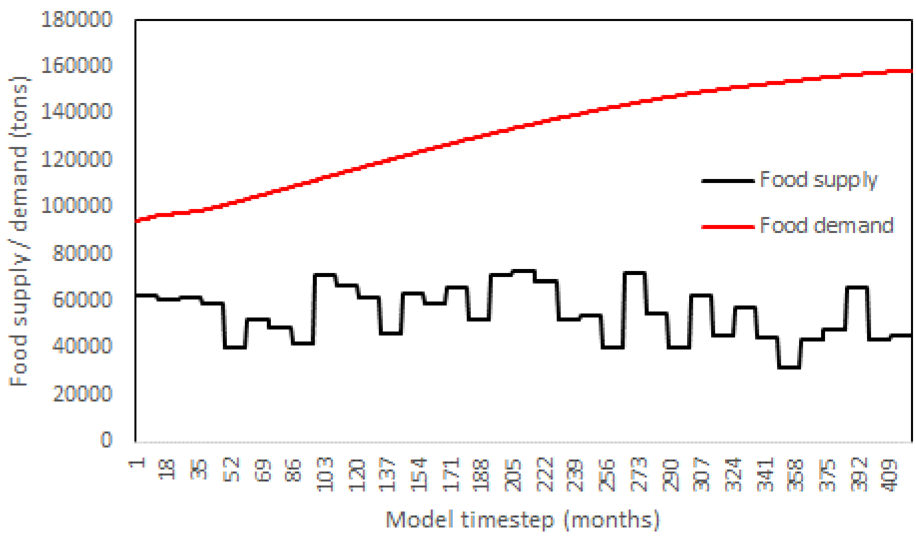

Figure 56: Food sector results for the Inkomati case study.

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2.5.4.4 Land

In the land sector (figure 57), forest land dominates the land cover, followed by grasslands. Rainfed and irrigated agriculture are also important land uses. Other categories are relatively minor. Land is used to modulate food production values, energy use, and carbon emissions impacts. Results presented here need validating. In addition, there is currently no change in land use areas over time.

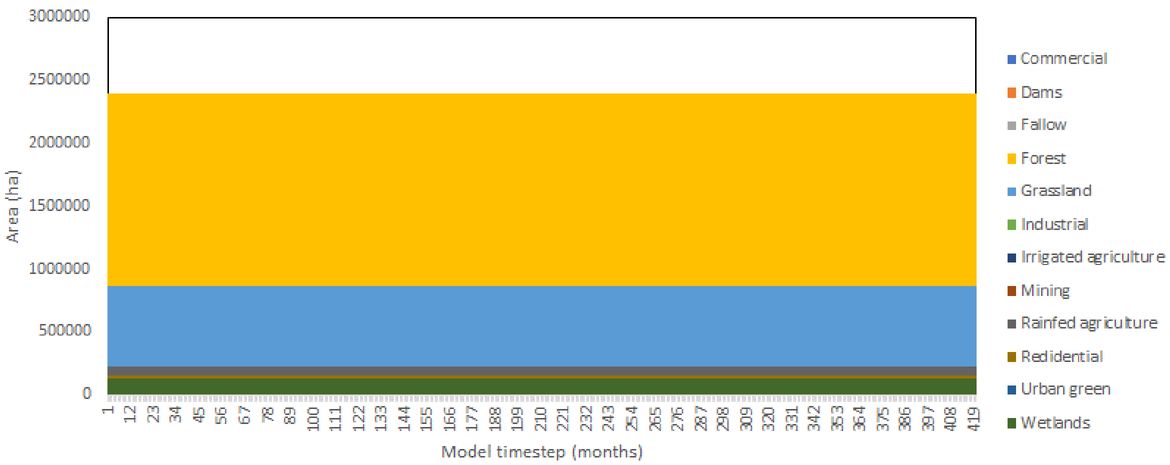
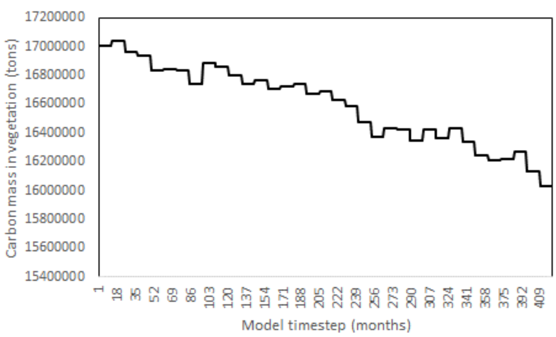


Figure 57: Preliminary results in the land sector of the Inkomati case study.

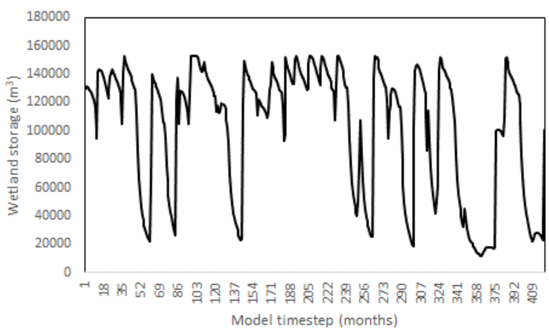
2.5.4.5 Ecosystems

For ecosystems, a number of metrics are currently tracked (figure 58). The carbon mass stored in vegetation (figure 58a) shows a gradually decreasing trend over time. Wetland water storage (figure 58b) is highly variable though on first inspection does not suggest a negative trend of reduced storage over time. The total above ground biomass (figure 58c) is stable. At the moment, nitrogen runoff is poorly represented in the model, and biomass in forests, and the mean species abundance for fish and mammals and plants do not have data. Similarly, data on carbon sequestration is missing. These are improvements for future iterations. Finally for ecosystems, how to represent the ecosystems sector with one meaningful value for all NEXOGENESIS case studies is still under research, to be included in the WEFE footprint.

(a)



(b)



(c)

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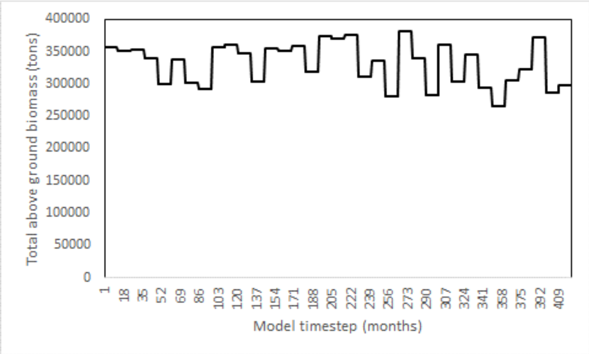

Figure 58: Preliminary results of carbon mass stored in vegetation (a); wetland water storage (b); and the total above ground biomass (c) for the Inkomati case study.

2.5.4.6 Climate

In the climate sector, only agricultural emissions and emissions from fossil fuel consumption have been quantified. Of these two, the emissions from fossil fuel consumption dominate, and are very likely to be unreasonably high (in the order 1017 tons CO2-e). This means that these data and emissions factors need checking and verifying. In addition, emissions need to be attributed to renewable energy consumption, mining activities, and livestock rearing, with data so far not available. At the same time, data on carbon sequestration are not available, representing another gap to fill and further work.

2.5.5 Next steps and further work

The next steps in the Inkomati case are stated in the following points:

1) Continue to iterate on model structure to harmonise with data available from WP2 sources and from local sources, to account for uncertainties, to update as needed, for example to disaggregate crop types or land use classes, and also to be able to incorporate policy packages in discussion with the CS lead partner (JAWS);
2) Finalise data requirements to suit modelling and CS needs, both from WP2 and from local sources (linked to point (1));
3) Related to point (1), integrate the policy packages identified, accounting for data restrictions;
4) Use data from all the RCPs and SSPs to fully represent uncertainty associated with scenario variability;
5) Development of the WEFE nexus footprint;
6) Carry out data analysis on input data to be able to run uncertainty and sensitivity tests on the model using Monte-Carlo procedures;
7) Finalise model output for discussion (including scenario analysis of the SSPs and RCPs, uncertainty and sensitivity tests, and policy impacts) and validation with stakeholders during future NEXOGENESIS CS stakeholder workshops.

This work will take place over a period of a few months, aiming to be completed by late 2023 or early 2024.

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3. Further work in NEXOGENESIS

The preliminary models described here will continue to be refined and developed in 2023 and the first half of 2024 until they are in a final state. The use of locally specific models in the case studies is essential to address the unique characteristics and needs of each case study. The case studies are highly diverse, ranging from Europe to South Africa, with varying geomorphological, policy, and biophysical characteristics. However, they all rely on consistent global data derived from WP2 to ensure coherence across the studies. In addition, each case study was required to tailor its approach to local specifications, carefully considering the feedback gathered from stakeholders throughout the co-creation process in Workshops 1-3. This iterative feedback loop allowed for the identification of specific challenges, needs, and priorities unique to each case study region. As a result, the models needed to be adapted to reflect these local conditions, ensuring their relevance and effectiveness.

This will require a variety of further work, including:

- Finalising data availability (with WP2 input), for example to account for all climate and socio-economic scenarios, to disaggregate crop and land use types, to account for case-study specific requirements such as transboundary water obligations, and to cover the ecosystems sector in an adequate way. These discussions are ongoing within the project;
- Define and incorporate calculation of the WEFE Nexus Footprint for all case studies;
- Data analysis to prepare for uncertainty and sensitivity analyses, neither of which are incorporated in these early prototypes;
- Inclusion of validated policy packages (with WP1 and 5 input). The policies to be modelled and assessed are not yet finalised for all case studies, and therefore are not at this stage included in the models;
- To account for the above point, refine model structures to account for data availability, uncertainty testing, scenario analysis, and policy impact assessment;
- Eventually (i.e. at a much later stage of model maturity in all CSs), addressing standardisation across all the SDMs (e.g. in variable naming convention) to help facilitate the work in WP4.

~~It is noted that in the project, the Nestos/Mesta CS and the Lielupe CS are 'frontrunner' cases as these have prior experience with the modelling process (from SIM4NEXUS). As a result, these two cases may progress as a more rapid rate than some of the others. This will lead to slight differences in modelling maturity as 2023 progresses and also helps understand differences in maturity of the prototypes described here.~~

~~Another aspect here is to validate model output with stakeholders. This will happen at future Case Study stakeholder workshops to happen later in 2023 (October-December) and in the first quarter of 2024.~~

~~Finally, the models presented here will be handed over and discussed with WP4 for incorporation into the machine learning and artificial intelligence tools and the development of NEPAT in NEXOGENESIS, ultimately leading to suggestions on optimal policy combinations to streamline water-related policies into the nexus.~~

The SDMs developed as part of WP3 have been presented at Workshops 3 in the case studies, and their structure (i.e. nexus linkages, policy entry points, policies to assess in the models, etc.), were discussed in these Workshops (the Workshops are described in the MS23

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documents – one per case study. These Milestones include the details of those workshops such as timing, locations, activities, outcomes, etc., and are thus not reproduced here). The prototype models presented here at the time of Deliverable submission, have since, via the workshops and distinct 'modellers workshops' held in Delft in November 2023 and January 2024, been finalized to include all data, scenarios (i.e. the SSP-RCP futures of which there are four), policies, and variables to calculate the WEFE Footprint. In the spring and summer of 2024, the finalized models were handed over to WP4 partners who have subsequently integrated these models into NEPAT tool (currently under development at the time of writing). The NEPAT allows users to fully explore policy impacts across WEFE sectors under the different SSP-RCP scenarios, as well as examine the impacts to the WEFE Nexus Footprint performance. The SDMs developed here are simply too complex, technical, and include too many policy combinatorial options (millions to billions of combinations, depending on the case study), to be useful for non-expert interaction and even for expert impact assessment. The NEPAT is developed to fulfill these roles in a fast, user-friendly way. Therefore, the SDMs form the crucial element underpinning NEPAT development, yet themselves developed through the NEXOGENESIS stakeholder co-creation and case study roadmap processes.

When the deliverable was submitted in August 2023, the final SDMs were not yet complete; therefore, only the prototypes were included. All information presented in the deliverable reflects the progress achieved as of the submission date, in alignment with the title of D3.4 and the Grant Agreement. The process followed for the validation of the SDMs from the stakeholders via the NEPAT tool is now detailed in the newly added disclaimer section and will be explicitly reported in the RP3.

It should be highlighted that neither the Grant Agreement nor the title of D3.4 stipulates the submission of final SDMs. The final versions of the SDMs have been delivered through the NEPAT tool.

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2nd **Revision** of the submission for the deliverable D3.4 "Complexity science models implemented for all the Case Studies-Prototypes and explanatory report/manual for each CS" and number "4" for the project "NEXOGENESIS (101003881)"

	Recommendations	Response
1	The deliverable explicitly states that the models are not yet final and have not been validated by the case study stakeholders, which is a crucial step to ensure their uptake in practice. It therefore remains to be seen whether this report should be replaced by a later, truly final version, once the models discussed here have been subjected to scrutiny by pilot users. It would then be useful to gain insight into why the use of locally specific models in case studies is only considered in certain cases.	A disclaimer section has been added on page 9 to address the specific feedback provided. This new paragraph includes the general disclaimer for the deliverable as well as an updated disclaimer tailored to the comments from the second revision. Additionally, new paragraphs have been added to the "NEXT STEPS" section to address the comments received.
2	The concluding chapter (Further work) remains unchanged and still discusses the work of the last few years (2023 and 2024) rather than the future ("The preliminary models described here will continue to be refined and developed during 2023 and the first half of 2024 until they are in a final state"). The process of model validation by stakeholders, including timing, methodology and participants involved, is missing, as well as clear information on how the final results will be integrated into planning and climate scenarios linked to policy analysis. The deliverable only states: "The model will be run with the policies only after validation of the results obtained by running the model without the policies. Simulated model results will be validated against observed data and stakeholder feedback".	Text is added to the conclusion stating how these SDMs were developed and validated in stakeholder participation processes, and the relevant Milestones detailing in depth these workshops are referred to. It is stressed at the same place that the model are indeed now finalized (including using a dedicated modellers workshop to harmonise modelling work). A statement is then added that the SDMs are the backbone to the NEPAT, which is the tool allowing fast, non-expert policy impact assessment, testing, and visualization, which due the SDM complexity, is totally unfeasible within the SDM framework. The conclusions section is edited to remove old text.
3	There is also no transparent discussion of the plan for further dissemination and integration of the	There is no such discussion, as it is not applicable within RP2. At that time, the NEPAT tool was still in the testing phase.

	models into the management process of each sub-pilot and transboundary area, including any Letters of Intent (LoI) or Memoranda of Understanding (MoU) that have been or will be established.	This information will be reported in RP3. Additionally, this topic falls under the activities of WP6, which focuses on dissemination and exploitation. Further developments on this subject are detailed in D6.4, “Communication Activities Report: Final,” which was submitted in October 2024.
4	Please, indicate all changes in a clear manner, preferably by using a different colour for the text.	All comments from the second revision have been addressed in the D3.4 document, with the changes highlighted in green text for easy visibility, while the comments from the first revision are marked in red.