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NEXOGENESIS
STREAMLINING WATER RELATED POLICIES

Deliverable 3.3

Final report on the application of biophysical models and stakeholder recommendations

Lead: UTH
Date: 31 May 2023

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Project Technical Report

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Abstract

This deliverable describes the integration of biophysical modelling developed in WP2 and stakeholder response (WP1) through innovative complexity science approaches, to assess the impacts of water-related policies in a nexus approach, under different scenarios for all the Case Studies. The report presents how the data provided from WP2 is used in the implementation of the SDMs with WEFE-related variables to support the modelling of the complex WEFE Nexus approach, including the integration of policy implementation, and highlights the methodology used. In NEXOGENESIS, biophysical and socio-economic models were developed centrally in WP2 for all Case Studies. A consolidated exercise is presented here, whereby each Case Study identifies the core relevant sectors and parameters, as well as the requirements for the models that will be needed for the development of the SDMs. In addition, case-specific models and sub-models (thematic models) that will be used by the Case Studies modelling teams, as well as data from local sources, are described.

This Deliverable is related to Deliverable 3.1, which preceded it (submitted in December 2022).

Keywords: variables, stakeholders, interlinkages, models, WEFE nexus.

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List of abbreviations

CS – Case Study

SDM – System Dynamics Modelling

WEFE – Water-Energy-Food-Ecosystems

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1. Introduction and purpose of the Deliverable

Deliverable 3.3 describes how the datasets delivered in NEXOGENESIS Work Package 2 (see Deliverable 2.1: Document information and consolidated modelling data available according to specific Nexus dimensions from repository and Inter-Comparison projects) are being used in the development of the system dynamics models (SDMs) of the water-energy-food-ecosystems (WEFE) nexus for each of the five Case Studies. The Deliverable shows how the data from WP2 are being used to populate the SDMs with WEFE-relevant variables to enable the modelling of the complex WEFE nexus systems, including incorporation of policy implementation. WP2 are complemented with locally-relevant statistical datasets as needed (e.g. to capture very specific issues not dealt with in the data sources in WP2) and with very specific additional modelling tools in some case studies, again to deal with site-specific issues and challenges. These local data and modelling tools are also detailed in this Deliverable.

At the time of writing, the SDM development, WEFE Nexus Footprint development, and policy selection and implementation into the SDMs are still under development, and have not yet been validated by Case Study stakeholders which is a crucial step in helping to ensure uptake. As such, the data lists and variables presented here are not absolutely final, as they may change as models continually develop, as policies are refined and further integrated into the SDMs, and as stakeholders offer feedback and validation of the modelling work. However, the SDMs as they currently are, are built upon stakeholder-validated conceptual systems maps, the SDM structure is unlikely to significantly change. As such, it is anticipated that the results presented in this Deliverable give a very close indication of the final datasets to be included in NEXOGENESIS modelling. More importantly, the Deliverable clearly demonstrates how WP2 data are used in system dynamics modelling, and how Case Study leaders have been involved in the data mapping and selection process throughout.

The rest of this Deliverable describes in detail the data mapping and selection process in Section 2, highlighting the role of CS leads in the process to guide data selection from the list of available variables, and how local data and models were selected to fill in the gaps. Section 3 outlines, on a Case Study basis, the datasets selected from WP2 data, and locally-relevant data selected, and any additional modelling tools used to feed into SDM development.

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2. From stakeholder requirements to models

In NEXOGENESIS, the entire modelling chain forms a logical, coherent, and consistent flow of activities. This starts, critically, with stakeholder involvement in each of the five Case Studies.

2.1 From conceptual maps to system dynamics models

The first step in the chain was to develop, for each Case Study, conceptual maps of the WEFE nexus, indicating the linkages within and between the WEFE sectors. These maps were developed with, and validated by, stakeholders, and the final conceptual maps are reported for each CS in Deliverable 3.1: Conceptual models completed for all the case studies. An example of just one of these conceptual maps (that of the Latvian side of the Lielupe River Basin Case Study) is shown in Figure 1.

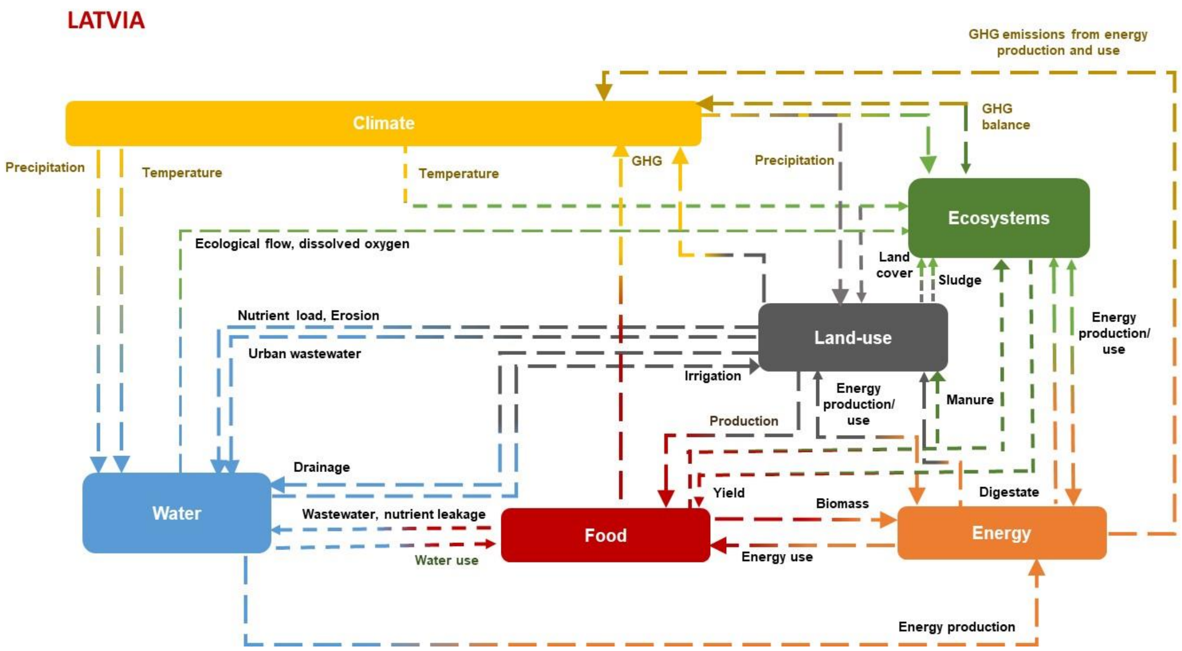

Figure 1. The high-level WEFE nexus conceptual map developed for the Latvian side of the Lielupe River Basin Case Study. All conceptual maps are reported in Deliverable 3.1.

The conceptual maps are used as the fundamental basis on which the SDMs are developed for each Case Study. At the initial stage, the conceptual maps are represented as closely as possible in the system dynamics framework, capturing the linkages and variables indicated therein. Figure 2a shows and example of this initial translation from the Inkomati-Usuthu Case Study. In Figure 2a, under the 'Total water consumption' category, a number of sectors are listed (e.g. energy, agriculture, mining, etc.). These same sectors have been represented in the SDM initial version (Figure 2b).

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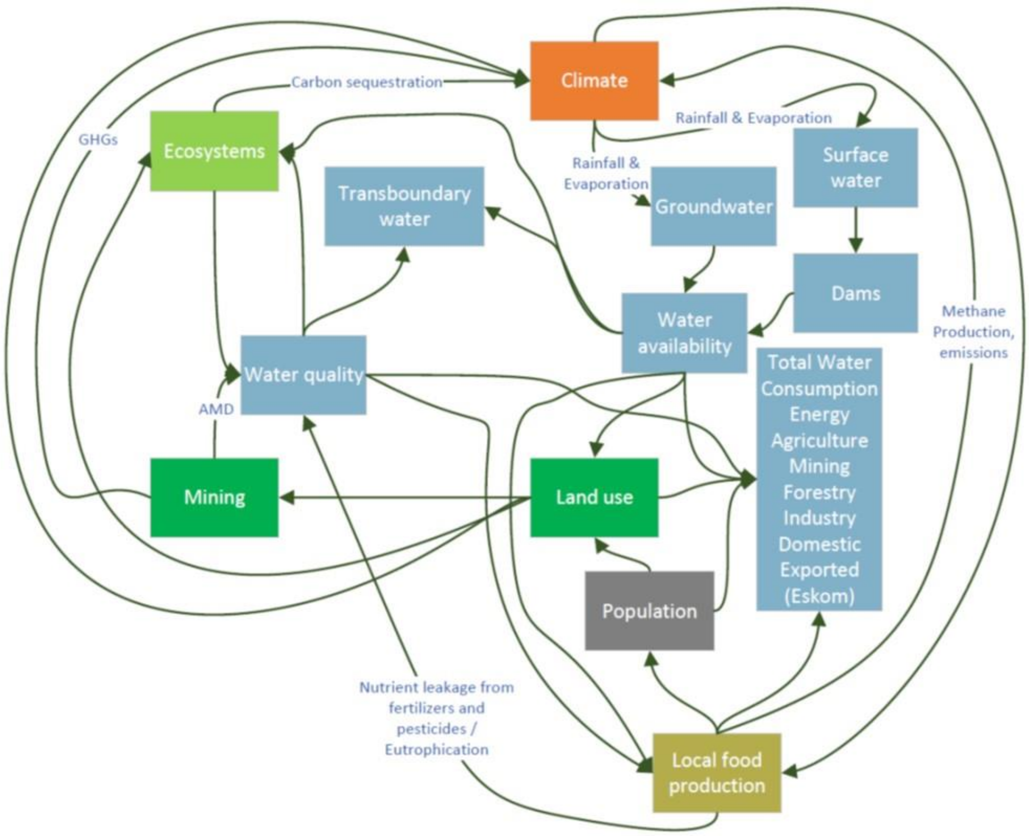
(a)



(b)

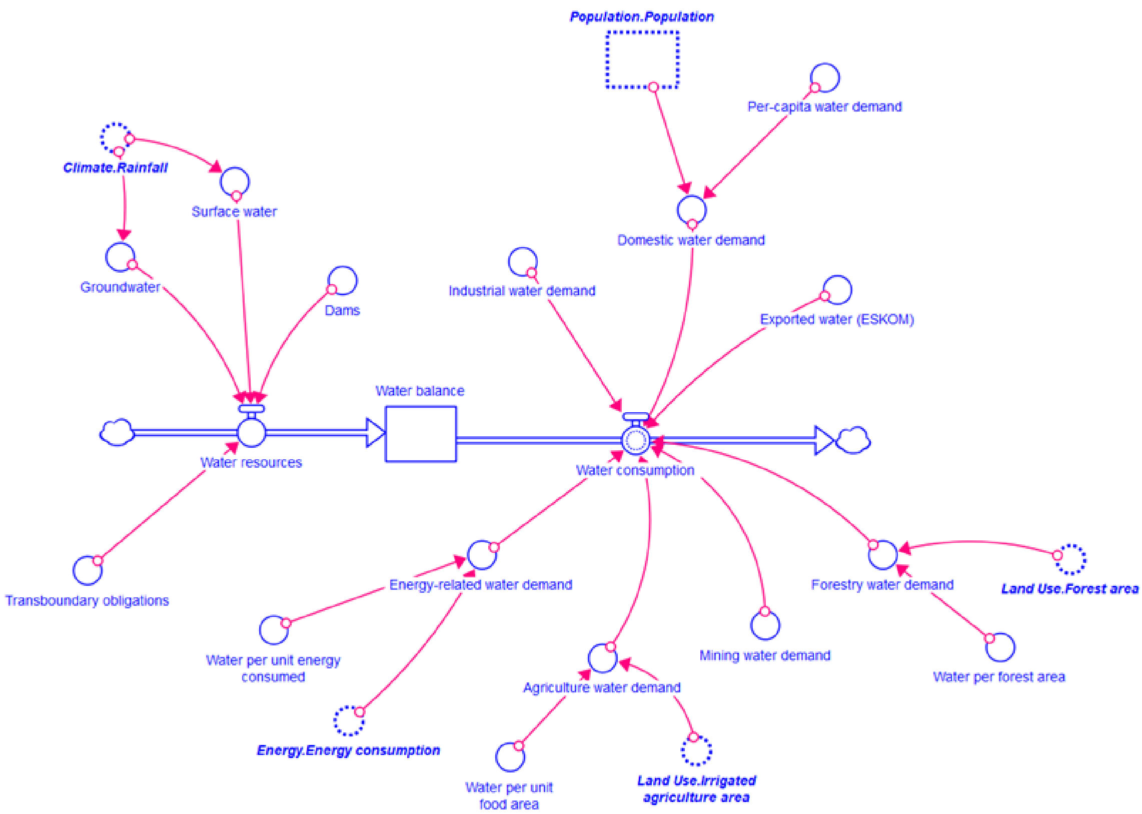


Figure 2. (a) the Inkomati-Usuthu water-sector conceptual map, and (b) the SDM translation.

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2.2 Data mapping

Once this initial SDM development was completed, a 'data mapping' exercise was carried out using a 'mapping matrix' Excel spreadsheet. In this spreadsheet, all variables appearing in the SDM are listed and compared with the variables lists available from the biophysical and socioeconomic model output from WP2. In this way, a first screening is made of a) which variables indicated in the SDM are directly available from WP2 datasets; b) which SDM variable may require locally-sources data for very specific issues not captured in WP2 datasets (e.g. in the Inkomati-Usuthu example, mining is a major concern, yet mining-specific data must be locally sourced as they are not captured in WP2 datasets). Online meetings between WP3 modellers, WP2 data providers and CS leads following the initial data mapping help to clarify any pending issues. For example, if the same variable(s) is available from multiple sources in WP2 data, guidance can be offered as to the best course of action. From this data mapping, the SDM can be refined and restructured to account for gaps that cannot be filled, remove variables that are deemed unnecessary, or add variables as needed. In addition, some structure changes may become apparent. For example, instead of estimating population from the time integral of the difference between birth rates, immigration, death rates, and emigration, it may be possible to use a base population figure and to force that with annual percentage changes estimated from WP2 socioeconomic data modelling outputs. This requires a small structural change in the SDM. Figure 3 shows the template used for the data mapping exercises.

2.3 Inclusion of policy instruments

In parallel, assessment of the policy instruments is carried out to determine which nexus sectors the policies are applicable to and then how they work (e.g. which SDM variables may be affected by the policies, and how). The policy instruments are validated with stakeholders at the third workshop (March-June 2023) and their inclusion into the SDM still need to be discussed with WP2 for data availability. However, CS leads have already provided the initial screening to which no significant change is expected. The SDMs are then updated to account for i) the results of the data mapping and ii) the required inclusion of the policy instruments and their data needs. This process may require 2-3 rounds of iteration to finalise the SDMs for simulation based on past experience.

2.4 Local modelling

As a final step, some NEXOGENESIS case studies are considering the use of very specific "thematic models" to represent highly specific aspects that either are not covered in WP2 datasets or may be covered by WP2 but not at the level of detail required by stakeholders. At the time of writing, the Adige and Nestos/Mesta case studies are considering the use of such external thematic modelling outputs to augment the system dynamics models. These are described in detail below under the respective case studies.

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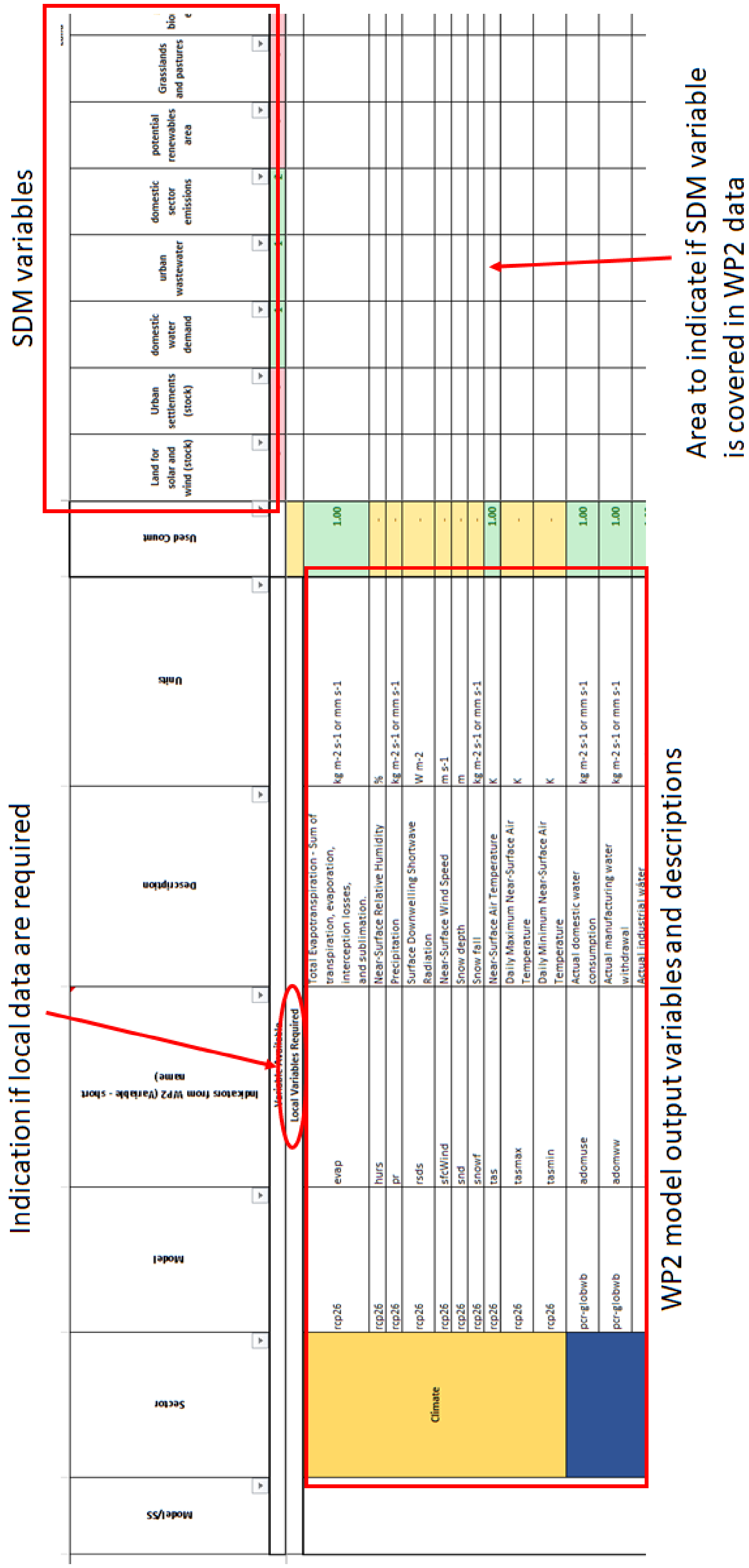

Figure 3. Data mapping template.

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3. Integration of biophysical and socio-economic data in the Case Studies

3.1 Case Study #1: Nestos/Mesta River Basin (Bulgaria – Greece)

3.1.2 Case Study requirements for biophysical and socioeconomic data based on the data mapping

The data mapping for the Nestos/Mesta Case Study reflects the needs of the draft SDM which was created by pairing the experts' knowledge and experience with local stakeholders' narratives. The process of data mapping was initiated and carried out by UTH following a screening approach among WP2 sourced data and local available datasets. Here, we describe and analyse the Nestos/Mesta Case Study requirements for biophysical and socioeconomic data from the WP2 portfolio of consolidated future data trends to feed the SDM complex structure and; thus, generate a strong interlinkage framework aligned to the full spectrum of the WEFE nexus dimensions.

In the **population** sector, we will consider the annual population growth rates up to 2050 from the G-RDEM model. By using locally-sourced data to capture the population allocation in the Case Study and define the initial number of residents living in the Nestos/Mesta river basin, we will be able to produce future projections by applying the growth rates. Estimating the evolution of the population is of crucial importance since a series of variables are directly related to the population fluctuation, such as domestic water and energy consumption, food consumption, etc.

In the **water** sector, a series of WP2-related variables are identified and will be used to feed the SDM. Domestic water consumption, manufacturing and industrial water withdrawals and consumption will be used to quantify the canvas of water demand sectors along with the agricultural sector which is locally-sourced. Additionally, nitrogen runoff rates form agricultural fields will be incorporated into the SDM to correlate the qualitative relevant parameters of the Nestos/Mesta River with the influxes from the agricultural sector.

In the **food** sector, the relevant variables that will be extracted from WP2 are imports and exports and food demand per capita.

Regarding the **energy** dimension, the total electricity gross output from G-RDEM will be probably used. The physical gross industry outputs which are available for different SSP scenarios are identified and will be used to define the industrial energy demand over the SDM modelling years. As for hydroelectric energy production which is the only energy generating sector of the Case Study, locally-sourced data will be implemented.

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In the **ecosystems** sector, the overall mean species abundance and the mean species abundance that quantify the flora and fauna of the Nestos/Mesta river basin will be used from the WP2 datasets in conjunction with the IUCN Red List Index dataset which is locally-sourced, to better estimate the biodiversity regime of the Case Study area.

3.1.3 Case Study requirements for locally-relevant data

The Nestos-Mesta Case Study consists of 12 sub-catchments (7 on the Bulgarian side and 5 on the Greek side) from which the waters that shape the river, originate. To this end, it is of crucial importance to feed the SDM with high spatial resolution datasets, where the availability from National Statistical Authorities (NSA) better captures the local requirements compared to WP2 sourced datasets, to match the sub-catchment spatial boundaries towards conducting a profound analysis of the system.

Regarding population, municipality level statistics will be incorporated for each sub-basin, provided by the corresponding NSAs. This historical locally-sourced data will define the population regime of the Nestos/Mesta Case Study for the year 2015 which is the starting point of the SDM. Future projections (up to 2050) will be formulated based on the population growth rates provided by the WP2 G-RDEM model on NUTS-2 level.

In the **water** dimension of the nexus, apart from the hydrological models constructed for each countries' sub-basins (described in section 3.1.4), a series of locally obtained water-related data is used to estimate the actual water consumption deriving from the agricultural sector. Crop types as well as their distribution in the sub-basins is calculated by combining Corine land use datasets with NSAs crop areas at municipality level (NSAs provide the full extent of crop types, the subsequent areas they occupy and if they are rainfed or irrigated). This combination allows for a better calculation of agricultural water consumption needs which is a fundamental component towards estimating the water balance for each sub-catchment, taking into account that the plethora of agricultural areas extract water for irrigation purposes directly from the river. Monthly irrigation data per crop type and unit area was obtained by data.gov.cy, which provides real monthly water needs for each crop type. The same methodology is followed to estimate water needs attributed to livestock. Regarding water quality parameters of the Nestos River, the Hellenic Centre for Marine Research [1] (HCMR) provides an extensive list of historical physico-chemical parameters (e.g. N-NO2, N-NO3, N-NH4, P-PO4), which will be used as a reference point to calibrate the chemical influxes from the adjacent areas.

In the **food** sector, crop and livestock yields per unit area and per head correspondingly are also provided by the NSAs and will be locally sourced.

Regarding **energy**, datasets obtained from the Public Power Corporation (PPC) will feed the SDM in relation to the historical and current hydroelectric operations of the dams favouring the analysis of the relationship between water outflow and electricity generation, contributing to the national energy production grid.

In the **ecosystems** sector, relative data such as protected areas are provided by geodata.gov.gr, while datasets regarding the biodiversity status of the transboundary areas will be used from the IUCN Red List Index database. A relevant publication conducted for the Greek part of the Case Study concerning the effects of resources management and policy interventions on biodiversity can be found here, while the same analysis will be implemented in the Bulgarian part to cover the whole area of the Nestos/Mesta Case Study.

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[1]This study used data from the project “Monitoring of the ecological water quality of rivers, and coastal and transitional waters of Greece to implement the Article 8 of Water Framework Directive 2000/60/EC” (MIS 375880, 375881, 375882, 375883, 375884, and 375885) funded by the Operational Program “Environment and Sustainable Development” 2007-2013, financed by the European Regional Development Fund. This study has been conducted under the project “Monitoring and recording of the status (quality, quantity, pressures, and uses) of surface waters of Greece” (MIS 5001676) funded by the Operational Program “Transport infrastructure, environment and sustainable development” 2014-2020, financed by European Regional Development Fund.

3.1.4 Case Study use of locally-specific models

The Nestos/Mesta river basin is one of the seventy-one transboundary river basins of Europe. The total catchment area is about of 5,500 km2 (Boskidis et al., 2011, 2012a, b) of which approximately 49 % (about 2,700 km2) belong to Bulgaria and 51 % (about 2,800 km2) belong to Greece (Gikas et al., 2020). The basin (Figure XXX) is mostly mountainous. The altitude ranges from 0 m a.s.l. to about 2,900 m a.s.l. with the mean altitude estimated at about 1,050 m a.s.l. The Nestos/Mesta River discharges in its delta, a unique ecosystem protected by the Ramsar Convention, and is considered as a first priority site under EU Natura 2000, forming a floodplain (about 600 km²) protected under the RAMSAR convention. During the 1990 decade, two large dams were constructed in the Greek part of the river, Thissavros and Platanovrisi (Boskidis et al., 2012). In addition, Dospat dam was constructed in the Bulgarian side in Dospat tributary of Nestos/Mesta River. In Figure 4 land uses according to Corine Land Cover 2018 within the river basin are shown.

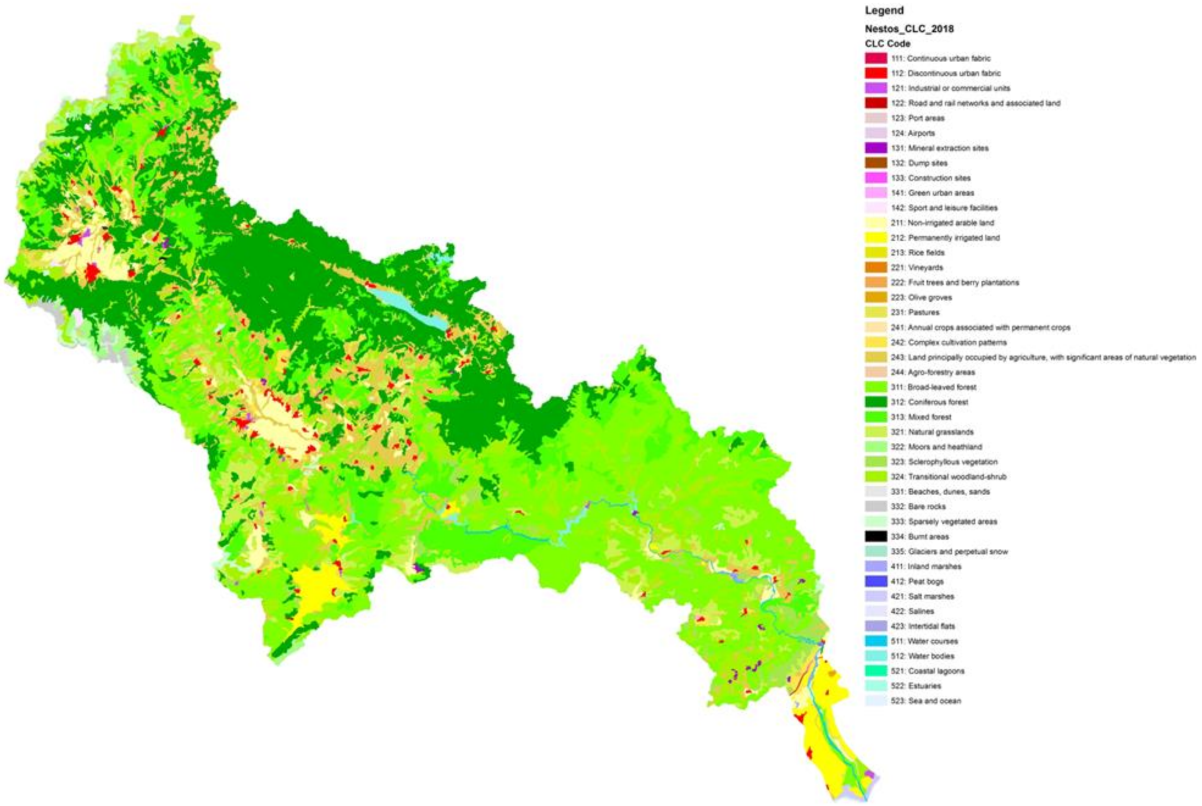

Figure 4. Nestos/Mesta river basin and land uses according to Corine 2018.

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For the Greek part of the Nestos/Mesta basin rainfall observations from 8 stations were available from 1980–1981 to 2018–2019 (according to hydrological year October-September), while for the Bulgarian part of the basin rainfall observations from 16 stations were available from 01/01/2000 to 01/01/2006. In addition, temperature measurements were available in one and in three stations in the Greek and Bulgarian part of the Nestos/Mesta basin, respectively. Finally, discharge observations, were available and employed for calibration – verification of the continuous hydrological model in 3 and 4 hydrometric stations in the Greek and Bulgarian part of the Nestos/Mesta river basin, respectively.

The HEC–HMS software used for all hydrological simulations was developed by the United States Army Corps of Engineers Hydrologic Engineering Center. It is designed for the simulation of all hydrological processes of dendritic watershed systems and can be used for both event–based and continuous simulation. HEC-HMS provides a wide range of mathematical models to simulate various hydrological processes [e.g., Surface runoff: Unit hydrographs (User specified, SCS UH, Clark UH, etc. kinematic-wave model), kinematic-wave model]. The user, has to choose between various models/methods) based on: (i) the objectives of the study, (ii) data availability, and (iii) time availability. The Greek part of the basin was divided into 5 sub-catchments (Figure 5), while the Bulgarian part of the basin was divided into 7 sub-catchments (Figure 5).

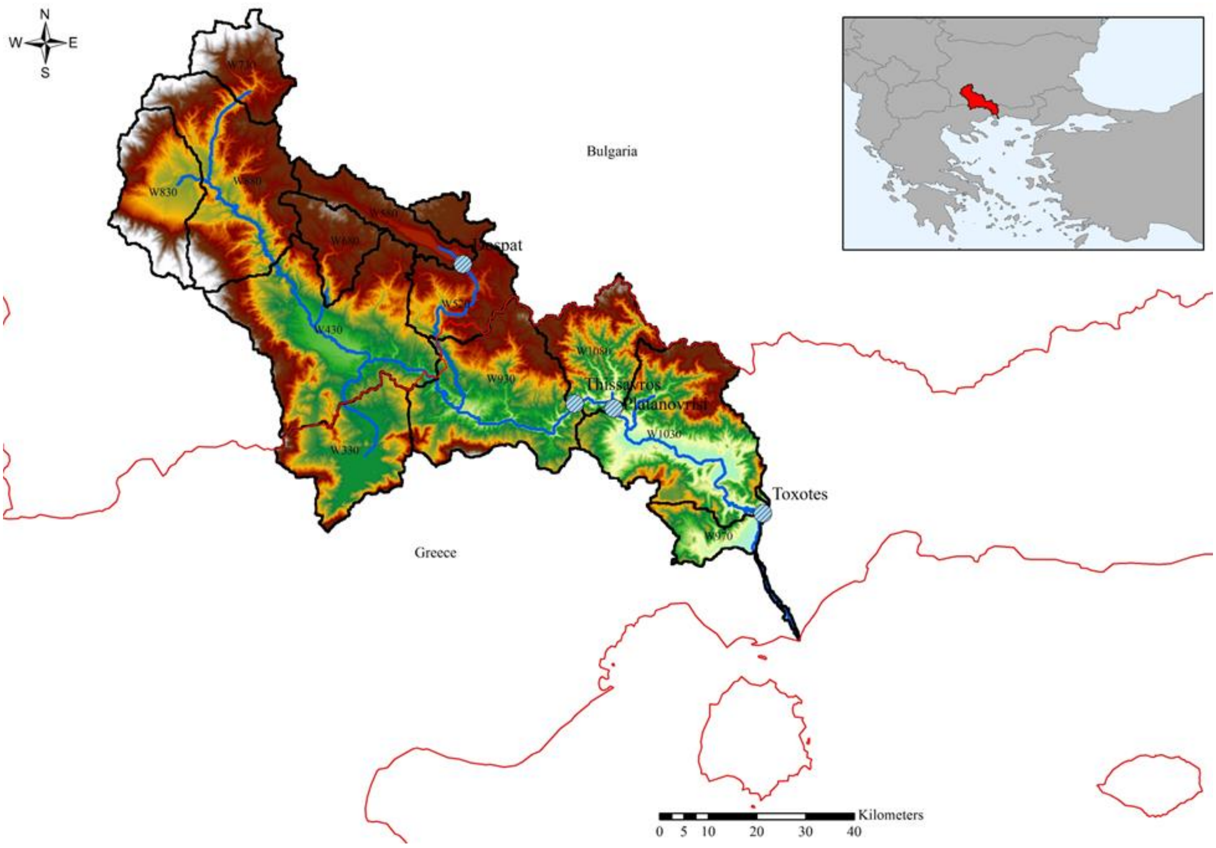

Figure 5. Nestos/Mesta river basin delineation.

In all the subcatchments of the hydrologic model the following methods were employed: Thiessen method for spatial interpolation of rainfall observations. Thornthwaite method to model Evapotranspiration Soil Conservation Service (SCS) Curve Number (CN) approach was used to model the losses. Based on the land use/land cover data from 2018 Corine Land Cover and the soil data for the study area, the area weighted average CN was estimated at about 70.

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The Unitless SCS Unit Hydrograph was selected as the transform method. The time of concentration, for each subcathment, was estimated employing the Giandotti empirical Equation. The Simple Canopy method was used to represent the precipitation intercepted by the plant canopy and used for evapotranspiration. The Deficit and Constant loss method was employed in order to describe infiltration processes in the soil layer. The Baseflow was modeled using the constant monthly baseflow method assuming a constant baseflow value is assumed for each month of the year.

Table 1. Description of the hydrologic model (HEC-HMS).

Case Study no.: 1	**Sub-unit (if applicable):**	
Model name: HEC-HMS		
Description: The HEC–HMS, developed by the United States Army Corps of Engineers Hydrologic Engineering Center, is designed for the simulation of all hydrological processes of dendritic watershed systems and can be used for both event–based and continuous simulation. HEC-HMS provides a wide range of mathematical models to simulate various hydrological processes.		
Documentation: Scharffenberg, B.; Bartles, M.; Brauer, T.; Fleming, M.; Karlovits, G. Hydrologic Modelling System HEC-HMS: User's Manual; US Army Corps of Engineers, Hydrologic Engineering Center: Davis, CA, USA, 2018		
Area coverage: River basin	**Time coverage:** Monthly (2000 to present)	
Reference/calibration data: Monthly discharges		
Model input parameter(s):	**Source**:	**Resolution:**
Land uses-land cover	CORINE Land Cover – Copernicus Land Monitoring Service	25 ha
Digital elevation model	Copernicus Land Monitoring Service	30 m
Soil	Harmonized World Soil Database	30 arc-second
Rainfall	Hellenic National Meteorological Service and Bulgarian National Institute of Meteorology and Hydrology	Daily
Temperature	Hellenic National Meteorological Service and Bulgarian National Institute of Meteorology and Hydrology	Daily
How are the input data bias corrected and/or pre-processed? *(or leave blank)*		
Will the model be updated/improved during NEXOGENESIS? *(if yes, please explain how)*		
Modelling dependencies: *(does the model depend on other simulations or data collected?)* In its current form the model does not depend on other simulations.		
Climate scenarios currently used:	Climatic variables from WP2 will be used as an input to the hydrological model in the next steps of the project	
Source (s) of	ISIMIP, CORDEX, HiResMIP,	

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future climate projections:				
Reference period:	*1950-2005*			
Future time periods:	*2006-2100 under climate scenarios: RCP 2.6, RCP 4.5, RCP 6, RCP 8.5*			
(please add)				
Output parameter(s):		**Resolution:**		
Rainfall losses (mm), Rainfall excess (mm), Discharge (m^3)		Monthly		
Analysis objectives:				
Assessment of the potential impact of climate change on the basin scale				
Modelling time line:				
Could your model easily be adapted to another CS?		**Y / N**	No. However the methodological framework can be easily adapted and used to other CSs.	

Table 2. In the following table, we include a list with model variables that were fed with data from WP2 and local resources

Sector	Variable description
Population	Annual population growth rates
Land	Agricultural crops yield
Water	RCP climate scenarios
Water	Agricultural water consumption (crop-specific)
Food	Agricultural crop yield
Food	Annual percent change in livestock numbers
Food	Annual percent change in per capita food demand

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Energy	Annual percent change in electricity generation
Energy	Annual percent change in per-capita electricity demand
Ecosystems	Mean species abundance evolution
Ecosystems	Carbon mass in vegetation

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3.2 Case Study #2: Lielupe River Basin (Lithuania – Latvia)

3.2.2 Case Study requirements for biophysical and socioeconomic data based on the data mapping

The formulation of a simulation model requires a parallel data mapping evaluation. By using the "mapping matrix" template presented in section 2.2 it was possible to align data requirements and availability for the Lielupe River Basin Case Study. On the one hand, data requirements come from an early-stage formulation of a System Dynamics simulation model, based on stakeholder validated qualitative mapping of the nexus. Considering the transboundary nature of the Lielupe River Basin, data requirements and availability refer to both countries – Latvia and Lithuania. Along with the validation of cross-sectoral interdependencies, stakeholders in both countries were providing their opinion on relative importance (important, moderate, low) of Nexus interlinkages. Data availability, on the other hand, comes from the extensive biophysical and socioeconomic data provided by NEXOGENESIS WP2.

Regarding the biophysical dimension, the proposed model will make ample use of the available data from WP2. A total of 39 variables were identified as very likely inputs for the CS simulation model. **Climate** related variables include temperature, precipitation, and evapotranspiration measurements. **Water** quantity related variables include water consumption and water withdrawals for different sectors (e.g., domestic, industrial, agriculture) as well as runoff, max/min discharge and storage in the basin. Stakeholders in both countries pointed out the importance of ecological flow in relation to ecosystems, while the water use for food production was considered as more important in Latvia. Water quality related variables include water temperature, nutrient concentration, and loads (nitrogen and phosphorous). Here the **land-use** activities are having pivotal role in both countries. **Agriculture** related variables include biomass yields, crop yields and nitrogen application rates for various crop types (e.g., wheat and rape seed). Finally, biomes/**ecosystems**-related measurements will include estimations of carbon mass (e.g., in vegetation and soil), species abundance (e.g., plants and overall) and vegetation coverage.

The simulation model will also make use of **socio-economic** data provided by WP2. A total of 34 variables were identified as very likely inputs for the CS simulation model. Most of these represent the physical gross output and demand of several Food and Energy commodities (e.g., meat and dairy products or gas and petroleum). Emissions related variables such as total GHGs emissions and emissions by production sector will be considered as part of the modelling exercise. Stakeholders in both countries evaluated the importance of GHG emissions originating from the Energy sector.

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3.2.3 Case Study requirements for locally-relevant data

Locally relevant data are essential for building a simulation model that accounts for the nexus interactions at a river basin scale. Despite there is great benefit of using cross-Case Study data from downscaled global models (i.e., WP2 biophysical and socioeconomic variables) coming, these models remain limited to account for the specific nexus dynamics that are evident at a river basin. This is the main reason for identifying and prioritising the data that would be needed from other local sources (e.g., public, private). Moreover, local data sets are to be distinguished separately in Latvia and Lithuania with relevance to the Lielupe River Basin scale.

Local data requirements can be mapped across the nexus sectors by reflecting sector specific characteristics and activities. **Land** related variables include current broad land-use area estimations (e.g., forest, grass, and arable lands) as well as more detailed information about area by crop types (e.g., energy and food crops) and their area by irrigation requirements (e.g., rainfed or irrigated). Regarding the **energy** sector, there will be a need to collect data on the current and potential availability of bioenergy sources (e.g. grass, forest and biomass) and their estimated (bio) energy generation potential (e.g. electricity and biogas). Data on the current energy generation using fossil energy sources will also be required (e.g., oil and gas). For the **food** sector, the simulation model will require data on current food production by crop type and irrigation requirements (e.g., rainfed, irrigated). Estimations about the use, type and availability of fertilizers will also be a requirement.

From another hand, data of local/regional relevance are attributed to specific coefficients, e.g., emission factors. In the **water** sector, it will be important to have estimates about the nutrient load in surface water coming from urban wastewater, and the diffuse source pollution from land-use activities. With relevance to **climate**, specific CO2 emission factors for each sector will be required to estimate the impacts.

In short, the variables considered for developing the SD model for the Lielupe Basin case study come from both WP2 and other locally relevant sources. Table 2 presents a summary of the set of variables considered across the different nexus sectors as well as their corresponding source.

Table 3. Summary of variables considered in the Lielupe River Basin System Dynamics (SD) model, classified by nexus sector (Water, Energy, Food, and Environment) and data source.

Sector	Variables	Source
Climate	CO2 emissions per MWh produced - natural gas	Local sources (government and NGO reports) and academic literature
Climate	CO2 emissions per MWh produced - solar PV	Local sources (government and NGO reports) and academic literature
Climate	CO2 emissions per MWh produced - wind turbines	Local sources (government and NGO reports) and academic literature
Climate	GHG emissions in well-drained agriculture land	Local sources (government and NGO reports) and academic literature
Climate	GHG emissions in undrained agriculture land	Local sources (government and NGO reports) and academic literature
Ecosystems	Species richness amphibians	WP2 Data

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Ecosystems	Species richness mammals	WP2 Data
Ecosystems	Species richness birds	WP2 Data
Ecosystems	Carbon mass in vegetation - deciduous forest	WP2 Data
Ecosystems	Carbon mass in vegetation - evergreen forest	WP2 Data
Ecosystems	Carbon mass in vegetation - grasslands	WP2 Data
Ecosystems	Carbon mass in vegetation - croplands	WP2 Data
Food	Nitrogen content in manure	Local sources (government and NGO reports) and academic literature
Food	Relative yield ratio field peas (Organic/Conventional farming practice)	Local sources (government and NGO reports) and academic literature
Food	Relative yield ratio maize (Organic/Conventional farming practice)	Local sources (government and NGO reports) and academic literature
Food	Relative yield ratio rapeseed (Organic/Conventional farming practice)	Local sources (government and NGO reports) and academic literature
Food	Relative yield ratio summer wheat (Organic/Conventional farming practice)	Local sources (government and NGO reports) and academic literature
Food	Relative yield ratio winter wheat (Organic/Conventional farming practice)	Local sources (government and NGO reports) and academic literature
Food	Crop yield - field peas	WP2 Data
Food	Crop yield - maize	WP2 Data
Food	Crop yield - rapeseed	WP2 Data
Food	Crop yield - summer wheat	WP2 Data
Food	Crop yield - winter wheat	WP2 Data
Nature-based solutions	Nitrate leaching rate	Local sources (government and NGO reports) and academic literature
Nature-based solutions	Bioreactor nitrogen removal efficiency	Local sources (government and NGO reports) and academic literature
Nature-based solutions	Constructed wetland nitrogen removal efficiency	Local sources (government and NGO reports) and academic literature
Nature-based solutions	Riparian buffers nitrogen removal efficiency	Local sources (government and NGO reports) and academic literature
Nature-based solutions	Organic farming nitrogen removal efficiency	Local sources (government and NGO reports) and academic literature
Population	Domestic per capita nitrogen generation rate	Local sources (government and NGO reports) and academic literature
Population	Population	WP2 Data
Renewable energy	Solar PV generation capacity per area	Local sources (government and NGO reports) and academic literature
Water	Surface water flow	WP2 Data

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3.2.4 Case Study use of locally-specific models

In the Lielupe Case Study locally-specific models are not being considered.

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3.3 Case Study #3: Jiu River Basin, Lower Danube (Romania)

3.3.2 Case Study requirements for biophysical and socioeconomic data based on the data mapping

The outcomes obtained by the exploration of the Jiu Case Study boundaries, the interlinkages between water, energy, food, and ecosystems (WEFE), as well as the main issues related to the WEFE sectors that the basin is currently facing and that is expected to face in the future, were captured in the conceptual maps collected in D3.1. A map for each WEFE nexus sector was developed by the Case Study principal investigators (PIs) and validated with the local stakeholders during the first workshop and experts to make it as much as possible representative of the area under study.

The validated conceptual maps were crucial because they became the solid base for initiating the Jiu Case Study data mapping and the system dynamic model (SDM) development. The data necessary for the SDM development could be from both local sources and/or WP2 which is in charge to provide bio-physical and socio-economic trends for both current and future climatic and socio-economic conditions up to 2050. In view of this, the PIs went through each conceptual map and identified the data needed to move from the qualitative (the conceptual maps) to the quantitative (the system dynamic model) assessment. Available local data were explored and their availability and sources were identified. At project level the preference is to use as much as possible the information provided by WP2. WP2 provides both bio-physical and socio-economic trends which are the results of simulations run by using specific models and driving forces. The biophysical data comes from models such as Watergap2-2c, Gepic, Lpjml, etc while the socio-economic variable from GRDEM, DEMETRA, and Magnet model (see details about the available models and the variable description in D2.1). In the Jiu Case Study only inputs from GRDEM model are used. The local data (in general available from 2014 to 2021) are mostly used to validate biophysical WP2 inputs and/or as a starting point for socio-economic WP2 information to assess future scenarios. In the WP2 database often the same variable is available from more than one model and this will give the opportunity to each Case Study to do the uncertainty analysis (D.3.5).

In the Jiu river basin, the data mapping was captured by using an Excel table (see details about the structure of the table in section 2.4) where each variable, currently indicated in the SDM, has been mapped against local and/or WP2 available data. Both SDM and data mapping have not been validated by local stakeholders, yet, but considering that both are built by using the validated conceptual map, not large changes are expected in the Jiu river basin SDM structure and data needs.

The main sectors identified in the Case Study are population, water, land, food, energy, ecosystems and climate. **Population**, which is linked to both water and energy, is computed by using the population growth delivered by WP2 (GRDEM model) and the local population as starting value to which the growth change is applied. The projections available on the local side will be used for calibrating the results delivered by the model.

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In the **water** (quantity) sector, consisting mainly in water supply (i.e., surface and groundwater inflow) and water consumption (i.e., domestic, hydropower production, agriculture, and industrial) all the input data, except for water for hydropower production and water for domestic use, are provided by WP2. Local data are available for all the input variables that will be used in the SDM to assess the water (quantity) balance. The local values will be used to validate the water quantity information coming from WP2. WP2 biophysical data are used also to assess the quality of water estimated in the Jiu river basin by considering the nitrogen load to water bodies. The water quality is estimated by using WP2 data that will be validated by with local data. Availability of data related to the amount of phosphorous load to water is currently under discussion and further arrangement in the SDM might be possible later to accommodate this source of pollution.

The **land** sector includes the areas cultivated by the four specific crops dominant in the region, i.e., maize, wheat, sunflower, and rapeseed. The area covered with the natural forest is accounted for in this sector as well. The needed data comes from WP2 (MagnetGrid model) as future trends, thus the availability of local data to be used as a starting point to compute future scenarios is essential. The local data are available for each crop considered relevant for the Case Study.

In the **food** sector the main crops are analysed in terms of both productions and uses in different sub-sectors such as human and animal consumption, import, export, etc. The supply side of the food sector is filled in by using biophysical information from available WP2, while the consumption is covered from the same WP, but by combining initial local values and WP2 socio-economic trends provided by GRDEM model. The local food data covers all the variables that are currently in the SDM. Some arrangements might need to be made in the model to accommodate some food variables available from WP2 only as aggregated categories (e.g., trade). When needed, only local data and trends will be used to allow the computation of important components for the Case Study such, as food losses, which are not available from GRDEM model.

The **energy** sector is closely linked to the water sector in terms of hydropower production and local data are used to make possible the quantification of this interlinkage. The data necessary to compute the energy production from other energy sources that are used in the basin (e.g., coal, gas, oil) and the industrial, agricultural, domestic energy use are collected and available from local reports and statistics and used in the model to estimate future scenarios by using the trends provided by WP2-GRDEM model. Slight arrangements to accommodate the WP2 available data are expected to allow the computation of the energy export.

In the **climate** sector, the greenhouse gas emission (GHG) balance is estimated by considering the emissions from the agricultural and energy sector while the sequestrations are computed considering the CO2 sequestered by the forests that cover the basin area. The data needed to compute the balance are all available from local sources.

The **ecosystems** that characterised the Jiu river basin are complex and the discussion around this sector is still ongoing. The ecosystems will be most likely quantitatively analysed by using local data which should capture more accurately the complexity at basin scale. The impact on aquatic ecosystems, especially in terms of water quality threatened by agricultural activities, and the key role of forests and protected areas in mitigating climate change will be explored.

The data mapping and the ongoing development of the SDM will be discussed during the next workshops organised by the PIs, in Romania. These workshops will aim at continuing the

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discussion about relevant issues in the Case Study, current and future policies and policies objectives, and co-designing and validating with local stakeholders and experts a tool (i.e., SDM) that will give the opportunity to assess the WEFE nexus status with and without the implementation of policies in the nexus sectors.

3.3.3 Case Study requirements for locally-relevant data

In the Jiu Case Study, the local data will be used for validating the biophysical trends (e.g., changes in water availability, water use, crop yield etc) and as a starting point to build future trends for the socio-economic variables (e.g., changes in population, food consumption, energy use, etc). Most of the variables currently identified as relevant to the Case Study to assess the current and future status of the Jiu WEFE nexus system are covered by both local and WP2 sources. The local sources are reports, statistics, published and grey literature. The data collected from the PIs so far are both biophysical and socio-economic data and, in general, they are available from 2014 to 2021. The local sources will be used mostly to validate WP2 biophysical data used to cover water supply, consumption and quality and food production. The local data will be also used as a starting point to WP2 socio-economic trends especially used to estimate the cultivated and the forest area, the food consumption, the energy supply and use in the different sector, as well as the GHG emission balance computed considering both emissions from different sectors and sequestration. The local data will be essential to cover the ecosystem sectors. This sector is still under discussion and inputs necessary to properly capture the Jiu river basin condition will come from the upcoming interactions between the PIs and the local stakeholders.

In general, the local data are currently able to cover the data needs in the water, land, population, food, energy, ecosystem, and climate sector. Both data mapping and SDM development are still a work in progress in the Jiu river basin and more interactions between PIs, WP2, and SDM developers (WP3) are needed, thus some changes to the model and data needs and availability are possible. Changes are also expected in view of the implementation of the policy objective in the model. This will require most likely the collection of further data coming from local and/or WP2 sources and arrangements in the SDM structure. The data mapping and SDM current structure is the result of a close interaction between PIs, WP2, and WP3. The ongoing work will be soon presented and discussed with local stakeholders whose feedback and inputs will be crucial to collect any potential further data and information and to SDM model improvements.

3.3.4 Case Study use of locally-specific models

In the Jiu Case Study locally-specific models are not being considered.

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

3.4.2 Case Study requirements for biophysical and socioeconomic data based on the data mapping

The data mapping for the Adige river basin was carried out with reference to the SDM draft. Before the SDM, the conceptual and causal loops models were developed integrating information coming from experts' knowledge, literature review and opinions of different stakeholders. The data mapping process has been carried out by Eurac and CMCC for the Adige river Basin, combining information from the global datasets, made available within the WP2 activities, with local datasets that can provide more accurate context-specific information. An initial selection of the data requirements for the data mapping exercise has been carried out considering (i) the SDM draft for the Adige river basin Case Study developed from the conceptual and causal loop models and (ii) checking the availability of data coming from the WP2. In particular, for the population sector, the variables population and population growth rate - by NUTS2 regions provide a valuable information to characterize the number of residents living in the Case Study area. These variables will be used on the baseline of local population (residents) to produce estimates of future population.

For the **water** sector, the variables water demand, domestic water consumption, household real water consumption, manufacturing and industrial water withdrawals and consumption, and total water consumption and demand have been identified during the data mapping exercise. Moreover, water quality, irrigation water consumption and withdrawals (potential and actual, irrigated and rainfed crops), livestock water consumption, soil moisture and potential evapotranspiration have also been selected. These variables are planned to be used to provide information on the water demanded by specific sectors, while also providing a term for comparison with the outputs coming from some of the physically based models (e.g., soil water balance crop model).

In addition, further variables for the **food** sector, in terms of food production, crop yields for multiple crops on irrigated and non-irrigated land, and imports and exports were identified and will be linked to the modelling of the agricultural sectors and the water demand associated to the expected production. Planting date and maturity dates were identified and will be considered as potential inputs to the physically based agricultural model.

For the **energy** sector, electricity physical gross output and demand from GRDEM were identified as well as the physical gross industry outputs available for different SSP scenarios, years, type of industry and at NUTS2 region which can be potentially implementation to characterize future conditions of industrial energy demand. Further data can be retrieved by locally available dataset to better characterise renewable energy production which plays an important role in the region of interest.

For **land use**, different types of land used for irrigated and non-irrigated crop, agriculture and energy production can be covered by the data from WP2 GRDEM dataset. In particular, the information on future conditions for different SSP and years offers a valuable input information for sectorial modelling in combination with local information.

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For the **ecosystems** sector a wide range of variables have been identified for supporting the analysis of the ecosystem services in the Adige river basin. Variables span according to the type of ecosystem service covered, such as phosphorous and nitrogen concentrations in catchments when referring to the river status and water quality. Population, energy consumption and import/export from industries are considered, among others, for carbon storage. For cultural services, variables consider an accommodation, food service, air transport, electricity, gas, real estate activities, recreational services, population as potential sectors to be included in the modelling using the ARIES platform.

In the **climate** sector, variables of temperature, precipitation, wind speed, solar radiation, and relative humidity are climate data at 10 km resolution available from WP2 data for both historical and future scenarios. Finally, for those variables that neither data from WP2 nor from local repositories is available would require to explore and potentially select appropriate proxy indicators or to modify some of the sectorial parts part of the SDM.

3.4.3 Case Study requirements for locally-relevant data

The Adige river basin Case Study is located in a data-rich region with a high number of local datasets covering different sectors and across years. For this reason, context-specific information will be mostly used and modelled beyond the data provided by WP2.

In the population sector, locally-available statistics will be used to give indications on the historic population within the Adige river basin both in terms of residents and seasonal tourists. In both cases local statistics at provincial or municipal level will be converted to the hydrological boundaries of the Case Study. Moreover, the growth rates derived from either the WP2 GRDEM models will be used to project the future number of residents. In the climate sector, historical weather station data coming from provincial environmental agencies for precipitation and temperature have been used as an input to the hydrological model. These values will also be compared with the data from WP2 in order to analyse and interpret future conditions.

In the **water** sector, local data in terms of historical streamflow in multiple locations of the river network, water stored and released by the artificial dam reservoirs have been use to calibrate and validate the hydrological model application at different outlet locations. Local information on the minimum ecological flows along the Adige river has been provided and will be integrated to evaluate the river ecosystem.

In the **food** sector, local information on the spread of different crop types, their location especially in the valley bottoms and in limited cases the water consumed is available and will be used for the modelling of water demand in agriculture. The energy sector shows limited accessibility to confidential data of renewable energy produced (for example for hydropower purposes). In cases of limited information and where possible, proxy variables will be considered to describe conditions of energy generation, energy use per-capita among others.

For the **land** sector, local statistics provides information on the amount of areas irrigated or rainfed that can be used for the agricultural modelling.

For **ecosystems**, local data requirements include high resolution biophysical parameters such as elevation, land use cover and soil type as well as the presence of protected areas and their extension in the study area. Finally, it is pointed out here that upon further discussion, it may

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be decided that not all these categories are crucial to the Case Study objectives. Where this is the case, the variables will no longer be sourced.

The variables considered for developing the SDM for the Adige River Basin case study come from WP2, were collected from other international, local repositories from environmental agencies or as results of other models (e.g., hydrological model). In Table XX we report a summary of the set of variables considered across the different nexus sectors as well as their corresponding source.

Table 4. Summary of variables considered in the System Dynamic Model (SDM) in the Adige River Basin, classified by nexus sector (Water, Energy, Food, and Environment) and data source.

Sector	Variables	Source
Climate	Emissions factor for fossil fuel consumption	International sources (government and NGO reports)
Climate	Emissions factor Renewable energy consumption	International sources (government and NGO reports)
Climate	Emissions factor the agricultural areas	Local sources (government and NGO reports) and academic literature
Ecosystems	Species richness amphibians	WP2 Data
Ecosystems	Species richness mammals	WP2 Data
Ecosystems	Species richness birds	WP2 Data
Ecosystems	Carbon mass in vegetation	WP2 Data
Ecosystems	Wetland storage	WP2 Data
Ecosystems	Carbon flux	WP2 Data
Ecosystems	Agricultural above ground biomass	WP2 Data
Food	Agricultural crop yield (per crop type)	Local sources (government and NGO reports) and academic literature
Food	Nitrogen leaching from agricultural land	WP2 Data
Food	Food consumption per capita	International sources (government and NGO reports)
Population	Population	WP2 Data
Population	Tourist	WP2 Data
Land use	Land cover area	Local sources (government and NGO reports) and academic literature
Land use	Crop area (per crop types)	Local sources (government and NGO reports) and academic literature
Water	Surface water runoff	Hydrological model
Water	Dam contribution	Hydrological model

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Water	Resident N load per capita	Local sources (government and NGO reports) and academic literature
Water	Tourist N load per capita	Local sources (government and NGO reports) and academic literature
Water	Domestic per capita water demand	Local sources (government and NGO reports) and academic literature
Water	Tourist per capita water demand	Local sources (government and NGO reports) and academic literature
Water	Leakage severity	Local sources (government and NGO reports) and academic literature
Water	Irrigation type	Local sources (government and NGO reports) and academic literature
Water	Irrigation efficiency	Local sources (government and NGO reports) and academic literature

3.4.4 Case Study use of locally-specific models

For the water sector, the Adige Case Study implement a physical-based hydrological model named ICHYMOD. It is a conceptual, semi-distributed rainfall-runoff hydrological model locally which was developed by the University of Padova (Borga, 2002; Borga et al., 2006; Norbiato et al., 2009). The model runs on an hourly time step and consists of a (i) snow routine, (ii) a soil moisture routine and (iii) a flow routing routine. The (i) snow routine represents snow accumulation and melt. The occurring of rainfall, snowfall and a mix of rain and snow is characterized implementing a range of threshold temperature. Moreover, ICHYMOD evaluates the potential evapotranspiration implementing the Hargreaves formula. The (ii) soil moisture routine represents the water storage capacity in spatial terms across the considered river basin. For the (iii) flow routing routine, in case runoff is occurring due to saturation of the soil, the value of runoff is added over the basin to give the total direct runoff. Storage representations of the fast and slow response pathways yield a fast and slow response at the basin outlet which, when summed, gives the total basin flow. Within the food sector, the physically based model SIMETAW# is considered. SIMETAW# is a soil-water balance model able to assess crop water use, irrigation requirements for a wide range of crops experiencing full or deficit irrigation. SIMETAW# provides a set of outputs: reference evapotranspiration (ETo), crop evapotranspiration (ETc), evapotranspiration of applied water (ETaw), the mean depth of infiltrated water (IW) into each quarter of the field. The impact of deficit irrigation on the actual crop evapotranspiration (ETa) is computed separately for each of the four quarters of the cropped field. SIMETAW# simulation adjusts ETo estimates for projected future CO2 concentration, and hence the model can assess climate change impacts on future irrigation demand allowing the user to propose adaptation strategies that potentially lead to a more sustainable water use (Masia et al., 2021; Mancosu et al., 2016).

The ecosystem services (ES) assessment has focused on the application of the ARIES (ARtificial Intelligence for Ecosystem Services) methodology, which is able to integrate different data and models related to ecosystem services. ARIES is an integrated artificial intelligent modeler based on the novel k.LAB technology assessing ES based on a list of available models embedded within ARIES. For each of the four ES categories (i.e. regulating, supporting, provisioning, cultural), one or more services has been defined based on literature review and collection of information from newspapers and local stakeholders. The collection of information led to the selection of the following ecosystem services: climate regulation with

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carbon storage; energy, food and water provisioning, recreational activities. For the analysis of carbon storage sequestration, the analysis is being conducted by implementing the carbon storage model (Rueschc Gibbs 2008), for which the organic carbon mass stored is the output indicator and is computed considering vegetation and soil carbon storage. The carbon storage is represented by the organic carbon which is the sum of carbon stored in the soil and the carbon mass stored in aboveground and belowground vegetation. The implementation of the pollination model based on the Crop Pollination model from InVEST was conducted to support the assessment of food provisioning; the output indicator of this assessment is represented by net value of pollination. Pollination by animals is an essential ES that directly links natural habitats to agricultural landscapes, as 70% of globally important crop species depend to some extent on pollinators. The pollination conceptualization used here produces spatially explicit, ranked estimates on the supply and demand for insect pollination services based on land cover, cropland, and weather patterns. The cultural services has being investigated through the recreational model (ESTIMAP model) based on the potential value of outdoor recreation and the net value of outdoor recreation, which is the difference between recreation supply and demand. Finally, the sediment retention model is being implemented as a regulating service, and the outputs are represented by two indicators: the potential soil removed mass and the soil retained mass by vegetation. The potential value (supply) of the sediment regulation ecosystem service is computed by calculating RUSLE equation twice, first using the best land cover data available, then changing all land cover to bare soil and differentiating the results to estimate the avoided soil erosion attributable to vegetation. The RUSLE is an empirical model that calculates long-term average annual soil loss due to sheet and rill erosion. The model considers six main factors controlling soil erosion: the erosivity of the eroding agents (water), the erodibility of the soil (including stoniness), the slope length and slope steepness of the land, the land cover and management (or human practices designed to control erosion). Water and food provisioning will be analysed in combination with the results and analysis of hydrological and crop model developed within the Case Study area. These models are all already included in the ARIES platform making them easy-to-apply. Moreover, users are allowed to create new models (e.g. machine learning, Bayesian networks), and let ARIES run them if the models already existing in ARIES are not performing well for the assessment of a particular ES or if there are local models which are more efficient.

Here below the tables with dedicated information for the three covered sectors of water, food and ecosystems are reported:

Table 5. Description of the hydrological model (ICHYMOD).

Case Study no.: 4	**Sub-unit (if applicable):**
Model name: ICHYMOD	
Description: Semi distributed conceptual hydrological model with inbuilt enhanced temperature index snowmelt module (TOPMELT).	
Documentation: Zaramella, M., Borga, M., Zoccatelli, D., & Carturan, L. (2019). TOPMELT 1.0: a topography-based distribution function approach to snowmelt simulation for hydrological modelling at basin scale. Geoscientific Model Development, 12(12), 5251–5265. Borga, M., 2002: Accuracy of radar rainfall estimates for streamflow simulation. Journal of Hydrology, 267, 26-39. Borga, M., S. Degli Esposti and D. Norbiato, 2006: Influence of errors in radar rainfall estimates on hydrological modelling prediction uncertainty. Water Resources Research, 42, W08409, doi:10.1029/2005WR004559.	

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<table>
<tr><td colspan="3">Norbiato, D., M. Borga, R. Merz, G. Blöschl and A. Carton, 2009a: Controls on event runoff coefficients in the eastern Italian Alps. Journal of Hydrology, 375, 312-325, doi:10.1016/j.jhydrol.2009.06.044.</td></tr>
<tr><td colspan="2">Area coverage: 6924km² (Adige at Bronzolo)</td><td>Time coverage: 1991-2019</td></tr>
<tr><td colspan="3">Reference/calibration data: 2000-2014</td></tr>
<tr><td>Model input parameter(s):</td><td>Source:</td><td>Resolution:</td></tr>
<tr><td>Precipitation/temperature</td><td>Hydrographic Office of Bozen, Bolzano</td><td>Hourly/Station</td></tr>
<tr><td>DEM/Glacier map</td><td>University of Padova</td><td>250m</td></tr>
<tr><td colspan="3">How are the input data bias corrected and/or pre-processed? (or leave blank)
Snow correction factor of 1.4 applied to precipitation prior to the model input.</td></tr>
<tr><td colspan="3">Will the model be updated/improved during NEXOGENESIS? (if yes, please explain how)
Model application extended up to Adige at Trento and Verona.
Glacier area retreat based on ice melt from model for current and future scenarios.
Integration of irrigation module for Verona
Consideration of other climatic scenarios (SSP126 andSSP585)</td></tr>
<tr><td colspan="3">Modelling dependencies: (does the model depend on other simulations or data collected?)
Better to have inputs at hourly scale with comparatively dense network of stations.</td></tr>
<tr><td>Climate scenarios currently used:</td><td colspan="2">SSP585</td></tr>
<tr><td>Source (s) of future climate projections:</td><td colspan="2">CMIP6</td></tr>
<tr><td>Reference period:</td><td colspan="2">2000-2014</td></tr>
<tr><td>Future time periods:</td><td colspan="2">2030-2100</td></tr>
<tr><td colspan="2">Output parameter(s):</td><td>Resolution:</td></tr>
<tr><td colspan="2">Runoff (Total, baseflow) and snow water equivalent</td><td>1) Basin scale 2) Available for 10 percentiles within each elevation band of 200m height.</td></tr>
<tr><td colspan="3">Analysis objectives:</td></tr>
<tr><td colspan="3">To simulate future runoff with different climatic scenarios considering glacier retreat to explore decision making options considering hydropower production and irrigation needs during drought events.</td></tr>
<tr><td colspan="3">Modelling time line:</td></tr>
<tr><td colspan="3">Inclusion of glacier melt retreat: April – June 2023
Climate scenarios and glacier melt retreat for future runoff: May – Aug 2023.
Integration of irrigation module for Verona: Aug 2023
Analysis of decision-making options: Aug - Dec 2023.</td></tr>
<tr><td>Could your model easily be adapted to another CS?</td><td>Y / N</td><td>Y</td></tr>
</table>

Table 6. description of the soil-water balance model (SIMETAW).

<table>
<tr><td>Case Study no.: 4</td><td>Sub-unit (if applicable):</td></tr>
<tr><td colspan="2">Model name: SIMETAW</td></tr>
<tr><td colspan="2">Description:
SIMETAW# is a physically-based soil water balance model that assesses crop water use, irrigation requirements, and generates hypothetical irrigation schedules for a wide range of crops experiencing full or deficit irrigation.</td></tr>
</table>

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<table>
<tr><td colspan="4">Documentation:
Mancosu, N., Spano, D., Orang, M., Sarreshteh, S., Snyder, R.L., 2016. SIMETAW# - A model for agricultural water demand planning. Water Resour. Manag. 30, 541–557. https://doi.org/10.1007/s11269-015-1176-7
Masia, S., Trabucco, A., Spano, D., Snyder, R.L., Sušnik, J., Marras, S., 2021. A modelling platform for climate change impact on local and regional crop water requirements. Agric. Water Manag. 255, 107005. https://doi.org/10.1016/j.agwat.2021.107005</td></tr>
<tr><td colspan="2">Area coverage: Provinces of Bolzano and Trentino</td><td colspan="2">Time coverage: 2015-2017; 2030-2100</td></tr>
<tr><td colspan="4">Reference/calibration data: 2015, 2016, 2017</td></tr>
<tr><th colspan="2">Model input parameter(s):</th><th>Source:</th><th>Resolution:</th></tr>
<tr><td colspan="2">Maximum and minimum temperature; Wind speed; Solar radiation; relative humidity; Precipitation; Available water capacity; Maximum rooting depth of each specific crop; Maximum soil depth; Planting or bud break and harvesting date of each specific crop; Elevation; Crops, rain-fed or irrigated conditions; Irrigation system</td><td>ERA5 reanalysis; Hengl & Gupta (2019b); FAO, 2012; USGS (SRTM)</td><td>Varying according to the considered input parameters</td></tr>
<tr><td colspan="4">How are the input data bias corrected and/or pre-processed? (or leave blank)
-</td></tr>
<tr><td colspan="4">Will the model be updated/improved during NEXOGENESIS? (if yes, please explain how)
Yes, it will be expanded to also cover the downstream area and interactions with the hydrological model will be explored</td></tr>
<tr><td colspan="4">Modelling dependencies: (does the model depend on other simulations or data collected?)
No</td></tr>
<tr><td>Climate scenarios currently used:</td><td colspan="3">ERA5</td></tr>
<tr><td>Source (s) of future climate projections:</td><td colspan="3">CMIP6</td></tr>
<tr><td>Reference period:</td><td colspan="3">2015,2016,2017</td></tr>
<tr><td>Future time periods:</td><td colspan="3">2030-2100</td></tr>
<tr><th colspan="2">Output parameter(s):</th><th colspan="2">Resolution:</th></tr>
<tr><td colspan="2">Reference evapotranspiration (ETo); potential crop evapotranspiration (ETc); evapotranspiration of applied water (ETaw); mean depth of infiltrated water (IW); actual crop evapotranspiration (ETa)</td><td colspan="2">Varying based on input data</td></tr>
<tr><td colspan="4">Analysis objectives:</td></tr>
<tr><td colspan="4">To estimate the agricultural water demand within the Adige river basin for the main crop types and simulate future conditions for different climate scenarios.</td></tr>
<tr><td colspan="4">Modelling time line:</td></tr>
<tr><td colspan="4">May-Sept 2023: calibration and validation
Sept-Dec 2023: integration of futures scenarios in relation to the hydrological model</td></tr>
<tr><td colspan="2">Could your model easily be adapted to another CS?</td><td>Y / N</td><td>Y</td></tr>
</table>

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Table 7. Description of the artificial intelligent modeller (ARIES).

Case Study no.: 4	**Sub-unit (if applicable):**	
Model name: ARIES		
Description: ARIES is an artificial intelligent modeller. ARIES chooses ecological process models where appropriate, and turns to simpler models where process models do not exist or are inadequate. Based on a simple user query, ARIES builds all the agents involved in the nature/society interaction, connects them into a flow network, and creates the best possible models for each agent and connection. The result is a detailed, adaptive, and dynamic assessment of how nature provides benefits to people (https://aries.integratedmodelling.org/).		
Documentation: Villa F., et al. 2014. A methodology for adaptable and robust ecosystem services assessment. Villa F., et al. 2017. Semantics for interoperability of distributed data and models: Foundations for better-connected information. Barquin J., et al. 2015. Coupling virtual watersheds with ecosystem services assessment: A 21st century platform to support river research and management.		
Area coverage: Adige river basin	**Time coverage:** 2020-2022; 2050-2100	
Reference/calibration data: 2020-2022		
Model input parameter(s):	**Source:**	**Resolution:**
Common parameters: land cover, elevation, slope.	Corine Land cover 2018 https://www.earthenv.org/DEM	Depending on the considered parameters.
Specific parameters: Vegetation carbon storage, soil carbon storage, ecofloristic region, continental region, presence of frontier forests, recent occurrence of fires (Carbon storage). Insect as pollinator occurrence, landscape suitability, flowering probability, insect as pollinator occurrence by weather, nesting as pollinator occurrence (pollination). Distance to: coast, water bodies, mountains, protected areas; demography, travelling connection, travel time (recreational model). Soil %, contributing areas, aspect, R factor (sediment	https://www.soilgrids.org/, https://cdiac.ess-dive.lbl.gov/epubs/ndp/global_carbon/carbon_documentation.html https://cgiarcsi.community/data/global-aridity-and-pet-database/ https://www.naturalearthdata.com/downloads/10m-physical-vectors/10m-coastline/ https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA https://forobs.jrc.ec.europa.eu/products/gam/ https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-adjusted-to-2015-unwpp-country-totals-rev11 https://hydrosheds.cr.usgs.gov/hydro.php	

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<table>
<tr><td>retention).</td><td colspan="3"></td><td></td></tr>
<tr><td colspan="5">How are the input data bias corrected and/or pre-processed? (or leave blank)</td></tr>
<tr><td colspan="5">Will the model be updated/improved during NEXOGENESIS? (if yes, please explain how)
In ARIES different models can be integrated, this is not a model specific only for ecosystem services assessment (i.e., they can be applied to other integrated modelling problems)¸therefore, whatever is the problem to be assessed, and there's the need to integrate different inputs parameter or models, ARIES allows users to do so. Indeed, it is the first operational example of semantically integrated, distributed, collaborative modelling. Other local models can be run into ARIES, the existing models can be modified according to the availability of data and to the characteristics of particular data.</td></tr>
<tr><td colspan="5">Modelling dependencies: (does the model depend on other simulations or data collected?)
Yes, ARIES is a collection of different models. Outputs of hydrological and crop models can be integrated within different global models already existing in ARIES. But more importantly, some input parameters such as land cover, soil type, elevation are needed by all the models, highlighting the importance of the integration among the ES and the models which represent them.</td></tr>
<tr><td>Climate scenarios currently used:</td><td colspan="4">RCP2.6</td></tr>
<tr><td>Source (s) of future climate projections:</td><td colspan="4">CMIP6</td></tr>
<tr><td>Reference period:</td><td colspan="4">2020-2022</td></tr>
<tr><td>Future time periods:</td><td colspan="4">2030-2100</td></tr>
<tr><td colspan="2">Output parameter(s):</td><td colspan="3">Resolution:</td></tr>
<tr><td colspan="2">- Net value of pollination
- Organic carbon mass stored
- Potential soil removed mass
- Soil retained mass by vegetation
- Potential value of outdoor recreation
- Net value of outdoor recreation</td><td colspan="3">Depending on the considered parameters</td></tr>
<tr><td colspan="5">Analysis objectives:</td></tr>
<tr><td colspan="5">Analyse how the different ES considered within the Adige Case Study interact among them, and how the WEFE nexus dynamics influence these interactions. Particularly, the analysis of one ES can help in understanding others or can contribute in the assessment. For example, analysing the water provisioning through the annual or seasonal water yield, we will be able to investigate how much water could be needed by agriculture for the definition of crop yield (food provisioning). Moreover, while estimating the recreational services it will be possible to consider other ES in order to analyse particular activities, such as water-related activities or the ecosystem health. Generally, ESs strongly depend on the type of land use/cover and this is why this parameter is common to all the models. In this analysis, ESs will be assessed to see how each output could be integrated within the assessment of others ESs and how climate change scenarios can alterate and modify the presence and interrelationships among the ESs.</td></tr>
<tr><td colspan="5">Modelling time line:</td></tr>
<tr><td colspan="5">The model will be applied in summer 2023. Further tests will be implemented by 2023/beginning 2024 in order to integrate ARIES with the hydrological and crop models.</td></tr>
<tr><td colspan="2">Could your model easily be adapted to another CS?</td><td colspan="2">Y / N</td><td>Y</td></tr>
</table>

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

3.5.2 Case Study requirements for biophysical and socioeconomic data based on the data mapping

The data mapping described here was done based on the initial draft of the SDM, which itself was derived from the stakeholder validated conceptual systems map of the study area and reported in D3.1. The data mapping so far has been carried out by Jones and Wagener (JAWS), the local NEXOGENESIS Case Study #5 leader with the assistance of the WP2 team. Additionally, JAWS are exploring local datasets that could be exploited. Stakeholder validation of the data mapping has not yet been carried out because the workshop for this exercise has not yet been done at the time of writing. However, no major changes or modifications are expected.

From the draft development of the SDM (deriving from the validated conceptual map, Section 2) for the Inkomati-Usuthu Case Study and by comparing this development with the data from WP2 using the data mapping Excel sheet, an initial screening of data requirements and availability has been derived.

In the **population** sector, only the population growth rate variable from GRDEM and/or the DEMETRA model was identified (final model selection to be determined). This variable will change a baseline local population taken from local statistics with the locally-specific growth rate to project population to 2050. This is important as population modulates domestic water demand, domestic energy demand and domestic food demand for example in the SDM.

In the **water** sector, a wide variety of WP2 variables were identified. In terms of water supply, groundwater storage, reservoir storage, groundwater recharge, surface and subsurface runoff, were identified. For water demand, domestic water consumption, manufacturing and industrial water consumption, and total South African water demand (to be scaled to the Case Study region) have been identified. It should be noted that there is no energy generation within the basin - therefore no WP2 variables were identified for water for energy, however there is a portion of water exported from the basin for use in the generation of energy within surrounding basins. This will be accounted for with the use of local variable. Additionally, irrigation water consumption (potential and actual, irrigated and ‘green water’ for rainfed crops), livestock water consumption, and potential evapotranspiration have been selected to inform overall water demand. In terms of water quality, Nitrogen application rates for various crop types have been identified from the WP2 variables.

Regarding the **food** sector, for food production, crop yields for multiple crops on irrigated and non-irrigated land (e.g. maize, soy), and imports and exports are considered as well as the food demand per-capita.

In the **energy** sector, in terms of production, the total electricity gross output from GRDEM may be of use, while in terms of consumption, the total South African energy demand (which will require downscaling to the study area), the total South African electricity demand (again

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requiring downscaling), and the energy consumption from GRDEM broken down by economic sector (e.g. mining, industrial) are the variables identified from WP2 data.

For **land use**, the WP2 GRDEM dataset offers land use by sectoral type (e.g. forests, agriculture). This may be too coarse or aggregated to be of use, and therefore local data (next section) will be considered as an alternative.

In the **ecosystems** sector, wetland storage, mean monthly water storage in wetlands, vegetation composition, the overall mean species abundance as well as the mean species abundance for plant and birds and mammals have been identified from WP2 data.

In the final sector, **climate**, the total emissions by production sectors, and the human greenhouse gas emissions by economic sector are available variables from WP2 data.

It is noted that for many of these variables, WP2 offers the same variable deriving from different source models (e.g. LPJmL, WaterGap, PCR-GLOBWB). The complete set of information for a given variable can be exploited within the SDM to allow for uncertainty analysis to be carried out as detailed in Deliverable 3.5. It is also noted that not every SDM variable can be identified in WP2 data, nor from local data (see Section 5.5.2). If this situation cannot be resolved, it implies changes to the SDM to omit these variables, representing a data-based limitation in nexus modelling. This situation applies to all the NEXOGENESIS case studies.

3.5.3 Case Study requirements for locally-relevant data

In the Inkomati-Usuthu Case Study, several local datasets will be utilised to capture very specific issues and requirements in the Case Study region that cannot be sourced with WP2 data sources. In the population sector, locally-available statistics will be used to give indications on the historic Iknomati-Usuthu population. These locally-sourced population numbers will then be extrapolated to 2050 by growth rates derived from either the WP2 GRDEM or DEMETRA models (from partner CAF), depending on which of these is most suitable (subject to a screening and validation by partners CAF and JAWS).

In the **water** sector, local data will inform information on transboundary flow obligations (acting as a water demand), water physically exported from the basin, the regional water balance, the water demand for mining activities, and nitrogen runoff rates from agricultural fields. Additionally to supplement the WP2 data for water demand, local data will be sourced to define baseline water demand per capita.

In the **food** sector, pesticide application rates, food imports and exports, nitrogen application rates, the livestock yield per-head, and food demand per-capita will be locally sourced. It is pointed out here that upon further discussion, it may be decided that not all these categories are crucial to the Case Study objectives. Where this is the case, the variables will no longer be sourced. This issue is to be discussed in future stakeholder workshops.

In the **energy** sector, energy generation (thermal power outside the study area), off-grid renewables generated inside the study area, access to energy (% of population), energy use per-capita, and energy used per unit of irrigated agriculture will be sourced from local sources.

In the **land** sector, local land-use statistics are required to capture the area of rainfed and irrigated agriculture, split by crop type, the mining area, forest area, and wetland area.

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For **ecosystems**, data include the biomass per unit forest area, and per-unit agricultural area, the protected areas in the study area, and the carbon sequestration from biomass.

There are no local data required in the climate sector.

It should be noted that all resources, and stakeholders are being consulted to supplement the WP2 variables with local data, where required. However, access to the data is proving challenging and data is not always available at a basin level. Where possible local data at a basin level will be obtained, however for some variables National, and provincial data will be downscaled to a basin level.

Table 8. A list of all WP2-derived parameters used in the Inkomati-Usuthu case study is presented below.

population projections
population projections
percent change in per-capita water demand
percent change in per-capita food demand
percent change in energy supply
percent change in per-capita energy demand
surface water runoff
water storage behind dams
industrial water demand
agricultural crop yield, broken down by crop
carbon mass stored in vegetation
gross primary productivity
nitrogen leaching from agricultural land
mean species richness
wetland water storage
agricultural biomass
crop water requirements, broken down by crop
carbon flux out of the atmosphere

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3.5.4 Case Study use of locally-specific models

In the Inkomati-Usuthu Case Study, locally-specific models are not being considered.

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4. Conclusions and future work

Deliverable 3.3 details the modeling approach adopted to meet stakeholder requirements identified during the workshops for each case study. It begins by explaining how the conclusions from these workshops were transformed into conceptual maps. The aim of this process was to capture the collective perceptions and insights of the stakeholders regarding the water-energy-food-ecosystems (WEFE) management within each River Basin District. This included feedback on critical subsystems that significantly influence resource management, as well as identifying key drivers, stresses, and impacts. Suggestions for potential responses were also recorded to inform relevant subroutines within the modeling frameworks.

Subsequently, the deliverable outlines how these conceptual maps were translated into conceptual models to identify the necessary modeling subroutines across the nexus sectors. The common subroutines applicable to all case studies are aligned with inputs from the central bio-physical and socio-economic models developed in WP 2. A coordinated effort was made for each case study to outline the relevant attributes needed from these central models for their respective System Dynamics Models. In relation to the socio-economic datasets detailed in D2.4, each case study applied percentage changes (percentage changes from 2015 to 2050 for a wide range of parameters was provided by D2.4) to the initial values of socio-economic parameters, ensuring an efficient analysis. WP2 datasets were downscaled to NUTS2 level, allowing for a precise representation of the local context in each case study. Additionally, all socio-economic data are available at both SSP2 and SSP4 levels. This approach, when integrated with RCP scenarios, offers a diverse range of potential future outcomes, enriching our understanding of how various socio-economic factors may evolve over time.

In addition to the attributes derived from the central models, the deliverable describes case-specific subroutines developed or collected from the modeling teams of the individual case studies. These case-specific routines may involve creating local sub-models and utilizing data from local sources. An example of such a localized model could include a hydrological model or a model focusing on the infrastructure pertinent to the case study area.

This comprehensive approach ensures that the modeling efforts are grounded in stakeholder insights and tailored to the unique contexts of each case study, thereby enhancing the relevance and effectiveness of the System Dynamics Models in addressing WEFE management challenges.

The information presented in this deliverable enhances the uncertainty analysis in SDMs (Task 3.4) for the five NEXOGENESIS case studies, which are centered on the water-energy-food-ecosystems (WEFE) nexus. Specifically, model parametric uncertainty will be employed to assess the reliability of the input parameters within SDMs. Additionally, scenario uncertainty will be applied to investigate how various external conditions or future scenarios influence model outcomes. This dual approach aims to provide a comprehensive understanding of the uncertainties involved, thereby improving the robustness of the SDMs. This methodoly is detailed presented in D3.5 "*Sensitivity and uncertainty analysis methodology*".

The WEFE nexus indices calculation (Task 3.5) was based on data provided by the case study SDMs models. WP3 contributed to this process by leading the modeling framework for the case studies SDMs models' development. More specifically, the output of the SDMs such as water-related parameters (water withdrawals, surface water resources, etc.), energy-related

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parameters (CO_2 emissions), food-related parameters (crop per drop), and ecosystems-related parameters (total protected area, total nitrogen load, species richness, forest area, etc.) provided essential input for the WEFE nexus index. Based on the provided data, indices for each nexus component will be calculated, and the global WEFE footprint indicator calculation as well. This process will be described in detail at the D3.7 *"Final report on the WEFE Nexus Index methodology and visualization."*

5. REFERENCES

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