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Multi-Stakeholder Development of a Serious Game to Explore the Water-Energy-Food-Land-Climate Nexus: The SIM4NEXUS Approach

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Abstract: Water, energy, food, land and climate form a tightly-connected nexus in which actions on one sector impact other sectors, creating feedbacks and unanticipated consequences. This is especially because at present, much scientific research and many policies are constrained to single discipline/sector silos that are often not interacting (e.g., water-related research/policy). However, experimenting with the interaction and determining how a change in one sector could impact another may require unreasonable time frames, be very difficult in practice and may be potentially dangerous, triggering any one of a number of unanticipated side-effects. Current modelling often neglects knowledge from practice. Therefore, a safe environment is required to test the potential cross-sectoral implications of policy decisions in one sector on other sectors. Serious games offer such an environment by creating realistic 'simulations', where long-term impacts of policies may be tested and rated. This paper describes how the ongoing (2016–2020) Horizon2020 project SIM4NEXUS will develop serious games investigating potential plausible cross-nexus implications and synergies due to policy interventions for 12 multi-scale case studies ranging from regional to global. What sets these games apart is that stakeholders and partners are involved in all aspects of the modelling definition and process, from case study conceptualisation, quantitative model development including the implementation and validation of each serious game. Learning from playing a serious game is justified by adopting a proof-of-concept for a specific regional case study in Sardinia (Italy). The value of multi-stakeholder involvement is demonstrated, and critical lessons learned for serious game development in general are presented.

Keywords: nexus; participatory modelling; serious game; system dynamics; water-food-land-energy-climate

1. Introduction

Water, energy, food, land and climate exist in a 'hyperconnected' state [1] and are bound together in an extraordinarily complex system in which each sector cannot be considered in isolation, as it has impacts on at least one of the other system sectors. The Bonn Nexus Conference in 2011 [2] focussed particularly on the water-energy-food (WEF) 'nexus'. Since then, the 'classical' WEF nexus has evolved to include land use, the environment, climate change, waste and/or the economy ([1,3–9] and www.flores.unu.edu/en/research/nexus). Others have used alternative terms to define a complex system connected at the global scale and in which actions of one sector can have significant impacts on other sectors (e.g., 'teleconnections', especially in the climate system; [10]). Global research teams, politicians and multinational corporations are showing increased interest in the nexus and its potential implications for business [1,3,8,11–13]. The nexus has global relevance and is extremely complex. However, global issues often require local actions [13]. Full understanding of this nexus and characterization of its internal feedbacks is required in order to be able to make informed, meaningful (policy) decisions [14]. Herein lies a current gap in understanding, as many previous studies either: (1) consider only one or perhaps two nexus sectors, neglecting impacts on the others [7,15]; or (2) consider more sectors, but only for very local, specific case studies that lack wider applicability [16,17]. Efforts are required, therefore, to consider many nexus sectors together at a range of scales from regional to international in order to develop a more general understanding of nexus behaviour, and the potential impact of climate, socio-economic and policy changes on this behaviour.

To enable full understanding of complex relations between natural resources and to promote the nexus concept as a means to enhance wider nexus-compliant practices require capacity building and education programs to engage current and future stakeholders. Learning is essential. However, the process of capacity building and education is complex, and there is a push to find innovative ways to make these processes more efficient, effective and scalable. A major opportunity to accelerate progress is through the utilization of opportunities provided by advances in and dissemination of information and communications technology (ICT).

One upside of ICT is the easy access to information and data, which is in turn related to one of its main downsides, namely the overabundance of information, not all of which may be useful, necessary or accurate. Consider the number of hits a search engine returns on a simple search, or the amount of online advertisements a typical Internet user may be exposed to during the course of day. According to [18,19], we are exposed to these sources at such a high rate, that it affects the way our brains process information. Today, we are immediately drawn to information mechanisms, for example, notifications from devices (mobile phones, tablets or computers) that 'pop-up', interact with us briefly and give us a very condensed information stream. This brings about additional challenges in learning and capacity building: besides having to make it more efficient and scalable, we also need to keep up with communication trends and technology to be able to attract the attention and interests of our target audience(s).

A serious gaming approach combines a learning objective with a fun activity in an attempt to increase the potential for learning uptake [20,21]. Perhaps one of the best-known applications of an electronic-based serious "game" is that of flight simulators used in pilot training. One of the main reasons for the success of this kind of application is that pilots need a very realistic learning environment, but also one that has minimal risk and allows them to make non-catastrophic mistakes from which they can learn. This learning-by-playing approach is commonly termed "meaningful play" [22], and a well-designed serious game environment provides a feedback mechanism that allows the player to reflect on his or her actions and adopt different approaches or strategies. The internalisation of actions and reactions stimulates learning, often resulting in an increase in self-learning and knowledge retention. Serious games, or games used for purposes other than mere entertainment [21], are often used for education, decision making and for public policy making. Since [23] introduced the notion of serious games, various applications have been developed, including, but not limited to, educational [24], science [25], training, psychology [26], military [27], government, corporate, healthcare [28] and water management domains [29]. However, no comprehensive serious game has been developed to deal with the water-energy-food-land-climate nexus, which represents a clear gap in the literature.

With respect to the above discussion, there is a clear need to: (1) improve scientific understanding of the water-food-land-energy-climate nexus in a holistic way and applicable at a range of scales; and (2) to develop serious games addressing the (global) water-energy-food-land-climate nexus, or parts thereof, at multiple scales from regional to international, and for a reasonable policy-relevant time dimension (decades at least). Such serious games should be grounded in robust science and analysis, using the latest data and state-of-the-art modelling tools and techniques. They should also be appropriately 'packaged' and targeted to certain users, namely those in decision-making or decision-influencing positions. These games should allow those users to explore nexus issues at many scales, allowing exploration of the trade-offs and synergies between sectors. They need to be coherent and understandable and convey clear policy-relevant messages and information based on the latest scientific understanding. The main purpose of these serious games should be to enable stakeholders to understand and learn about the medium and long-term implications of nexus-related policies applied to each case study. Using gaming (not necessarily as an ICT tool) has long been established as means for understanding policies [20], leading to acceptance, mitigating conflicts and compromise. Moreover, Medema et al. [30] discuss how serious games offers stakeholders an opportunity to voice their perspectives, and Gurung et al. [31] show how useful serious gameplay can be in the development of trust and empathy among stakeholders, as well as an improved understanding of systems and complex issues at play. A similar conclusion is reached by [32], who asked farmers in conflict over water allocations to play a simulation game in which the farmers swapped roles for one round of the game. When the roles of the farmers are swapped from upstream to downstream villages and vice versa, it was very effective at sharing different perspectives. This paper introduces a serious gaming approach, based on these concepts, aiming at creating an understanding of nexus issues related to food, energy, water, climate and land, across various stakeholders and the long-term implications of different policies that may be implemented at the regional, national or international level.

The work presented in this paper refers to an ongoing (2016–2020) EU Horizon2020 project "Sustainable Integrated Management FOR the NEXUS of water-land-food-energy-climate for a resource-efficient Europe (SIM4NEXUS; www.sim4nexus.eu)". SIM4NEXUS aims at developing serious games for each of the project's case studies, using an innovative methodological approach, described in this paper. The serious games in SIM4ENXUS will be operable at scales ranging from regional to national, to continental, to global, as well as at different time horizons: short-, medium and long-term to 2050. A specific project case study (Sardinia) and its serious game are presented, which was selected from the start of the project as a "fast-track" proof-of-concept exercise. The term "fast-track" refers to the time frame (as fast as possible) during which the serious game was developed, as well as to some relatively simplified approach in the modelling; we are interested in a methodological innovative high level approach, rather than detailed simulation of the region. On the other hand, the paper is meticulous in detailing the nexus approach and all the steps leading from "raw" data to the development of a serious game for a specific region; this same approach is being followed for all case studies (still an ongoing exercise until 2020). Furthermore, it has a wider potential for further applications and, to the best of our knowledge, does not exist in the literature.

While previous efforts have considered nexus elements either in complete isolation or only in 'partial integration' (i.e., considering only a few nexus elements at one time), SIM4NEXUS aims to address all the water-food-land-energy-climate elements together (Figure 1) and to account for the possible impact on these elements in response to climate and relevant policy changes. SIM4NEXUS aims to address both research and knowledge gaps regarding the global nexus at multiple scales and communicating critical results to policy-makers via a state-of-the-art serious game built on robust science. Considering Figure 1, the image on the far left reflects the 'traditional' approach with sectoral modelling (e.g., from models such as CAPRI (Common Agricultural Policy Regionalised

Impact Modelling System) or E3ME (energy-environment-economy[E3] macro-economic model)). The middle image reflects the most current advanced approaches (e.g., impact assessment tools, integrated assessment modelling, integrated water resources management). There is partial integration, e.g., linking the model MAGNET (Modular Applied GeNeral Equilibrium Tool) with IMAGE, used to assess cross-sectoral impacts of climate, social and/or policy changes, but complete nexus understanding is still missing. SIM4NEXUS integrates thematic models within a system dynamics modelling framework to integrate the knowledge and data from thematic models and local experts. SIM4NEXUS adds the learning from playing the serious game and testing nexus-compliant policies. In addressing nexus-wide interconnections, system-wide trade-offs and synergies can be sought, with benefits for multi-sectoral policy development and planning [14].

The objectives of this paper are two-fold. Firstly, the general process of serious game development in SIM4NEXUS that is common for all 12 case studies is presented. In this way, the consistent mode of game development in SIM4NEXUS, running from case study nexus qualitative conceptualization and problem mapping, right through to serious game development and implementation, is presented. Herein lies the first novelty: inclusion of local-level stakeholders from the very beginning, with each case study led by a local expert. The second objective is to highlight the central novelty of SIM4NEXUS. To the best of our knowledge, no other serious game has been developed that covers the range of nexus sectors (water, energy, food, land and climate), the range of spatial scales (regional to global) and that also includes comprehensive case study-relevant policy analysis to help frame and guide model and game development. In this sense, many of the gaps alluded to above regarding nexus modelling and serious gaming are being addressed in SIM4NEXUS. It is pointed out that SIM4NEXUS is ongoing (started June 2016, ending May 2020). Therefore, this paper does not present completed or final models or serious games, but focusses instead on the process and on intermediary results from a pilot fast-track study in the project. Lessons learned from the fast-track are presented. These lessons are useful not just in SIM4NEXUS, but for other serious game development exercises.

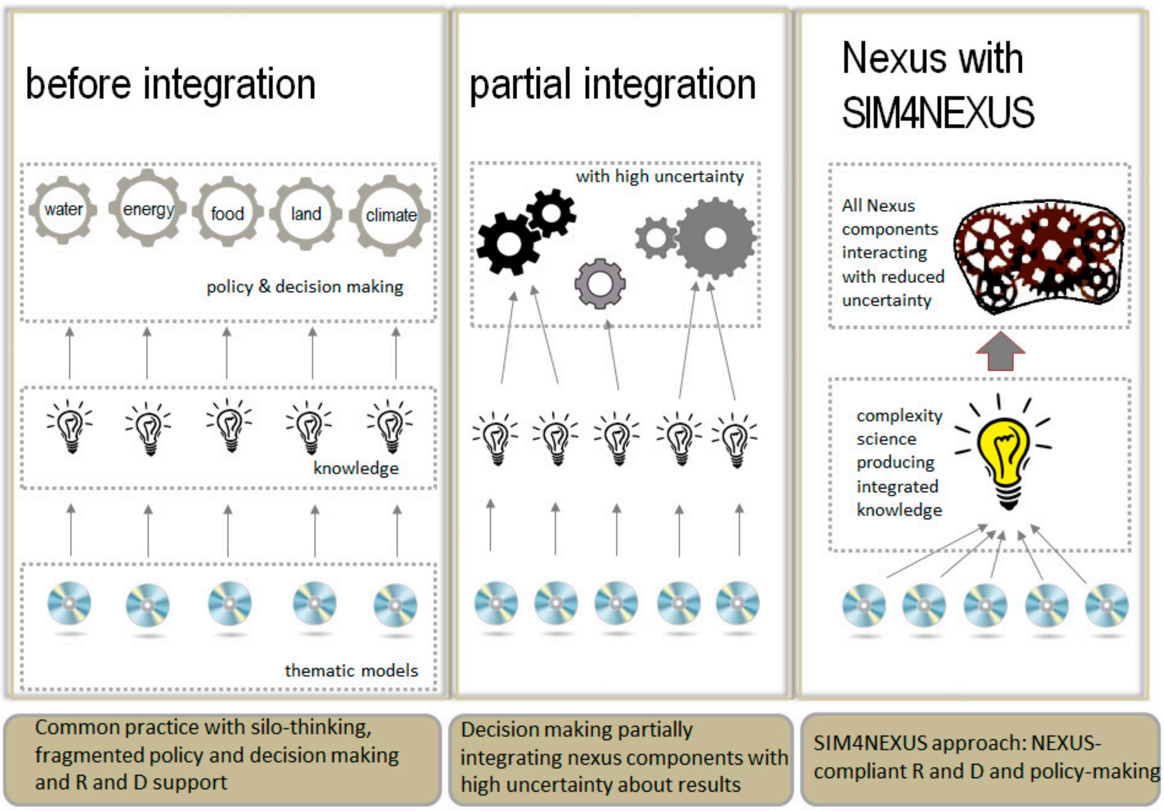


Figure 1. The SIM4NEXUS integration concept.

2. Serious Game Development: Process Overview

SIM4NEXUS will develop serious games for 12 case studies, ranging in scale from regional (e.g., southwest England, Sardinia) to global. For each, the general process of model development leading to serious game design and implementation will follow a similar path, only changing specific details particular to each case study. There are five main steps in the overall general model and serious game development process comprising: Step 1. Case study nexus system description, framing and conceptualisation; Step 2. Thematic data identification and collection; Step 3. System dynamics integration modelling and conversion to R script (www.r-project.org); Step 4. Communication of model output to the Knowledge Elicitation Engine; Step 5. Design and development of the serious game front-end. These five steps are elaborated in the following sections (Sections 2.1–2.4). For each step, the general process/methodology to be used in all SIM4NEXUS case studies is described, followed by the application to the pilot fast-track case study of Sardinia.

2.1. Case Study System Conceptualisation and Data Identification (Steps 1 and 2)

This step is concerned with framing the key nexus issue(s), within the remit of SIM4NEXUS, to be explored in each case study. Together with project case study leaders and diverse stakeholder groups, the main case study nexus issue(s) is identified in stakeholder workshops. For example, in Sardinia, the central issue is the long-term resilience of reservoir water supply to changes in climate and agricultural factors, while in the Netherlands, it is centred on biomass generation and a switch to a low-carbon economy. From the central theme, interactions with other nexus sectors are identified, including important feedback processes. A dedicated Work Package in SIM4NEXUS on nexus policy analysis is critical in offering input to this process, as it provides a first idea of the most pertinent nexus-relevant policies, goals and instruments for each case study. The central theme/issue identified by case study leaders and stakeholders can be cross-checked with the policy analysis to begin to identify likely policy scenarios/goals to be modelled and implemented in the serious game so as to have relevance for local players. Therefore, even at this early stage, stakeholder involvement is critical, and input is taken from case study-level policy analysis.

The end product is a conceptual (qualitative) diagram that defines the central nexus issue and that elaborates the key interactions with other nexus sectors. Key policies to potentially be played in the final game are already identified, but subject to changes. Data requirements for quantitative modelling are identified at this stage, and data are gathered.

In this paper, the general modelling process is elaborated in relation to a 'fast-track' proof-of-concept carried out in SIM4NEXUS using Sardinia as the pilot case study (Figure 2). The fast-track approach was adopted to test each step in the development process, identifying and addressing any major difficulties and issues before rolling out the process in detail for all 12 SIM4NEXUS case studies. Sardinia was chosen as the fast-track because knowledge of system dynamics modelling to assess resilience of reservoirs to meet multiple water demands (i.e., agriculture, domestic/tourism, hydroelectric) under climate change was already available from the EC FP7 project Water Availability and Security in Southern EuRope and the Mediterranean; 'WASSERMed' (see www.cmcc.it/projects/wassermed-water-availability-and-security-in-southern-europe-and-the-mediterranean for a general project description and [33] for results). Therefore, the team was not starting from a 'blank slate', allowing a facilitated process to integrate further nexus sectors and feedbacks in the quantitative modelling.

To articulate the conceptual framing of the Sardinia case, interactive workshops with local experts and stakeholders, including academics, public authorities, decision makers and unions, were carried out to define the key nexus sectors to consider, identify sector drivers, relevant key policies and, crucially, how sectors and policies interact. At the end of the process, the model was expanded in terms of: (i) nexus sectors, which now include energy, land and food, that were not included in the WASSERMed version; (ii) spatial scope, from district level to integrating sectorial interactions for the whole of the Sardinian region; and (iii) increasing the detailed representation of nexus sectors in the model, including the policies that affect them. Figure 3 shows the conceptual system diagram developed for the Sardinia fast-track, on which further quantitative model development was based.

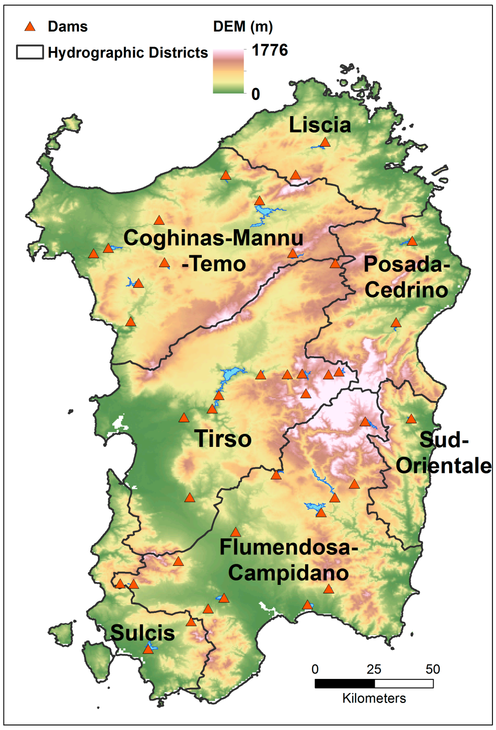


Figure 2. Map of Sardinia, showing the seven hydrological districts and the locations of the reservoirs studied.

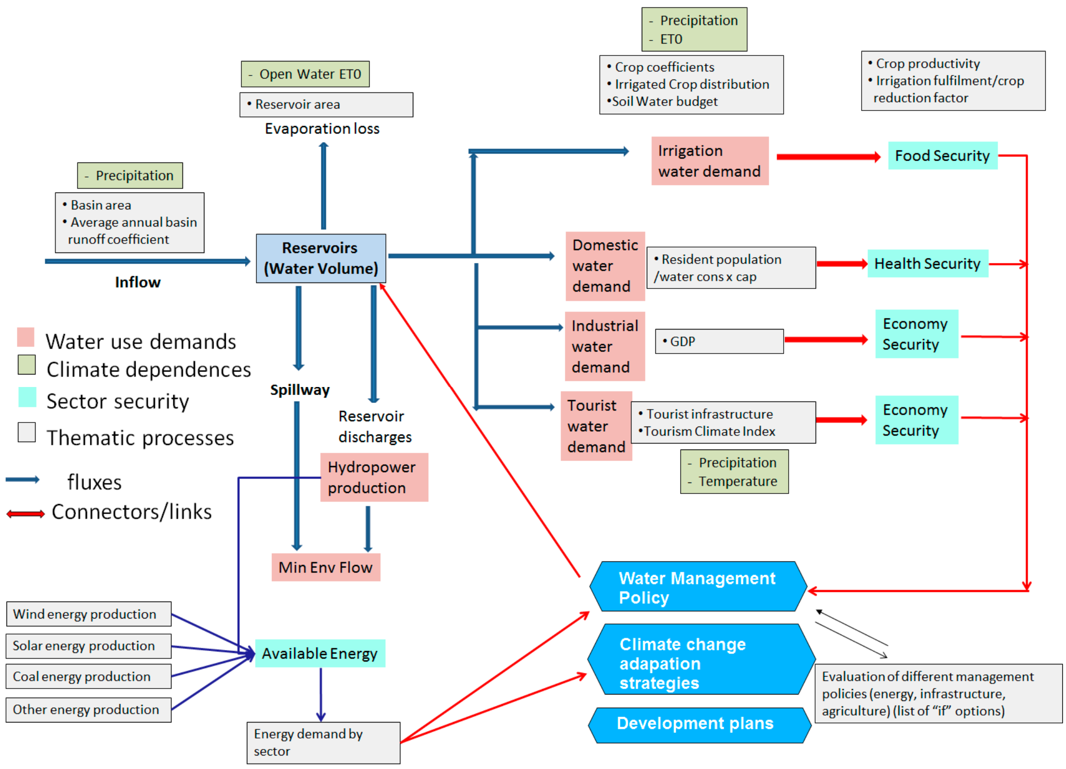


Figure 3. Conceptual diagram describing the major nexus components relevant for the Sardinia case study. ETO is reference evapotranspiration.

Based on the above conceptualisation, it was possible to identify the relevant 'thematic models' from within SIM4NEXUS from which data would be required. Here, data from CAPRI (a global agricultural and production model; [34]), the Global Trade Analysis Project (GTAP) database (www.gtap.agecon.purdue.edu/), E3ME (a global economic and energy model; [35]), downscaled climate data from HadGEM2-ES from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) [36], as well as locally-relevant data (e.g., for reservoir operating rules and environmental flow regulations) were acquired. Data for 2010 (the baseline) and 2030 under RCP Climate Scenarios 4.5 and 8.5 [37] and Shared Socioeconomic Pathway 2 (SSP2) were gathered and used for quantitative model development. The conceptual framework will be further elaborated and improved during the SIM4NEXUS project, although the present framework already gives a reasonably accurate representation of the nexus in Sardinia. For full model development in SIM4NEXUS case studies, projections to 2050 will be simulated.

2.2. System Quantification: System Dynamics Modelling (Step 3)

Based on the conceptual framework (Figure 3), the qualitative descriptions of the case studies will be 'translated' into quantitative system dynamics nexus models built in STELLA Professional (www.iseesystems.com). STELLA is a system dynamics modelling (SDM; [38]) software that allows for the exploration of complex systems. STELLA, like most SDM software, uses the concepts of stocks, flows and convertors (see [38] for a description of these elements) to create models of the system under study. SDM is ideal for modelling complex systems governed by feedback, delay and cross-disciplinary problems. STELLA can integrate data from many disciplines. SDM is ideally suited to studying the trajectory of system parameters under change and for dealing with uncertainty. SDM is proven in modelling complex systems in a diverse range of disciplines and for communicating with non-expert stakeholders (e.g., [39–42]).

For the Sardinia case study, the main focus of the SDM was the representation of the reservoir water balance for the island, accounting predominantly for water supply and for water demand related to agricultural, energy and domestic/tourist consumption. Energy generation and consumption were also important along with the mode of generation and sector of consumption, as was modelling the change in crop types (i.e., land use and food production changes) and the crop water requirements associated with potential crop and cropped area changes, as well as in response to change in the local climate. While water is the central focus, this model is not only concerned with Sardinian hydrology and is not a hydrological model, but considers other nexus sectors including energy, climate, food and land use.

On the water supply side, the model (Figure 4) accounts for inflows to the reservoirs based on precipitation partitioning to runoff over the catchment area upstream of reservoirs. For the purposes of the fast-track, water supply for the 40 main reservoirs and multiple demands were aggregated at the island level. However, final case study results will aim at a more articulated disaggregation within seven hydrological districts in Sardinia (see Section 4).

For water demand, the model considers: (1) open-water evaporation from reservoir surfaces; (2) discharges for hydroelectric generation; (3) spillways in times of overflow; (4) irrigation requirements; (5) industrial demand; (6) domestic and tourist water requirements; and (7) environmental flows (i.e., the minimum amount of water needed to preserve ecological functions and values in watercourses). With irrigated agriculture being the largest water consumer, this sector was modelled in more detail. The crop water requirements per unit-area, and the area planted, were taken into consideration for 13 major crops in Sardinia as a function of current and changing climatic conditions.

Energy production is modelled from sources including oil and gas, solar, wind and hydropower, while energy demand comes from the agricultural, domestic, industrial and service sectors. Touristic fluxes and relative water demands are modelled based on a Touristic Climate Index [43] and socio-economic scenarios. Climate change will have an impact on evaporation rates, crop water requirements, precipitation recharge to reservoirs, but also touristic fluxes. Data from thematic models provide projected changes of irrigated area by crop (CAPRI), energy production and demand by sector (E3ME) and socio-economic factors (GTAP). All other data are from local Sardinian sources.

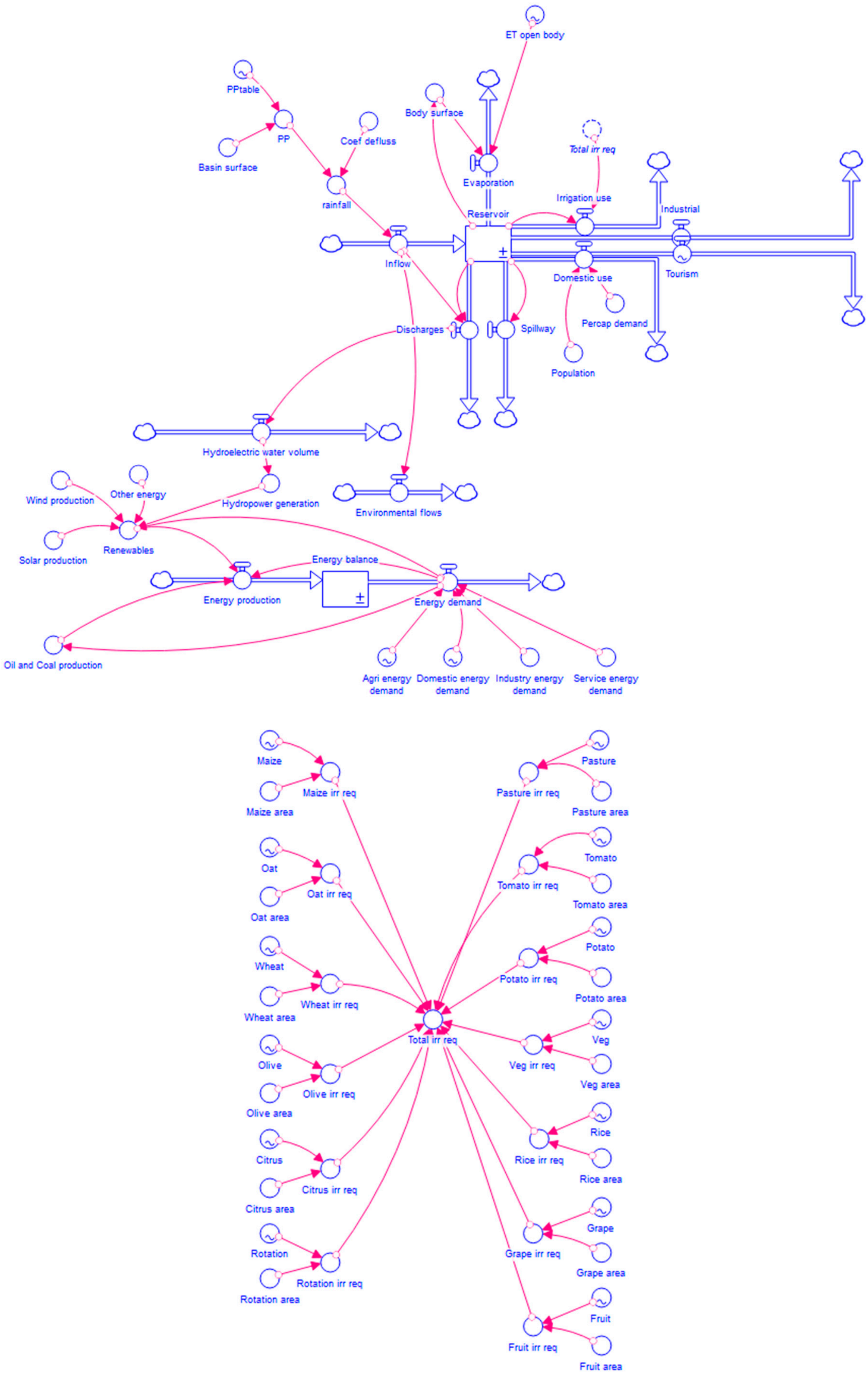


Figure 4. The developed system dynamics model for the Sardinia fast-track.

The model for Sardinia runs simulations for 2010 and 2030 for both the RCP4.5 and 8.5 scenarios. The model has a total of 73 variables accounting for each nexus sector and the interlinkages between the sectors. The modelling time-step is monthly, with all data scaled to this resolution. The model for Sardinia runs with five different climate models, accounting for inter-model variability. The variables of concern for the fast-track were chosen by the case study partner in SIM4NEXUS in consultation with local stakeholders.

Once the model structure was deemed representative (in consultation with local stakeholders), appropriate data were inputted into the model and the model outputs (in terms of the general trends of key variables such as the reservoir water balance over the year; see Section 3) were discussed with local case study experts to verify if the model was yielding sensible results. Once an agreed SDM representation was defined, the next step was to convert the model into an R script.

The primary reasons for the conversion of SIM4NEXUS STELLA models into an R script are that R is a freely-available open-source platform that can be distributed to all stakeholders, and the R script can be integrated easily with the Knowledge Elicitation Engine (KEE; Step 4) and the serious game (SG; Step 5). This conversion will therefore greatly speed up gameplay and will allow for much easier communication between the model, the KEE and the serious game.

The general conversion of the STELLA models to R is facilitated by the STELLA functionality allowing model equations and parameters to be exported to a text format (.txt; known as the 'equation file'). To achieve the conversion process, a Python script was created that reads the equation file and generates the R script and corresponding lookup files required for the R script to run. The script allows for policy changes to be implemented in the game front-end. In addition to the main R script, a number of accompanying files are produced (Table 1).

Table 1. Data outputs from STELLA conversion to R.

File	Purpose
R Function File	Contains details relating to time-series lookup tables used by the main script along with mathematical functions
Time-Series Files	Input data within the STELLA model are stored as time-series CSV files that are referenced within the R function file
Coefficient Files	A coefficient file is generated for each time-series variable to allow for policy implementation at a monthly scale, e.g., specific crop area can be reduced by 20% from June to August by switching the coefficient variable from 1.0 to 0.8 for those months.
Dynamic Variable Equations	Values within the SDM that change over time and/or are dependent on conditions of other dynamic variables are stored as a reference so that these lines can be substituted by variations of that line to allow for policy changes to be implemented

In order to implement and analyse the effects of policy changes (e.g., changes in energy mix or changes in cropping patterns) with the SDM file, variables within either the coefficient files or one of the dynamic variable equations (Table 1) can be altered to reflect new policy rules or conditions. To highlight the implementation of a policy change for the Sardinia case study within the R script, a working example looking at environmental flows is summarised in Table 2, which shows the present policy implemented in the SDM for Sardinia to foster ecosystem services and biodiversity downstream from the reservoir. Within the R code, the cases depicted in Table 2 are represented in Equation (1).

$$\begin{gathered}\text{Environmental\_flows} = \text{IFELSE (Reservoir/2000} > 0.20\text{, Inflow*0.1,} \\ \text{IFELSE (Reservoir/2000} > 0.1 \text{ \& Reservoir/2000} \leq 0.20\text{, Inflow*0.05, 0)) *} \\ \text{Environmental\_flows\_Policy\_Coeff}\end{gathered} \quad (1)$$

where 'IFELSE' is the R representation for the IF-ELSE logic, 'Reservoir' is the volume of water stored in Sardinian reservoirs at a given time-step (in million cubic meters; Mm^3), 'Inflow' is the inflow volume to reservoirs in that time-step (Mm^3 $month^{-1}$) and 'Environmental_flows_Policy_Coeff' is a coefficient that can be changed to reflect different policy conditions. The number '2000' represents the cumulative maximum reservoir storage capacity.

Table 2. Policy rules to foster ecosystem services and the biodiversity of ecosystems downstream of Sardinian reservoirs.

Case	Rule
1	If water in the reservoir is above 20% of the reservoir capacity, then 10% of the monthly basin run-off is allowed to be environmental flow.
2	If water in the reservoir is below 20% of the reservoir capacity, then 5% of the monthly basin run-off is allowed to be environmental flow.
3	If water in the reservoir is below 10% of the reservoir capacity, then 0% of the monthly basin run-off is allowed to be environmental flow.

Once the policy changes are implemented within the R script, the script can be run, and resulting outputs from the R systems model can be exported as CSV or JSON files and referenced by the Knowledge Elicitation Engine (Step 4).

2.3. Knowledge Elicitation Engine (Step 4)

The Knowledge Elicitation Engine (KEE) in SIM4NEXUS focuses on integrating knowledge and strategies at different spatial and temporal scales, with resource-efficient land use, agricultural productivity improvements, sustainable water management and low carbon energy transition. The KEE enables the analysis of interactions within existing regulatory frameworks and barriers to implementation (Steps 1 and 2). The KEE provides the serious game with the system-wide impact of each action implemented under a case study or specific scenario, considering the interactions modelled in the SDM (Step 3). Moreover, the KEE permits a top-down learning approach based on serious game front-end user decisions (Step 5) and a bottom-up approach based on classical machine learning methodologies applied to data. Top-down learning focuses on expert validated decisions made by users playing the game and how they affect the nexus system being played, giving feedback explaining the consequences of the decisions they have made. The bottom up learning focuses on discovering new knowledge in the form of unknown relations between systems, basing its learning on the data generated by the SDM from different geographic and temporal scale points of view. All learning and relevant knowledge for the nexus are stored in a semantic repository, which is supported by a cross-domain ontology. This simplifies information exchange between different nexus components and fosters better understanding of nexus interactions from a holistic point of view.

The KEE comprises three main items: (i) the game decision support system (GDSS), which focuses on recommending serious game user actions to be taken considering the current status of the game (polices applied, indicators, etc.), the objectives of the scenario and the learning goals to be achieved; (ii) the inference engine, which generates new knowledge based on machine learning algorithms applied to previous user decisions playing under different scenarios; and (iii) an agent-based module, which acts as artificial intelligence-based players when required by the specific case study. Thus, the KEE integrates knowledge coming from Steps 1 and 2, nexus complexity science from Step 3 and the serious game front-end (Step 5).

The KEE modules rely on the SIM4NEXUS database and metadata ontology (semantic repository), which contains general information and knowledge about the nexus, specific information regarding each case study, historical data about user actions while playing the game and all necessary pre-calculated information (e.g., climate information such as precipitation projections) to accelerate real-time computational needs and to feed the serious game front-end to represent the different elements in the scenario. The semantic repository is focused on support of the fast-track described in this paper, with the resulting simplified schema of the current ontology shown in Figure 5. Historical data about user actions are used to create an artificial intelligence able to simulate human players in the game, when needed. Finally, pre-calculated information is used to assure appropriate response time while playing the game, as some calculations require a long time and high computer power to be executed.

The ontology (Figure 5) represents the SIM4NEXUS knowledge and scope. Currently, the top concept is the 'Session', which represents a game session in the serious game front-end. Linked to the 'Session' there is a 'User', representing the player, and a 'Case Study' (at the moment this is only Sardinia), which in turn is related to a specific 'Model' (currently the SDM for the Sardinia case). In order to represent the nexus state through the game, the 'Session' has a list of 'StateEvolution', which represents the changes from one state ('State') to the new state ('State'), after the user decides to apply certain polices ('Policy'). The 'State' is defined by a collection of 'NexusComponent' (for instance, 'Climate and environment' or 'Water'), and these components have specific related variables ('Parameter').

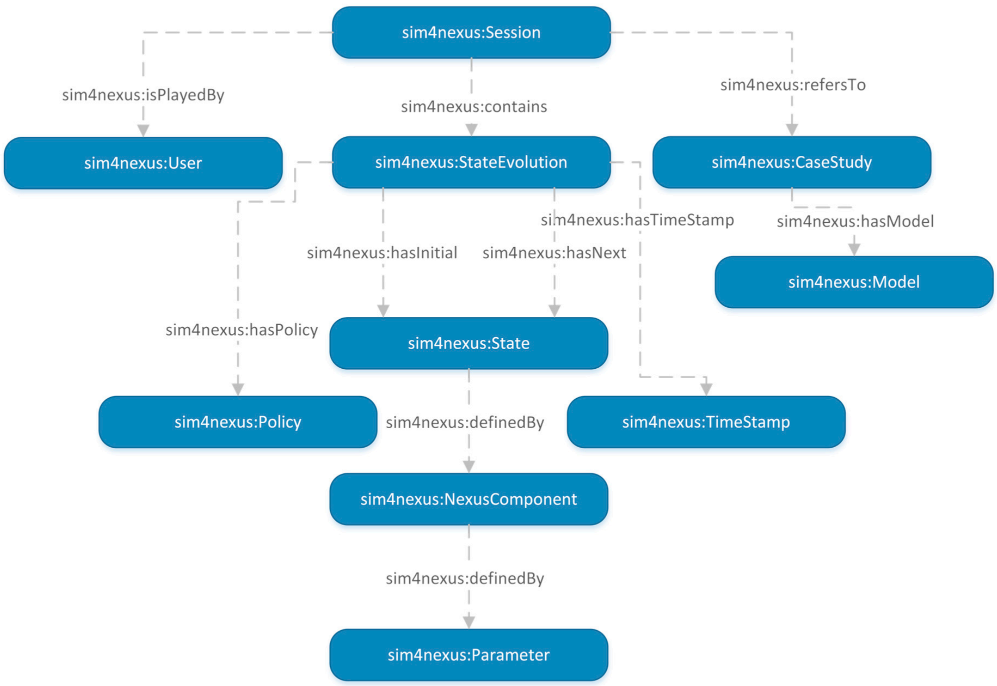


Figure 5. Simplified ontology schema for the Sardinia fast-track. See the text for details.

The ontology is defined using the Web Ontology Language (OWL), a semantic web language designed to represent rich and complex knowledge about things, and relations between things. Some existing ontologies, related to the nexus, have been included in the SIM4NEXUS context:

(1) WatERP ontology [44], developed under the EC FP7 project 'WatERP' (see HTTP://WWW.WATERP-FP7.ORG/ for a general project description), which reflects the water manager's expertise for managing water supply and demand. The novelty of the WatERP ontology lies in including interactions with natural processes as a mechanism to understanding how to affect changes in water resources management so as to achieve the objective of matching supply with demand. These interactions could range from infrastructures to management decisions.

(2) The WEFNexus ontology [45], which concerns water, energy and food derived from the European Directives: Article 2 of EU Directive 98/83/EC that defines the water intended for human consumption; Article 2 of EU Directive 2003/30/EC that defines bio-fuels; and Article 2 of EU Regulation 178/2002/EC that defines food.

For the Sardinia fast-track specifically, the KEE focuses on: (i) storing information about the case study in the Semantic Repository (e.g., climate data, CAPRI data, E3ME data, local reservoir operating rules); (ii) storing historical data about user actions for future analysis; and (iii) providing a standardised communication interface between the serious game front-end and the SDM simulations. The KEE needs to run SDM models repeatedly for each case study during a game session. At the moment, the computational requirement of the Sardinia model allows for real-time simulation, but this computational load will increase as models become more sophisticated. To enable this, the R script is called when necessary from a Python script, which is included and published in the SIM4NEXUS web services layer. This layer establishes the communication mechanisms among the different modules. The deployed web service follows the OpenGIS® Web Processing Service (WPS) Interface Standard [46] for standardizing the inputs and outputs for geospatial processing services. The standard defines how an execution of a process has to be requested by a client and how the process output is handled. It defines an interface that facilitates the publishing of geospatial processes and clients' discovery of and binding to those process.

Using this web service, the serious game front-end is able to send the current status of the scenario, define the policies to be applied and define the time-step. The web service runs the SDM to calculate the evolution of the scenario under that context and sends it back to the serious game front-end. Finally, that information is presented to the user, and new policies to be applied are offered.

2.4. Serious Game Front-End (Step 5)

The SIM4NEXUS development of the serious game front-end for each case study uses the AquaRepublica serious game developed by DHI [47] as a starting concept, but further develops that game for the specific requirements of each case study in SIM4NEXUS. The goal of the game is to bridge the gap between science and policy stakeholders by translating complex modelling results into an interactive virtual world. The serious game will be used in stakeholder workshops to explain and provide learning opportunities about the potential impact of different policies on the nexus and how these policies impact a case study through a "learning by playing" approach (Figure 6).

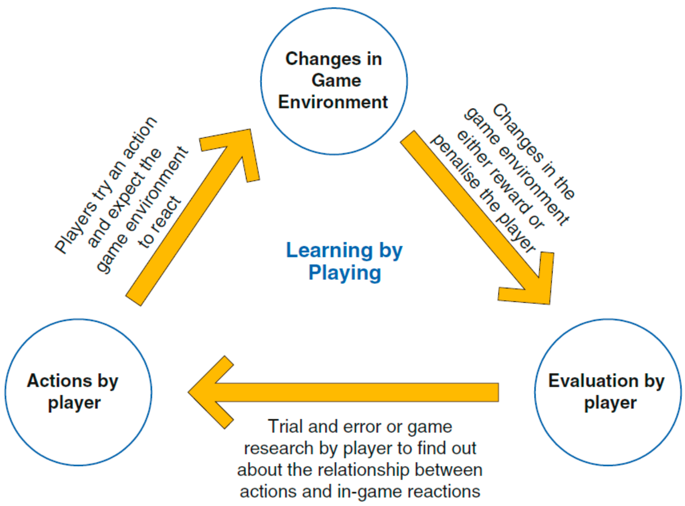


Figure 6. Learning by doing flowchart.

Based on these concepts, the serious game of SIM4NEXUS attempts to create the same understanding of nexus issues across stakeholders in food, energy, water, climate and land. The setup of the serious game is as follows:

As a player, you represent decision makers in the various sectors in a particular area: food, energy, water, climate and land. Your aim is to achieve the targets (objectives) set out by the national or international bodies by changing or adapting new policies in your area and to implement practices to comply with local policy objectives. To succeed in the game, you must learn how to achieve these targets by mixing and matching various cross-sectoral policies without compromising the existing 'goal attainment' of the other sectors.

The main content in the serious game is provided both through the interfaces and the logics that the game contains, as well as through the KEE (Step 4) that provides information and further knowledge to stress the immersions of the game user for each case study. The identification and formalization of the content to be imparted is important for the game logics requirements definition, as the logics behind the game must guide the user through these contents in order to impart the knowledge to be conveyed. This identification is required for the construction of the KEE, as well as the way both the game and the KEE architecture will communicate the knowledge and information. Therefore, Steps 4 and 5 are critically linked. This content is divided into three main parts:

1. Core experience: What are the players experiencing as they play the game?

The core experience is to play the role of policy makers in food, energy, water, climate and land management. The player will typically start off with separate "silo-thinking" approaches towards decision making and policy implementation. Over the course of playing the game, they will be encouraged to change towards a more integrated nexus-compliant policy implementation approach and decision making.

2. Base mechanics: What does the player do?

The player will have a target at the start of each turn of the game and he/she will have to implement policies to try to achieve the target. The turn ends when the player has decided on the policies to be implemented to achieve the targets and clicked on a "next turn" button. The game will compute the policies, and an analysis of the decisions will be displayed in the following turn, with a new target to achieve for the turn. The targets are envisioned to be displayed in a step-by-step manner to the player. This will help guide the player on what to do during the game play.

3. Penalties and Reward (P&R) system: What behaviour within the game is encouraged or discouraged?

Silo-thinking in decision making and policy implementation within the game is discouraged, whereas integrated nexus-wide decision making is encouraged. For every target in each turn, the player is encouraged to look at policies in all sectors and consider them to achieve a target. The P&R system will be provided in three parts:

(i) Key indicators across all nexus components. These key indicators will be defined with case study partners to ensure the game is suitably targeted for the local context. Local stakeholder meetings will be used to elucidate these indicators.

(ii) Events within the game. Events are news happening "on the ground", which add a societal and cultural aspect to the game. These events will be narrated in the same tone as the shared socioeconomic pathways (SSPs; [48]) and will be triggered based on the decisions the player made in the game. There will be uncertainties in event triggers to add more realism in the game (e.g., the occurrence of extreme events such as economic crisis or disaster events). There will be three categories of events: (a) informational events, which are neutral; (b) negative events, which will penalize the player by deducting points; and (c) positive events, which will reward the player with bonus points.

(iii) Score. There will be a score for the player. The score will indicate how successful the player is at applying nexus-compliant decision making to achieve the targets in the game. Every progression in the time-step of the game will add to the score to encourage the player to continue, with every policy implemented and events occurring adding further points to this score. The score is computed as follows:

$$S = 1 - \sum_i w_i \frac{\left(\max\{0,\ m_i(g_i - x_i)\}\right)^2}{\left(g_i - x_{0i}\right)^2}$$

where:

- the score S is based on a weighted sum of squared, normalized, differences between indicators x_i and targets g_i;
- the x_{0i} stands for the starting value of the indicator at the beginning of the game;
- for indicators that must be maximized $m_i = 1$, and for indicators that must be minimized $m_i = -1$;
- the sum of the weights $\sum_i w_i = 1$;
- $S = 1$ is the maximal score to be attained (full compliance with all targets).

Such a score can be computed over all indicators and per policy area, making clear on which areas to focus in order to improve the general score. Thus, it can serve as a basis to advise users and explain opportunities to improve their performance in nexus management.

In SIM4NEXUS, nexus-compliance refers to the degree to which policy choices made by the player tend to lead towards/away from policy objectives for that case study, as elucidated by both the detailed policy analysis work in SIM4NEXUS and by relevant nexus policies/objectives as indicated by stakeholders during the case study formulation and framing phase (Steps 1 and 2). The detailed nexus policy mapping will help define the scoring system for each case study. This may lead to some not necessarily 'bad' decisions (e.g., climate-neutral energy generation) perhaps not being scored as highly as expected if they do not fit strongly within the policy framework defined for a case study. However, through the policy work and stakeholder discussions, such instances should be minimized. Emphasis is placed on minimizing detrimental cross-sector impacts from a given policy choice.

The feedback between spatial scales is facilitated by the KEE. The KEE collects data about players' policy choices and the resulting consequences for the nexus components. This mechanism will be used to feed new targets resulting from games at the global or continental scale, into games at the national or regional scale. For instance, some policy may result from playing a game on the European level. This policy may entail new targets set at national and regional levels. By playing games with these new targets with national and regional policy makers, data can be collected about their reactions and the consequences for the nexus components. The KEE will then inform the policy makers at the European level (Figure 7).

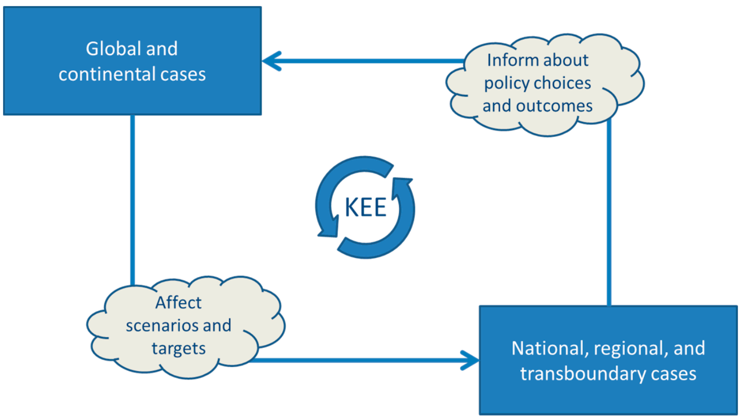


Figure 7. Feedback across spatial scales facilitated by the Knowledge Elicitation Engine (KEE).

The game can be played in different modes. It can be used by a single player, controlling all policy options. It can be used for playing the game in sessions led by a trainer or group facilitator, where participants play roles of policy makers in particular nexus domains. Single- and multi-player games can both be played. Lastly, it can be played with artificial agents. In the latter case, users take the roles of particular policy makers, while other roles are fulfilled by artificial agents, based on data collected by the KEE.

- Single-player controlling all policy options

The user has opened a new game session and initialized a predefined scenario. The user does not select a role as policy maker in a particular nexus domain. In the main gameplay screen, the user is presented with policy options enabled for all nexus domains. While playing subsequent turns, the user can adjust policies in all domains, attempting to achieve a balanced set of targets across the nexus. This setting for playing the game is particularly suitable for education and training to offer insight into relations across the entire nexus.

- Multiple players, each taking policy makers' roles on particular nexus domains

Playing games with groups where participants take different roles requires a group facilitator to set up the game. In the simplest case, the facilitator asks the players for their policy decisions and enters these into a game set up as in the single-player case described above.

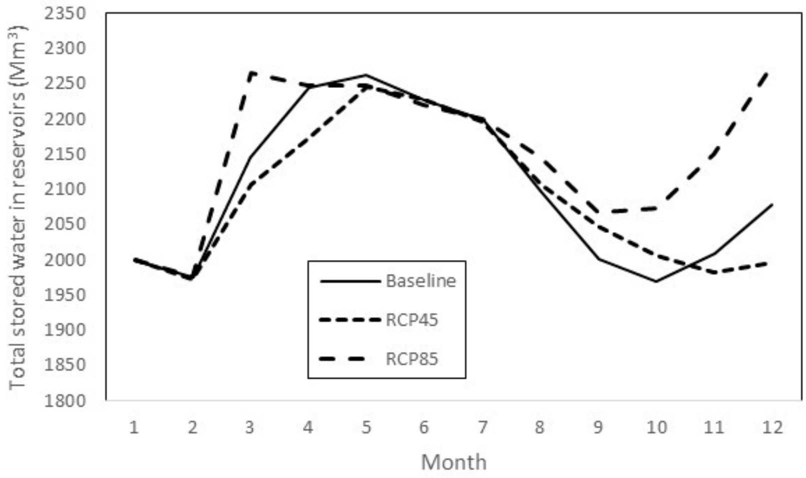
As a future extension, a more advanced multi-player setting is envisaged, where the facilitator starts a game and assigns the players roles as policy makers in a particular nexus domain. The game logic is running on a central server, but players are presented with an individual gameplay screen in which all policy options and indicators are visible, but only the policy options related to the selected role can be changed. Turns are synchronised on the central server, and the next time-step is not taken until all participants have made their policy choices. Individual players are able to try various policy options available to them and check the consequences, but only have to commit to a policy once they are happy with it. At this point, the policy option and its consequences are revealed to other players. This stops exploratory and sub-optimal policies affecting other players too often, causing a disruption to the game play.

- Playing the game with artificial agents

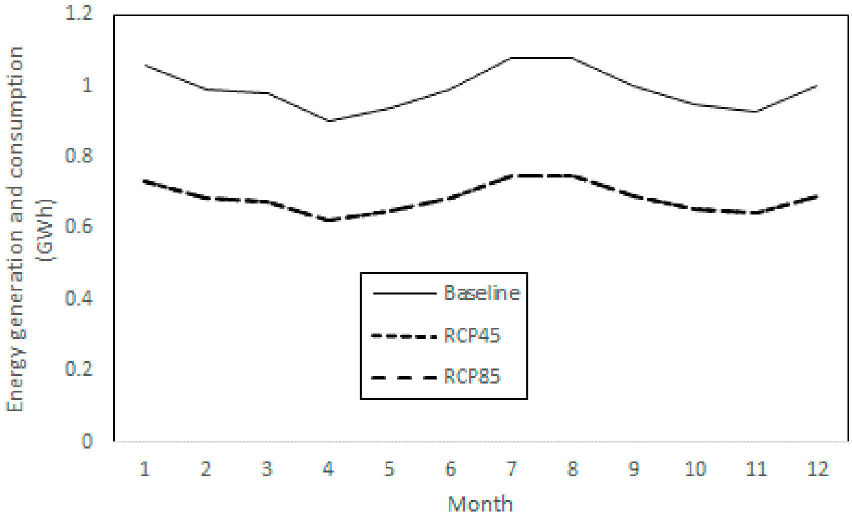
As another future extension, it is envisaged to have artificial agents participating in the game. During the games described above, the KEE collects data on the policy choices the players make and the resulting outcomes in terms of indicators. Since users have supplied information on their background and expertise when registering for the game, the KEE can learn the behaviours of policy makers in particular domains. To this end, several machine learning techniques will be tested, including, but not limited to: decision trees, nearest neighbour and support vector machines. Combined with other knowledge, the collected data and generated knowledge and models can be used to design artificial agents, playing the roles of policy makers. The results attained by human players can be used to configure agents on a scale ranging from a focus on one particular nexus domain to full awareness of all domains. In this setting, users can select a role as policy maker in one of the nexus domains and then play the game as in the multiplayer setting. Moreover, game designers and academics are able to understand the usual behaviour of specific stakeholders, helping them tailor the contents of the game sessions to better fit their needs and to fulfil the learning goals.

3. Results from the Sardinia Fast-Track

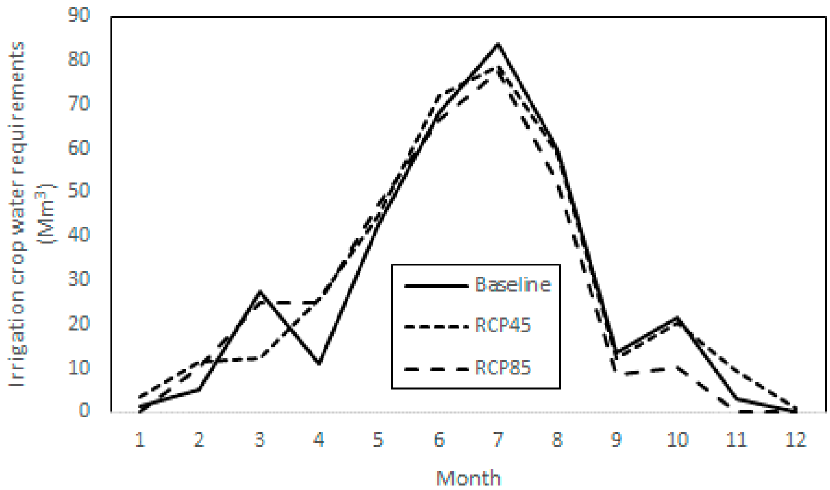
Here, results from the fast-track SDM for Sardinia are shown. Since the Sardinia island-wide reservoir system was represented for simplicity as an aggregated system (i.e., geographically lumped; see the conceptual framework in Figure 3 and the model schema in Figure 4), an overestimated efficiency of the system to capture and manage water was introduced, thereby overestimating resilience to changes in water supply and demand (in Mm^3 $month^{-1}$). However, the model did accurately capture the *pattern* of reservoir filling and emptying through the year (Figure 8a), and it captured the fact that energy supply and demand (in GWh $month^{-1}$) are balanced over a year (Figure 8b).



(**a**)



(**b**)



(**c**)

Figure 8. (**a**) Showing the results of the Sardinia fast-track simulation for the baseline (2010) and for 2030 under RCP4.5 and 8.5. Results show the total water stored in all Sardinian reservoirs. (**b**) Energy generation and consumption for the baseline and both RCP scenarios. Energy generation equals consumption in each month. The predicted generation/consumption in the RCPs are the same. (**c**) Irrigation crop water requirements.

An interesting feature regarding energy generation is the predicted reduction in 2030. This is largely due to a reduction in fossil-based energy generation, which is not fully replaced by greener energy sources. Demand is still expected to be met, but increasing pressure from the tourist sector, especially in the summer months, could strain the system. It could be expected that the replacement with a greener energy system may take longer than planned if system strain becomes too large.

Figure 8c shows the modelled baseline and future irrigation crop water requirements. The irrigation requirements are similar in terms of the summer peak in all three simulations; however, the annual totals are slightly higher in the RCPs due to the increase in requirement in the spring months. It is expected that these requirements will increase further by 2050, increasing pressure on the water system and on the energy system for increasing pumping.

As an additional element for the Sardinia fast-track, a working prototype front-end for the serious game has been developed (Figure 9). The prototype includes a photo-realistic map of the study area, together with a toggle display of key nexus indicator values. In Figure 9, example indicators for the water sector are displayed. A timeline slider is shown at the top illustrating how far through the game the player is. Future extensions will include boxes/options to adjust various key nexus and policy parameters and to observe the nexus-wide impacts of these changes. It is noted that Figure 9 is a prototype. It will be further developed and refined throughout SIM4NEXUS. It is shown here as an illustrative example of what the final serious game front-ends may look like.

Figure 9. Screenshot from the developed prototype serious game front-end for the Sardinia fast-track case study.

4. Lessons Learned and Future Developments in SIM4NEXUS

The general process of serious game development in SIM4NEXUS has been presented, going from initial case study nexus framing and conceptualization, through to serious game development. Two key findings and general conclusions are found:

(1) Collaborative and constructive stakeholder involvement from project inception is critical in the development of meaningful models and games that are more likely to have impact. Suitable policy analysis is an important aspect in appropriate case study framing and model/game design and;

(2) Appropriate spatial scale selection for the case study and nexus sectors is important in producing reliable model outputs. Deciding on the spatial scale and potential disaggregation of a case study is intimately linked to Lesson 1 above.

These lessons were learned from direct feedback from stakeholders regarding model outputs to case study leaders and model/game developers, from case study leaders themselves and from academics within the project through development iterations. At present, feedback is based on the model outputs: the game is not yet developed due to the stage within the project, although discussions on game expectations are ongoing.

It is shown through the Sardinia fast-track (and reinforced as more case studies get further into the development process) how stakeholder interaction, contribution and verification of model veracity are critical from the very beginning, the value of which can be overlooked in serious game development. Case study-level policy analysis is central in guiding case study development, another element that can easily be neglected, but something that is centrally built into SIM4NEXUS. Critical and constructive stakeholder involvement, along with relevant and detailed policy analysis to aid case study framing and gameplay, are key conclusions that can be adopted in many serious game development exercises, but they must be well thought through and implemented from early stages.

The second key conclusion, linked to the first, is deciding on appropriate levels of model/game spatial disaggregation. Discovering the appropriate spatial scale might depend on a number of iterations, but will depend on the feedback from local expert stakeholders. It was only during the verification process for the Sardinia fast-track that it was found that while the timing of reservoir filling and emptying processes was correct, the modelled volume of water entering the system was vastly overestimated. This would have had significant implications for any subsequent analysis and potential policy recommendations. As a result, for the final SIM4NEXUS Sardinia model, the island will be disaggregated into a number of hydrological basins to better reflect spatial variability. Cross-checking with stakeholders will remain an integral element. As seen from the Sardinia fast-track results, it is important to articulate correctly the spatial scale of any model for the case study under consideration and for the nexus sectors being modelled. In future developments, Sardinia will be split into seven hydrological basins to better capture hydrological dynamics across the island. Aggregation to the island scale will take place a posteriori.

During the Sardinia fast-track, a number of different groups and individuals were involved at different stages in the process. Without this cooperation, the process could easily stall or fail, or a poor/unrepresentative model could be developed, with consequences for the robustness and veracity of the messages being communicated by the game. It could also mean limited uptake and therefore limited impact of the game and the results. It is important to invest time and resources in bringing together individuals with different experience, integrating their knowledge and focusing discussions on interactions between different sectors. As anticipated, difficulties emerged during stakeholder interactions with respect to expanding the experience of individuals beyond their specific sectors (i.e., breaking 'silo-thinking'). Only by including stakeholders in cooperative forums could these difficulties start to be addressed and compromises found. It is expected that similarly diverse groups will contribute to the full development of all 12 SIM4NEXUS models and serious games. Indeed, other case studies (Andalucía, Greece, The Netherlands, Latvia and the southwest U.K.) are all currently at various stages of development within the project. In each case, a wide range of relevant, but diverse stakeholders is actively involved to determine: (i) the case study nexus sectors(s) of key importance based on locally-relevant policy issues; (ii) critical interactions between nexus sectors; (iii) data availability; (iv) the main (policy-relevant) questions that the game(s) should try to address; (v) what the game might look like, how it might be played and the added value for participants; and (vi) how best to market and 'sell' the game in order to reach as wide and diverse an audience as possible. These lessons are generally applicable for other serious game development projects.

The lesson on correct spatial representation is important because better information and knowledge will be generated for policy and decision making, with results more accurately expressing on-the-ground situations. By sticking with a lumped approach, model results would not have been representative, and therefore, confidence in the results and the implications for nexus sectors discovered during game play would not be taken seriously. This finding has already had important implications for model development in other cases (e.g., Andalucía, Greece, southwest England), where accounting for local level dynamics will be critical for modelling success and by extension for providing the end-user of the serious game(s) with robust policy-relevant messages. By taking the pilot case seriously and rigorously assessing the outputs, important implications were highlighted. By intense and ongoing cross-project communication, these important lessons were noted and are being implemented by other project case studies. Within-project learning also follows as a critical lesson. As with the first key lesson, this lesson of tailoring spatial detail appropriate to the study under consideration is generally applicable, with the appropriate scale perhaps only becoming apparent after trial-and-error and the analysis of initial results.

The findings resulting from the SIM4NEXUS fast-track are more generally applicable. This is not to say that implementing these lessons is easy, but where possible, time and effort should be appropriately invested in these activities to ensure robust and policy-relevant modelling activities and serious game development (including the aims, objectives and game-play criteria). These lessons are being implemented within SIM4NEXUS and could prove useful for similar coupled modelling-serious gaming exercises.

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