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NEXOGENESIS
STREAMLINING WATER RELATED POLICIES

Deliverable 3.5

Sensitivity and uncertainty analysis

Lead: IHE
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Project Deliverable

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Abstract

This NEXOGENESIS Deliverable describes the methodological approaches to be employed within the System Dynamics Models (SDMs) for each of the five Case Studies regarding: scenario analysis; sensitivity analysis; what-if testing; and uncertainty analysis. It outlines why these methods are essential for improved policy-relevant information. It describes how data provided through Work Package 2 will be exploited to assist is these analyses, how further work to be carried out in WP4 will utilise the uncertainty/sensitivity analyses in the Machine-Learning techniques, and how the results can be communicated to stakeholders via a visual decision support tool to be developed. The combination, robustness, and comprehensiveness of the techniques to be used in NEXOGENESIS for uncertainty and scenario analysis will lead to novel scientific and societal impact, and will greatly advance the current state-of-the-art in nexus-relevant research, especially once Machine-Learning methodologies are coupled with, and exploit, the analyses described in this Deliverable.

List of abbreviations

CS – Case Study
RCP – Representative Concentration Pathway
SDM – System Dynamics Modelling
SLNAE – Self Learning Nexus Assessment Engine
SSP – Shared Socio-economic Pathway
WEFE – Water-Energy-Food-Ecosystems

Keywords

Case studies; Sensitivity analysis; uncertainty, WEFE nexus.

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1. Introduction and purpose of the Deliverable

Deliverable 3.5 introduces techniques and methods for scenario and uncertainty analyses that will be implemented in the System Dynamics Models (SDMs) in Work Package (WP) 3 and in the Self-Learning Nexus Assessment Engine (SLNAE[1]) in WP4.

Sensitivity, scenario, and uncertainty analyses are essential when dealing with complex systems, external model data, and future projections. Scenarios are used to define multiple plausible futures. This is because it is not known exactly how the future will play out, and therefore a suite of likely pathways is required to capture the most likely developments. In NEXOGENESIS, the scenarios are captured by the Representative Concentration Pathways and Shared Socio-economic Pathways (RCPs and SSPs, respectively). Sensitivity analysis assesses relative output response to systematic changes in input variables. In this way, the most sensitive input variables, in relation to changing the outputs, can be identified. This is important in the NEXOGENESIS context as policy makers will have more information to identify those leverage points in the WEFE nexus that will likely lead to the greatest system response, positive or negative. Positive responses can be maximised, while negative responses can be avoided. What-if analysis can help modellers and stakeholders to ‘stress test’ a system and see the impacts on output response. These tests may not be realistic per-se, but can be instructive to determine potential thresholds in system states that should not be approached or crossed. Finally, uncertainty analysis allows for the variability and unknown knowledge in data to be characterised and quantified, including its impact on model outputs. Coupled with stakeholder-relevant visualisation, such uncertainty analysis can be highly beneficial in portraying the most likely system responses, but also the extreme responses to, for example, precipitation or river flows. The combination of all these aspects in NEXOGENESIS (scenario analysis, sensitivity analysis, what-if tests, uncertainty analyses, and visualisation), will lead to novel scientific and societal information about policy implementation in the WEFE nexus, and together with stakeholder assessment of results, will help validate the implementation of NEXOGENESIS nexus models.

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

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[1] Within the project, a new name for this ‘tool’ is being considered, making it less opaque and more marketable.

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2. Sensitivity, scenario, and uncertainty analyses in NEXOGENESIS

2.1 Sensitivity analysis

The objective of sensitivity analysis is to ascertain the relative response of specific output variables of a model to changes in given input parameters. Due to the complex nature and feedback inherent in the SDMs developed in NEXOGENESIS, some input variable changes will elicit relatively large changes to certain output variables, whilst barely affecting output variables. Changes to other input parameters may elicit relatively large responses in many output variables, while yet others may have relatively negligible change to outputs. If output variable changes are relatively large for a given input change, this is referred to as a sensitive parameter. Likewise, if large input changes reveal little change in output parameters, then this is an unsensitive situation.

There exist many techniques to perform sensitivity tests. Sensitivity analysis tends to proceed by changing one variable at a time to differing magnitudes and observing the response in specific (critical) output variables of interest. Those outputs that change the most are sensitive to changes in the input conditions of the model, and vice-versa. Within NEXOGENESIS, it may not be possible to test every multi-parameter sensitivity test that is possible due to the high dimensionality of the models, however for select variables or sectors, this will be considered. Identifying sensitive parameters in a model is important for a number of reasons:

1) If outputs are seen to be highly sensitive to the value of specific input parameters, then it is critical to ensure that those input parameters are as accurate as possible. Small changes in those inputs (e.g. due to inaccuracies in data collection) could lead to large responses in model output variables, with outputs potentially no longer being representative or reasonable for a given variable. As such, it can be seen where to focus effort in ensuring that model inputs are as accurate as possible;
2) For identifying the potentially most effective policy levers for systemic change. Identifying the most sensitive output variables in response to changes in inputs can help in highlighting which potential policy changes may lead to the greatest impacts on the system state, and can also indicate if there may be significant unintended consequences on other system variables that were not anticipated. The nature of that impact can also be assessed – is the impact on the system as desired (a positive impact) or not (a negative impact)? As such, if negative impacts are noted, then the policy changes leading to that impact could be reconsidered. Alternatively, if a potential policy action is seen to have a great positive impact on output parameters (due to them being highly sensitive to input changes), then this could indicate that those policies should be focussed on to leverage potential WEFE nexus improvement gains. This process may lead to a 'fine-tuning' of policies themselves.

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Sensitivity analyses are widely used in modelling studies for the purposes described above. Bakhshianlamouki et al. (2020) conceptualise, develop, and run a system dynamics model (cf. Ford, 2009) of the Urmia Lake Basin, Iran. The model is designed to test the effectiveness and explore potential unintended consequences of implementing a suite of lake restoration activities. As part of the study, a sensitivity analysis on model input parameters was performed. In the study, the sensitivity of the area of Urmia Lake, and the inflow from rivers to Urmia Lake was explored by changing various input parameters. Results (Figure 1) showed that lake level for example is not sensitive to changes in precipitation volumes, but is very sensitive to changes in the area of the lake.

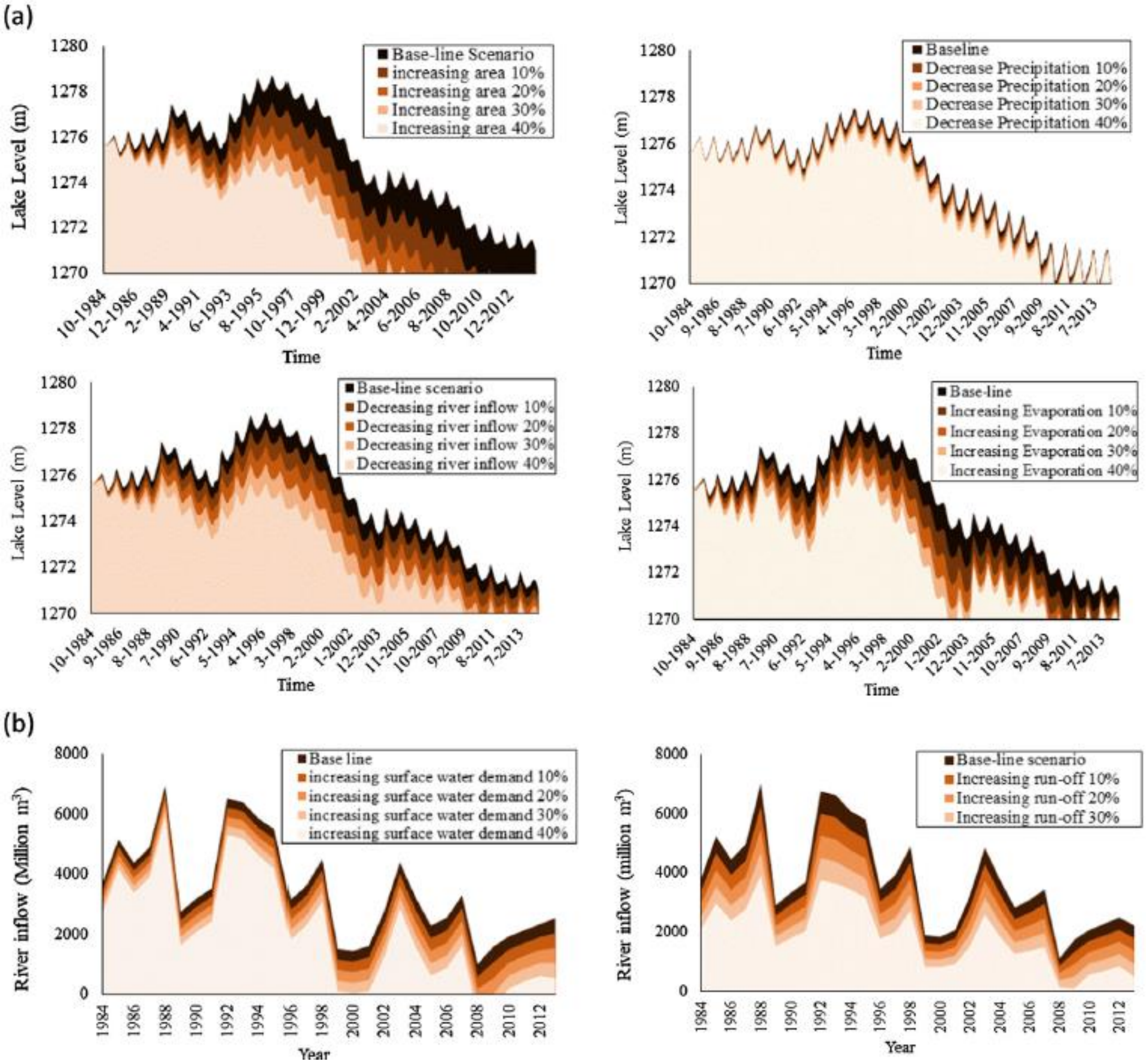

Figure 1: sensitivity analysis on Urmia Lake level (a) and Urmia Lake river inflow volumes (b) to changes in various input parameters. Figure from Bakhshianlamouki et al. (2020).

Similarly, Purwanto et al. (2021) also develop and run a system dynamics model of the water-energy-food-societal nexus in Karawang Regency, Indonesia. The sensitivity of the availability of water, energy, and food resources per-capita was tested by changing a wide range of model input parameters (Figure 2). Full details of the parameters adjusted are given in Purwanto et al. (2021) – a similar approach of selecting a reasonable range of parameter values will be considered in NEXOGENESIS. As with Bakhshianlamouki et al. (2020; Figure 1), a wide range of output responses was observed, with some variables being very sensitive to certain changes and others showing very low sensitivity.

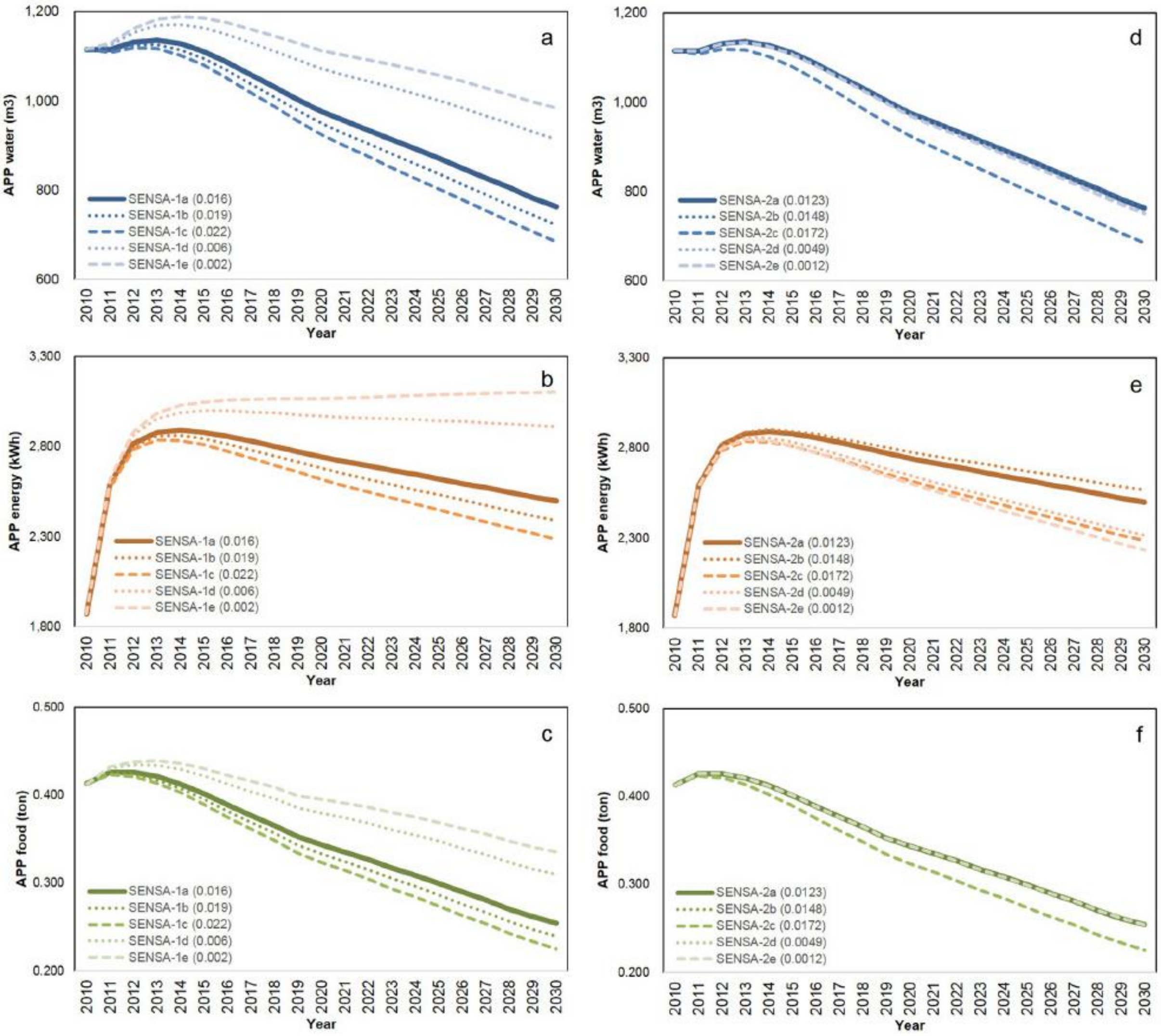

Figure 2: sensitivity of the availability of water (a, d), food (b, e), and energy (c, f) resources per-capita in response to changing various model input parameters. See Purwanto et al. (2021) for full modelling details.

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2.2 Scenario analysis

Scenario analysis aims to assess system response, or the response of key system state variables, to widespread changes in system inputs (e.g. due to climate change that may alter many variables) rather than in isolated parameters as in sensitivity tests. These changes may be forced from external (exogenous) factors such as global climate change (e.g. represented by the RCPs) and socio-economic development (e.g. as given by the SSPs), or by internal (endogenous) factors such as imposed policy changes due to changes in policy ambitions. Different 'futures' of a system, represented through different RCPs, SSPs, policy implementations, etc., are referred to as scenarios. The reason for running such scenarios is that the future is not known with certainty. Therefore, a range of (plausible) futures is simulated – these are the scenarios. The setup envisaged in NEXOGENESIS is as follows. Until 2015, there is a singular observed history (i.e. based on known and established driving factors and system conditions together with data observations and statistics). This known past is called the '**baseline'** in NEXOGENESIS. In NEXOGENESIS, 2015 marks the departure point from the known history, to multiple unknown futures. For the futures, NEXOGENESIS will consider two scenario sets (Figure 3):

1) The '**reference scenarios**'. The reference scenarios in NEXOGENESIS refer to the widely-accepted and globally used RCPs and SSPs. In NEXOGENESIS, *RCP2.6* and *RCP8.5* (consistent with low/high end for CMIP5/6 data and 5th/6th IPCC reports) are used for the climatic futures, while *SSPs 2 and 4* (representing a 'middle of the road' and the current societal trajectory respectively) are used for the socio-economic futures. This gives a total of 2 x 2 = 4 reference scenario combinations. Parameters produced under the RCPs include variables such as precipitation, runoff, and temperature, while SSP-related parameters include population projections, societal productivity, etc. These data are provided by Work Package 2 in NEXOGENESIS from coherent data sources and models for all the case studies, allowing for consistency and comparability between the cases.
2) The '**policy scenarios**'. This set of scenarios represents modifications to the reference scenarios by imposing case study relevant policies onto them. These policies will by definition be different for each NEXOGENESIS case study, in terms of the number of policies to test, their content, and their impacts. The same policy, or group of policies, can be imposed on the different reference pathways, thereby assessing their impact under different potential futures. It is possible that the impact of implementing a policy (e.g. "Policy A") under a given reference pathway (e.g. Reference Pathway 1; see the line labelled 'A1' in Figure 3) is very different if the same policy is applied under a different Reference Pathway (Reference Pathway 2; Figure 3). The same idea can be applied to a different policy ("Policy B") and a different reference scenario. This is important information for stakeholders and policy makers – they should gain knowledge on the impact of an action under a range of future pathways, none of which are known with much certainty in advance. Knowledge of these differences could help policy and decision makers to be better prepared and more able to cope with changing futures (i.e. be more adaptable).

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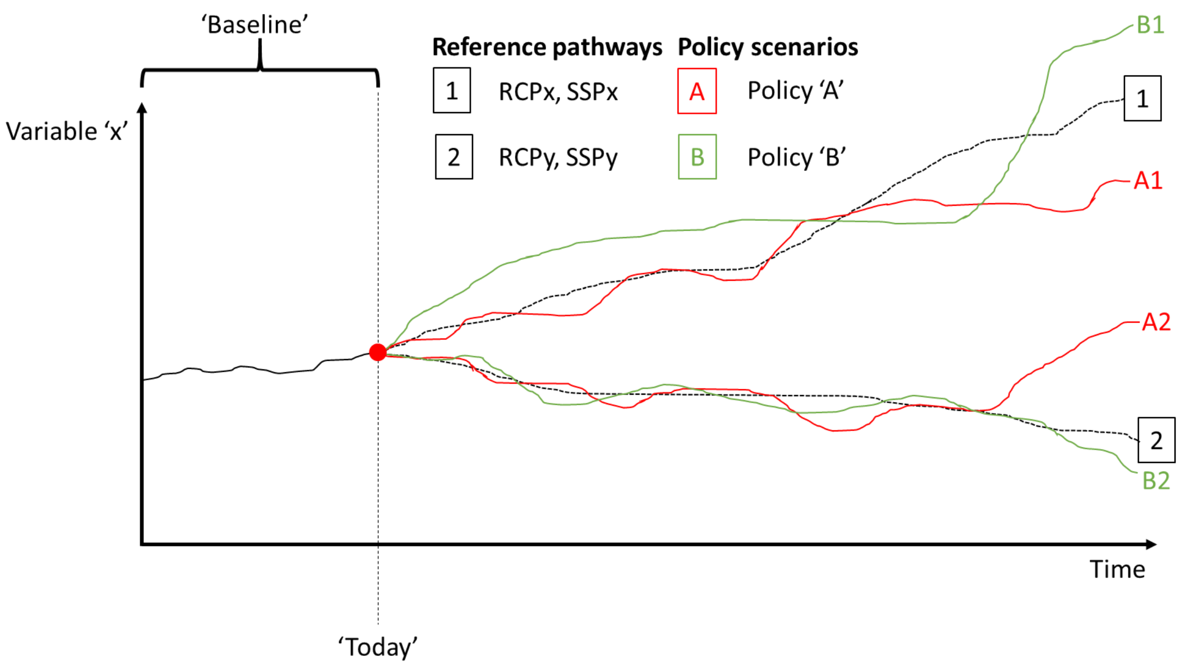

Figure 3: illustrating the scenario concepts in the text. The 'baseline' (solid black line), 'reference scenarios' (dashed black lines), and 'policy scenarios' (red and green lines) concepts are shown. 'Today' in NEXOGENESIS is the year 2015. Note that the given impact for any specific policy (Policy 'A' or 'B') can change depending on the underlying reference scenario ('1' or '2') on which it is imposed (denoted 'A1', 'A2', 'B1', 'B2'.). Note that this concept does not define a single 'business as usual' future.

Various studies have used scenarios to assess the potential future impacts of actions imposed on a system. Bakhshianalmouki et al. (2020) simulate a suite of scenarios to assess the potential impact on long-term Urmia Lake water level – one set based on climate change scenarios using the RCPs, another set based on planned restoration measures for Urmia Lake, and a third set based on a combination of restoration policies to assess synergies and trade-offs between them (Figure 4). In a similar way, Purwanto et al. (2021) models a range of scenarios to assess the impact across all nexus sectors in Karawang, Indonesia. One of the scenario simulation results is shown in Figure 5.

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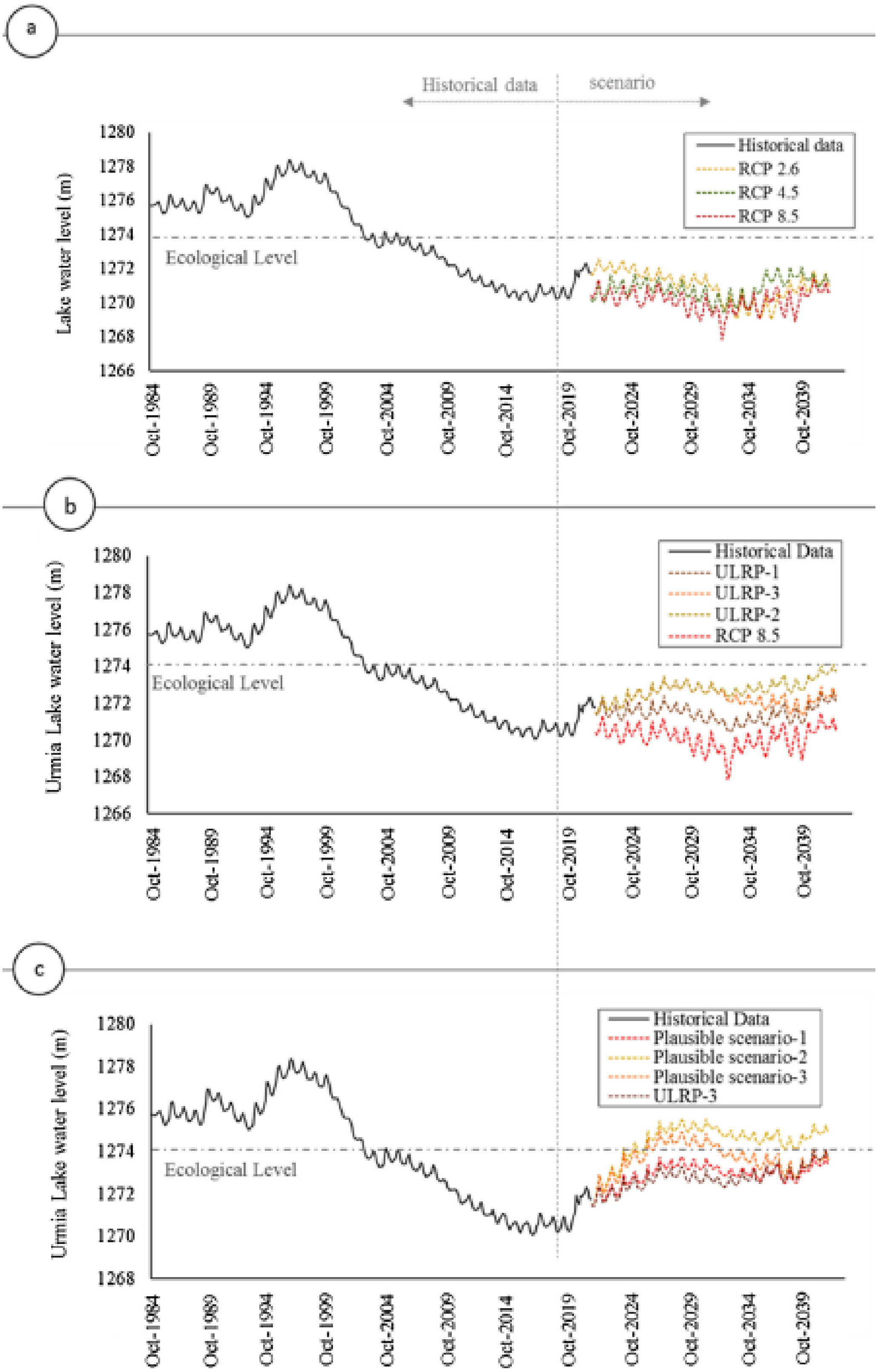

Figure 4: scenario results simulated in Bakhshianlamouki et al. (2020) showing the potential impact on Urmia Lake water level. Full scenario definitions are given in Bakhshianlamouki et al. (2020).

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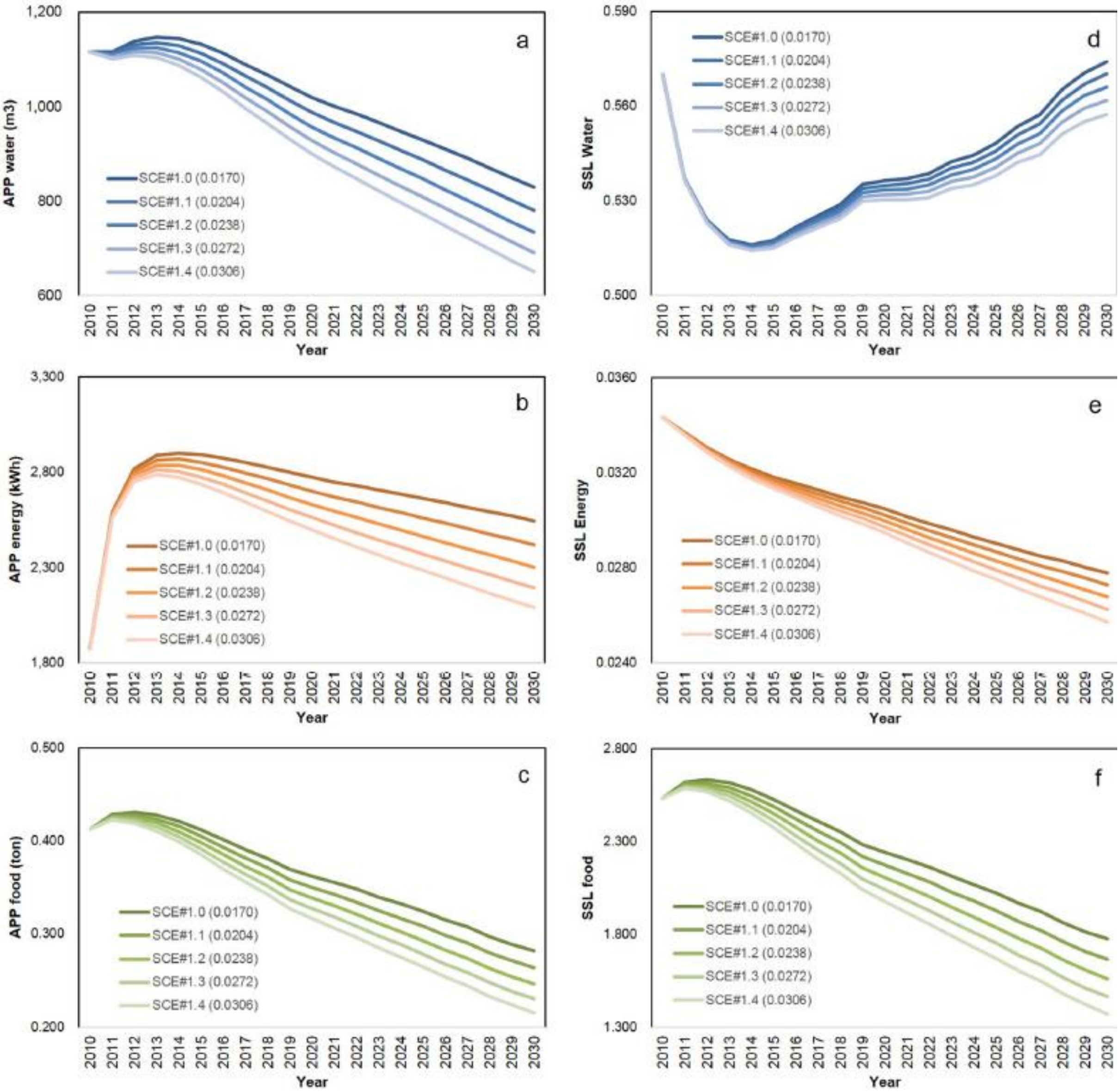

Figure 5: scenario simulation results testing different migration rates on nexus resources in Karawang. (a) and (d) water resources, (b) and (e) energy resources, and (c) and (f) food resources. Figure from Purwanto et al. (2021).

As another example, Sušnik et al. (2013) carry out a range of scenario analyses to assess the impact on a coupled water-agricultural system on the Nile Delta, Egypt (Figure 6) Scenarios show best- and worst-cases for water availability in the region, and the corresponding impact on crop yield and total crop revenue, important metrics in the dominant agricultural sector of the Nile Delta.

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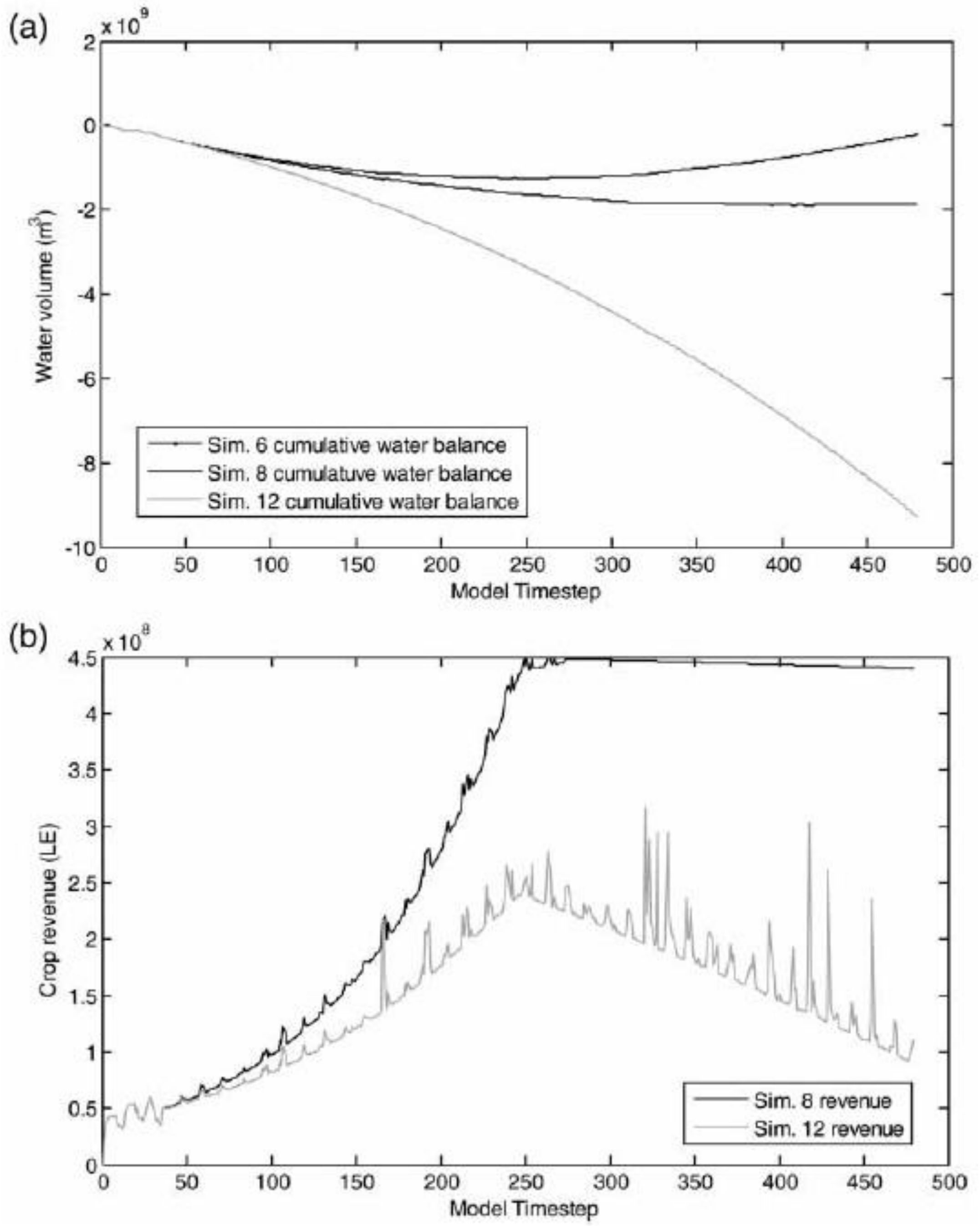

Figure 6: scenario analysis from Sušnik et al. (2013), showing the best and worst case scenario results on water volume available (a) and total crop revenue (b).

Finally, Wang et al. (2023) test a series of policy implementation scenarios, assessing their impacts across the WEF nexus. In this study, a series of plausible, but hypothetical policies reflecting WEF nexus interventions in Hunan Province, China, are tested in an integrated WEF nexus system dynamics model. It is shown that the impact of different policies has widely differing impacts within each nexus sector, but also across sectors (Figure 7). An analysis of implementing multiple policies together demonstrates that while there are synergies among some policies, there are also considerable trade-offs. The study helped to highlight these interactions, not only among the WEF sectors, but also among policies, thus providing new insight and information for decision makers.

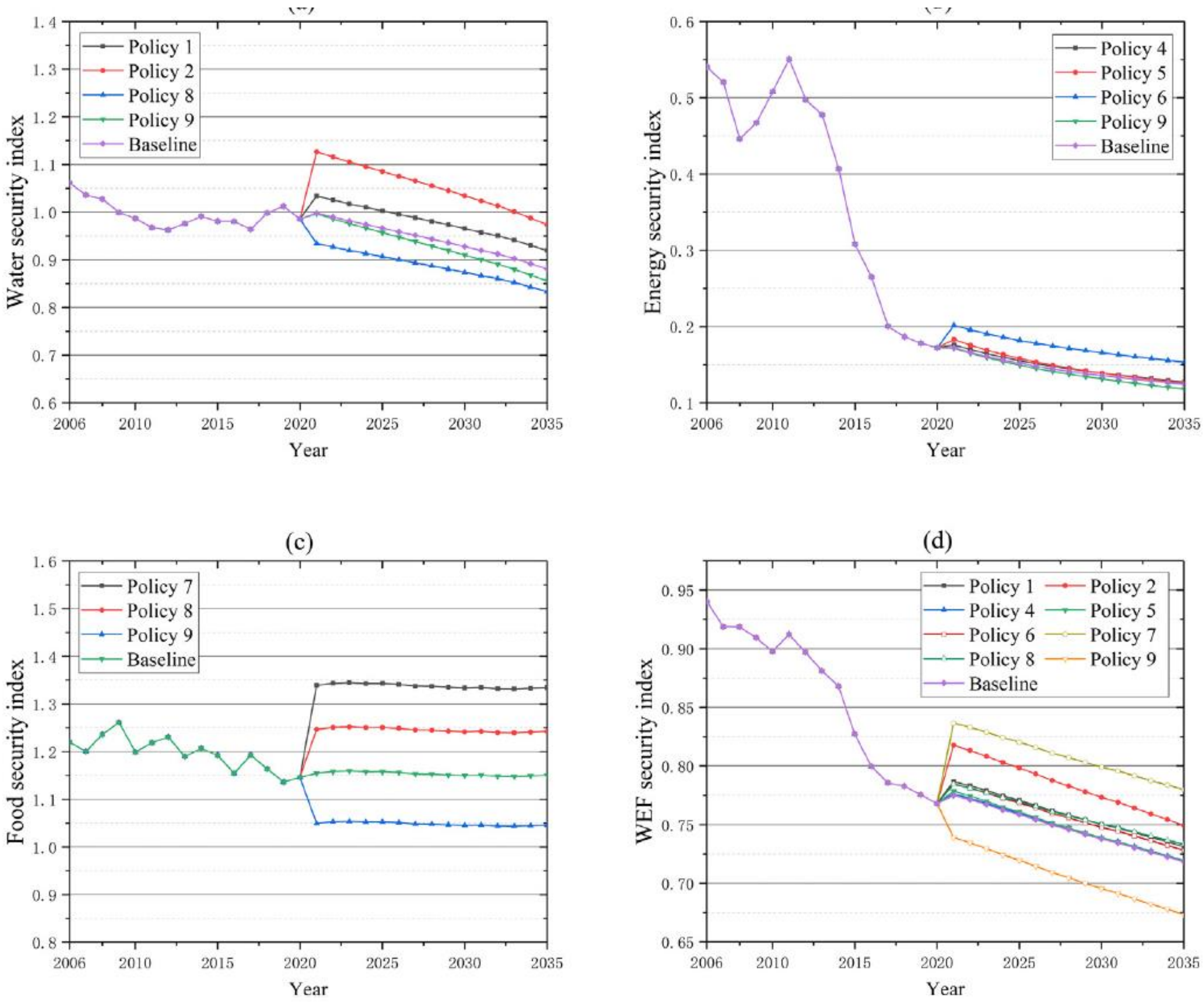

Figure 7: policy scenario analysis from Wang et al. (2023), showing how different policies impact the water, energy, and food sectors in very different ways.

2.3. What-if analysis

What-if analyses are subtly different to sensitivity and scenario analyses. They are concerned with asking questions of ‘what if such an event were hypothetically to occur? What would be the system response?’. So, what-if analyses do not necessarily need to reflect reasonable ‘futures’, but can be used to stress test systems to see for example where collapse points lie – is there a threshold beyond which system behaviour qualitatively changes or beyond which a certain system parameter (e.g. water availability) collapses (e.g. water is no longer available). Such analyses can be at least instructive, and can start to demonstrate where such thresholds may lie. As such, real-world variables can be monitored, and warnings can be sounded if they start to approach a critical or threshold value that may lead to undesirable system states or behaviour. Mereu et al. (2015) use a what-if analysis to analyse at which (unrealistic) point a reservoir on Sardinia, Italy, starts to show signs of stress, and ultimately fails (i.e. empties and never refills) as total water demand increases. At five times the current demand levels, the reservoirs started to show signs of vulnerability, while at 10 times the current demand levels (not at all realistic), the reservoir system collapsed. While not realistic, the results indicate that perhaps if demand were to double or triple, measures may want to be imposed to avoid vulnerable situations.

As evident, what-if analysis in simulation models allows safe, fast, and efficient testing of an unrealistic or dangerous situation (e.g. that would be unsafe, expensive, unethical) to carry out in the real world to determine system response and to identify potentially undesirable effects. Such analyses can be instructive for real-world decision making.

In NEXOGENESIS, what-if testing will be discussed with each Case Study to assess their needs and preferences. What-if tests can then be carried out within the SDMs, for example on individual policies, extreme climate scenarios, etc. As an extension of this, the SLNAE tool will allow the user to run their own, self-defined, what-if tests to determine policy impacts. This will add value, impact, and novelty to NEXOGENESIS outputs.

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2.4 Uncertainty analysis

Uncertainty analysis is carried out to recognise the fact that there is always unknown (uncertain) knowledge and variability in model structures and in data, as well as when projecting an unknown future. In order to cope with uncertainty in data input, and the potential impact on model output, NEXOGENESIS will use a number of approaches. Approaches to characterise uncertainty feed forward to model outputs, and can be used to communicate uncertainty in model outputs to different groups of stakeholder groups (e.g. via a decision support tool as part of WP4). This is important as it aims to make non-experts aware that in models dealing with future projections, the outputs are never certain. Showing and recognising this uncertainty can help stakeholder groups think about the uncertainty and account for it in future decision making. To be clear, in NEXOGENESIS, there will not be uncertainty assessment across different Reference Pathways (RP) or scenarios at the same time since each CS is modelled by its own different SDMs. Uncertainty assessment will be run for each SDM (i.e. each Case Study) separately, taking into account SDM input data distributions (probabilities) for that case study from data provided in WP2. In NEXOGENESIS, a user-friendly graphical decision support tool (WP4) will be developed, and as part of this, uncertainty assessment will be communicated to the user using data coming from the WP3 SDMs.

In principle, the basic idea is the same, although the details differ, between the two approaches that will be used. Essentially, a distribution of values will be pseudo-randomly selected (sampled) many times by the system dynamics models of the nexus systems in the case studies which will be run for each of the selected (sampled) values. The corresponding model output for each of the selected (sampled) values will be recorded and analysed to assess the impact on that output. In short, a distribution of values input to the models will lead to a distribution in model output values that can be summarised and shown to non-experts. The details arise in the type of distributions to be sampled, and in the model sampling procedure. These are explained below.

2.4.1 Uniform distributions

Uniform distributions are the simplest conceptually. Lower and upper bounds of values are defined, and an equal probability of occurrence (given by P(x)) of values (x) is assumed for all values between the lower and upper bounds. Values outside the lower and upper bounds are given zero probability of occurrence, and therefore are not considered. This is illustrated schematically in Figure 8. Such distributions are useful for example when literature studies give a range of values for a particular process (e.g. the amount of energy needed to treat a given volume of raw water, which can vary by location type and treatment level, but which also falls within a relatively narrow range). In these cases, the entire reported range can be sampled assuming a uniform distribution to represent the range of values in the literature, representing the most reasonable/reported cases.

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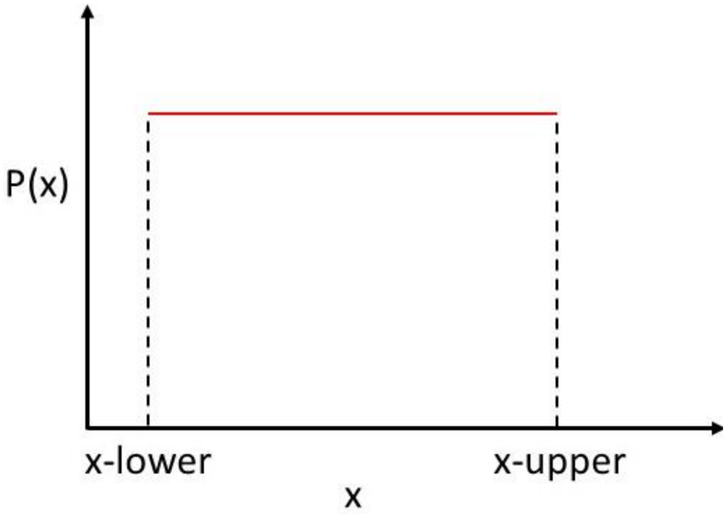

Figure 8: schematic illustration of a uniform distribution. All values of ‘x’ have equal probability of occurrence ‘P(x)’ between the lower and upper boundaries. Values outside the boundaries (vertical dashed lines) are not considered (i.e. their probability of occurrence, P(x) = 0).

2.4.2 Non-uniform distributions

Not all data are uniformly distributed. Normal (bell-shaped) distributions are common, as are non-normal distributions which tend to elongate ‘tails’ and are skewed to the left or right. Non-normal distributions (e.g. Weibull, log-normal, Gamma) are often used to represent extreme-value statistics, for example associated with floods and droughts.

In order to determine the statistical nature of the data distribution, the following process can be used. Firstly, all data for a given variable (Figure 9) can be ‘collapsed’ to form a distribution curve. For example, the data shown in Figure 9 are synthetic, but could be taken to represent an annual precipitation time series. These data can be analysed (for example using statistical analysis packages in the R programming language) to determine the statistics of the distribution that best fits the data series. In the case of Figure 9, the data are normally distributed, and form the basis for the normal distribution curve shown in Figure 10. The synthetic data in Figure 9, and therefore the normal distribution, has a mean = 0, and a standard deviation = 1. With knowledge of these statistics, the underlying data series can be ‘replicated’ by repeatedly sampling from a theoretical distribution with a specified mean and standard deviation of 0 and 1 respectively (in this example). The more times the theoretical distribution is sampled, the closer one will get to the ‘real’ underlying data series. Through such sampling of the statistical distributions of underlying data, the full spectrum of uncertainty / variability in the data can be captured and used in the NEXOGENESIS system dynamics models. This will feed through to give probabilistic model output. It should be noted that due to the complexity of the SDMs, a given distribution in input data will not necessarily give the same distribution in output results (i.e. a non-linear response). The next section details the process of Monte-Carlo sampling that will be used in NEXOGENESIS.

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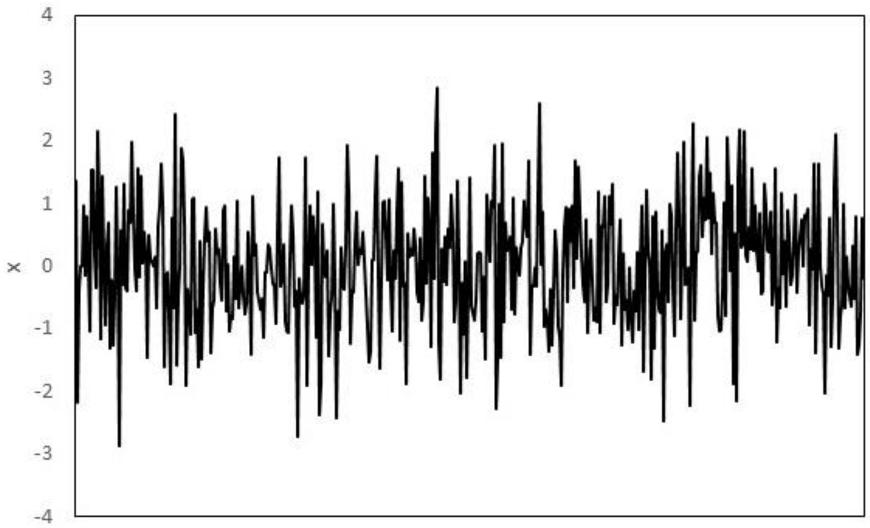

Figure 9: a synthetic data (time) series of normally distributed values (x) with mean = 0, and standard deviation = 1. The data series in this figure yield to normal curve in Figure 10.

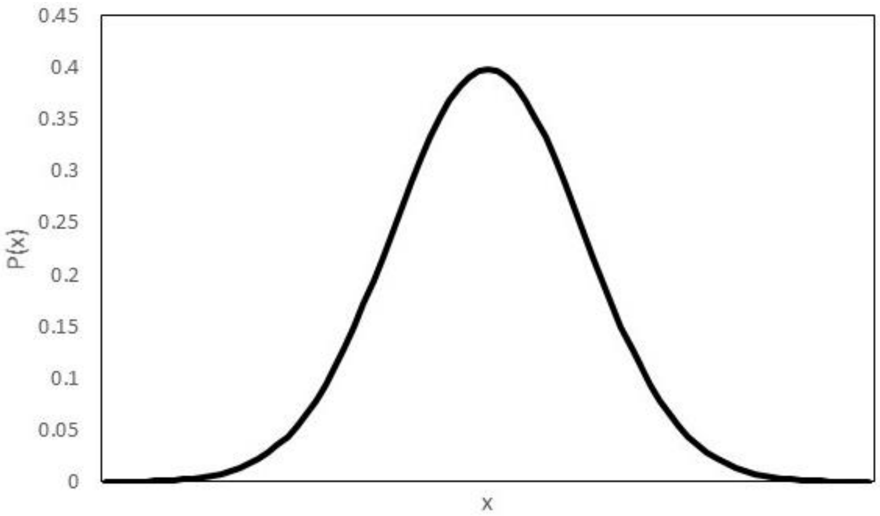

Figure 10: normal distribution with mean = 0, and standard deviation = 1, and showing the probability of occurrence (P(x)) for different values of x in the sample.

2.4.3 Monte Carlo sampling in the system dynamics models

Once a data series has been condensed into a best-fit statistical distribution (e.g. using specialised packages for data analysis in R), Monte-Carlo sampling techniques (Thomopoulos, 2013) can be used, exploiting functionality built into STELLA (the SDM software being used in NEXOGENESIS; see the extensive Help documentation for STELLA, including sections on sensitivity analysis and sampling from statistical distributions, at https://www.iseesystems.com/resources/help/v3/Default.htm). Given a statistical distribution, Monte-Carlo routines pseudo-randomly sample a number from within the given distribution (which statistically represents the underlying data series). The more times the sampling is carried out, the closer one approaches the data. Sampling 100 or 1000 times often gives a reasonable approximation without overly burdensome computational load. Because the procedure uses the statistical distribution, in the case of the normal distribution in Figure 10 for example, most numbers (about 67%) would fall within +/- 1 standard deviation of the mean (= 0 in this case). However, very occasionally (e.g. maybe 2 times out of 1000), the procedure will return a number at the very extremes of the distribution (e.g. very high or low values). In the case of river flow data, these values might represent very low probability low flows (during droughts) or high flows (during extreme floods). Such events could be identified with stakeholders in each Case Study and be an option for users to simulate/test using the SLNAE. Every time a number is sampled, the SDM is simulated, and model outputs are given. Therefore, if the input distribution is sampled 1000 times, there are 1000 probabilistic model outputs. In this way, uncertainty about the future can be incorporated into the NEXOGENESIS models, and fed through to the SLNAE in WP4.

Because of the model complexity, uncertainty in input can be assessed in terms of the impact on model output. Using the probabilistic model outputs derived from the repeated sampling of input distributions, a series of data are generated as output. Continuing the example above, in this case 1000 values of model output would be generated. As such, this output can be turned into a probability distribution, reflecting the likelihood of different model responses to uncertainty in a given input parameter. When summarised, this can give an idea of the most probable range of system response behaviour in a given model output when uncertainty in a given input is considered. Likewise, an idea can also be given of the ‘extreme’ modes of model/system response. This information can help planners by suggesting where most of the system responses are likely to fall, but also by highlighting potentially undesirable extreme behaviours, including an analysis of how this may change over time. This information could be used to make policy and decisions more flexible and adaptable, accounting for uncertainties. As an example, the potential probability of exceeding certain thresholds (e.g. low water levels in reservoirs) in response to climatic, socio-economic, and policy drivers can be assessed. This information can be used to determine pathways that will give the best chance of remaining within acceptable values, refraining from undesirable extreme levels. Figure 11 summarises the process described in this section.

In NEXOGENESIS, such uncertainty will be captured in the SDMs, will be fed forward to the nexus assessment engine (in WP4), and will be summarised and presented to users via the visual decision support system supporting the SLNAE (WP4).

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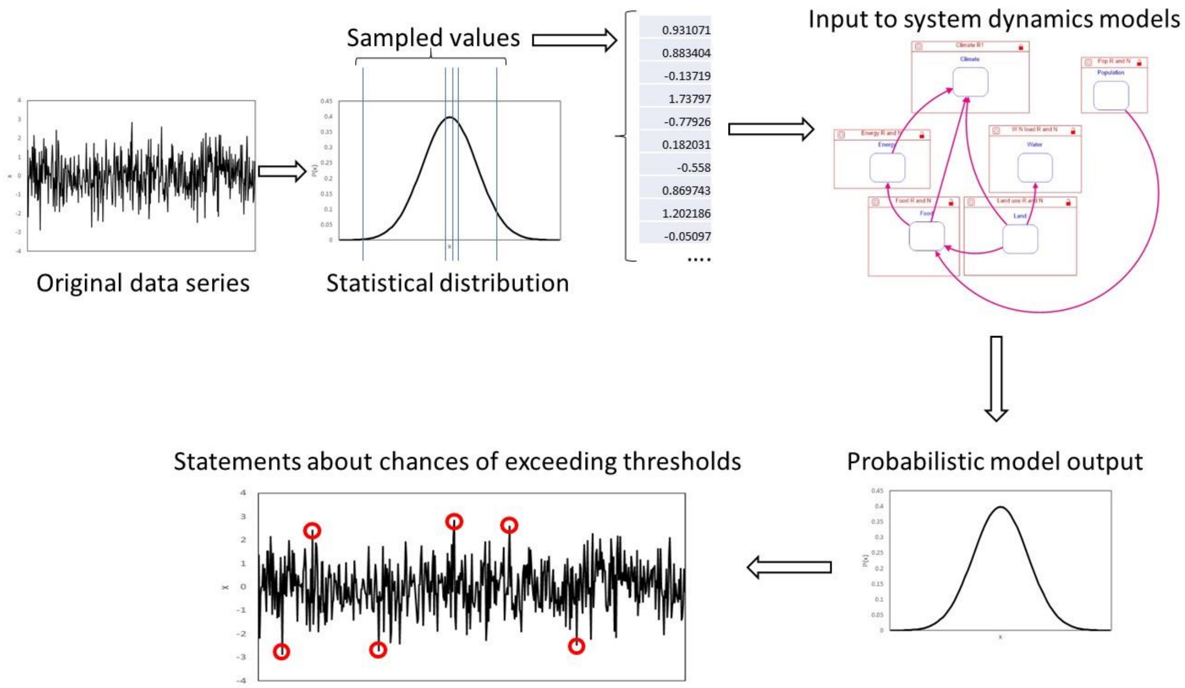

Figure 11: schematic representation of the Monte-Carlo sampling procedure and the utility of this in SD modelling as described in Sections 3.4.2 and 3.4.3. Note that in this schematic example, the output probabilistic distribution is the same as the input, which in real SD simulations will not necessarily be the case. The input data series is normally distributed with mean = 0 and standard deviation = 1.

As an example of uncertainty characterisation in practice using system dynamics, Sušnik (2018) includes the uncertainty in global datasets within SDMs developed to assess long-term trajectories of global WEF futures. A process similar to that described here was carried out – the statistical distributions of datasets were assessed and quantified. These were then built into SD models and subsequently sampled 100 times using Monte-Carlo algorithms built into the STELLA SD software. In simulations, 87 years were simulated, with 100 iterations, giving a total of 8700 model output datapoints. The output was then also summarised as mean, median, and 10th/90th percentile values, giving the most likely figures for future WEF resource use amounts, as well as extreme values (Figure 12). Such assessment may be useful when planning national, continental, or global-scale societal resource policy actions. A similar study demonstrates stochastic parameter characterisation using an SDM framework is reported by Terzi et al. (2021).

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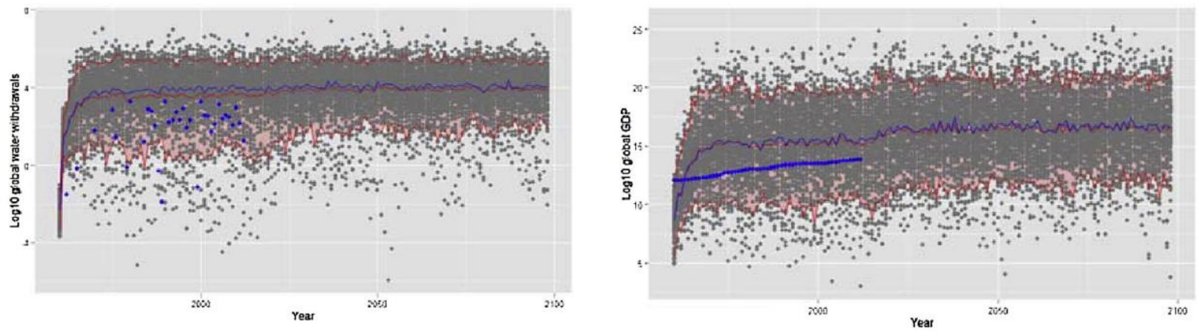

Figure 12: simulation outputs from Sušnik (2018). Every grey point is an individual model output from 100 Monte-Carlo simulations sampling from statistical distributions of input data. The total output datapoints = 8700. The mean and median (red and blue lines) and 10th and 90th percentiles (shaded region) indicate extreme values for the parameters (water withdrawals, right, and GDP, left). A similar process will be used in NEXOGENESIS.

2.4.4 Uncertainty characterisation in NEXOGENESIS from the biophysical and socio-economic data (from WP2)

Uncertainty is characterised differently in the biophysical and socio-economic model outputs in NEXOGENESIS (WP2) due to the fundamentally different approaches to these two aspects.

For the *socio-economic data*, NEXOGENESIS uses two SSPs – SSP2 and SSP4. Future changes in parameters from the socio-economic models (GRDEM/DEMETRA – see D2.1) are expressed as percentage variations, which themselves change under the different SSPs. To represent uncertainty in these percentage variations, a random perturbation (noise) will be applied to each SSP. The full range of percentage variation values given as a result of the perturbation will be ‘collapsed’ into statistical descriptions and fed into the SDMs as described in Sections 2.4.1 to 2.4.3 above.

For the *biophysical data* (see D2.1), the characterisation is different. Here, multiple models from projects such as ISIMIP and CMIP contribute to NEXOGENESIS input data. Each model in these projects gives unique output for a given parameter such as temperature, evaporation, runoff, or precipitation. The whole output of a parameter from all models is known as the ensemble. For each parameter to be used in NEXOGENESIS, the statistics of the variation in the ensemble can be described as explained in Sections 2.4.1 – 2.4.3, thus representing the uncertainty across multiple models. As explained above, these statistical descriptions will then be fed through the SDMs and utilised in WP4 to offer additional information for policy making.

In this way, uncertainty in both the biophysical and socio-economic data will be captured in NEXOGENESIS. It is important to note that this is different to the variations given by the different policies, which will be captured in the ‘policy scenarios’ to be superimposed on the

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‘reference scenarios’ as described in Section 2.2. The input data uncertainty analysis is yet an additional uncertainty characterisation on top of the policy scenarios. Together, the policy scenarios and the data uncertainty characterisation will lead to a comprehensive and robust assessment and communication of uncertainty in complex WEFE systems modelling, going beyond previously attempted.

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3. Further use in NEXOGENESIS

The uncertainty will be characterised and assessed within the SDMs to be developed as part of WP3. However, WP4 will also make use of the uncertainty assessment during the development of the SLNAE and accompanying visual and intelligent decision support tool aimed at policy makers and stakeholders.

The uncertainty will be considered in the Machine-Learning framework to be employed within WP4. The probabilistic SDM outputs will be made use of when considering ‘optimal’ nexus policy solutions within the approach adopted in WP4. The uncertainty results could be communicated in a way similar to that depicted in Figure 11, but the exact form of this visualisation is being carried out in WP4 in consultation with CS leads and stakeholder groups. In this way, not only will suitable policy sets be communicated to stakeholders along with their nexus-wide impacts, the full potential range of impacts can also be communicated thanks to the uncertainty characterisation and assessment in the SDMs in WP3. This will lead to more comprehensive policy recommendations, accounting for system complexity, unanticipated consequences, and uncertainty to a degree never-before attempted. This will lead to novel scientific and societal output and impact delivered by NEXOGENESIS. Finally, all this analysis may lead to existing policies being fine-tuned to account for the results of uncertainty in simulations and/or entirely new policies being defined as a result of NEXOGENESIS outputs.

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4. Conclusions

Sensitivity, scenario, and uncertainty analyses are essential when dealing with complex systems. Scenarios are used to define multiple plausible, yet uncertain, futures. In NEXOGENESIS, the scenarios are captured by combinations of the Representative Concentration Pathways and Shared Socio-economic Pathways (RCPs and SSPs, respectively). This is important in the NEXOGENESIS context as policy makers will have more information to identify those leverage points in the WEFE nexus that will likely lead to the greatest system response. The use of scenario and uncertainty analysis will be applied to each of the five NEXOGENESIS case studies. What-if analysis (for example by asking hypothetically “what if we implement policy A? What happens in the system?”. These questions will be able to answered through the implementation of the NEXOGENESIS online decision support system, the SLNAE, or NEPAT. Uncertainty analysis in the SDMs allows for the variability and unknown knowledge in data to be characterised and quantified, including its impact on model outputs.

The combination of all these aspects in NEXOGENESIS (scenario analysis, what-if tests, uncertainty analyses, and visualisation), will lead to novel scientific and societal information about policy implementation in the WEFE nexus, and together with stakeholder assessment of results, will help validate the implementation of NEXOGENESIS nexus models. NEXOGENESIS will use uniform distributions of large datasets to characterise the uncertainty in the SDMs. What-if analyses will be able to be tested in the NEPAT/SLNAE in each case study, along with visualisation of the RCP-SSP scenarios, which are implemented directly in the SDMs and utilised in the SLNAE / NEPAT.

In terms of the DOA, this work contributes to the following Objectives:

Objective 1: Identify and model WEFE nexus interlinkages using complexity science and innovative artificial intelligence technology, accounting for climate change and variability, socio-economic development, and the introduction of policies.

Objective 2: Reduce uncertainties of how new policies and stakeholder behaviour affect the nexus through the integration Self-Learning Nexus Assessment Engine (SLNAE) output and policy feasibility assessments, along with validation of findings by stakeholders.

Objective 3: Develop and apply a new WEFE Nexus Footprint in a similar vein to the urban water blueprint to track progress of policy objectives.

Objective 5: Support out-scaling of the NEXOGENESIS framework to other basins and wider spatial areas through a consistent approach.

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