IMPROVING PREDICTIONS AND MANAGEMENT OF HYDROLOGICAL EXTREMES

Deliverable D13.1
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Deliverable D13.1

Generic Integrative Modeling Approach Guideline
Deliverable 13.1 | Generic Integrative Modeling Approach Guideline

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**Abstract**

This document is a guideline for using a generic integrative modelling approach to integrate multi disciplinary knowledge on essential drivers of a decision context. It is a living document that will be further developed during the course of IMPREX. The case study of the Júcar River Basin is used as illustration. And additional case study (the Lake Como) is presented in Annex 5.

We show the steps to follow and illustrate how different data sets can influence decision-making and the importance of data accuracy for short and long term management planning.

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Preliminary remarks

The purpose of this document is to provide a guideline using a generic integrative modelling approach to integrate multidisciplinary knowledge on essential drivers of a decision context. With this guideline we intend to address the challenge of interdisciplinary knowledge integration, coming from different sources, at different temporal and local scales and under different socio-economic influences. Interdisciplinary knowledge integration (IKI) is an essential element for climate services provision, starting the process of condensing multiple knowledge sources (climate models, economic models, hydrological models, etc) into a conjoint model that can be used to support science-based user decisions. Formal knowledge, as well as knowledge from of local users and experts, is of high value for this approach. It is a living document that will be further developed during the course of the IMPREX project.

This document is a demonstrator and as such shows how integration could be implemented. We have chosen the case study of the Júcar River Basin as an example. In the following months after this deliverable, the first working prototype of the model integration will be available (MS22). An additional possibility of integration as implemented in the case study Como Lake is also presented in the annex 5 of this document.

Our IMPREX-IKI approach is intended to address the incomplete knowledge of a complex system dynamic to support well-informed decisions and policy making for adaptation. IMPREX-IKI follows the subsequent structure:

a) problem identification and structuring using individual model building exercises;

b) problem analysis using group model building exercises;

c) a family of coupled models (with different complexity levels) to provide results that can be used at the local level for making decisions, and

d) simulations showing efficiency tendencies when it comes to the optimization of the decision process.
1 OVERALL APPROACH – Following a participatory modelling approach

Participatory modelling is key in system dynamic modelling, providing the basis for the inclusion of all complex system perspectives. In essence approach builds a quantitative modelling structure for a given decision context (e.g., a water resources management problem) allowing the analysis of multiple decision drivers and their interactions. It supports the inclusion of transdisciplinary knowledge through the participation in the model creation process of stakeholders and researchers. The participants actively go through the problem structuring and identification phases, as described by Pohl and Hirsch Hadorn (2007), and is a key element for successful climate services creation.

The aim of these issue identification phases is to emphasise the production of knowledge required to recognise and identify problems and options to mitigate these in the given decision topic, for instance dealing with hydrological extreme events that challenge societies’ sustainability. Therefore, the sub-models forming the building blocks of the modelling structure should not only support the understanding of extreme events as perceived by researchers, but also fill knowledge gaps as prioritised by societies carrying a sustainability challenge.

As a central tenet of the integration of knowledge through working on problems in the context of application, as opposed to disciplines, participatory modelling can produce stimulating discoveries and interactions across various fields (Mauser et al., 2013). This means it not only allows for the consideration of non-formal knowledge, but also facilitates the integration of knowledge from different disciplines. Scientific researchers must engage with “others” who have a stake in the decision, creating a process of ‘extended peer review’ of the modelling process (Funtowicz and Ravetz, 2008). Finally, the robustness of the produced knowledge will be tested against the use of the service provided through the modelling approach, and also by the possible impact in the decision system in the face of extreme hydrological events.

Through this modelling and knowledge integration, we aim to reach the highest-level possible in transdisciplinary design (see figure 1). These steps are designed to include a co-design and co-production step for climate services deployment. These steps support the creation of scientific evidence guided by the societal challenges and needs when confronted with extreme hydrological events.

Figure 1: The three “co”-steps (Mauser et al, 2013)
integration belongs to the co-design of the product and/or services to be used. In our case, we have developed conceptual models with individual stakeholders that will be used in the future (see section 2.2). In this same phase, we have defined with them their research priorities and management needs (see Table 1). The second phase of integration, “co-production”, starts together with the final completion of the prototype of the modelling structure (which will be addressed with the milestone MS22 in Month 24). In this phase we will start the real interdisciplinary and transdisciplinary integration of knowledge to facilitate the use of the IMPREX results into the management of hydrological extreme events. The last phase, “dissemination of results” corresponds to the work that will be developed until month 44 of the project and that will be reflected in D13.4 (Month 40) and D13.5 (Month 44).

Main positive effects of this way of integrating knowledge starting with a participatory modelling phase (see section 2.2 and 0) are:

- the developed model is more relevant to stakeholders' needs;
- the model integrates scientific and local knowledge, therefore enhancing its quality and integrity;
- stakeholders have a better understanding of the model, which increases the confidence in it, and thus are more willing to use it.

2 MODELLING STEPS - Starting the process of IKI-IMPREX

The modeling steps we propose for IKI-IMPREX are the following:

1) **Conceptual qualitative modeling step**
   - Individual interviews – individual conceptual models
   - Group exercise – group model building

2) **Quantitative modeling step** – Selection and combination of Family of sub-models

3) **Scenario building step** – Impact analysis step

In the following we explain the modeling phases. We are going to concentrate the efforts of this document in Step 1) and 2). Step three will be included as an analytical part of the modeling in D13.4 (Month 40).

2.1 **Conceptual qualitative modeling design**

Conceptual modeling is the overarching definition for a variety of modeling efforts based on diagramming techniques. They are regularly used during the system definition and data requirements analysis phase of the system. They are designed to capture, specify, communicate and document both
static and dynamic phenomena of a real-world domain and intended to be supported by an information system (Wand and Weber 2002).

The conceptual model design includes a syntax that allows the analyst to identify fields of interest and possible system bottlenecks. There are different conceptions of grammars possible depending on the problem to be specified during the design of the conceptual model.

For IKI-IMPREX we decided to use Group Model Building (Vennix, 1996) as a basis for developing our conceptual models. Group model building (GMB) is a participatory approach that is widely used to enhance the capacity of practitioners to think in a systems way (Siokou et al., 2014). The dynamic patterns and the relations between crucial variables in the system are pictured while talking and analysing. It results in a better understanding of the system, identifying the main variables and relationships between them.

The main characteristics of GMB are:

- Starting point is very open, e.g. individual interviews;
- Important to have (at least) two moderators structuring and leading the discussion and reporting the process, as well as building the model simultaneously;
- Model serves as (group) memory.

The sequence of generating the model includes several key steps (see Figure 2). The construction of the model starts with the process of stakeholder selection. As a primary rule, all players with a significant role within the analyzed system must be included in the process. To get a broad view and understanding, for the IMPREX topical domain of water resource management it is necessary to have a good representativity to cover the range of sectors that influence the use and availability of water resources.

Once the stakeholders are selected, the next step in the sequence is carrying out individual interviews with each of them to (1) identify the key variables within the system and (2) describe the relationships among these variables. It also provides insights into the particular perception and understanding of the system by the stakeholders. During the interview, a qualitative individual model is co-produced with the stakeholders.

Lastly, the combination of all the individual models allows building a group model that includes the main parameters identified, based on the knowledge and perception of stakeholders, within the system.
Stakeholder analysis and selection

A key initial decision for this first step is the proper selection of the stakeholders with whom to work. Stakeholder analysis must be an iterative, action-oriented exercise in social analysis.

Participation in group problem-solving processes is important to ensure that the decision-making process includes the greatest possible number of stakeholder interests; to generate broad support for decision-making; and to facilitate the implementation of decisions.

The selection of stakeholders must respond fundamentally to the criterion of representativity (taking into account all relevant domains) to collect the greatest number of "realities" of the system, and most importantly, to specify if the collected perceptions correspond to the actuality of the system.

Establishing an appropriate stakeholder group size is one of the most relevant considerations for conducting the analysis efficiently. The most frequent challenge is to limit group size so that members are allowed to actively participate in both individual interviews and group workshops. According to our previous experience in this type of study, a group size of 7 to 14 stakeholders is optimal, though this
might vary depending on the stakeholder analysis done in advance. Nevertheless, most important in the process is to have a number of stakeholders that represents the whole system. In this regard, it is important to invite stakeholders who might have official authority to make decisions on the issue addressed, with power to implement or block solutions / decisions, and also those that are affected by the outcome, however wield limited power. A single stakeholder may have a variety of interests, and several stakeholders may have similar interests. It is crucial to avoid a scenario in which a large number of stakeholders have very particular interests.

2.2 Individual interviews

The purpose of the interviews is to enrich the vision of the analyzed system with additional local knowledge that may be used to generate the conceptual model. To that end, semi-structured interviews and cognitive mapping were used as diagramming techniques (McGeorge and Rugg, 1992). This allows the respondent to answer the interview questions by constructing their own individual causal model. This type of product has the advantage of being easy to integrate into the group model of the system (Hare, 2011).

Unlike closed surveys with fixed questions, a semi-structured interview is more flexible and open to new ideas that can be raised during the interview, based on the responses of the interviewee. This can be an initial activity to understand a problem with different stakeholders, or use it at a later stage for in-depth research. Semi-structured interviews with conceptual mapping provide a large amount of qualitative data and also have the potential to generate a deeper understanding of the system.

During the course of the individual interviews in which the individual models of each stakeholder are generated, a syntactic rule\(^1\) has to be followed (see figure 3), based on the Capital Approach Framework (Carmona et al. 2017). This approach combines insight from the Millennium Assessment Framework on Ecosystem Services (Millennium Ecosystem Assessment, 2005), Sustainable Livelihoods Framework (Scoones, 1998), Ecosystem Services Framework and Poverty Reduction (Fisher et al., 2013). This syntactic rule allows us to create individual conceptual models and to characterize recurring variables to define the group model.

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\(^1\) With syntactic rule we mean the set of rules that will govern the structure of the model when interpreting it.
Legend to figure 3: The colors represent different blocks of knowledge: The green colors is related to the natural capital and all natural resources in use. The blue color represents knowledge systems and activities based on these knowledges. The orange color stays for management actions and decisions instances around the natural capital. The violet colors represent the threats as perceived by stakeholders.
2.3 Qualitative modelling

Digitalized version of the co-produced cognitive map

A digitalized version of the co-produced individual conceptual models is formatted identically as the pictured version. The idea is to facilitate the post-processing of data, allowing further simulations with different scenarios.

After the digitization of the qualitative model, a post-process of the information and data has to be undertaken with the purpose of (1) homogenizing the language (the same variables identified) among all stakeholders, (2) identifying the main variables, and key relationships between them, and (3) adding all missing information, with the assistance of interview recordings, incorporating knowledge mentioned during the interview but not represented in the initial model.

Group model

By combining all the individual models (see Annex 2 Specific individual conceptual models in the Júcar river basin), a group model that integrates all the existing knowledge provided by stakeholders can be generated according to the following criteria:

- The common variables are represented, as well as the relationships among them, identified by the set of stakeholders interviewed
- Influence of external drivers (e.g. improvements in prediction of hydrological extremes – IMPREX-) on the dynamics of the system.

Figure 4: Group Model of the Júcar River Basin
Summary for the Júcar Case Study - Main variables identified and influenced by IMPREX results

The efficient allocation of water resources is a fundamental variable identified by all stakeholders interviewed in the Júcar river basin. Meteorological droughts affect both the quantity and the quality of water. In terms of quantity, a severe drought event may lead to forced restrictions on uses, the agricultural sector being the one most affected by restrictions. Droughts also affect the quality of surface water, causing an increase in the concentration of all types of microorganisms and toxics, with negative consequences such as higher costs of treatment and insufficient capacity of treatment plants.

In addition to droughts, overexploitation of aquifers is another impact that aggravates the situation. Groundwater is an important source of supply in the region, especially in the eastern part of La Mancha (in Spanish, la Mancha Oriental), even though the economic (energy) cost of pumping water from aquifers is high. The reuse of wastewater is a potential source of supply, although some stakeholders argue that the cost of pumping water to high altitudes is too high and not economically viable. The compensation of losses of production with respect to the expectations allows farmers to transfer the risk of meteorological drought to the agricultural insurance. However, this insurance only
applies to rain-fed crops and excludes irrigated crops. Occurrence of droughts, however, may alter the allocation of area between rain-fed and irrigated agriculture.

IMPREX analysis the effects of the potential improvement of predictions of extreme hydrological events. Less uncertainty in short-to-medium and long-term prediction models would increase the efficiency of the water allocation in the Júcar river basin test-site to cope with droughts. On the other hand, more accurate prediction models would allow medium- and long-term investments to increase the performance and capacity of water treatment plants. Even though it is well known that predictability has limitations, the minimum enhancement on it would support better decision-making.

An example of the information that needs to be enhanced through IMPREX (see table 1) to improve decision making was extrapolated from the individual conceptual model in our case study (see Annex 1 and 2 for more information). Voinov and Bousquet (2010) clearly point out that “the knowledge, data, and priorities of stakeholders should have a real, not just cursory, impact on model development both in terms of selecting a modelling platform and in setting model assumptions and parameters”. We will use this table for exploring different scenarios and tendencies in the systems that might be influenced by changes in those parameters.

Table 1: Information needed by the Jucar River Basin Stakeholders

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### Acronyms:

- **CHJ OPH** - Confederación Hidrográfica del Júcar (Oficina de Planificación Hidrológica)
- **CHJ OE** - Confederación Hidrográfica del Júcar (Oficina de Explotación)
- **JCRMO** - Junta Central de Regantes de la Mancha Oriental
- **CJT** - Comunidad General de Usuarios del Canal Júcar-Turia
- **EMSHI** - Entidad Metropolitana de Servicios Hidráulicos
- **Albacete** - Suministro Agua Potable a la ciudad de Albacete

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**P** - Precipitation  
**T** - Temperature  
**ET** - Evapotranspiration  
**Q** - Flow in natural conditions  
**Wd** - Volume of water demand  
**Q** - Flow after regulation  
**V** - Volume of reservoirs  
**D** - Forecast Demand  
**PfD** - Probable Forecast Deliveries  
**Gw** - Groundwater storage
2.4 Transition from Qualitative to Quantitative modelling

A description of stages of quantitative System Dynamics (SD) model development, as provided by Vennix (1996), distinguishes the following steps:

1) Identification of state variables, or “stocks”, their quantification and units assignment,

2) Equation formulation for flows (Vennix 1996 makes a distinction of material and information flows),

3) Consistency checks (notably, unit checks),

4) Model calibration (or parameter estimation).

After these steps of model development are successfully completed, the following steps of quantitative SD are: analysis of model behavior (testing and sensitivity analysis), model evaluation, policy analysis, model use/implementation.

In regard to qualitative system dynamic models presented in this report (or analogous qualitative models) – for example, the group model presented in Section 2 and combined from individual models – at least two broad approaches for translating qualitative models into quantitative ones might be adopted. We explain the essence of these approaches on a particular example of the group model from Section 2.

In the first approach, referred below to as indirect SD quantification, the group model (especially its variables and relations between them) serves as guidelines for selection (or, where necessary, for development) of related disciplinary models, that later play the role of modules to be coupled into the interdisciplinary model structure. For instance, the analysis of the group model as presented in Section 2 above, reveals the following list of disciplines (research areas), with a subset of group model variables that might be related to each element of the list:

1) Climate science,
2) Hydrology,
3) Ecology,
4) Agriculture,
5) Economics,
6) Policy

(NB: the list above is not necessarily complete).

For every element of the list, the relevant disciplinary model might be either chosen from existing models (if available), or developed by the modelers themselves. The criteria for selection from a set of existing disciplinary models (or, alternatively, the guidelines for new model development) derived from a group model are the following: (i) the variables from the group model should simultaneously be the variables of the disciplinary model, (ii) the relationships between the variables from the group model should agree with (or, at least, should not contradict) the results of disciplinary model simulations.

The second approach, referred below to as *direct SD quantification*, implies the development of a quantitative group SD model along the lines of Vennix (1996), where the corresponding equations linking the SD model elements are formulated as (simplified) relations that (with reasonable accuracy) reproduce (mimic) the relations between variables as provided by simulations with complex and detailed disciplinary models. Therefore, a detailed disciplinary model is used to derive a simpler relation between the different variables. (As an analog from climate modelling, also in its essence common to modelling of many other natural and technical systems, we might refer here to *impulse-response-function (IRF) models*, with impulse response functions calibrated against the state-of-the-art global climate models – e.g. the model NICCS described in Hooss et al. (Hooss et al., 2001).

Generally, in the case when the second (‘direct’) approach is adopted, the resulting (integrated) models might be (on average) less complex than in the case of the first (‘indirect’) approach. This is due to the available disciplinary modules (that are, in many cases, highly detailed and complex models) being coupled ‘as is’ (meaning the complexity of disciplinary modules is fully inherited by the integrated model) in the ‘indirect’ approach, while the ‘direct’ approach to the integrated model, by design, is based on ‘reduced’ information derived from disciplinary models.
Within both approaches to SD quantification outlined above, the resulting integrated model is a collection of linked processes, where each process can be represented quantitatively with either a comprehensive disciplinary submodel or its stylized representation (e.g. with a response function). Whether the direct or the indirect SD quantification should be preferred depends, among other things, on the availability of detailed disciplinary models (or of their simulation results) and the extent to which these models are documented; on the complexity of the models, on the particular case study etc.

Within IMPREX, both approached are/will be implemented. E.g. for the Jucar River Basin case study (see figure 4) we are going to have a more sophisticated linkage of existing modeling approaches (indirect SD quantification); for the Rhine case study (not yet covered by modeling example in the present deliverable) the output data of BfG and other models will be used as input data for the integrated model (direct SD quantification).

The next section provides some examples of implementation of the first (indirect) approach towards SD model quantification of the two approaches outlined above.

Figure 5: Jucar River Basin Available Water Resources

Figure 4 represent an integrative system model structure for the Jucar River. The model in this case integrates on the blue side information coming from hydrological modules, climatic/weather modules, hydraulic modules and in the orange side urban water demand module, agricultural water demand module, industrial and animal husbandry water demand modules. Additional it integrates a decision-making module represented in the yellow box.
In the blue side of the picture the water sources of the river basin are represented including: a) desalinated water (DW); b) surface water (SW); groundwater (GW), re-use water (RW) and transfer water from other systems (EW). All these water sources entering the system compose the total available water resources in the basin. Decision making bodies as the River Basin Partnership in the Júcar River, are dependent on the best information available for calculating the total amount of water resources available. So for example, any changes in the run-off will affect the figure about total available water and based on this information, decision making processes might be also affected (see Carmona et al, 2017).

The main box of the figure (Available Water Resources) is not only fed by the five different water sources of the system but it is only influences by the water uses represented in the orange side of the figure. The orange side of the figure represents the main water demands in the basin. Four main water users are described: a) irrigation agriculture (Ir); b) urban consumption (U); industrial water (In); and animal husbandry (C). The integrative system model shows also the composition of uses (amount of water demand from the 5 different sources represented in the blue side of the figure) for the four different main water users. So, for example, the subsystem represented within the triangle shows all water demands affecting the groundwater availability. Groundwater availability might vary extremely if one particular user (as for example the irrigation sector) increases the amount of water pumped from the system.

On the other side, decision making processes during hydrological extremes might imply the increase of water uses coming from a particular source to deliver the minimal requirements for a particular use (e.g. water pumping from wells as an emergency measure in a drought period (Carmona et al, 2017)).

The integrative system model shows easily the impacts that particular information on run-off, for example, might have in the system, increasing or decreasing the numbers of the total available water resources. This will influence, for example, how much land will be dedicated to irrigation, e.g. increasing or decreasing the water demand for irrigation. This is an important decision in the Jucar, since around 80% of water resources are used by the agricultural sector.

It also shows how important accurate information is, when it comes to extreme hydrological extremes and decision-making processes. Additional sensitivity analysis can be made to create “what if would – worlds” and test different scenarios imposing different decision-making
processes. Scenarios analysis will support decision making under different conditions allowing decision makers to start adaptive management approaches.

2.5 Quantitative modelling

“Family of models” - Introducing a concept of generic model family

The Generic integrative modelling approach described in the present report should be distinguished from a concept of “a generic model”. We mean by this that this modeling approach can be understood as universal to the extent that it can be “localized” to any case study of EU H2020 IMPREX project or outside the project by e.g. merely tuning the model parameters to fit the model to available regional and/or sectoral data. As pointed out e.g. by Hasselmann and Kovalevsky (2013), (at least) two possible viable strategic alternatives to (as argued above) fruitless attempts at developing “universal” models of socio-natural systems are either model hierarchies or model ensembles.

Model hierarchies are developed in a bottom-up way from simple (conceptual, or “toy”) models to more complex ones: “At the lowest model level, only a few, relatively simple processes are included. Once these are properly understood and tested against data, a next level of detail is introduced, and so on, until a level of complexity is reached in which the model has too many free parameters to be reliably tested against data or to provide a readily interpretable picture of the system dynamics” (Hasselmann and Kovalevsky, 2013; Hasselmann, 2009). Again, given the interdisciplinary character of EU H2020 IMPREX project and, in particular, the vital role of climate science in its research program, it is worth mentioning that the fundamental problem of modeling the response of the climate system to external forcing (notably to anthropogenic forcing) has historically also led to gradual evolvement of a hierarchy of climate models over decades: from pioneering simple theoretical zero-order models of the past, to state-of-the art Earth System models of the present (e.g. Trenberth, 1992, p. 16).

If simple models are understood as aggregate models, the fundamental challenges related to aggregation (important for natural science models and, probably, even more important for socioeconomic models) and/or to describing the complex system dynamics in terms of (often just a few) average variables, should be considered. One of the challenges is, for example, how to define state variables and data that represent the state of the system at a very generic level? (For instance, global mean precipitation is not a very good descriptor of the intensity of the global hydrological cycle.)

Model ensembles (in the context of the current discussion) differ from model hierarchies by having several simple root models at the bottom of the model system, as opposed to only the one (Grimm and Railsback, 2012; Grimm et al., 2005).

Within our approach, we would prefer using the term generic model family, in its meaning closer to the model ensemble (as defined above – with emphasis on multiple root models), but also
acknowledging that these root models (and respective more detailed models at upper levels) might be tailored to model different processes and answer different research questions, be based on different modelling methodologies, and be applicable to different spatial and temporal scales. The word “generic” here is justified by the fact that a specific member of the model family tailored to answer the specific research question may in many cases be “localized” to a number of similar case studies by e.g. tuning the values of model parameters.

Given the interdisciplinary nature of the systems under study, the members of a model family should normally have a modular structure, with modules from different disciplines (climate science, hydrology, ecology, economics, social sciences etc.) linked together by mutual feedbacks involving common variables (see Figure 5). This modular architecture paves the way for exploring and comparing the models with alternative versions of the same module (say, a hydrological module). Various combinations of modules can be assembled in a coupled model along these lines. However, from the methodological point of view, a reasonable strategy would be to link the modules with a comparable degree of complexity (i.e. linking a very detailed regional economic model to a “toy” hydrological model is an imbalanced approach to coupled modelling, as well as the opposite extreme).

Below we outline two members of generic model family (one model is applicable at spatial microscale and at seasonal timescale, another at regional geographic scale and at long-term (decadal) time scale).

It should be pointed out that the second model (applicable at long-term time scale) is an extension of a simpler model (the root model). A technical description of the root model can be found in Annex 3. This illustrates the general idea of bottom-up development of model family members towards an increasing degree of complexity.

**An example of a SD model applied to seasonal time-scale**

The design of the first model is primarily based on the information obtained from the following stakeholders: AGROSEGUNRO, CENTRAL IRRIGATION BOARD OF LA MANCHA ORIENTAL. The model covers a subset of relationships as identified in the qualitative group model of the Júcar River Basin as shown in Figure 4 above.

**The first SD model**, that might support decision making in seasonal term, focuses on the decisions of irrigators (farmers) on how to distribute land between irrigated or rainfed agriculture. Expectations of sufficient precipitation stimulate the allocation of more land for rainfed agriculture, which, unlike the irrigated land, can be insured from shortage of rainfall, and might also reduce consumption of water and energy. Simultaneously, if the real precipitation dynamics deviate from those forecasted, this might lead to severe damages of crops.
In order to maximize crop yields, in addition to minimizing losses in the event of drought, it is common practice for farmers in the upper Júcar River Basin to make two key decisions prior to the start of each planting season:

1) distribution of the crop area (what proportion of the land surface will be used for irrigation and what proportion for rainfed);

2) willingness to insure the dry land portion to the risk of the meteorological drought.

By means of agricultural insurance, the farmer transfers the risk of not meeting production expectations based on a reference yield in the event of a meteorological drought. The insurance compensates the difference between expected and actual (reduced by drought) crop productivity in accordance with market prices. A simple crop growth model (growth affected by precipitation and temperature as external “forcing”)\(^3\) – serves as a module simulating the crop yield dependent on meteorological conditions.

As examples on how the family of models works, we present here a decision making module including a simplified hydrometerological model based on run-off simulations.

This module, as explained before, is based on the narratives captures during the qualitative modeling phase, particularly on two of the stakeholders: AGROSEGUROS (insurance company) and Junta de Regantes de la Mancha Oriental (Irrigation Scheme Community). Their narrative suggested that decisions on the amount of irrigated land are done on a yearly basis and based on possible predictions for the season to come and the experiences of the past on weather evolution. This information is key when deciding the amount of land that will be dedicated to irrigation or to rain-fed agriculture. Rain-fed fields can be insured through an insurance police while irrigation fields cannot be insured. In the case of a drought or a heat wave, the losses by irrigated fields might be higher than by rain-fed fields, because an insurance police redistributes the risk between the farmer and the insurance company.

This simple decision “having more or less hectares of rain-fed agriculture that can be insured” have broader implications for the basin. Less water will be taken out of the system and therefore the system might have more resources available.

The module presented here is based on optimal insurance policy theory assuming the maximization of the expected value of agent’s utility function (Borch, 1960) under different assumptions about the agent’s perception of risk (Slovic, 2000). While finding the optimal insurance strategy in any single

\(^3\) I.e. initial simple versions available in the literature on which detailed models developed later like WOFOST (http://www.wur.nl/en/Expertise-Services/Research-Institutes/Environmental-Research/Facilities-Products/Software-and-models/WOFOST.htm), EPIC (http://epicapex.tamu.edu/epic/) are based (cf. van der Velde et al., 2012).
agricultural year is technically modelled as a maximization of expected utility, the system dynamics approach at inter-annual time scale is also included in the modelling scheme by simulating the dynamics of number of farmers who follow alternative decision-making strategies over years dependent on goodness/poorness of seasonal weather forecasts in previous years. This explanation is implicitly represented in figure 4, by the decision making

The SD model is tailored to address, among others, the following three main questions:

1) what the optimal decision should be (in economic terms);
2) what risks would cause inadequate forecasts, particularly regarding unexpected extremes;
3) how good/poor performance of seasonal weather forecasts might affect the change of decision-making of the farmers with respect to insurance at inter-annual time scale.

Following data that will enhance the simulations: a) data series (observational or modeled) on the dynamics of the following meteorological variables in the target area – Júcar River Basin: maximum daily air temperature, minimum daily air temperature, run-off; and b) Information on the predictability of precipitation at seasonal time scales in the target area. (If predictions are available, but people have no skill to interpret them, the information provided may make the decision worse.)

Examples of SD models applied to long-term time-scale

The design of the second SD model is primarily based on the information obtained from the following stakeholders: JÚCAR RIVER BASIN AUTHORITY, EMIVASA.

The second SD model, that might support decision making in the long term (years to decades), is a model representing the regional economy. It operates under assumptions that investments are made at regional level in long-term increase of efficiency of water use (for adaptation to droughts). The increase in efficiency of water use, caused by improvements in irrigation systems, is understood analogously to energy efficiency: the more efficiency in water use, the less water demanded for a certain level of productivity. Investors develop a long-term strategic plan for the development of technical and administrative measures aimed at increasing the efficiency of water use, for which improved (probabilistic) information on the frequency and magnitude of extreme events (droughts). In the long term (which in turn could be affected by climate change) is necessary.

The model of regional economy is based on the extension of the root model described in Annex 3. It is coupled with a simple hydrological model. For the first version of the coupled model, the ‘abc’ hydrological model proposed by Fiering (1967) (see Kuczera, 1982; Todini, 2007; Vogel and Sankarasubramanian, 2003, sec. 2.1) is used. The ‘abc’ model is a simple SD model of a watershed,
Deliverable D13.1

Driven by precipitation as external ‘forcing’, and, according to conventional classification of watershed models (Singh, 1995), falls under definition of lumped models. Despite the cited authors (and Fiering himself) claiming the model was developed mostly for ‘didactic’ and ‘pedagogical’ purposes, its simplicity makes it suitable for the illustrative purpose. However, the intension during the course of the project is to add more complexity later, including more variables and relationships to better simulate real hydrological conditions (see e.g. figure 4).

The economic module depends on Net water demand by regional economy, where

\[
\text{Net water demand} = \text{Raw water demand} \times \text{‘efficiency of water use’} \tag{1}
\]

On the right-hand side, the first factor is linked to the water resources allocation, while the raw water demand can be gradually increased by (costly) investment, as more efficient irrigation schemes.

This ‘abc’ derived model is based on the linear version of the root model described in Annex 3 and is therefore one step up in the model hierarchy originating from this root model. The production function of the AK type adopted in the root model, with physical capital acting as the only production factor, is now replaced with Leontief production function dependent on two production factors: the stock of physical capital \( K \) in the regional economy, and water use \( Q \):

\[
Y = \min (A^*K, f*Q) \tag{2}
\]

where \( A \) is the technology parameter of the production function representing an increase in irrigation technology.

In cases of water shortages caused by droughts, this naturally induces sudden drops in regional output (that were introduced in the root model described in Annex 3 in an ad hoc manner. At the same type, the parameter \( f \) entering the Leontief production function, is related to the efficiency of water use and can therefore be gradually increased by purpose-oriented investment. In the extended model, the

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4 In the ‘abc’ hydrological model, the temperature is not a forcing variable; a simple parameterization of evapotranspiration is included in the modelling scheme (Vogel and Sankarasubramanian, 2003).

5 The AK production function is used e.g. in a textbook AK model of economic growth (Barro and Sala-i-Martin, 2003).

6 The Leontief production function or fixed proportions production function is used in economics when we imply that the factors of production might be used in fixed proportions because there is no substitutability. The function is of the form \( q = \min \left( \frac{x_1}{a}, \frac{x_2}{b} \right) \) where \( q \) is the quantity of an output produced and \( x_1 \) and \( x_2 \) stay for the outputs produced.
flow of investment in physical capital $K$ is supplemented by the second flow of investment in increase of the efficiency of water use (i.e., of the parameter $f$).\footnote{The technical description of the actual coupled hydroeconomic model is provided in Annex 4. This will be further developed during the course of work.}

With the integrated hydroeconomic model, it is possible to explore various socioeconomics scenarios, including adaptation scenarios. Figure 6 and Figure 7 below provide illustrative examples of exploring the “business-as-usual” scenario (no investment in adaptation), as well as quantitatively different adaptation scenarios (the difference is in the adaptation investment rate) under scenario of hypothetical annual decline of precipitation (Figure 6; gradual precipitation decline scenario; Figure 7: stochastic variability of precipitation superimposed on gradual trend). The interesting finding provided by the integrated quantitative model is the “affordability of adaptation” (under assumptions adopted): efficient adaptation policy is possible with only a relatively small share of regional investment channeled into climate adaptation infrastructure improvement.

Figure 6: The dynamics of GRP (gross regional product) simulated with a coupled hydroeconomic SD model under scenario of gradual decline in precipitation and different adaptation scenarios (“business-as-usual” scenario and adaptation scenarios with different “green investment” rates, e.g. sigma)
The model is tailored to address the following two main questions:

1) what the optimal long-term investment plan should be;

2) what the impact of using inadequate long-term climate projections and/or projected dynamics of statistical properties of droughts under changing climate is.

Natural-science information necessary for simulations and their justification:

1) Data series (observational or modeled) on precipitation in the target area – Júcar River Basin (preferably monthly to yearly time step), and/or statistical properties of precipitation in the target area (if available).

2) Information on the range in climate projections used for “what-if” simulations with the model.

2.6 Scenarios to be analyzed and sensitivity studies

An overarching hypothesis that is at the heart of the integration modelling within the IKI approach is the statement that better hydroclimatic information is going to reduce vulnerability to extreme events.
in some of the key case study areas (van den Hurk et al., 2016). However, given that the systems under study are coupled socio-natural systems, a priori this statement should be still considered only as a plausible hypothesis. Indeed, to what extend reducing the uncertainty in the natural science part of the interdisciplinary model would make the projections provided by the full model more reliable, given the uncertainty of its socioeconomic part, and also admitting that socioeconomic processes, due to their enormous complexity, are inevitably to a lesser degree understandable and predictable that natural science phenomena?

Many pros and cons could be easily identified for the hypothesis specified above. A number of reasons could support a positive answer: better predictions give less surprises for extreme events, smaller bandwidth of scenarios gives a clearer picture of the problems that are caused by climate change etc. However, socioeconomic factors per se might still control the dynamics of a socio-natural system much stronger, and so the hydroclimatic information might appear to be not the most important driver. Modelling results might suggest, for instance, that short-term economic dynamics is a much stronger driver. Also, in short term current governance might be not able to impose necessary changes in the water management.

Still, on “physical” side (natural science/engineering), the uncertainty should not be underestimated either: for instance, it might well be that improved weather forecasts are much less important than adequate information on the amount of water in the reservoirs.

The model system to be developed will address this hypothesis, and the multi-level uncertainty related to systems under study, by sensitivity studies understood in a broad way, including exploring the parametric and structural uncertainty of the models (Tebaldi and Knutti, 2007), uncertainty with respect to socioeconomic scenarios (e.g. Kovalevskiy et al., 2016), and uncertainty to hydroclimatic information. Sensitivity study techniques will include, among other widely used tools, Monte Carlo simulations with varying the model parameters, and also probabilistic numerical experiments simulating the stochastic system dynamics driven by different realizations of hydroclimatic forcings.

An example

The next level of SD hydroeconomic model hierarchy, a substantially more detailed SD model than that outlined above, is shown in Figure 5. Both SD hydroeconomic models presented in this section cover corresponding subsets of relationships as identified in the qualitative group model of the Júcar River Basin as shown in Figure 4 above; however, the substantially more detailed model as shown in Figure 5 covers a substantially more extended subset of the group model.

Using this model we represent the basin as expressed by stakeholders and use mainly local data to feed the model. We reproduced the total amount of available water resources including decision making processes. The accuracy of data input into the blue side of the model sketch of figure 4 is very important because it might determine the amount of water available for distributing into the system.
For showing how important accuracy is, we have forced the model with three different data sets (two more close to reality and based on actual data and one not taking into account the particularities of the basin but simulating a non-existent run-off for the basin). This means in the real world, the Jucar River Basin Authority might change decision-making in the future. For example in the case of different data sets as shown in the following Figure 8, the third run (called current2) shows a very favorable situation for the basin in which water resources are not scarce anymore. With this kind of simulations we can force different future scenarios that might give decision makers the basis for simulating different behaviors and reflecting on the consequences of those management behaviors. We use this modeling approach to generate “what-if” scenarios, but with very accurate data sets based on enhanced climate projections in the long run or weather prediction in the short run, the decision making process under extreme events would be enhanced.

Figure 8: Runoff simulation changes
3 Conclusions and outlook

The present report describes the IKI-IMPREX generic integrative modelling approach. It is planned to concentrate further efforts on the quantification of qualitative SD models already developed in the course of the IMPREX project, on further development of the generic model family, and on applications of the approach described to test sites and case studies relevant for IMPREX research agenda.

For models developed within the proposed approach (including e.g. the seasonal and the long-term time scale model described in previous sections), an analysis of the sensitivity of the results to errors in the quantitative descriptions of the relationships is important. Particularly, it is crucial to identify which relationship is most crucial for the outcome, and to make a distinction between sensitivity to weather/climate model information, to local physical information, and to the model description of the nature of the interactions between the stakeholders (structural sensitivity in the latter case).
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ANNEXES

Annex 1  Case Study Júcar River Basin

Geophysical and climatological frame

In Spain, the hydrological system is divided into hydrographic districts (see Figure 9). These hydrographic districts are managed by Hydrographic Authorities.

Figure 9: Spanish River Basins

The Júcar River Basin Authority (CHJ by its Spanish acronym) is the entity in charge of public hydraulic control in the area of the Júcar River Basin. It comprises all the rivers that flow into the Mediterranean from the Cenia River to the Vinalopó River (see Figure 10). The largest river in the area is the Júcar (512 km long and 21,580 km² total area), which gives the name to the basin. The Júcar river has its origin in the mountain known as Montes Universales (in Cuenca, Spain) and flows into the Mediterranean in the town of Cullera (Valencia). The following rivers are the river Turia (280 km long and 6,400 km² of total area) and the river Mijares (156 km long and 4,300 km² of total area).
respectively. These three basins represent 75% of the total basin area (42,989 km²). The Júcar River Basin Authority is comprised by nine exploitation water systems (or subwatersheds) that include all the rivers of the District.

Drought and flood episodes are highly recurrent in the Júcar River Basin, with an irregular hydrology characteristic of the Mediterranean rivers. The Jucar River Basin is one of the most vulnerable areas to drought in the western Mediterranean region. The water demand for agriculture represents almost 80% of the total of the demand. Agricultural demand stabilizes in the coming years or decreases while urban and industrial demands are expected to increase. In the coastal plain of Valencia, between the mouths of the Júcar and Turia rivers, is located the Albufera, a shallow lake with an associated wetland. Both water bodies, lake and wetland, depend on the return flows of irrigation from the Júcar and the Turia rivers, in addition to groundwater flows.

Figure 10: Jucar River Basin

Figure 11: Jucar River Basin

Hydrographic network and digital elevation model of the Júcar River Basin Authority (Confederación Hidrográfica del Júcar, 2016a)

The district suffers from dry periods that in some cases are long lasting. In this regard, one of the most difficult challenges that the Júcar River Basin Authority faces are pluviometric droughts, making extremely important the efficiency in management of water resources. This situation has led to a greater use of unconventional resources in recent years, such as the waste water reuse or seawater desalination, although to a lesser extent in the latter case.
The Mediterranean climate of the area, characterized by hot-dry summers and mild winters, additionally presents remarkable pluviometric variability both on the temporal and the spatial scale. The annual average temperatures ranges from 8°C in the Northwest mountainous areas, to 20°C in the Southern coastal part of the basin (Confederación Hidrográfica del Júcar, 2016a) (see Figure 12).

Figure 12: Spatial Distribution of mean annual temperature (°C)

Spatial distribution of mean annual temperature (°C) in the Júcar River Basin District for the entire period 1980/81–2011/12 (Confederación Hidrográfica del Júcar, 2016a)

The rainfall has highly spatial and temporal variability. Mean annual precipitation for the whole basin is about 500 mm, ranging from 300 mm in the driest years to 800 mm during the most humid ones (Confederación Hidrográfica del Júcar, 2016b) (see Figure 13). The persistence of dry years produces significant drought periods. Conversely, episodes of high intensity precipitation take place in short periods over the months of October and November.
Figure 13: Spatial distribution of total annual precipitation

Spatial distribution of total annual precipitation (mm / year) in the Júcar River Basin District for the entire period 1980/81–2011/12 (Confederación Hidrográfica del Júcar, 2016a)

Figure 14 shows the pluviometric variation in the Júcar River District of two time series, a recent series 1980/81–2011/12 compared to the complete series 1940/41-2011/12. This variation has been not homogenous in the whole District. While in the coastal areas the annual average rainfall has slightly increased, thus producing more runoff, in the upper parts of the basin as well as in inland areas the average rainfall has decreased to values greater than 15 mm per year.

Figure 14: Precipitation reduction
Percentage of precipitation reduction between the recent series (1980/81-2011/12) compared to the complete series (1940/41-2011/12) (Confederación Hidrográfica del Júcar, 2016a)

Groundwater plays an important role in the basin (see Figure 15). There are large calcareous aquifers in the North-western upper parts, where the rivers Turia and Júcar are born, providing base flows. There are also important aquifers in the middle part of the Júcar river basin, such as the aquifer of La Mancha Oriental, which provides important base flow to the Júcar River. This is one of the most extensive aquifers in Spain (7,260 km²) (Sanz et al., 2011).

Figure 15: Groundwater bodies

Delimitation of groundwater bodies in the Júcar River District (Confederación Hidrográfica del Júcar, 2016a)

However, it is overexploited by irrigation perimeters, which is causing the inversion of flows, so the river nowadays delivers water to the aquifer in spring and summer. And finally, the coastal alluvial aquifer of La Plana de Valencia occupies the coastal plain, which is a big groundwater reservoir to the lower parts of the Turia and Júcar.

Socio-economic characteristics

Demography

The permanent population in 2012 in the whole Júcar River District is close to 5,178,000 inhabitants, with an estimated total of equivalent-population (including tourism) of 5,697,000 inhabitants.
The population density is approximately 120 inhabitants per km², higher than the national average (92 inhabitants per km²).

**Urban demand**

The total demand for water for urban domestic consumption is currently 277 hm³ per year, with an average amount of water supplied resulting in 133 liters per day per equivalent inhabitant (Confederación Hidrográfica del Júcar, 2016a).

Figure 16: *Territorial distribution of the total equivalent population*

According to estimates published in the last Júcar Hydrological Plan, based on the Statistics National Institute (INE by its acronym in Spanish) (Instituto Nacional de Estadística (INE), 2017) it is expected that in 2033 the population of the District Júcar will decrease up to 12% (Confederación Hidrográfica del Júcar, 2016a).

**Agriculture**

Regarding the agricultural sector, the Júcar river basin has a relevant agricultural area of approximately 390,000 ha, mainly concentrated in the Plana de Castellón, Valencia and the lower basin of the Turia, the Eastern Mancha, the Ribera and the low-basin of the Júcar and the irrigations of the valleys of Vinalopó and Monnegre.

Future predictions of irrigated area are subject to multiple causes (expectation of benefits, urban pressure on main irrigated areas, availability and cost of resources, agricultural policies, etc.).
Industrial sector

The use of water for the electric energy production includes the generation of hydroelectric energy and the use in thermal, nuclear, solar thermal and biomass plants, especially for refrigeration.

Figure 17: Territorial distribution of hydroelectric activity

(Confederación Hidrográfica del Júcar, 2016a)

The manufacturing industry includes a heterogeneous set of activities of transformation and production of goods. Its socioeconomic characterization in the Júcar River District has been made on the basis of Gross Value Added (GVA) and registered employment data for the different subsectors.

Regarding GVA, the subsector that generates the most is food, beverages and tobacco, with € 3,055 million (23%), the chemical industry with € 2,067 million (15%) and thirdly the other minerals non-metallic, going from the first place in 2009 as a generator of GVA in the area of the Júcar River District to the third place in 2012 with 1,573 million euros (12%).

Recreational uses

In addition to the usual uses of water supply, irrigation, industry and electric energy production, a set of activities associated with recreational non-consumptive uses (e.g. nautical sports, adventure sports in the aquatic environment, sportive fishing, swimming, etc.) are carried out in the Júcar River District, which, by their nature, are mainly included within common water uses.
Droughts

There are different types of droughts in the JÚCAR RIVER BASIN:

- **Meteorological drought**: Caused by a continued lack of precipitation.

- **Agricultural drought**: Caused by the insufficient soil humidity after the meteorological drought. That decreases the crop yields due to the crop needs not being met in a particular time and place.

- **Hydrological drought**: The long meteorological drought causes a decrease in surface and groundwater water resources availability, in particular water exploitation systems for a specific time period, compared to the average values. It may take months, even up to one year, from the start of the rainfall shortage.

- **Operational drought**: Comprises the term in which the supply failures do not reach the purposed water uses in Water Exploitation Systems.

- **Socio-economic drought**: Represent socio-economic and environmental impacts caused by water scarcity. It produces economic or personal damages on the affected population. Water demand is higher than the availability.

The first three types of droughts are related to climate variability and the two latter are linked to the water resources management. The major historical recent drought events have occurred in the last part of the 20th and the beginning of 21st centuries (Confederación Hidrográfica del Júcar, 2016a), with the most recent one occurring over 2005 - 2008 that had the classification of an extreme event (Andreu et al., 2009).

Historically, the most severe impacts have affected all sectors. Currently, agriculture and hydroelectricity are most affected, since urban water supply and environmentally sensitive areas (e.g. protected wetlands) have priority over other water uses. But economic impacts also affect municipalities, since they have to pay more for water in order to purchase water rights or alternative sources of water; and they also affect society, because they have to cover the costs of environmental measures during droughts. In the future, impacts are expected to be higher, at least economically, and for agriculture it will be more difficult to get an adequate supply.

From year 2001, Spanish Water Law requires the River Basin Partnerships to develop Drought Special Plans (DSPs) in order to turn the traditional reactive crisis management approach into a proactive approach. The DSPs for the Júcar River Basin include monitoring for early drought detection, drought
stages definition, and measures to be applied in each of the stages (Confederación Hidrográfica del Júcar, 2016a).

The Júcar River Basin Partnership developed the DSPs in 2007 during the severe drought episode of 2005 - 2008 (Ministerial order – MAM698/2007). The management system for the different drought scenarios established in the SDP required the establishment of the Permanent Drought Commission (PDC) when the emergency scenario is reached and a Royal Decree32 is passed by the national government. The aim of this Commission is to take decisions on water management during a drought in order to reach equilibrium between the interests of different sectors and to mitigate the impacts of the drought.

Even though the DSPs were not developed until 2007, since the year 2001 the Júcar River Basin Partnership initiated a drought monitoring indicator system to control the hydrological status of the different water exploitation systems of the Júcar River Basin as well as the development of periodical reports (Confederación Hidrográfica del Júcar, 2016a).
Annex 2  Specific Individual conceptual models in the Júcar River Basin

Stakeholders selected in the Júcar River Basin case-study

According to the previously established premises, a set of 11 stakeholders were selected for the case study of droughts in the Júcar River Basin:

- **AGROSEGURO**: The insurance company covers losses with respect to production expectations in rainfed crops and irrigated crops, although in the latter case only when losses are caused by adverse climatic events, regardless of lack of water (heat waves, hail, frost, etc.), when the farmer cannot do anything to avoid it.

- **GENERAL USERS COMMUNITY OF THE JÚCAR-TURIA CHANNEL**: The General Users Community of the Júcar-Turia Channel (CGU Canal Júcar-Turia by its Spanish acronym) is the body in charge of regulating the general operation of the Júcar-Turia channel (1) in relation to irrigation users and (2) in relation to suppliers of water resources.

- **JÚCAR RIVER BASIN AUTHORITY**: The Júcar River Basin Authority (CHJ by its Spanish acronym) manages the water resources, allocating it among urban (Valencia, Albacete and Sagunto cities), agricultural (USUJ, Júcar-Turia Channel and JCRMO users association) and industrial (IBERDROLA power company) users.

- **OFFICE OF THE INTEGRAL WATER CYCLE OF THE CITY OF VALENCIA**: The Integrated Water Cycle office (CIA by its Spanish acronym), within the Valencia Town Hall, develops its activity from the Júcar and Turia rivers water collection: its treatment and distribution to the end users. The waste water is collected and distributed to wastewater plants, and then returned to the environment with similar conditions as natural.

- **GENERALITAT VALENCIANA – DIRECTORATE GENERAL FOR WATER**: The Directorate General for Water (DGA by its Spanish acronym) is the governing body that assumes functions in planning, management and protection of water resources, hydraulic infrastructure projects in the Region of Valencia, excluding those related to irrigation infrastructures, construction and operation. Planning and management of the internal basins of the Region of Valencia, reuse and saving of water, except for irrigation, control and protection of water quality and discharge authorization.

- **EMIVASA**: The Mixed Entity of Valencia (EMIVASA by its Spanish acronym) is a mixed company, mainly represented by Aguas de Valencia, in charge of the collection, supply and distribution of water to the city of Valencia.

- **PUBLIC ENTITY OF WASTEWATER SANITATION OF THE VALENCIAN COMMUNITY**: The Public Entity of Wastewater Sanitation of the Valencian Community (EPSAR by its Spanish acronym) manages the operation of the installations and to carry out the works of sanitation and...
purification that the Administration of the Generalitat Valenciana determines, as well as those that may be entrusted to them by the local entities or other organisms.

- **NEW WATER CULTURE FOUNDATION:** The New Water Culture Foundation (FNCA by its Spanish acronym) is an Iberian (Spain and Portugal) non-profit organization including members from academia, research institutions, public administration, private sector, stakeholders and citizens, aiming at promoting a change towards a more sustainable water management and a new water culture.

- **IBERDROLA:** IBERDROLA is the second Spanish electricity group. It is mainly engaged in the production, transportation and distribution of electrical energy. IBERDROLA uses the Júcar River to produce hydroelectric power. The Cortes-La Muela plant is the largest pumping station in Europe.

- **CENTRAL IRRIGATION BOARD OF LA MANCHA ORIENTAL:** The Central Irrigation Board of La Mancha Oriental (JCRMO by its Spanish acronym) is a corporation whose fundamental mission is to regulate the use of water resources for irrigation (primarily use) and other uses (supply, industrial, etc.), to ensure the rational use of the resource. In addition, the Central Irrigation Board of La Mancha Oriental (JCRMO) represents and defends the rights of all its members, detect possible irregularities and resolve disputes and defend the ecosystem.

- **JÚCAR USERS UNION:** The Júcar Users Union (USUJ by ist Spanish acronym) is a partnership of traditional irrigators of the Júcar (50% share) and IBERDROLA (50% share).
AGROSEGURO

AGROSEGURO covers losses with respect to production expectations in rainfed crops and irrigated crops, although in the latter case only when losses are caused by adverse climatic events, regardless of lack of water (heat waves, hail, frost, etc.), when the farmer cannot do anything to avoid it.

Narrative out of the simplified qualitative model:

Crop producers and farmers still face the risks of natural disasters and meteorological extreme events, although the agricultural insurance allows them transferring the risk.

Insurance schemes eligible determine the level of compensation for production losses based on a production reference performance, due to a natural disaster in question (rainfed agriculture droughts are included) that exceed a certain average agricultural production threshold, independently of rainfall shortage events, heat waves, hail, frost, etc. are risks potentially covered by AGROSEGURO.

The expected increase in frequency of extreme hydrological events will probably generate the need to contract more agricultural insurance products by farmers.
GENERAL USERS COMMUNITY OF THE JÚCAR-TURIA CHANNEL

The General Users Community of the Júcar-Turia Channel (CGU Canal Júcar-Turia by its Spanish acronym) regulates the general functioning of the channel. On the one hand, the urban supply (approximately 2 million people, mainly to Valencia and Sagunto) supposes an average consumption of 150 Hm3/year. On the other hand, irrigation at 25,000 hectares distributed in 20 Irrigation Communities supposes an average consumption of 95 Hm3/year.

Narrative out of the simplified qualitative model:

The users of the channel can use two types of irrigation systems: pumping irrigation to the upper parts (left margin of the Júcar-Turia channel) and by gravity to the lower parts (right margin of the Júcar-Turia channel).
channel). The average cost per unit of volume of water used in the right margin is 0.10 €/m³ whereas in the left margin is 0.16-0.18 €/m³.

It is expected that 70% of irrigation infrastructures will be modernized (drip system). The cost will be evenly distributed 50% users (20 irrigation communities) and 50% public funds.

The expected increase in frequency of meteorological droughts in the region will be likely affecting the availability of water resources in the system, but also the natural cleaning of trees. A decrease in the latest may promote the existence of pests, causing therefore damages to the flower or fruit with severe implications on the productivity.
JÚCAR RIVER BASIN AUTHORITY

The Júcar River Basin Authority (CHJ by its Spanish acronym), through its Office of Hydrological Planning, has as main functions (1) the elaboration of the Júcar Hydrological Plan, as well as its monitoring and review, and (2) ensuring the good state and functioning of water bodies and ecosystems.

Narrative out of the simplified qualitative model:

The main objective of the Hydrological Plan of the Júcar River Basin is to achieve a good state and adequate protection of water bodies, meet the demands of water and preserve the balance and harmonization of regional and sectoral development. The CHJ is in charge of carrying out the necessary work and studies for the elaboration, monitoring and revision of the Hydrological Plan of the Júcar river basin.
Management and distribution of water resources, rights of use and concessions to the users (agricultural, urban, industrial, etc.) is a relevant task done by the CHJ in line with the specifications established in the hydrological plan.

Hydrological extremes (i.e. droughts and floods) are the major risk-events concerns of the Office of Hydrological Planning of the Júcar river basin authority (CHJ). However, for both cases are special plans including guidelines on how to proceed whenever such events occur.
INTEGRAL WATER CYCLE OFFICE

The Integrated Water Cycle office (CIA by its Spanish acronym) of the City of Valencia is in charge of the integral management of the supply (through EMIVASA) and of the water purification. Among their functions, they carry out impact studies on climate change and the implications for the water system.

Narrative out of the simplified qualitative model:

The integral management is based on the knowledge of the water network state of the municipal district of Valencia, preventing and alerting emergency situations (e.g. industrial pollution that may affect the process of wastewater treatment, floods, extraordinary rains, etc.), modelling of flows and sizing of collectors, determination of new infrastructures (regulation tanks, etc.), modelling the potential impact of discharges to natural channels, among others.
In spite of the global effects of climate change, the City of Valencia, through the Office of the Integral Water Cycle (CIA), carries out studies on the local implications of climate change.
GENERALITAT VALENCIANA – DIRECTORATE GENERAL FOR WATER

The General Directorate of Water (DGA by its Spanish acronym) plans and manages water resources in the Valencian Community. On the other hand the DGA carries out projects of hydraulic infrastructures to face extreme hydrological events, particularly droughts and floods, in the region.

**Narrative out of the simplified qualitative model:**

The DGA assumes functions of planning, management and protection of water resources, projects of water infrastructure and urban irrigation, within the geographical framework of the Valencian Community. The DGA is also responsible for hydraulic infrastructure at hydrological extremes such as droughts and floods.
EMIVASA

The Mixed Entity of Valencia (EMIVASA by its Spanish acronym), 80% made up of Aguas de Valencia, regulates the urban water supply network to Valencia and other municipalities. To this end, EMIVASA is in charge of the treatment and distribution of water to the end users. The monitoring of hourly consumption per household is one of the indicators of consumption patterns that EMIVASA is currently assessing.

Narrative out of the simplified qualitative model:

EMIVASA (80% represented by Aguas de Valencia and 20% by the Valencia City Council) is responsible for the water treatment from different sources (5-10% of total is groundwater and 90-95% is surface water of the rivers Júcar and Turia). Regulation and monitoring of the distribution network are additional activities carried out by EMIVASA.

The increase in frequency of hydrological extremes might have an impact on the operation of EMIVASA. Droughts cause algae proliferation, increase in pathogen concentration, etc., which are
generally phenomena that the current treatment plants may not be able to efficiently address. The capacity of the treatment plants is also limited when flood events occur. A better information provided by IMPREX would positively influence the decision-making process regarding long-term investments.
PUBLIC ENTITY OF WASTEWATER SANITATION OF THE VALENCIAN COMMUNITY

The Public Entity of Wastewater Sanitation of the Valencian Community (EPSAR by its Spanish acronym) manages the operation of the installations and to carry out the works of sanitation and purification that the Administration of the Generalitat Valenciana determines, as well as those that may be entrusted to them by the local entities or other organisms.

Narrative out of the simplified qualitative model:

EPSAR ensures compliance with the quality objectives of wastewater. Out of the total wastewater treated by EPSAR, it is estimated that about 60% is returned to the system and 40% is effluent direct to the sea. The reuse of treated wastewater is a potential source of water resources, particularly necessary for drought periods.

Flash-floods have a negative impact on the waste water treatment plants, because of the not sufficient capacity (volume) and the damage of turbidity in some parts of the plant. Besides those
related to hydrological extreme events, one of the main concerns of EPSAR is the lack of regulation for mud post-treatment.
NEW WATER CULTURE FOUNDATION

The New Water Culture Foundation (FNCA by its Spanish acronym) ensures the sustainable use of water resources and the protection of the ecosystem. In addition, the FNCA carries out scientific dissemination and research and direct participation. The protection of uses and activities derived from the exploitation of the river is another of the pillars on which the mission of the FNCA is sustained.

Narrative out of the simplified qualitative model:

The FNCA is a non-profit foundation that ensures the sustainable use of water resources. To safeguard uses and activities that derive from the fluvial ecosystem, whether at the consumptive or non-consumptive level, is one of the main functions of the FNCA. In addition, the FNCA is actively involved in research, scientific dissemination and direct participation activities.
IBERDROLA uses the water flow of the Júcar-Turia system for the production of hydroelectric energy (non-consumptive use) to cover the energy demand of the market. IBERDROLA is part of the Union of Users of Júcar (USUJ).

Narrative out of the simplified qualitative model:

IBERDROLA produces hydro-electrical energy though several stations within the Júcar River Basin. The generation of energy depends on the market demand. Being a non-consumptive use, the use of water for energy production is subject to the concession to the irrigator farmers downstream. In this regard, in case of droughts, the concession must be restricted, thus affecting the potential production of...
hydroenergy. The most important hydroelectric station is located in Cortes-La Muela, in which a dam-reservoir regulation takes place. The generation of hydroenergy in this station is sensitive to the energy price fluctuations, which are notably influenced by wind energy production.
CENTRAL IRRIGATION BOARD OF LA MANCHA ORIENTAL

The Central Irrigation Board of La Mancha Oriental (JCRMO by its Spanish acronym) focuses on four main objectives: (1) ensuring the sustainable use of water resources, (2) establishing crop-based consumption limits, (3) risk analysis and (4) informing society. Complementarily, one of the tasks in which JCRMO currently focuses the attention is on the modernization of irrigation infrastructures to improve the efficiency of the use of the resource, as well as the substitution of pumping in the region.

Narrative out of the simplified qualitative model:

One of the main activities that the JCRMO carries out is the promotion of the sustainable use of water resources in the geographical demarcation of La Mancha Oriental. Water scarcity risk analyzes carried out by the JCRMO, being a potential decrease in rainfall and the increase of temperature the main concerns, imperiously require maximizing efficiency in the use of water resources. To this end, the...
modernization of risk infrastructures is a fundamental goal, promoting the installation of drip irrigation systems. The replacement of pumping systems is another of the needs that the JCRMO and the CHJ have agreed to undertake in the short-medium term. Limiting resource use is a key measure to balance demand with the volume of water resources in the system. Lastly, providing information to society in order to raise awareness of the need for sustainable use of water resources is one of the pillars on which JCRMO works.
JÚCAR USERS UNION

The Júcar Users Union (USUJ by its Spanish acronym), made up of irrigation communities and the energy company IBERDROLA, focus primarily on the defense of users' rights. USUJ owns the Alarcon Reservoir, although the use and operation has been transferred to the Public Administration. As compensation, there are projects for modernization of irrigation infrastructures, exemption of rates and the guarantee of a reservoir curve in case of drought.

Narrative out of the simplified qualitative model:

The USUJ is evenly conformed by irrigators and IBERDROLA, with the main goal of ensuring the rights of users. By means of the Alarcon Agreement, the USUJ (owner of the Alarcón Reservoir) agreed with the Public Administration to transfer the management of the reservoir in exchange for a series of...
compensations: (1) guarantee the reservoir reserve curve (especially in anticipation of potential droughts), (2) exemption from fees and (3) modernization of irrigation infrastructures.
Annex 3 A hierarchy of integrated hydroeconomic models: the root model

Dmitry V. Kovalevsky, María Máñez, Josep Osorio

Abstract

The reduction of vulnerability of regional economies to extreme hydrological events can be achieved only through improved understanding of the stochastic dynamics of future disrupting features that may be very different from today’s reality. In the present Annex, we study the changes of regional economic dynamics (as simulated by a stochastic system dynamics economic model SDEM) affected by extreme hydrological events, the latter introduced in the model as exogenous random shocks. Linear and nonlinear versions of SDEM are explored, with stochastic damage functions incorporated in previously deterministic modelling framework.

Introduction

System dynamics (SD) models (Forrester, 1971; Sterman, 2000), as well as models based on dynamic systems theory (Strogatz, 1994) – the latter seen by the authors as a “theoretical sister science of [applied] system dynamics“, – are extensively used in describing economic dynamics and economic decision making (Lorenz, 1993). SD modelling has an extended track record of applications to environmental and climate economics, as well as to the analysis and the assessment of climate and environmental policymaking, starting from the influential World3 model described in ‘The Limits to Growth’ (Meadows et al., 1972, 1992, 2004).

If the goal of a SD-based modelling study in the domain of climate economics is an assessment of long-term socioeconomic impacts of gradual climate change, then the corresponding SD model may well be deterministic. However, when it comes to modelling the impacts of weather- and climate-related extreme events on the economic dynamics, introducing the stochasticity in the SD modelling scheme is inevitable.

In the present Annex, we develop a new stochastic version of a SD model SDEM (the Structural Dynamic Economic Model), to take into account the stochastic climate damages caused by extreme hydrological events and affecting the regional economic dynamics as exogenous random shocks.
Earlier versions of SDEM were developed in (Barth, 2003), then the model was further developed in (Kovalevsky, 2014, 2016; Kovalevsky and Hasselmann, 2014). The nonlinear version of SDEM on which the current paper is based is adopted (with certain modifications) from (Kovalevsky, 2016).

In the context of group model building process (Vennix, 1996) as applied to EU H2020 IMPREX project goals, the SD model presented below might be viewed as a ‘minimal preliminary model’. (A definition of preliminary models and an in-depth discussion of their place and role in the group model building process may be found in (Vennix, 1996)). At the same time, in the context of the strategy for developing the integrated model hierarchies in IMPREX, the same model may be viewed as the root model of a hierarchy of hydroeconomic models (Harou et al., 2009) (see Sec. 2.5 above).

**SDEM: model description**

The present version of SDEM schematically describes regional economic dynamics affected by exogenous shocks caused by natural hazards (extreme hydrological events). SDEM is a SD model, and the extreme events are described as exogenous random processes, hence the climate damage functions (reducing the output of regional economy) are random functions as well.

SDEM is developed in Vensim® DSS software. A simplified Vensim sketch of the model is shown on Figure 18. The state (level) variables of the model are shown on the figure as colored boxes. Not shown on the figure are sketches from other “views” of full Vensim model developed for integration of dynamic equations for moments of state variables in the stochastic version of the model, following the methodology discussed in depth in (Pugachev and Sinitsyn, 1985).

Essentially, SDEM is a SD model of a closed economy, where the macroeconomic dynamics is shaped by a conflict of interests of two powerful aggregated actors: entrepreneurs and wage-earners. The model state variables are: the per capita physical capital ($\bar{k}$), and the average wages ($\bar{w}$).

The per capita output $y$ of the regional economy depends on physical capital, and is also reduced by climate damages:

$$y = (1 - d) \cdot \nu k^\alpha$$  \hspace{1cm} (1)

where $\nu$ is the (constant) technology parameter, $\alpha$ is the (constant) exponent, and $d$ is the climate damage function that can be decomposed into the (constant) deterministic ($d_0$) and the (time-varying) stochastic ($\delta(t)$) components:

$$d = d_0 + \delta(t)$$  \hspace{1cm} (2)
The system of dynamic equations takes the form

\[ \dot{k} = (1 - \rho_d) \left[ k^\alpha - (1 - \theta)w \right] - (\lambda_k + \lambda_L)k, \quad (3) \]

\[ \dot{w} = \lambda_w \left[ \frac{q}{1 - \theta} \left( k^\alpha - (\lambda_k + \lambda_L)k \right) - w \right], \quad (4) \]

In Eqs. (3)-(4):

- \( \rho_d \) is the (constant) control parameter describing the investment decision-making of entrepreneurs,
- \( \theta \) is the (constant) fraction of entrepreneurs in regional population,
- \( \lambda_k \) is the (constant) physical capital depreciation rate,
- \( \lambda_L \) is the (constant) population growth rate,
- \( \lambda_w \) is the (constant) wage adjustment rate,
- \( q \) is the (constant) parameter describing the negotiating power of entrepreneurs in wage negotiations with wage-earners (see further details of modelling the wage dynamics (Eq. (4)) e.g. in (Hasselmann and Kovalevsky, 2013; Weber et al., 2005)).

For the detailed description of SDEM the interested reader is addressed to the papers (Kovalevsky, 2014, 2016). In (Kovalevsky, 2014), the production function in Eq. (1) was assumed to be linear in physical capital \( (\alpha = 1) \). Hence, the major part of the paper (Kovalevsky, 2014) was devoted to the linear version of SDEM. On the contrary, in the subsequent paper (Kovalevsky, 2016) a nonlinear version of SDEM with \textit{increasing returns to scale} \( (\alpha > 1) \) was explored. The assumption of increasing returns to scale led (for certain range of model parameters and initial conditions) to a dynamic regime referred to in (Kovalevsky, 2016) as the ‘explosive’ (or singular) growth: the state variables of the dynamical system go to infinity, and become infinite at some \textit{finite} time. Obviously, this means that a more realistic model developed along these lines should have taken into account additional stabilizing negative feedbacks.

In the present Annex, we consider both the linear version of SDEM \( (\alpha = 1) \), and the nonlinear version with \textit{decreasing returns to scale} \( (0 < \alpha < 1) \). For illustrative purposes, we start with the deterministic version of the model, however, the major focus of the paper is on stochastic climate damages and their effects on the economy.
Simulation results: deterministic case

In the present section, for illustrative purposes, we consider the deterministic version of linear and nonlinear models, respectively. That said, we assume that in Eq. (2) only the (constant) deterministic term \( d_0 \) is retained, while the (time-varying) stochastic component \( \delta \) is eliminated:

\[
d = d_0.
\]  

Consider first the linear deterministic version of SDEM \( (\alpha = 1) \). The graphs of per capita GDP (equal by definition to \( y \)) and of average wages are provided in Figure 19 and Figure 20, respectively, for three values of (deterministic) climate damages:

- \( d_0 = 0.1 \) (10 per cent reduction of global output),
- \( d_0 = 0.3 \) (30 per cent reduction of global output),
- \( d_0 = 0.5 \) (50 per cent reduction of global output).

We draw the attention of the reader to the dramatic dependence of long-term economic growth on the magnitude of climate damages. The analysis of the system (which in the case of the deterministic linear system can be performed by analytical methods, where the numeric simulations may be avoided) shows that in the long term the economy exhibits, in first approximation, the exponential growth. However, the numeric values of exponents are very sensitive to the magnitudes of climate damages: for the three cases above, the long-term economic growth rates are equal to 9.7, 5.2, and 1.7 per cent per annum, respectively.

The nonlinear deterministic version of SDEM with decreasing returns to scale \( (0 < \alpha < 1) \) does not exhibit infinite growth, instead, the state variables of the model asymptotically converge to their steady values (Figure 21 and Figure 22, respectively). Again, as seen from the figures, the corresponding steady states are remarkably sensitive to the magnitudes of climate damages.

Simulation results: stochastic case

In the present section, we discuss the stochastic simulations parallel to the deterministic simulations reported above.

We note that different ways of including the climate- and weather-related stochasticity in economic models are reported in the literature (Naqvi and Rehm, 2014). For instance, Weber (2004), when
developing a stochastic version of the MADIAM model (Weber et al., 2005), introduces the climate-related stochasticity in the form of a Poisson point process with Rayleigh amplitude distributions. Hallegatte et al. (2007) introduce in the previously developed non-equilibrium model of economic dynamics NEDyM (Hallegatte et al., 2008) stochastic climate-related damages caused by Large-scale Extreme Weather events (LEWE) as a random process with a Weibull distribution of economic losses from any single extreme event (see also (Hallegatte and Ghil, 2008)).

In the present paper, in all stochastic simulations we assume that the stochastic component of climate damages in Eq. (2) is modeled as a Gaussian white noise with zero mean and the standard deviation equal to the deterministic component \( d_0 \) – see one of possible realizations of the random process given by Eq. (2) in Figure 23.

Consider first the linear stochastic version of SDEM \((\alpha = 1)\). Again, for the linear case a (semi-)analytical treatment of the system is possible by applying the methods of the theory of linear stochastic differential equations (Pugachev and Sinitsyn, 1985). A similar program was performed for the linear version of SDEM in (Kovalevsky, 2014), however, there the parameter \( q \) entering Eq. (4) was treated as a multiplicative noise, not the climate damages. In brief, the dynamics of average state variables remains the same as for the parallel linear deterministic model; also, it is possible to calculate (semi-analytically) the dynamics of their standard deviations. These results (together with several realizations of corresponding random processes) are shown in Figure 24 to Figure 29 for the mean values of the now stochastic climate damages equal to 0.1, 0.3, and 0.5, respectively.

For the nonlinear stochastic version of SDEM, random fluctuations of state variables near the corresponding stable points are shown in Figure 30 and Figure 31 for the same mean values of stochastic climate damages as above.

**Conclusions and outlook**

A simple stochastic SD model briefly described in the present Annex can be further developed in several directions.

First, within the developed stochastic modelling framework the risks related to extreme hydrological events (broadly defined as a product of probability of the extreme events and of the related monetized economic losses) can be assessed quantitatively.

Second, as it is projected that both intensity and frequency of extreme hydrological events may increase in many regions as a consequence of anthropogenic climate change in the future, a topical problem is to develop a similar model with exogenous shocks modeled by a non-stationary random processes (e.g. under assumptions of gradually increasing intensity and/or frequency of these shocks).
Third, for the stochastic simulations presented above probably the simplest approximation of a random shock (although widely adopted in stochastic models, especially in those from the ‘theoretical’ part of model spectrum) was used. Namely, the white noise (that is, by definition, an uncorrelated, ‘memoryless’ process) has been chosen as a stochastic component in Eq. (2). The related hydrological processes, in their turn, generally have memory. In view of this, other approximations for exogenous random shocks with more realistic statistical properties are planned to be explored.

Fourth, it is planned to make simulations driven by real-world, region-specific, natural science based data, instead of ‘heuristic’ random shocks.

The fifth step would be the development of a policy evaluation model assessing the alternative strategies of climate adaptation in the face of the changing statistics of extreme hydrological events.

The authors are planning the further development of this model (and similar models) along the lines sketched in this concluding section.
REFERENCES TO ANNEX 3


[Conference paper in Brigham Young University ScholarsArchive, URL: http://scholarsarchive.byu.edu/cgi/viewcontent.cgi?article=1211&context=iemssconference]


Figure 18: A simplified Vensim sketch of the stochastic version of SDEM model. The state (level) variables of the model are shown as colored boxes. Not shown sketches from other “views” of full Vensim model developed for integration of dynamic equations for moments of state variables in the stochastic version of the model.
Figure 19: Model SDEM, linear deterministic version (for references), GDP dynamics. Climate damages are assumed to be constant in time (for references), reducing the regional output by a factor of 0.1, 0.3, and 0.5 respectively. Note the dramatic dependence of long-term growth on the magnitude of climate damages.
Figure 20: Same as Figure 19, but for wages dynamics
Figure 21: Model SDEM, nonlinear deterministic version (for references), GDP dynamics. Climate damages are assumed to be constant in time (for references), reducing the regional output by a factor of 0.1, 0.3, and 0.5 respectively. Note the convergence to steady state in the long term (the corresponding steady states are indicated by horizontal lines).
Figure 22: Same as Figure 21, but for wages dynamics
Figure 23: One of possible realizations of climate damage as a random process
Figure 24: Model SDEM, linear stochastic version, GDP dynamics. Shown are: the average GDP (same as in deterministic case presented in Figure 19), standard deviations for GDP, three random realizations of stochastic GDP. The mean stochastic climate damage is equal to 0.1.
Figure 25: Same as Figure 24, but the mean stochastic climate damage is equal to 0.3
Figure 26: Same as Figure 24 and Figure 25, but the mean stochastic climate damage is equal to 0.5.
Figure 27: Model SDEM, linear stochastic version, wages dynamics. Shown are: the average wages (same as in deterministic case presented in Figure 20), standard deviations for wages, three random realizations of stochastic wages. The mean stochastic climate damage is equal to 0.1.
Figure 28: Same as Figure 27, but the mean stochastic climate damage is equal to 0.3
Figure 29: Same as Figure 27 and Figure 28, but the mean stochastic climate damage is equal to 0.5
Figure 30: Model SDEM, nonlinear stochastic version, GDP dynamics (random fluctuations near the stable point). The mean stochastic climate damages are equal to 0.1, 0.3, and 0.5 respectively. The corresponding steady states (stable points) are shown by horizontal lines.
Figure 31: Same as Figure 30, but for wages dynamics
Annex 4  A hierarchy of integrated hydroeconomic models: the level 2 model (technical description)

This Annex provides the technical description of the level 2 model from the hierarchy of integrated hydroeconomic models. The general outline of the model is provided in Sec. 2.5 above.

The model consists of regional economic dynamics module based on a modification of SDEM model (see the description of the root model of the hierarchy in Annex 3 above) coupled with a simple lumped watershed hydrological module (the ‘abc’ model).

The model is developed in Vensim ® DSS software. Simplified Vensim sketches of economics and hydrological modules of the coupled model are shown in Figure 32 and Figure 33Figures 1 and 2, respectively. The state (level) variables of the model are shown on sketches as colored boxes.

The table below presents model equations in the form inspired by reporting guidelines for system-dynamic socioeconomic models as proposed by Rahmandad and Sterman (2012), however, adjusted for our purposes.

This way we intend to simplify the understanding of the scientific basis behind the modeling approach
<table>
<thead>
<tr>
<th>Formulations and comments</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Economic dynamics module</strong></td>
<td></td>
</tr>
<tr>
<td><strong>State (level) variables</strong></td>
<td></td>
</tr>
<tr>
<td>$k(t) = k(0) + \int_0^t [(1-\sigma)(1-\rho_d)(y-(1-\theta)*w) - (\lambda_k + \lambda_l)k] , dt$</td>
<td>EUR</td>
</tr>
<tr>
<td>The stock of per capita physical capital in the regional economy, $k$, increases due to investment flow and decreases due to depreciation and regional population growth.</td>
<td></td>
</tr>
<tr>
<td>$w(t) = w(0) + \int_0^t \lambda_w [q*(y-(\lambda_k + \lambda_l)*k)/(1-\theta)-w] , dt$</td>
<td>EUR/year</td>
</tr>
<tr>
<td>The mechanism of average wage dynamics ($w$) is described e.g. in (Hasselmann and Kovalevsky, 2013; Kovalevsky, 2014, 2016; Weber et al., 2005)).</td>
<td></td>
</tr>
<tr>
<td>$f(t) = f(0) + \int_0^t \mu \sigma y , dt$</td>
<td>EUR/mm</td>
</tr>
<tr>
<td>The efficiency of water use, $f$, can endogenously increase due to flow of investment targeted at modernization of relevant regional infrastructure.</td>
<td></td>
</tr>
<tr>
<td><strong>Auxiliary functions</strong></td>
<td></td>
</tr>
<tr>
<td>$y = \min(\nu*[k/k(0)]^{\alpha}, f^*Q_{av})$</td>
<td>EUR/year</td>
</tr>
<tr>
<td>The production function of regional economy (GRP = Gross Regional Product), $y$, depends on two production factors: per capita physical capital ($k$) and available water ($Q_{av}$).</td>
<td></td>
</tr>
<tr>
<td>$Q_{av} = \xi*Q_{v}$</td>
<td>mm/year</td>
</tr>
<tr>
<td>Available water ($Q_{av}$) is proportional to runoff ($Q_{v}$, computed in hydrology module).</td>
<td></td>
</tr>
</tbody>
</table>

**Scenario (policy) parameters**
### Dimensionless Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>sigma</td>
<td>The fraction of total regional investment flow channeled in modernization of regional infrastructure relevant for adaptation to droughts, sigma.</td>
</tr>
<tr>
<td>rhod</td>
<td>The parameter determining the dividend of regional entrepreneurs (see e.g. (Kovalevsky, 2014, 2016)), rhod.</td>
</tr>
</tbody>
</table>

#### Auxiliary parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>theta</td>
<td>The fraction of entrepreneurs in regional population, theta.</td>
</tr>
<tr>
<td>lambdak</td>
<td>The depreciation rate of physical capital, lambdak.</td>
</tr>
<tr>
<td>lambdal</td>
<td>The regional population growth rate, lambdal.</td>
</tr>
<tr>
<td>lambdaw</td>
<td>The wage adjustment rate, lambdaw.</td>
</tr>
<tr>
<td>q</td>
<td>The parameter describing the negotiating power of entrepreneurs in wage negotiations with wage-earners, q (see e.g. (Hasselmann and Kovalevsky, 2013; Kovalevsky, 2014, 2016; Weber et al., 2005)).</td>
</tr>
<tr>
<td>mu</td>
<td>1/mm</td>
</tr>
</tbody>
</table>
The efficiency of investment in endogenous increase of the efficiency of water use, mu.

\[ \text{nu} \quad \text{EUR/year} \]

The technology parameter in the production function, nu.

**alpha**
Dimensionless

The exponent in the production function, alpha.

**xi**
Dimensionless

The conversion factor of runoff to available water, xi.

### Hydrology module

**State (level) variable**

\[ S_v(t) = S_v(0) + \int_{t_0}^{t} \left[ (a \cdot P_v - c \cdot S_v) / \tau \right] dt \quad \text{mm/year} \]

The dynamic equation for the groundwater storage, \( S_v \).

**Auxiliary function**

\[ Q_v = (1 - a - b) \cdot P_v + c \cdot S_v \quad \text{mm/year} \]

Streamflow (= runoff), \( Q_v \) is dependent on precipitation and groundwater storage.

**Scenario (policy) function**

\[ P_v(t) = P_{v0} \cdot \exp(-r \cdot t) \cdot (1 - \beta \cdot RU(t)) \quad \text{mm/year} \]

The precipitation, \( P_v \), should be specified as (time-dependent) external forcing. In the model, it might be either deterministic or stochastic. The formula above shows a simplified stochastic scenario with
Gradual decline of average precipitation, and also with superimposed variability caused by a random process generated by random uniform distribution, $RU(t)$.

<table>
<thead>
<tr>
<th>Auxiliary parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
</tr>
<tr>
<td>A parameter of abc model, $a$.</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>A parameter of abc model, $b$.</td>
</tr>
<tr>
<td>c</td>
</tr>
<tr>
<td>A parameter of abc model, $c$.</td>
</tr>
<tr>
<td>tau</td>
</tr>
<tr>
<td>A unit conversion parameter, $\tau$.</td>
</tr>
</tbody>
</table>
REFERENCES TO ANNEX 4


Figure 32: A simplified Vensim sketch of the level 2 hydroeconomic model: the economic module. The state (level) variables of the module are shown as colored boxes.
Figure 33: A simplified Vensim sketch of the level 2 hydroeconomic model: the hydrological module. The state (level) variable of the module is shown as colored box.
Annex 5 Development of IKI for the lake Como

Lake Como system

Lake Como (Figure 34) is the third largest lake in Italy with a total volume of 23.4 km³, of which 254 Mm³ are regulated through a dam on the outflowing Adda river. The river serves a dense network of downstream irrigation canals, which convey water to four agricultural districts with a total surface of 1400 km², mostly growing maize and temporary pasture for feeding livestock. The same releases are also sufficient to feed eight run-of-river hydroelectric power plants. These releases are managed from 1946 by the Adda Consortium with the twofold purpose of water allocation to the downstream users and flood protection along the lake’s shoreline, particularly in Como city (Galelli and Soncini-Sessa, 2010).

Figure 34: Map of the Lake Como system and the main sectors involved
The lake is fed by a 4,552 km² Alpine watershed characterized by a highly varied terrain elevation, which provides a huge hydropower potential exploited through 16 small to medium artificial reservoirs operated by different power companies. With a total storage of 545 Mm³, more than twice the active capacity of the lake, the alpine reservoirs have a significant influence on the downstream streamflow and therefore on the Lake Como water storage variations through seasons.

The natural hydro-meteorological regime is characterized by a double peak pattern: one more pronounced peak corresponding to the snow-melt season, in late spring, and another, more variable, produced by autumn rains. For both the lake and the hydropower reservoirs, the snow-melt represents the main contribution to the creation of seasonal storage (Denaro et al., 2017). However, the result of the combined upstream reservoirs’ release policies is often conflicting with the lake water allocation goals: in summer, when agricultural irrigation demand is at its maximum, the upstream reservoirs, filled with the contribution from the snow-melt, limit their releases to profit by higher electricity prices in winter. This conflict has been exacerbated by the advent of renewables, particularly after 2009, when the Italian government largely subsidized solar power production. As a result, hydropower production was extensively allocated to fill the sharpened electricity price peaks in winter, further reducing summer releases.

Beside the competing interests of energy production (upstream hydropower companies), irrigation supply (downstream farmers), and flood protection (citizens of Como), water management in the system impacts on additional water-related sectors, such as the navigation sector which involves 42 docks and over 7 million passengers per year (both tourists and local people), the fishery sectors with several commercial fisheries relying on lake fishes (e.g., agone or lavarello), and the lake environment associated to both fish biodiversity and presence of wetlands.

**Integrated model**

The integrated model of the Lake Como system is composed by the following main components (see Figure 35):

- **Catchment model** – a physically-based, fully distributed TOPKAPI-ETH hydrological model, working on a regular grid (250x250 m), which simulates the hydrological processes in the lake catchment, including also the snow and glaciers dynamics, and also accounts for the presence of the hydropower reservoirs and river diversions. Specifically, the operations of these infrastructures is modelled by means of closed-loop control policies (i.e., a mathematical function mapping the current system conditions, such as the day of the year and the reservoir level, into release decisions) designed by maximizing the hydropower revenue according to the national electricity price determined by the Italian energy market (for details, see Giudici et al., 2017).
• **Lake Como model** – the lake dynamics is described by a mass-balance equation assuming a modelling and decision-making time step of 24 hours, where the lake releases depend on the lake operating policy. This policy represents a specific compromise (trade-off) balancing flood protection and water supply to the downstream users (for details, Giuliani et al., 2016). According to the daily time step of the simulated lake dynamics, the Adda River can be hence described by a plug-flow model to reproduce the routing of the lake releases from the lake outlet to the intake of the irrigation canals. This diversion of the water from the Adda River into the irrigation canal is regulated by the water rights of the agricultural districts.

• **Agricultural districts model** - the dynamic processes internal to the irrigation districts are described by three distinct modules devoted to specific tasks: i) a distributed-parameter water balance module (grid 250x250 m) that simulates water sources, conveyance, distribution, and soil-crop water balance (Facchi et al., 2004); ii) a heat unit module that simulates the sequence of growth stages as a function of the temperature (Neitsch et al., 2011); iii) a crop yield module that estimates the optimal and actual yields, accounting for the effects of stresses due to insufficient water supply that may have occurred during the agricultural season (Steduto et al., 2009). The water balance module partitions the irrigation district with a regular mesh of cells with a side length of 250 m, which allows the representation of the space variability of crops, soil types, meteorological inputs, and irrigation distribution.
Figure 35: Schematic representation of the integrated simulation model of the Lake Como basin

Beside accounting for the main physical processes and the primary sectors driving the water management of the system (i.e., hydropower, floods, and agriculture), our integrated model allows capturing the interests of the other stakeholders, namely navigation, fishes, and environment, and evaluate via simulation a suite of indicators reflecting their satisfaction.

These indicators were constructed adopting a bottom-up approach over years of interactions and stakeholders’ meetings organized as part of several research activities we developed on the Lake Como system (e.g., the TwoLe project funded by Fondazione Cariplo with the goal of testing the Participatory and Integrated Planning procedure for the design of River Basin Plans requested by the
Water Framework Directive (2000/60/EC)). The result of these interactions was the formulation, testing, and validation of a hierarchy of indicators reported in Figure 36 modeling the multi-sectoral interests involved in the system, both upstream and downstream of the lake. Specifically, the hierarchy is structured in multiple layers capturing specific aspects of the stakeholders interests as in the illustrative example of Figure 37 which refers to the navigation sector.

Figure 36: Hierarchy of indicators reflecting the multi-sectoral interests involved in the Lake Como system management
Testing Plan

The combination of the integrated model of the Lake Como system, which includes both the natural and human components active in the basin, with the hierarchy of multi-sectoral interests defined through a bottom-up stakeholders’ participatory process provides a viable mean for exploring the multidimensional tradeoffs across the competing stakeholders’ interests under both current and future climate conditions.

This tradeoff analysis is expected to identify the most conflicting sectors in the system under the current conditions. Moreover, it will contribute understanding if the impacts of the projected climate are expected to exacerbate the historical conflicts, ultimately suggesting the need of timely adapting the strategic planning decisions in the area for managing future climate extremes.
References


