Deliverable 3.1: METHODOLOGICAL SOURCEBOOK OF THE MULTI-SYSTEM, MULTI-MODEL ENSEMBLE FRAMEWORK

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Executive summary

This deliverable presents the actionable socio-hydrology-inspired modeling framework adopted and developed in TALANOA-WATER. The deliverable is structured in three parts. Section 1 provides the context for this deliverable. Section 2 surveys the literature on socio-hydrology and ensemble experiments that is relevant for our research, and identifies the key gaps that TALANOA-WATER methodological framework is set to address. Section 3 presents the modeling framework adopted in TALANOA-WATER, detailing the relevant modules (microeconomic, macroeconomic, hydrological, agronomic, climate) and the models explored within each of them, as well as the protocols developed to connect them (static and dynamic setting); and details the key contributions of the modeling framework in light of the gaps identified in the previous section. Finally, Section 4 presents the rapid assessment option that will be used during exploratory workshops (workshops 1-4) and to support interactive tools for decision-making applications (notably serious games).

Contents

1. Preamble

The objective of TALANOA-WATER is to inform and catalyze the adoption of robust transformational adaptation strategies to water scarcity under climate change that contribute to the Integrated Water Resources Management (IWRM) objectives of social equity, economic efficiency and environmental sustainability. To this end, TALANOA-WATER will develop a groundbreaking ecosystem of innovation that combines an inclusive and transparent stakeholder engagement method, the *Talanoa Dialogue* (UNFCCC, 2018), with an actionable modeling framework inspired in interdisciplinary *socio-hydrology science* (Sivapalan et al., 2014), in order to design, realize and demonstrate performance of transformational adaptation strategies at various levels (from farm to basin, from user to economic sector) in six large-scale '*pilot water laboratories*'. To this end, TALANOA-WATER is structured across three pillars: 1) Talanoa Dialogue; 2) **actionable socio-hydrology science and uncertainty sampling**; and 3) pilot water laboratories.

This deliverable presents the actionable, socio-hydrology-inspired methodological approach adopted and developed in TALANOA-WATER. The deliverable summarizes the work conducted in T3.1 by USAL, CMCC, INAT, INRAE, GPAI and AUB, under the leadership of USAL and CMCC, over multiple bi- and multi-lateral meetings, extensive lab and scientific work, and a major workshop where collective knowledge and understanding was consolidated, and the key pillars of the framework agreed (see Annex I for the workshop minutes). This collaborative work has already crystalized in several working papers and publications containing the major methodological breakthroughs towards the development of the TALANOA-WATER actionable socio-hydrology modeling approach (Pérez-Blanco et al., 2022, 2021; Pérez-Blanco and Sapino, 2022).

The deliverable is structured in three parts. In Section 2 we survey the literature on socio-hydrology and ensemble experiments that is relevant for our research, and identify the key gaps that TALANOA-WATER methodological framework is set to address. Section 3 presents the modeling framework adopted in TALANOA-WATER, detailing the relevant modules (microeconomic, macroeconomic, hydrological, agronomic, climate—albeit the delimitation is not strict and some functionalities can appear in different modules, such as agricultural production functions in microeconomic models) and the models explored within each of them, as well as the protocols developed to connect them (static and dynamic setting). Finally, Section 4 presents the rapid assessment option that will be used during exploratory workshops (workshops 1-4) and to support interactive tools for decision-making applications (notably serious games).

2. State of the art on socio-hydrology science and uncertainty sampling

Standard decision making and consolidative modeling bring a known set of possible states and related probabilities into a single modeling package which, after its validation, can be used "as a surrogate for the real world" (Weaver et al., 2013). Learning is acquired through observation, interpreting signals that constrain the set of possible states and updating probabilities according to Bayes' rule. Although standard decision-making works under some conditions, it is difficult to apply where the suggested plan is sensitive to simplifications and mathematical assumptions about the feasibility and likelihood of states and model structure. More often, "experts do not know or the parties to a decision cannot agree upon (i) the external context of the system, (ii) how the system works and its boundaries, and/or (iii) the outcomes of interest from the system and/or their relative importance" (Lempert et al., 2003, p. 11)—a situation that is typically referred to as "**Knightian**" or "**deep uncertainty**". Climate change consideration typically implies deep uncertainty. Deep uncertainty often leads to forecasting errors that limit our ability to anticipate policy impacts, as is often the case in complex socio-ecological systems such as human-water systems (Anderies, 2015; Ostrom, 1999). Several examples of forecasting errors due to deep uncertainty conditions are available in complex socio-ecological systems, e.g. during the recent floods in Germany and China, and heatwaves in the North Western US, where scientists acknowledged their predictions were significantly biased.

Three fundamental sources of deep uncertainty can be distinguished: 1) uncertainty arising from scenario assumptions and design (Marchau et al., 2019); 2) "parameter and structural uncertainties" within models (Tebaldi and Knutti, 2007); and 3) uncertainty arising from the missing or "overly simplistic" representation of the interconnected dynamics of complex adaptive human-water systems (Pande and Sivapalan, 2017).

The first two sources of uncertainty have been addressed with relative success. The Society for Decision Making under Deep Uncertainty has developed tools to address uncertainty arising from scenario assumptions and design through exploratory modeling approach (Groves et al., 2015; Lempert and Groves, 2010). Exploratory modeling and analysis works as a "prosthesis for the intellect" (Bankes, 1993), using computational experiments representing the consequences of alternative sets of feasible assumptions to discover the implications of *a priori* knowledge -including domains of previously unforeseen contingencies. This information can then be used to illustrate relevant tradeoffs, and revise scenarios and policy adoption in successive iterations leveraging on stakeholder and expert feedback until a robust policy is agreed upon (Marchau et al., 2019).

An ensemble of models can be used to sample uncertainty arising from parameter and structural uncertainties. Economic and natural sciences have been successful at developing scientifically sound conceptual models capable of representing the essence of critical systems within the human-natural conundrum. These include microeconomic models to represent the behavior of individuals or firms (Graveline, 2016), macroeconomic models to study interrelations among sectors and regions of the economy and their impact on aggregated indicators (Hertel and Liu, 2016), climate models to study the interactions between atmosphere, oceans, land surface and ice (IPCC, 2021), agronomic models to emulate complex biological environments (ISIMIP, 2022), and hydrologic models to study the movement, distribution, and quality of water at different scales (Blair and Buytaert, 2016), among other modeling families. There is consensus in the literature that the combination of scientifically sound prediction methods in perturbed physics and multi-model ensemble experiments (i.e. grouping multiple models and exploring alternative values for critical parameters) can be used to sample parameter and structural uncertainties through the ensemble spread (Athey et al., 2019). This approach has been widely used in natural sciences and ecological modeling such as hydrology, climate and agronomic modeling (AgMIP, 2022; CMIP6, 2022; IPCC, 2021; ISIMIP, 2022; LUMIP, 2022), also in combination with exploratory modeling (note that exploratory modeling in ecological ensemble experiments is treated as an additional layer to the ensemble, referred to as 'initial condition ensemble') (Tebaldi and Knutti, 2007).

On the other hand, the adoption of ensemble experiments in socioeconomic sciences and modeling is significantly more recent and limited, albeit recent studies have already used ensemble experiments of socioeconomic models to address water resources management challenges (Graveline and Mérel, 2014; Sapino et al., 2020).

Regarding the interconnection and integration of human and natural systems, advances in socioeconomic and ecological sciences have been considerably more limited (Pande and Sivapalan, 2017). Conventional ecological (socioeconomic) models perceive pressures from socioeconomic (natural) systems, if considered at all, as external forcings. Where socioeconomic and natural models interact, for example in hydro-economic models, responses to policy shocks or other *stimuli* are typically assessed using an external economic sub-model, which is subsequently integrated in the architecture of the hydrologic model through piecewise equations. This offers the advantage of a more straightforward and effective representation of causal relationships and interdependencies, while reducing computational costs since shocks do not require to be represented separately for each sub-model (Harou et al., 2009). Yet, such holistic models do not capture the interrelationships or two-way feedbacks between human and natural systems that shape adaptive responses (Pande and Sivapalan, 2017). As a result, the effects of policy- and climate-induced adaptation and feedback responses between socioeconomic and ecological systems dynamics are still "poorly understood" (Borgomeo et al., 2018).

There is a basic need to better understand the dynamics of complex adaptive human natural systems, and human-water systems in particular, and to represent them in modeling tools that can be used to effectively inform policy makers. To this end, the transformative discipline of *socio-hydrology* has called for the development of integrated approaches that "explicitly account for the two-way feedbacks between human and water systems" (Sivapalan et al., 2014). Socio-hydrology shares a modeling and scientific approach to Coupled Human And Natural Systems (CHANS), but stands out for its "perseverance and dedication to reminding the mainstream hydrologists about the need for taking the human factor into account" (Madani and Shafiee-Jood, 2020). Recent socio-hydrology-inspired science has explored feedback responses between human (typically water users) and water systems (Blair and Buytaert, 2016; Essenfelder et al., 2018). In parallel, economics has also developed new tools to explore feedback responses in complex human-human systems, notably between micro- and macro-economic systems (Blanco et al., 2017; Hasegawa et al., 2016; Parrado et al., 2020, 2019). These contributions run standard models at each system level independently in *modules*, which are defined as specialized, self-contained mathematical elements (simulation/calculus or optimization) that process information and generate outputs; and connect them through sets of *protocols*, which are defined as rules designed to manage interrelationships (e.g. two-way feedbacks) between systems' modules (Csete and Doyle, 2002). Modularity offers potentially higher detail in the representation of each system, which can be independently developed and adjusted (Harou et al., 2009). This makes possible the addition of nonlinearity to each element of the system, so that "surprises are not so surprising" and can be adequately understood, and their repercussions transferred from one system to another (Levin et al., 2013). Note that while nonlinearities can also be incorporated in integrated/holistic models, the computational cost may be expensive for the scale of analysis pursued in TALANOA-WATER.

Naturally, not all the processes occurring in the human-water system must be (nor can be) represented through full-fledged models. Depending on the problem at hand, systems can be divided (e.g. micro- and macro-economic) or grouped (e.g. hydro-economic system) (Arnold et al., 1998). Single differential equations that relate the function with its derivatives (as it is done in holistic models) can be used to represent less relevant processes and reduce computational requirements (Sivapalan and Blöschl, 2015). The extent to which differential equations should be relied upon reflects on the tension between simulation and understanding in coupled socio-ecological systems modeling. On the one hand, holistic models that use differential equations to capture as many systems as possible in comprehensive numerical models have significant practical value, and continuing increases in computational power means they can be systematically upgraded and adjusted to more accurately represent observed responses in human-water systems (Goddard et al., 2009). On the other hand, it is reasonable to say that "we typically gain some understanding of a complex system by relating its behavior to that of other, especially simpler, systems" (Held, 2005). It is through hierarchies of systems of increasing complexity, amenable to experimental manipulation, that experimental sciences such as biology have made steady progress in e.g. deciphering the human genome (International Human Genome Sequencing Consortium, 2004). Recently, climate research has put a stronger emphasis on model hierarchies as a means to link the complexity of high end holistic simulations with a deeper understanding of the processes at work provided by conceptual models, so to discover previously unaccounted futures and explore their implied consequences (IPCC, 2014). Analogously, to the extent that we can divide complex human-water systems into components that can be tested and developed in isolation, a hierarchy of human and water systems would make possible a more comprehensive understanding of the relevant processes involved through the use of conceptual models that capture their essence, and of the interrelationships among them through layers of feedback protocols (Csete and Doyle, 2002).

In TALANOA-WATER, recent advances in the construction of protocol-based modular frameworks provide the backbone for the development of interdisciplinary modeling hierarchies that connect multiple systems through two-way feedbacks (*multi-system hierarchy*). Each module within the hierarchy will be populated with multiple models (*multi-model ensemble*) and combined with scenario discovery techniques that explore scenario uncertainty through varying initial states and forcings (e.g. climate change scenarios, policy scenarios). The result is a large database of simulations in which each simulation represents the economic and environmental performance under one specific scenario and modeling setting. This information can be used to identify futures where proposed policies meet or miss their objectives, explore potential tipping points, and inform the development of robust policies that show a satisfactory performance under most conceivable futures.

3. Methods

This deliverable presents the methodological background adopted for the development of the protocol-based modular multi-system and multi-model ensemble framework. **Modularity** means models at each system level will be run independently in modules; and then connected through sets of **protocols**, which are defined as rules designed to manage interrelationships (where feasible through two-way feedbacks) among systems' modules (Csete and Doyle, 2002). Modules will be populated with models that have been used in cutting-edge ensemble experiments at the level of each relevant system, including the EURO-CORDEX, ISIMIP and/or CMIP6 ensemble experiments in the climate module (CMIP6, 2022; EURO-CORDEX, 2022; ISIMIP, 2022); the HEPEX, CMIP6 and/or ISIMIP ensemble experiments in the hydrological module (Cloke et al., 2013; CMIP6, 2022; ISIMIP, 2022); the ISIMIP, AgMIP and/or CMIP6 ensemble experiments in the agronomic module (AgMIP, 2022; CMIP6, 2022; ISIMIP, 2022); mathematical programming ensembles in the microeconomic module (see e.g. Pérez-Blanco and Sapino, 2022; Sapino et al., 2020); and Computable General Equilibrium (CGE) and Input Output (IO) modeling ensembles in the macroeconomic module (Koks et al., 2015; Parrado et al., 2020, 2019). We will leverage on partners' sub-national macroeconomic models (notably CMCC's ICES) calibrated at the regional scale (NUTS2) to produce a more accurate and detailed coupling with physical models and microeconomic models. Through co-development (WP1), we will work alongside stakeholders in pilot water laboratories to explore the relevant models to be included in each module, identify critical parameters and conduct sensitivity analyses. Detailed progress on this co-development task will be reported in lab reports (D4.2 and D4.5) and Talanoa Dialogue reports (D1.2 -5).

Below we present each module and the different models explored within; and the protocols used for interconnecting them using a i) time-invariant and ii) time-variant setting.

3.1. Modules

3.1.1. Microeconomic module

This module represents the behavior and responses of agricultural water users (as well as rainfed farmers to account for potential transitions to and from irrigated agriculture) through microeconomic modelling. In microeconomic agricultural models, the agent (i.e. a farmer or a representative group of farmers) decides on the crop portfolio (yearly or plantation decisions for multiple years) and timing, water withdrawals and capital investment, so to maximize its utility in accordance to one (single-attribute) or multiple (multi-attribute) utility-relevant attributes and a number of constraints defining a domain. Literature typically simplifies this decision-making process by representing each possible combination of crops, timing, water application (if production functions are incorporated to the decision making problem, then water application is an input rather than a separate crop) and capital as a separate crop with unique characteristics, so that the utility maximization problem is reduced to a decision on the crop portfolio x within a domain $F(\mathbf{x})$ (Graveline, 2016):

$$\operatorname*{Max}_{x} U(\mathbf{x}) = U(z_1(\mathbf{x});\ z_2(\mathbf{x}); z_3(\mathbf{x}) \dots z_m(\mathbf{x})) \quad [1]$$

$$\text{s.t.:} \quad 0 \leq x_i \leq 1 \quad [2]$$

$$\sum_{i=1}^{n} x_i = 1 \quad [3]$$

$$x \in F(\mathbf{x}) \quad [4]$$

$$\mathbf{z} = \mathbf{z}(\mathbf{x}) \in R^m \quad [5]$$

where $\mathbf{x} \in R^n$ is the crop portfolio or decision variable, which is represented by a vector containing the land share devoted to each individual crop x_i $(i = 1, \dots, n)$. Note that each crop i has a unique combination of utility-relevant attributes $\mathbf{z}(\mathbf{x})$ attached (notably profit, but also risk or management complexity aversion). Attributes are quantities of dimension one, obtained dividing their observed values by the maximum value they can possibly attain in the model (accounting for the domain). Increasing the provision of any given attribute improves agent's utility, provided the provision of the remaining attributes is kept constant ("more is better"). Convexity holds, i.e. increasing the provision of a utility-relevant attribute will reduce the provision of another utility-relevant attribute; otherwise there is no tradeoff and the choice between the two attributes becomes irrelevant, meaning one of them is not utility-relevant and can be discarded. The domain $F(\mathbf{x})$ is defined by a set of quantifiable constraints, including agronomic (e.g. crop rotation), policy (e.g. Common Agricultural Policy rules), information (e.g. know how), land (i.e. agricultural and irrigable area) and water availability constraints.

The attributes in the utility function and their parameter values can be elicited using normative methods based on value judgments by experts (e.g., the agent aims to maximize total profit); or positive methods that use mathematical programming models to identify the utility-relevant attributes and *calibrate* the parameters that more accurately reproduce observed decisions. Positive methods are typically preferred by researchers due to their ability to more accurately reproduce observed behavior (Graveline, 2016). Most frequently used positive models include Linear Programming (both single- and multi-attribute), Positive Mathematical Programming – PMP (single-attribute), and Positive Multi-Attribute Programming – PMAP (multi-attribute). A comprehensive description of the domain and attributes used by the models in the microeconomic ensemble is available in the annexes, which include the mathematical formulation of the domain F(x) (Annex II) and the attributes explored, which include expected profit (the only relevant attribute for single-attribute models), risk avoidance, and management complexity avoidance (of which the latter can be measured through various proxy attributes, such as hired labor avoidance) (Annex III). These two pieces of information in the annex are critical to gather all the necessary inputs to setup and run the microeconomic module and ensemble in the labs, and have been handed over and thoroughly explained to local labs over a series of meetings between USAL and lab scientific coordinators.

Each mathematical programming model used in the ensemble (Positive Mathematical Programming—PMP, Linear Programming including Weighted Goals Programming—WGP, Positive Multi-Attribute Programming—PMAP) has a unique calibration method, which are conceptually discussed below (for a mathematically stated representation of the calibration methods used by each model, the reader is referred to the key references provided below).

LP models including WGP can be calibrated in two ways: one method specifies all the constraints related to technical processes, and differentiates between technologies or soil-climate conditions to multiply the number of activities (Galko and Jayet, 2011); the other increases the degrees of freedom of the model (Bartolini et al., 2007). LP calibration methods impose several constraints that often lead to corner solutions: the agent chooses the crop that maximizes utility until a constraint becomes binding and prevents further specialization. The "historical crop mixes" approach developed by McCarl (1982) avoids extreme specialization, but introduces additional rules to the model, which becomes "overly constrained" (Graveline, 2016). An additional limitation of LP is that inputs are used in fixed proportion, making this approach inadequate to simulate some adaptation options (e.g., deficit irrigation). Some have criticized the inability of LP to "approximate, even roughly, realized farm production plans and, therefore, to become a useful methodology for policy analysis" (Paris, 2011). Yet, despite these limitations and criticism, LP remains to date one of the most frequently used models to asses agent's responses to water and other agricultural policies (Graveline, 2016). The microeconomic module ensemble will explore several LP models, including the weighted goals programming calibration method developed by Sumpsi et al. (1997) (termed WGP), which relies on the degrees of freedom approach.

PMP is the most widely used mathematical programming method (Graveline, 2016). PMP models are calibrated using "information contained in dual variables of calibration constraints, which bound the solution of the original LP problem to observed activity levels" to "specify a non-linear objective function such that observed activity levels are reproduced by the optimal solution of the new programming problem without bounds" (Heckelei and Britz, 2005). To this end, a calibration in three steps is proposed. First, a land use constraint is introduced in the domain $F(\boldsymbol{x})$ to bound the simulated crop portfolio to observed choices, and the dual values associated to such constraint are obtained for each crop i in the portfolio. Second, dual values are used to introduce a non-linear shadow cost to the objective function, usually through a quadratic function. Third, the resultant non-linear objective function obtained in the second step is maximized subject to the same domain that was used in the first step, which perfectly represents observed irrigators' choices. PMP has several advantages: it guarantees increasing (decreasing) marginal cost (yield), and can be readily used even when relevant primary data is not available (Graveline, 2016). In addition, although PMP models are single-attribute and use expected profit as the sole utility-relevant attribute, the non-linear term in the objective function can implicitly capture other factors (missing attributes, constraints) driving the behavior and crop portfolio choices of farmers (Heckelei and Britz, 2005). On the other hand, the most common criticism to PMP refers to the economic/technological rationale (or lack thereof) behind the non-linear terms in the objective function, which makes necessary the use of ad-hoc arguments to explain the outcomes of the model after a policy shock (Heckelei and Britz, 2005). The microeconomic module ensemble will explore several PMP models, including the original dual cost variable approach developed by Howitt (1995) and the approach developed by Cortignani and Severini (2009).

PMAP models elicit the parameters of a multi-attribute objective function by means of equalizing the slope of the indifference curve, or marginal rate of substitution, to the tangency point along the efficiency frontier, or marginal rate of transformation (Essenfelder et al., 2018). This yields as many candidate objective functions as possible combinations of utility-relevant attributes are explored, which are subsequently ranked according to their performance/calibration residual metrics in order to determine the most accurate representation of the objective function. While all the PMAP calibration techniques available in the literature share the calibration process described above, they differ in the method used to approximate the efficiency frontier (Gómez-Limón et al., 2016; Gutierrez-Martin and Gomez Gomez, 2011). PMAP models offer the advantage of smooth and realistic calibration results while avoiding the use of ad-hoc dual variables in the objective function. On the other hand, since PMAP models use a limited number of assumptions (no dual variables, no fixed proportions, no limitation in the number of utility-relevant attributes), in those cases where there is a large number of choices within the portfolio and cross-sectional variation is low (time-series variation might be confounded with other trends), the calibration may be unstable and challenging to rationalize (e.g., "jumpy behavior" in parameter values when additional attributes are considered); and occasionally unfeasible (Gutierrez-Martin and Gomez Gomez, 2011).

3.1.2. Macroeconomic module

Macroeconomic modelling examines dynamics of aggregate quantities such as goods and services produced, income, capital employment, and prices at the regional (Carrera et al., 2015; Dixon et al., 2011), national (Bosello et al., 2012a; Ciscar et al., 2011) and global levels (Hertel, 1997; Lenzen et al., 2013). The two most used models for assessing the broad economic impacts of environmental changes are Computable General Equilibrium (CGE) and Input-Output (IO) models.

IO models reflect the economic interdependencies between sectors and regions within an economy, through intermediate supply and final demand, based on linear relations (Koks et al., 2015). Linear IO models applied to water typically combine input-output matrices and water accounts and apply a structural decomposition analysis that disaggregates the effects of a given shock on economic outputs and water use at different levels, from urban (Wang et al., 2009) to multi-regional (Wan et al., 2016). Because of their descriptive nature, researchers have frequently resorted to IO models to determine which sectors consume more water (directly and indirectly) (Bogra et al., 2016), estimate their productivity (apparent and induced) (Duarte et al., 2002), assess their exposure and vulnerability to shortages (Zhao et al., 2015), and support the design of water and agricultural policy (González, 2011; Llop, 2008). Despite much progress, linear IO models still tackle two major issues insufficiently: (i) disruptions, such as droughts, are most often a disruption in the supply-side of the production chain; and (ii) modelling the substitution capabilities of other regions and/or other industries. Non-linear optimization has been combined with IO modelling techniques to overcome these issues, thus providing the simplicity of IO modelling (i.e. Leontief production function) while allowing for some more flexibility (Baghersad and Zobel, 2015; Oosterhaven and Bouwmeester, 2016). One such approach can be found in the MultiRegional Impact Assessment (MRIA) model (Koks and Thissen, 2016). With the use of the MRIA model, the first aforementioned issue is tackled by using optimization techniques to solve the model, which allows for taking endogenous import and supply constraints into account in an essentially demand-determined model. This overcomes two potential concerns: (i) the need for translating the supply-side shock into a demand-side shock and (ii) the need for using a supply-driven IO model. The second issue is tackled by introducing (multiregional) substitution possibilities, i.e., allowing products to be produced by different industries in the same or other regions. This approach allows for an endogenously determined new post-disaster optimum with shifts between main suppliers within the boundaries of the existing (trade and) production structure of the (regional) economy.

In **CGE models**, agent behavior is calibrated from observed economic flows registered in Social Accounting Matrices (SAM). The main features of these models are based on a neo-classical formulation assuming perfect competition, full employment of production factors, and savings-driven investments. The economy is modeled through representative agents that minimize private expenditure to attain a given utility level. Markets are always in equilibrium meaning the demand equals supply and are cleared by adjustments in prices. Changes in prices provide a signal for all markets highlighting the intertwined nature of the underlying SAM data. Depending on the calibration data (SAM) CGE models are usually available at the national and multi-regional level with some extensions at the subnational level. Moreover, these models have been also used for water related research in different contexts. Water use in CGE models can be represented either implicitly (irrigated land, which itself embodies water) or explicitly. The latter approach is used, e.g. by Darwin et al. (1995) for the US, although replication of this approach elsewhere can be challenging due to limited information on water use, value and prices. On top of that, the shadow price of water may not meet the gap between irrigated and rain-fed production to pay for the returns to water. Accordingly, in Berrittella et al. (2007), irrigated land production is represented by using a nested Constant Elasticity of Substitution (CES) function in which water and other inputs enter in a fixed proportion. Water demand responds to a water rent, which in turn derives from supply constraints. Calzadilla et al. (2011) use a more flexible three-level CES production function, which allows for different degrees of substitutability between inputs at each level and permits two ways of reallocating water: substituting other inputs for water and reducing demand for water intensive products. Yet, since rain-fed and irrigated production appear as part of the same aggregate national production function, it is not possible to stop irrigating an area in favor of rain-fed agriculture –a major weakness that complicates policy assessment (e.g. irrigation restrictions). Finally, Parrado et al. (2020, 2019) couple a version of the ICES CGE model where water is modeled implicitly and land explicitly with a microeconomic model where land and water are both modeled explicitly. Thus, the microeconomic model provides information on water and land use decisions, the latter of which are fed to the CGE to model to assess impacts on input and output price dynamics, which in turn again condition microeconomic decisions. The **ICES CGE model**, developed by CMCC, has been extended at the subnational level (NUTS2) to support more granular research analysis and **is the default model used in the macroeconomic module**. The basics of the ICES CGE model are detailed in Annex IV.

3.1.3. Climate module

The climate module will be populated with conventional multi-model ensembles developed in the context of major ensemble experiments, namely CMIP6 (2022), EURO-CORDEX (2022) and ISIMIP (2022). TALANOA-WATER will not conduct any additional simulations using climate models. All data imported from climate modeling will force the agronomic and hydrologic modules following a one-way protocol. Human system modules will adopt Shared Socio-Economic Pathways coherent with the RCP scenarios used in the climate module.

3.1.4. Hydrologic module

Hydrological models are simplified representations of real-world water systems (e.g., surface water, soil water, wetland, groundwater, estuary) that aid in understanding, predicting, and managing water resources. TALANOA-WATER puts focus on the study of flow quantity, albeit quality of water will be also reported.

A large pool of *hydrologic* models is available from the literature to populate the hydrologic module (see e.g. http://hydrologicmodels.tamu.edu/models.htm). Two key families of hydrological models can be distinguished: 1) global hydrological models used to characterize global water and energy fluxes and stores and to model their future trajectories; and 2) regional hydrological models used for individual river basins, which require more detailed input data, have higher spatial resolution to represent the modelled processes, and are tuned specifically to represent the observed hydrological processes and discharge dynamics (Harou et al., 2009). The literature shows that global models typically have a less satisfactory performance in terms of reproducing monthly and annual runoff values, with the regional models outperforming them—albeit it is noted that both global and regional models can generally reproduce the observed seasonal and interannual runoff variability. Thus, "while the land surface and global hydrological models cannot adequately simulate the actual runoff time series and long-term average volumes, they can reasonably simulate the monthly and interannual runoff variability and trends and can therefore be reliably used for broadscale or comparative regional and global water and energy balance assessments and simulations of future trajectories" (Zhang et al., 2016). A key advantage of global models is that the use of an ensemble of hydrological models is less costly and therefore more frequently used, mainly due to the large effort needed to setup and calibrate regional models. TALANOA-WATER aims to setup an ensemble of hydrological models to assess the impacts of adaptation strategies. To this end we will use, preferably, regional models; albeit global models or mixed approaches can be used where the efforts needed to setup such ensemble exceed available resources.

Due to their simplistic setup and calibration, global models are typically compatible with the protocol-based modular framework in TALANOA-WATER. For example, all global models available in the ensemble experiment (ISIMIP, 2022) have been successfully coupled with human system models in the Spanish lab to assess the economic repercussions of selected climate change scenarios in the Cega Catchment (see Figure 1). These models should be preferably used to force Decision Support Systems used by river basin authorities, so as to more accurately reproduce local conditions (e.g. AQUATOOL, as was done in the Spanish lab, but also WEAP in the Tunisian and Egyptian labs, or TOPKAPI in the Italian lab) (Hadded et al., 2013). This is discussed more in detail in the next section. On the other hand, to be compatible with the protocol-based modular framework in TALANOA-WATER, hydrologic models must meet some criteria, namely:

1) be regional hydrologic models –i.e. working at a watershed or catchment scale;

2) be spatially distributed –i.e. fully or semi-distributed models, to be capable of representing responses from economic agents; and

3) have a land management module –i.e. be capable of connecting land management actions taken by the different economic agents and hydrological responses (Essenfelder et al., 2018).

Following an *ad-hoc* literature review, 12 hydrologic models complying with these criteria were identified (see Table 1). The selection of hydrologic model candidates was based on: 1) model structural characteristics –i.e. the most diverse the models in terms of capabilities and applications, the better; 2) data requirements –i.e. availability of data in the case study areas must be compatible with the basic data input requirements of the models; and 3) computational and human resources. This selection criteria are consistent with those used in existing ensembles of regional hydrologic models (Cloke et al., 2013; Duan et al., 2007; Huang et al., 2017; Velázquez et al., 2013). The list can be expanded to include other regionally calibrated models that are relevant to each lab.

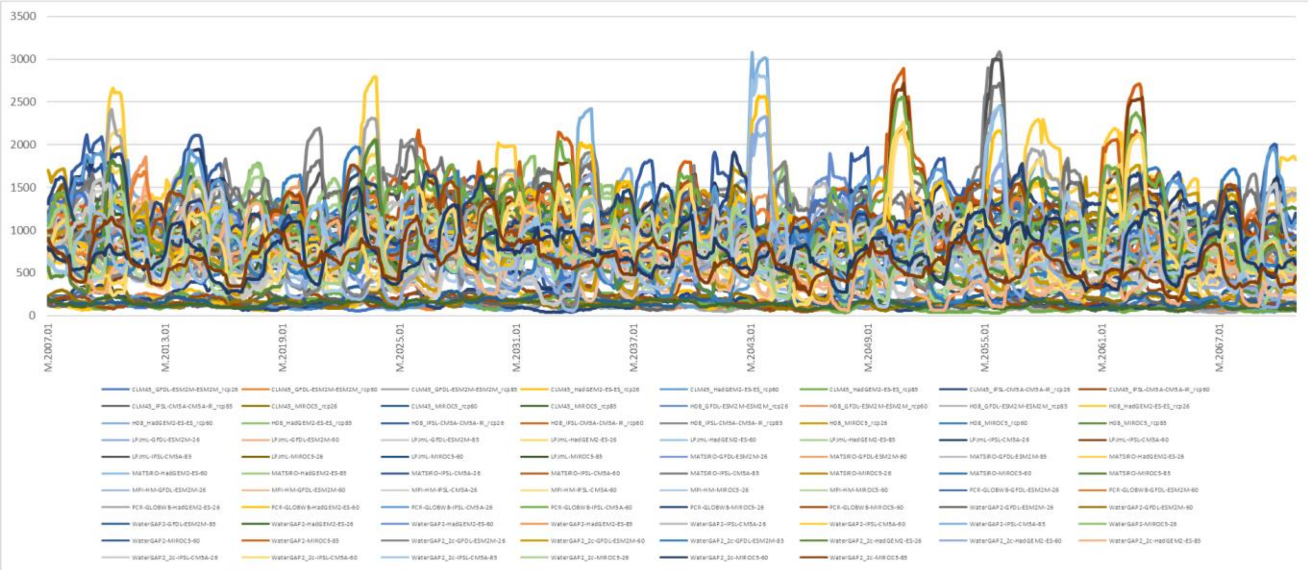

Figure 1. Ensemble of coupled climatic and hydrological models, input for socio-hydrology simulations in the Cega Catchment

Table 1: *Hydrologic model candidates. Legend: OG: Orthogonal Grid; HRU: Hydrologic Response Units –may refer to a variety of size areas, characterized by being an homogenous, lumped area.*

Name	Spatial Distribution	Discretization Type	Temporal Scale	Main reference
Annualized Agricultural Non-Point Source Pollution Model - AnnAGNPS	Fully-Distributed	OG	Daily/Sub-daily	Young et al., 1989
Areal Nonpoint Source Watershed Environment Response Simulation – ANSWERS 2000	Fully-Distributed	OG	Daily/Sub-daily	Bouraoui and Dillaha, 2000
airGR based Integrated Water Resource Management R package - AirGrIWRM	Semi-distributed	OG	Daily	Dorchies, 2022
Agricultural Policy / Environmental eXtender Model - APEX	Semi-Distributed	HRU	Daily	Gassman et al., 2009
Semi-Distributed Physically-Based Hydrologic Model using Remote Sensing and GIS - DPHM-RS	Semi-Distributed	HRU	Sub-daily	Biftu and Gan, 2004
US Army Corps of Engineers - Hydrologic Engineering Center - Hydrologic Modeling System – HEC-HMS	Lumped/Semi-Distributed	OG	Daily/Sub-daily	US Army Corps of Engineers, 2015
Hydrological Simulation Program FORTRAN - HSPF	Semi-Distributed	HRU	Daily/Sub-daily	Donigian et al., 1995
HYdrological Predictions for the Environment - HYPE	Semi-Distributed	HRU	Daily/Sub-daily	Lindström et al., 2010

European Hydrologic System – MIKE-SHE (*academic license provided by USAL*)	Fully-Distributed	OG	Daily/Sub-daily	Refsgaard and Storm, 1995
Soil and Water Assessment Tool – SWAT	Semi-Distributed	HRU	Daily/Sub-daily	Arnold et al., 2012
Soil and Water Integrated Model – SWIM	Semi-Distributed	HRU	Daily	Krysanova et al., 2005

The multi-system ensemble may also include models used by relevant authorities in case study areas (notably river basin authorities) that are compatible with the protocol-based modular framework above.

3.1.5. Water allocation (management) module

Climate and hydrology models will estimate current water resources and their future trends. Yet microeconomic and agronomic modeling will require an estimate of the water availability for each crop, in a specific climate condition and soil type, to provide an accurate estimation of crop yield, land allocation and market value. To this end, there is a need of a water management module that resolves the water balance equations at river basin scale and for medium to long term horizon and allocates resources, while accounting for key infrastructures along the basin and their operation. A large set of water management tools are developed and made available for water managers to assist the identification of acceptable allocation solutions. Some of these tools are listed below:

- RIBASIM http://www.wldelft.nl/soft/ribasim/int/index.html : River Basin Simulation Model is a generic model package for analyzing the behavior of river basins under various hydrological conditions.
- WEAP http://www.weap21.org/ : Water Evaluation And Planning" takes an integrated approach to water resources planning. It is a microcomputer tool for integrated water resources planning. It provides a comprehensive, flexible and user-friendly framework for planning and policy analysis.
- MIKE BASIN http://www.dhisoftware.com/mikebasin/Description/: Addresses water allocation, conjunctive use, reservoir operation, or water quality issues. It couples ArcGIS with hydrologic modeling to provide basin-scale solutions.
- MODSIM http://modsim.engr.colostate.edu/ : MODSIM is a generalized river basin Decision Support System and network flow model designed specifically to meet the growing demands and pressures on river basin managers today.
- WBalMo http://www.wasy.de/english/produkte/wbalmo/index.html: Water Balance Model is an interactive simulation system for river-basin management. WaBalMo has been used to identify management guidelines for river basins, design reservoir systems and their operating policies, and perform environmental-impact studies for development projects.
- AQUATOOL https://aquatool.webs.upv.es/aqt/en/home/: AQUATOOL is a development environment for Decision Support Systems (DSS) for watershed planning and management or

water resource systems that provides resources to help the analysis of various problems related to the water management. It is the main DSS for river basin planning in Spain.

3.1.6. Agronomic module

The agronomic module will be populated with conventional multi-model ensembles developed in the context of major ensemble experiments, preferably ISIMIP (2022). TALANOA-WATER will import global data from the ISIMIP ensemble simulation runs. In addition, initiatives from water labs to implement agronomic modules, for their specific study areas, will enrich global data from ISIMIP. CROPWAT[1] an WEAP[2], integrating the FAO crop library, and using crop water requirement and production models (Allen et al., 1998) are effective tools to characterize the relationships between water allocation and crop production, and will be explored in the project e.g. in the context of the Tunisian lab.

All data imported from agronomic modeling will force the human system (yield) and hydrological system (where key variables such as evapotranspiration are relevant) following a one-way protocol. Outputs from the agronomic ensemble will be imported into the modeling framework observing coherence among climate and other key scenarios (e.g., the RCP forcing the agronomic module is compatible with the SSP forcing the macroeconomic module).

3.2. Protocols

The modules presented above are interconnected via protocols, which are rules designed to manage interrelationships (where feasible through two-way feedbacks) among systems' modules (Csete and Doyle, 2002). By building links among modules, using two-way or single-way protocols, we define a hierarchy of modules that can be run to assess the impacts of a given shock over all relevant systems. The hierarchy is activated after a shock/forcing affects one of the modules, and the effects are subsequently propagated throughout the remaining modules of the framework via the established protocols. Shocks/forcings involve a policy/adaptation strategy and/or a scenario or set of scenarios (notably climate change scenarios via Representative Concentration Pathways—RCPs) and modified BDC / withdrawals.

Protocols for interconnecting modules in TALANOA-WATER can adopt two alternative settings: i) time-invariant and ii) time-variant.

If we adopt a **time-invariant** setting the analysis is circumscribed to a specific period of time and an iterative process is activated and repeated until convergence is reached, at which point predictions are stable and consistent, allowing for a comparative statics analysis. Convergence can be assessed through a convergence test (Hasegawa et al., 2016; Ronneberger et al., 2009). This time-invariant static approach

[1] https://www.fao.org/land-water/databases-and-software/cropwat/en/
[2] https://www.weap21.org/

is typically used to assess changes in the equilibria of systems following a shock through comparative statics (Bosello et al., 2012b; Dixon et al., 2012; Parrado et al., 2020, 2019; Pérez-Blanco et al., 2016; Taheripour et al., 2016).

On the other hand, under a **time-variant** setting, information is carried forward in time from one module to another for a predetermined number of years. While convergence could be part of the analysis the time dimension opens the possibility to explore adaptive pathways of specific shock or policies without the need to achieve convergence, by slightly modifying the protocols to allow for a time lag in the feedback processes of the system. Time-variant settings are particularly useful to explore *dynamically robust strategies*, that is, a set of possible actions designed to allow the policy maker to adapt dynamically from one action to another over time in response to how the future unfolds (Walker et al., 2010). Dynamically robust strategies can be developed using modeling approaches such as Dynamic Adaptive Policy Pathways (DAPP) (Haasnoot et al., 2013) or Real Options Analysis (ROA) (Steinschneider and Brown, 2012). In essence, modeling approaches such as DAPP or ROA represent decision makers' evolving hypotheses about the most important uncertainties, relationships, measures and decision levers, where decision levers represent policies that can be taken to influence the system, with the aim of "finding a plan that is successful in a wide variety of plausible futures" that happen *in succession* (Kwakkel et al., 2015). Another option is to use backcasting "hierarchies": starting from a desired agricultural extension scenario, we can assess what crops and what distribution or value channels we want and explore, and what this would require in terms of prices, regulatory setting and water allocation/sharing.

Both time-variant and time-invariant approaches are designed to be flexible, and protocols will change depending on the systems considered and the models explored within each module. Below we present two illustrative cases of a i) time-invariant and ii) time-variant protocol setting.

3.2.1. *Time-invariant protocol setting*

The first case is an exemplar time-invariant socio-hydrology-inspired modeling framework operating through a recursive modular approach that enables the simulation of interconnected dynamics and two-way feedback responses between human-water and human-human (i.e., micro-macro-economic) systems. The coupling approach is presented more in detail in Pérez-Blanco et al. (2022). The resulting framework is designed to be flexible and to allow each module to be populated with alternative models. The models used in this exemplar time-invariant application are: i) the Soil and Water Assessment Tool (SWAT), as the hydrological module (Arnold et al., 1998); ii) A multi-factor, non-linear Positive Multi-Attribute Utility Programming (PMAUP) model, as the microeconomic module (Essenfelder et al., 2018; Gutierrez-Martin and Gomez Gomez, 2011); and iii) a Computable General Equilibrium (CGE) model calibrated at a regional level, as the macroeconomic module (Bosello and Standardi, 2015). The protocols' connection between the different modules is done through the land-use component of each module, while information exchanged among the models includes commodity prices, water availability and water allocation changes, among others. This model has been tested with applications in the Cega Catchment (Spanish lab), as well as basin-wide over the entire Douro River Basin where the Spanish lab is located, to inform alternative strategies within the basin.

The static hydro-micro-macro-economic recursive modular framework (depicted in Figure 2) works as follows:

- In step 1, a policy shock (in this illustrative example, water charging) is applied to the microeconomic model, whose solution provides reallocation of land among crops based on the preferences of economic agents.
- In step 2, land use changes and/or agricultural supply/quantities (depending on the detail offered by the macroeconomic model) as simulated by the microeconomic model in step 1 are aggregated and fed into the agricultural sector of the case study area's corresponding region in the macroeconomic model; a macroeconomic simulation is then performed with the new input information to find a new economic equilibrium and to provide a set of production quantities and commodity prices that are consistent with economy-wide effects.
- In step 3, changes in crop commodity prices in the relevant region are fed back into the microeconomic model, and economic agents in the case study area reassess their initial crop portfolio decision. Steps 1 to 3 occur iteratively until convergence is reached (Hasegawa et al., 2016; Ronneberger et al., 2009). Note that the coupling protocol between the micro- and macro-economic modules through land use and crop price changes yields a stable system (i.e. the micro- and macro-economic modules are in equilibrium simultaneously), as shown in Parrado et al. (2019).
- In step 4, resulting land use choices and water use by economic agents are fed into the corresponding consolidated land areas of the hydrologic model, which simulates the effects of the socioeconomic system on the water dynamics of the river basin.
- In step 5, relevant effects on the water system (i.e. water availability for irrigation) are passed as spatially-distributed information to the corresponding microeconomic agent. If the water availability constraint strengthens following the hydrologic simulation, forcing economic agents to adapt, the iterative process in step 1 to 3 is repeated until convergence is reached (i.e. models predictions are stable and consistent).

Note that for climate-induced responses (e.g. climate change scenario analysis), simulations would run from the hydrologic (external climate forcing) to the microeconomic to the macroeconomic model (i.e. step 4 and 5 as first steps, followed by 1-3). The same rationale is valid for macro-economic induced responses, such as macroeconomic shocks due to COVID19, for instance. The overall simulation from steps 1 to 5 follows the rules established in the protocols' connection and is repeated in successive iterations until convergence of results provided by both water and human systems is reached.

Convergence between systems is assessed through a convergence test[3] (Hasegawa et al., 2016; Ronneberger et al., 2009). Convergence refers to a situation when information exchanged between models does not result in meaningful changes between two succesive simulation iterations (Hasegawa et al., 2016; Ronneberger et al., 2009). To check if the framework is in equilibrium (i.e., there is convergence), one should empirically test results by running at least two complete iterations (steps 1 to 5) and assessing the degree of change in the value of predetermined variables. The framework depicted in Figure 1 has two convergence variables (one for the human-human/micro-macroeconomic coupling and another for the human-water coupling, which in our case are land allocation and crop prices as

[3] This static approach assumes economic agents know their best management alternatives by having *a priori* access to reliable and accurate information on future prices and hydro-meteorological variables. The assumption of *a priori* access to reliable and accurate information implies that even if agents' expectations are wrong, they are on average correct; in other words, "agents' expectations are not systematically biased and collectively use all relevant information in forming expectations of economic variables" (Muth, 1961). Without the assumption of *a priori* access to reliable and accurate information, the integration would be dynamic in time: one year run of each model following steps 1→2→4→5→3 without convergence tests, carrying the information forward in time. Note that the dynamic setting does not ensure convergence and therefore precludes a comparative statics exercise.

detailed in Section 2.2), which are subject to the convergence test. The framework is in equilibrium only when convergence is simultaneously achieved in the human-human/micro-macroeconomic and in the human-water coupling. In this example, the framework is assumed to be in equilibrium when the values of the convergence variables for the last two successive iterations experience a change below a predetermined threshold set at 0.00001% ((Parrado et al., 2020; Pérez-Blanco et al., 2022). If convergence is not achieved, the recursive modular framework continues, and additional convergence tests are conducted after each complete iteration (steps 1 to 5) until the framework is in equilibrium. Note that the efficiency of convergence tests is limited by the amount of information exchanged between models, which conditions the number of convergence variables to be considered. Accordingly, the more variables are included in the information exchange between models, the more computationally expensive and time consuming will become the convergence process. Thus, it is necessary to carefully assess how many variables are coupled between modules to keep tractability of the convergence process and the whole modelling framework, while accurately representing the relevant socio-ecological system.

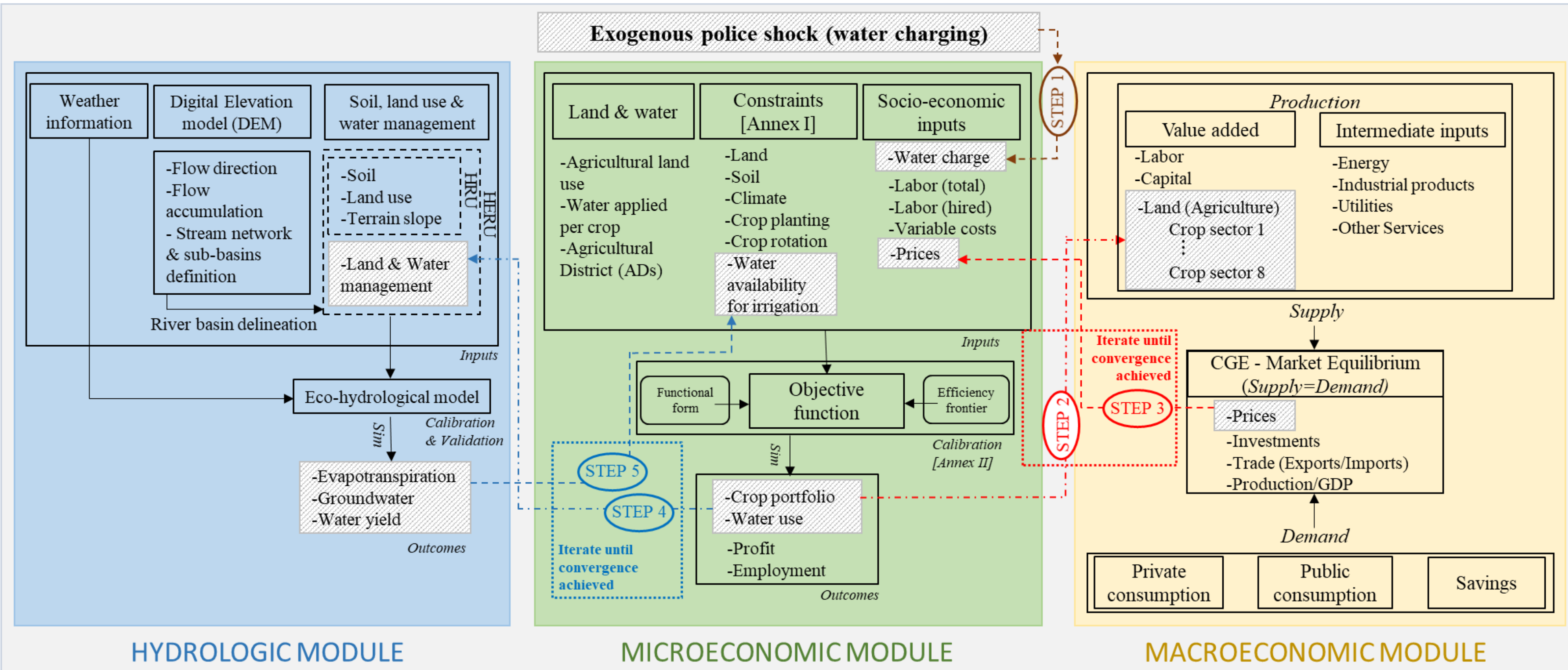

Figure 2. *Conceptual representation of the coupled hydro-micro-macro-economic modeling framework under a time-invariant setting* (Pérez-Blanco et al., 2022).

This is but an example of a flexible and replicable hierarchy framework targeting the assessment of pressures introduced in human-water systems by an adaptation strategy (water charging in this case). The hierarchy can be populated with several models per system, to carry out ensemble experiments that assess the implications of alternative scenarios, initial states and adaptation strategies. Other modules and protocols could be developed and used, for example by explicitly including Regional Circulation Models to assess climatic pressures on the system. Note that as we include additional modules and protocols, models and scenarios, computational costs increase significantly.

3.2.2. *Time-variant protocol setting*

The second case is an exemplar time-variant socio-hydrology-inspired modeling framework that connects, in a sequential and recursive fashion, a microeconomic and a hydrologic module using bidirectional protocols. The adoption of bidirectional protocols allows the simulation of the two-way feedbacks occurring in human-water systems and their impacts. The resultant time-variant modeling framework was designed in the early stages of WP3 in TALANOA-WATER to assess the impact of selected strategies in the Cega Catchment (Spanish water lab) over a number of meetings with the Douro River Basin Authority, and is explained in detail in Pérez-Blanco et al. (2021). The framework has been successfully scaled-up to the entire Douro River Basin at the request of the Douro River Basin Authority, and used to inform dam construction projects and environmental flows impacts.

The modeling framework has two modules for the water and human system. The water/hydrologic module is populated with the Decision Support System (DSS) of the Douro River Basin Authority, AQUATOOL; while the human module is designed to be populated with any of the models within the microeconomic module listed above. We develop two bidirectional protocols connecting human and water systems.

- In the *first protocol*, information on the water allocation for each economic agent (Agricultural Water Demand Units—AWDUs) is transferred from the hydrologic to the microeconomic module at the beginning of the irrigation campaign in April.
- In the *second protocol*, information on the effective amount of water used by each agent/AWDU (a function of the crop portfolio choices, x) is transferred from the microeconomic to the hydrologic module. Note that AQUATOOL runs simulations at monthly time steps, while microeconomic models predict crop portfolios (and related water use) for the irrigation campaign (annual timescale). Thus, in the second protocol the information on aggregate water use in the microeconomic module is distributed over the months of the irrigation campaign.

The protocol sequence is conditional on the type of shock assessed in the model. For an adaptation strategy that revises minimum environmental flows, the exogenous policy shock first impacts the hydrologic module, which runs a simulation to assess the water allocation for each agent, including AWDUs, in the year *t*. Next, information on water allocations for each AWDU is conveyed to the microeconomic module, which runs a series of simulations (one per agent/AWDU) to assess agents' crop portfolio responses (and related water use, income, employment, etc.) to year *t* water allocation constraint. Note that due to preferences and other constraints (e.g. crop rotation), effective water use needs not match the water allocation for all agents and can indeed be lower. The information on effective water use is then transferred to the hydrologic module in *t*, and is combined with hydrological input data for the following months to assess the status of the water system in *t+1*, including water allocation for economic agents. This process is repeated in sequence for a predefined number of years (Figure 3).

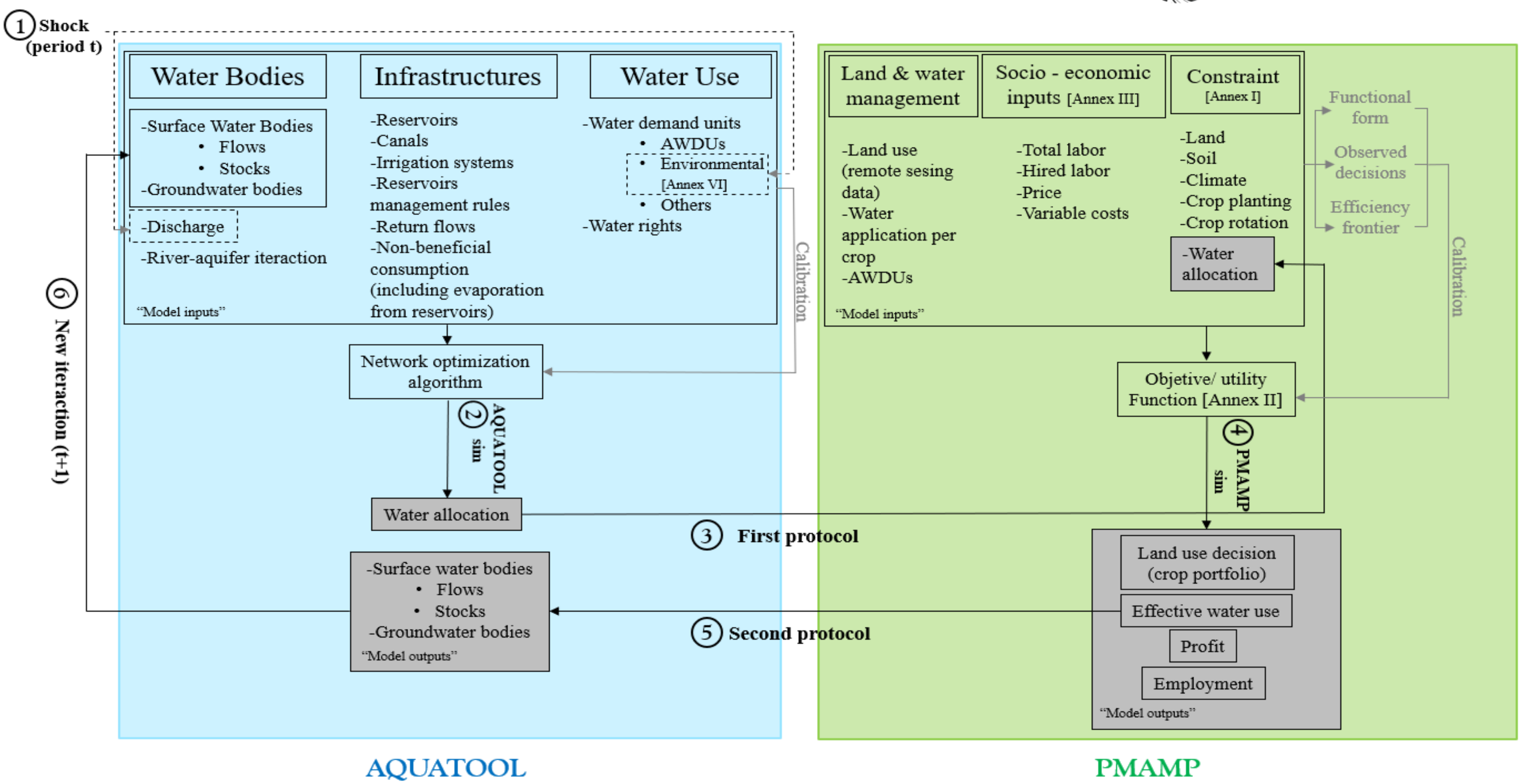

Figure 3. *Conceptual design of the time-variant coupled human-water modeling framework (Pérez-Blanco et al., 2021). Step 1 introduces a shock (new minimum environmental flows under climate change), which forces the AQUATOOL model and yields the new water allocations for each AWDU (Step 2). In Step 3, the new water allocation constraints are conveyed to each economic agent/AWDU in the microeconomic model (in this case, a PMAMP model has been chosen, but any other microeconomic model could be used) through the first protocol, and a simulation is run to determine land use and water application decisions (Step 4). In Step 5, information on effective water use is conveyed from the PMAMP to the AQUATOOL model through the second protocol, and this information is used to estimate the status of the water system (stock and flows of surface and groundwater bodies). Steps 1 to 5 occur over the same period t. Finally, in Step 6, the status of the water system in t is used as an input to start a new iteration by simulating a new period t+1.*

Note that the protocol sequence above applies to shocks affecting first the water system. For a shock affecting first the behavior of agents/AWDUs in the human system (e.g. an increase in water charges), the sequence would be different: 1) simulate agents' responses in the microeconomic module; 2) activate the second protocol; 3) simulate impacts on the hydrologic module; 4) activate the first protocol; and 5) repeat the process iteratively. Also note that although the coupling is designed to be flexible and alternative models could be used at the level of each system, the description and conceptual design of the hierarchical framework in the text above and in Figure 1 is applicable to the PMAMP-AQUATOOL modeling framework. Ad-hoc transformations may be needed to adapt the proposed framework to alternative hydrologic models (the PMAMP model could be replaced by alternative normative, linear programming and positive mathematical programming models without any change to the model setting).

4. Rapid assessment

The detailed analysis in the full-fledged multi-system modeling framework above will be complemented with a rapid assessment option that uses a simplified version of the modeling framework to process multiple scenarios and transformational adaptation strategies within a computational time that is acceptable for workshop deliberations. Rapid assessments make possible to run multiple stock-taking iterations during a single workshop, thus allowing for a rapid response to stakeholders' feedback and demands. The rapid assessment option will be used during exploratory workshops (workshops 1-4); and to support interactive tools for decision-making applications (e.g. serious game). It is stressed that the use of rapid analysis is mostly only appropriate, and will be limited, to the exploratory workshops (workshops 1-4). Workshops 5-6 will entirely rely on simulation results from the full-fledged modeling framework.

The literature distinguishes two types of rapid assessment (Ebrey et al., 2021):

- Fast access to risk information and adaptation analysis, e.g. to allow indicative analysis of emerging issues, and compile some brief information on risks and adaptation. This typically includes non-modelling approaches, e.g. databases, look-up tables. In the context of TALANOA-WATER, this type of rapid assessment involves access to the database of plausible futures generated through the modeling framework in D3.2 & D3.3 and via co-generation (*bottom-up approach*). This information can be complemented with a rapidly growing group of *top-down* tools that can provide a first glance of the repercussions of key scenarios (including climate scenarios), such as the WaterRiskFilter, Copernicus services, WaPOR, or Aqueduct. This is the default approach used in TALANOA-WATER.
- Use of fast and simplified models or methods that are able to process multiple scenarios and policy options within acceptable computational time, and are therefore suitable for decision-making applications or used within interactive tools that can be applied in a stakeholder meeting. Not all models in the multi-system framework satisfy this condition, thus this approach should be used

with caution and after a careful check of its applicability for stakeholder engagement (and ideally tested first in small stakeholder meetings, before its use in major workshop events).

It should be highlighted that most rapid assessment tools available nowadays are *top-down*. They are hosted in global, EU or national scale data portals. They often concentrate on improved projections of climate change and focus on matching users' resolution needs through improved downscaling techniques and better impact data. Although essential, projections of impacts are only one of the elements needed to support adaptation decisions. In fact, while providing much information on the consequences on scenarios, top-down approaches do not provide information on the repercussions of adaptation strategies—a key aspect to be assessed in TALANOA-WATER. A more stakeholder-led approach where parties to the decision can inform modelers so that they can produce assessments on the repercussions of selected adaptation strategies would be beneficial. In this view, the question shifts from 'what are the expected impacts under assumptions of future scenarios?' to 'at what level do I need to act, and what are the consequences of the adaptation strategies I design?'. This approach can also support the adoption of *robust* adaptation strategies by exploring their consequences under multiple plausible futures.

TALANOA-WATER will deliver a *bottom-up* rapid assessment that builds on the database of plausible futures created with stakeholders through co-generation approach. Bottom-up approaches require involvement of local stakeholders and much engagement with WP1 and WP4. In fact, rapid assessment research shows that "the more localized the decision making, the higher the importance to integrate preferences and objectives of stakeholders and the need for collaborative modelling techniques" (Ebrey et al., 2021). This calls for the integration of data from multiple sources and the communication of results using recognizable indicators with visual tools such as maps and dashboards. As regret is likely to emerge and be significant under uncertainty, decision-makers need to be informed also of the multiple plausible outcomes that exist through tools that sample and effectively communicate uncertainty. The application of these tools is often still limited and seldomly used. Thus, a major goal of TALANOA-WATER is to include the principles of robustness and flexibility more and more in the rapid analysis methods, for example, by including adaptation assessments against multiple scenarios, using metrics for 'regret' of decisions.

In any case, it is highlighted—again—that the use of rapid analysis should be limited for exploratory analysis and complemented with full-fledged models before any meaningful policy decision is undertaken. Time and resource constraints, including in large scale projects, often mean that there is a growing push for rapid and simplified assessments that can be readily used by decision-makers. Much evidence shows, though, that rapid analysis is "neither appropriate nor applicable to all decision-making contexts" (Kondrup et al., 2022). Researchers should carefully weight the potential regret from selected adaptation strategies and the stage of planning. For the labs in TALANOA-WATER where planning is at an early stage and regret is potentially high (e.g., dam construction in the Spanish lab, shift to desalination in the Tunisian lab), rapid assessments are better used in the early stages of planning to gather feedback from stakeholders for instance with multicriteria participative assessments and prioritize efforts towards more rigorous assessments later down the road.

Ebrey et al. (2021) identify the following contexts for the use of rapid assessment: "1) in a screening or exploratory phase when awareness needs to be raised, potential risks need to be identified and prioritized and adaptation actions for further evaluation need to be selected; 2) when the consequent decisions have low regret potential, for instance in case of small often repeated projects with known benefits; 3) when more extensive analysis simply is not feasible given the constraints of the decision-making process". TALANOA-WATER rapid assessment will be applied in context 1), with the **goal of raising awareness and gathering information towards co-generation of scenarios, Basin Determined Contributions and adaptation strategies, as well as validation of mechanisms that are represented in models, and to facilitate learning and mutual understanding that pave the road for a more thorough analysis using full-fledged models**. This will occur during the exploratory workshops 1 to 4. The interest of discussing processes before including them in models (or for their validation) is that stakeholders will not face the "black box" effect with models. Discussing/validating mechanisms with stakeholders around the rapid assessment stake can increase the confidence of stakeholders in the modeling suite. This is the philosophy for example of the ComMod approach (https://www.commod.org/en).

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Annex I: Minutes of the Talanoa-Water modeling workshop - 1st April 2022

April 1st, 2022
12:00AM-13:30PM CET
Minutes of the Modeling Work Package Meeting
Organized by C. Dionisio Pérez-Blanco Ramiro Parrado and Arthur Hrast Essenfelder
Writing: Héctor González & C. Dionisio Pérez-Blanco

Meeting Agenda

Introduction

Session 1: Multi-system modeling framework – The TALANOA Approach

Session 2: Refinements to the TALANOA modeling approach

Next steps discussion

Meeting Attendants (19)

C.Dionisio Pérez-Blanco (USAL), Arthur Hrast Essenfelder (CMCC), Ramiro Parrado (CMCC), Héctor González-López (USAL), Laura Gil-García (USAL), Francesco Sapino (USAL), Gabriele Standardi (CMCC), Nina Graveline (INRAE), Paolo Mazzoli (GECO), Marta Debolini (INRAE), Issam Nouiri (INAT), Mohamed Fethi Ben Hamouda (INAT), David Dorchies, Ángel Sánchez (USAL), Roya Mourad (AUB), Rim Hazimeh (AUB), Abddrabbo Shehata (GPAI), Samir Sahal (CRDA Médenine), Guillaume Thirel.

Introduction

C. Dionisio Pérez-Blanco starts the meeting with a briefly presentation of the relevance of the WP3 which is focused on the modelling framework that are supposed to be used in Talanoa Water Project. Although this modelling framework is flexible, will must be developed considering some basic features that should be done by all water labs. It is proposed the protocol-based modular framework, which has already been used over the last five years in Spain and Italy and consists of the aggregation of modules such as climatic, hydro(geo)logic, agronomic, micro-, and macro-economic by bidirectional soft links. This modelling framework is supposed to be used for all water labs, so the collaboration among the different water labs will be needed in order to help those one that have not used this modelling framework.

Session 1: Multi-system modeling framework – The TALANOA Approach

Part 1

Ramiro Parrado presents the economic modules within a multi-system modeling framework. In this presentation are shown the different analysis scale (microeconomic and macroeconomic) as well as the way to link them (holistic vs modular), highlighting the advantages and disadvantages of using the different approaches. The holistic modelling approach allows an effective representation of the interdependencies between micro- and macro-economic systems, with the integration of the micro-economic system within the macroeconomic model, which avoids the need to assess shocks separately. Nonetheless, there are some limitations such as the limited spatial details and simplifications due to the wide range of study. On the other side, the modular approach, as the micro- and macro-economic modules works separately, allows to represent more detailed results from each module. Another advantage is the viability of representing feedback between both modules. This means on the other side, the need of calibrate and execute each system separately.

Then the CMCC's ICES (regionalized CGE model) is presented. This multi-region, multi-sector computable general equilibrium model is based on GTAP model and database and is characterized by representing the iterations of agents and markets within countries and as international trades.

As a modular linking approach, there are two main ways to proceed. The first one is the one directional link where the effects of impacts and policies are assessed allowing to produce aggregated indicators (e.g. GDP). Another alternative is to consider two-way feedback approach, in this case the information is exchanged between both models, the Partial Equilibrium model and CGE.

The protocol of coupling micro- and macro-economic models works as follow: i) the water policies are charged to the micro-economic model; ii) then the micro-economic model computed what are the changes in the value added; iii) these outputs are used as inputs in the Regionalized CGE model which outputs changes in crop's prices that change the original water policies. This loop protocol is applied until the feedback process reaches a convergence. Another example of application is using the land use changes instead of using changes in GVA.

Part 2

After the Ramiro Parrado presentation, Arthur Hrast Essenfelder presents the hydrologic-microeconomic modelling system. Although this presentation shows a specific methodology with specific models, it is flexible to be used with different models or modules considering the different specifications by each water lab.

The way of developing the integration between the economic and hydrology in this case is usually used at a watershed scale or river basin scale but could be developed for a wider scale. This framework connects three main modules: i) the microeconomic module which is fed with a policy shock (e.g. reducing water use available);ii) the macroeconomic module that uses the land use changes output from the microeconomic module and give back as output the crop price changes (this is called human-human system), this trigger into new changes in land use through the microeconomic module that are used as input in the hydrologic module; iii) finally the hydrologic module gives feedback to the microeconomic module using as outputs the water available (this is called human-water system). This framework is able to be initiated with policy shocks also in the macroeconomic and hydrologic module, following the same loop.

Within this modelling framework SWAT is presented as the hydrologic model. This model uses at the first step the topography, soil type and land use of the area for the watershed delineation and its subdivision into sub-basins, so this information overlayed together form the HRU i.e. Hydrological Response Units. Into this network the Agricultural Water Demand (AWDUs) are added for adding the micro-/macro-economic information to the previous HRU becoming it into HERU.

Different results obtained in previous studies are shown for demonstrating the relevance of using this modelling framework.

Q&A

Paolo Mazzoli asks about the customization of the SWAT model in order to compliment hydrology and economy within the model, then Arthur Hrast Essenfelder replies that is not necessary to use SWAT for linking both economy and hydrology inputs, it depends on the study area characteristics (e.g. in groundwater dynamics studies, SWAT is not the most indicated), the main thing here is to understand how the protocol works and be able to reproduce it with different hydrologic or economic modules. Arthur Hrast Essenfelder highlights as well that there is not feedback between human and water systems, the impacts of the humans over the environment are considered external.

To this discussion C. Dionisio Pérez-Blanco explains that the outputs expected from each water lab through this modelling approach are presented in the Task 3.2.

Marta Debolini asks about what variables are considered for water resources management in SWAT apart of the land use changes, due to in Frances they have permanent crops. To this Arthur Hrast Essenfelder answers that it depends on the different hydrological model that are used, in the case of SWAT it is possible to assign the growing crop season and add information referring to the fertilizers, but in the case of this modelling framework where we must to link the economic and hydrologic modules, the variables used are the water used by farmers for irrigating and which sort of crop is growing in each specific piece of map.

The second question of Marta Debolini is regarding the way of introducing the economic agents into the hydrologic module, ¿is it possible to represent the farmers crop choice? To this C. Dionisio Pérez-Blanco replies that indeed the crop change choices are represented since the farmer behavior is the main variable from the micro- and macro-economic models and in a modular approach like the case of the hydroeconomic approach is the key variable to be exchanged between both modules.

Nina Graveline suggests incorporating agronomic model in order to assess the crop production in more detail beyond just the water stress. Arthur Hrast Essenfelder adds that SWAT is able to simulate this crop production as well.

Issam Nouiri asks about how to proceed with crops of trees that depends on the groundwater instead of hydrologic dynamics. The second question is referring to with sort of economic information is needed for the economic agent layer for overlaying it with the land use, soil type and slope layers in SWAT. Issam Nouiri adds that in their case study they barely have surface water, they are focus on the groundwater availability and they use to this end a coupling between WEAP and MODFLOW for manage the water availability and simulate the groundwater dynamics, ¿ Is the integration of SWAT needed in this case?.

Arthur Hrast Essenfelder answers that in this case for sure will be needed to change the hydrologic module. It is a good point to start the research investigation to know how to link the groundwater with the economic module. To the second questions replies that the economic information is a special overlayed of the economic agent with the characterization of the study area. In the case of Spain there is not information for each piece of land, there are aggregation of farmers that behave in a same way. To the third questions Arthur Hrast Essenfelder thinks that is not necessary to add SWAT to the coupling between MODFLOW and WEAP and offers himself to have a call in order to understand how this models work and help with the integration with the economic modules.

C. Dionisio Pérez-Blanco adds that it has no sense to change all models that Issam Nouiri are using, just keep using the current model and improving them with the macroeconomic that could have a better suitability with WEAP.

Session 2: Refinements to the TALANOA modeling approach

Ramiro Parrando presents the data exchange in TALANOA-WATER. First, it is highlighted the possibility of adding another output from the micro-economic model which serves as input to the macro-economic model as suggested Nina Graveline. Another question is the addition of more macroeconomic model's outputs to the crop's prices such as input prices (e.g. primary factors, fertilizers, etc.), so any suggestion will be helpful. Then the alternatives of different setups are shown. These alternatives are the static setup which triggers into short-term horizon or Dynamic setup which triggers into medium- to long- term horizon and could be possible to assess the Climate Change impacts. In this last case would be needed the consideration of including dynamics in model-linking. To linking the models different sort of links are suggested such as recursive linking where there is not a convergence in each year and link with convergence in each year. Another alternative is adding an external impact like Climate change.

Nina Graveline suggests adding fertilizers as the microeconomic model outputs.

C. Dionisio Pérez-Blanco presents the main two key challenges of TALANOA WATER Project. The first one is the system linking and how to link different modules for water management. The second challenge is the uncertainty assessment, so the suggested procedure in Talanoa water should be the development of more than one model for making ensemble multimodel that allows to assess the model and coupling uncertainty.

Q&A

Paolo Mazzoli asks about what the next step within each water lab should be. C. Dionisio Pérez-Blanco answers that the idea is to start a round of contacts with all water labs in order to identify the different characteristics and needs from each case study and stablish the approach within the proposed framework. Another point is to take a conversation with stakeholders as well regarding to the selected approach and discuss the most needed scenarios for each case study.

Annex II: Domain of the microeconomic module

- *Land use limits*. The sum of all alternative land uses, including fallow land, must be 1 (see Eq. [3]).
- *Water use limits.* Agricultural water use must be equal or lower than the total water allotment, i.e.:

$$\sum_{i=1}^{n} w_i x_i \leq W \qquad \text{[A.II.1]}$$

where w_i are the water needs of crop i (in m^3/ha), x_i is the share of land allotted to crop i and W is the total water allotment for the agent (m^3/ha).

- *Climate and soil constraints.* Only crops that can be planted under the climate and soil conditions of the area are eligible. The set of eligible crops is based on the historical crops observed and agronomic studies (Essenfelder et al., 2018):

$$\sum_{i=1}^{n} y_i x_i = 0 \mid y_i \in \{0,1\} \qquad \text{[A.II.2]}$$

where $y_i = 0$ for eligible crops and $y_i = 1$ means the crop is not eligible for that specific location.

- *Crop specific constraints.* Selected crops cannot be higher/lower than a predetermined surface (e.g. irrigable surface). The upper threshold of crop specific constraints is as follows (for the lower threshold, the inequality would be the opposite and the right-hand side of the equation would be a sum):

$$\varphi_i x_i \leq (1 - b_i) x_i^0 \mid \varphi_i \in \{0,1\};\ 0 \leq b_i \leq 1 \qquad \text{[A.II.3]}$$

Where φ_i is a binary vector that (de)activates the constraint, b_i is the upper threshold (in %) and x_i^0 is the *observed* share of land devoted to crop i. For ligneous crops, the maximum/minimum threshold is set at ±1% of the observed land share, to prevent large (dis)investments with potentially large impacts on e.g. carbon sequestration, whose economic value is not accounted for in the models, which focus on yearly market variables (notably profit) (Essenfelder et al., 2018).

- *Crop rotation.* Agronomic rotation patterns are based on observed historical data and agronomic studies for that area:

$$\sum_{i,j} g_{i,j} x_i \leq \sum_{i,j} h_{i,j} x_i^0 \mid g_{i,j} \in \{0,1\};\ h_{i,j} \in \{0,1\} \qquad \text{[A.II.4]}$$

where $g_{i,j}$ and $h_{i,j}$ are binary vectors that (de)activate the constraint for each specific crop.

Annex III: Potentially relevant attributes of the microeconomic module

Following Gómez-Limón et al. (2016) Gutiérrez-Martín and Gómez (2011) and Pérez-Blanco and Gutiérrez-Martín (2017), we explore the relevance of three attributes in multi-attribute models: expected profit; risk avoidance; and management complexity avoidance, which can be measured through multiple proxies (in this case we illustrate this attribute through one possible proxy: hired labor avoidance per unit of revenue). Note that for single-attribute models such as LP and PMP, the only relevant attribute is expected profit.

- Expected profit is measured as the expected gross margin (z_1). It is obtained as the summation of the expected per hectare gross margin of each crop π_i (obtained as price (in EUR/kg) times yield (in kg/ha) plus coupled subsidies minus the variable costs (in EUR/ha)) multiplied by that crop's land share (x_i):

  $$z_1(\boldsymbol{X}) = \sum_i x_i \bar{\pi}_i \quad \text{[A.III.1]}$$

  where $\bar{\pi}_i$ is the average gross margin for each crop *i* in the period 2008-2015, i.e. the summation of the observed gross margin of crop *i* for every year during the period 2008-2015, divided by the number of years with available data in the series.

- Risk avoidance (z_2) is measured as the difference between the profit variability of the profit maximizing crop portfolio $\widehat{\boldsymbol{X}}$ and that of an alternative crop portfolio $\boldsymbol{X}$ (Bartolini et al., 2007):

  $$z_2\,(\boldsymbol{X}) = \widehat{\boldsymbol{X}}^t VCV(\pi)\widehat{\boldsymbol{X}} - \boldsymbol{X}^t VCV(\pi)\boldsymbol{X} \quad \text{[A.III.2]}$$

  where $VCV(\pi)$ is the variance and covariance matrix of profit in the time period for which data is available (2008-2015). The first term in the right-hand side of the equation, $\widehat{\boldsymbol{X}}^t VCV(\pi)\widehat{\boldsymbol{X}}$, yields the risk of the profit maximizing crop portfolio, while the second term, $\boldsymbol{X}^t VCV(\pi)\boldsymbol{X}$, yields the risk of the observed crop portfolio. Provided there is a tradeoff between risk and profit (the higher the profit, the higher the risk) (Gutierrez-Martin and Gomez Gomez, 2011), risk avoidance ($z_2\,(\boldsymbol{X})$) will be positive.

- Hired labor avoidance (z_3) is measured as the difference between the number of hired labor used in the profit maximizing crop portfolio and that of an alternative crop portfolio x:

  $$z_3(x) = \bar{H} - H\,(x) \quad \text{[A.III.3]}$$

  Where H (x) = $\sum_i x_i H_i$ is the labor requirement per hectare to produce the crop portfolio x.

  $\bar{H}$ is the hired labor requirement per hectare to produce the profit maximizing crop portfolio.

Annex IV: The ICES CGE model

The theoretical structure is based on the Global Trade Analysis Project (GTAP) model (Hertel, 1997). The neoclassical structure implies that in each region investments are saving-driven, factors of production are fully employed and perfect competion holds in the markets. The behavior of the representative agents (household, government, firms and factors) is driven by the changes in the relative prices which clear the markets, meaning that for each commodity the supply is equal to its demand, thus creating the new equilibrium in the economic system. The CGE aggregated database includes 15 economic sectors and the 17 NUTS2 Spanish regions, the rest of EU28 and the rest of the world as shown in Table 1. There are 8 aggregate crop sectors which are mapped considering data from the PMAUP model. Data inputs for the macroeconomic module are described in Annex III.

Table A.IV.1. *Regional and sectoral aggregation of the regionalized CGE model.*

Regions		*Sectors*	
Spain (disaggregation in NUTS 2)	1) Galicia	Crops	1) rice
	2) Asturias		2) wheat
	3) Cantabria		3) other cereals
	4) Pais Vasco		4) vegetables and fruits
	5) Navarra		5) oil seeds
	6) La Rioja		6) sugar cane and beet
	7) Aragon		7) plant-based fibers
	8) Madrid		8) crops not elsewhere classified
	9) Castilla y Leon		
	19) Castilla y Mancha		
	11) Extremadura	Industry	9) livestock
	12) Cataluña		10) extraction, fishing and forestry
	13) Valencia		11) food industry
	14) Balears		12) rest of industry
	15) Andalucía		
	16) Murcia	Services	13) utilities
	17) Canarias		14) construction
	18) Rest of EU-28		15) services
	19) Rest of the world		

Supply side

A representative firm in each sector minimizes output costs (y) under a Leontief technology between value added (va) and intermediate inputs (in):

$$\underset{va_{j,s},\, in_{j,s}}{\mathrm{Min}} \left(pva_{j,s} va_{j,s} + pin_{j,s} in_{j,s} \right) \qquad [A.IV.1]$$

$$\text{s.t.:} \quad y_{j,s} = \min\{va_{j,s}, in_{j,s}\} \qquad [A.IV.2]$$

where $pva_{j,s}$ and $pin_{j,s}$ are respectively the price of the value added composite (calculated as the weighted average of the prices of each value-added component: labor, capital and land) and the price of intermediate inputs in sector j of region s.

Value added is modelled though a Constant Elasticity of Substitution (CES) function which allows for substitution between primary factors (Labour, capital, land and natural resources). Labor and capital are used by all sectors, while land is specific to the agricultural sectors (sectors 1-9) and natural resources to the extractive sector (sector 10). The CES function depends on v_f primary factors, with sector-specific elasticity of substitution σ_j. Input augmenting or biased technical change is represented with the parameter $\eta_{f,j,s}$ for each primary factor f in sector j and region s.

$$va_{j,s} = F\left(\eta_{f,j,s}, v_{f,j,s}, \sigma_j\right) \quad ; \quad \sigma_j > 0 \qquad [A.IV.3]$$

Primary factors are used domestically since they are not internationally tradable. Labor and capital are perfectly mobile across sectors within a region. In the standard version of the model land supply at the sectoral level is modelled through a Constant Elasticity of Transformation (CET) which allocates the (exogenous) overall regional land to agricultural sectors according to sector-specific land rents (Bosello and Standardi, 2015; Parrado et al., 2019). However, for this study we modify the land allocation among crops in order to be set exogenously according to changes in land use dictated by the PMAUP model following Ronneberger et al. (2009).

Demand side

Income from primary factors accrues to each regional representative household which disposes it following a Cobb-Douglas per capita utility function (Hertel, 1997).

$$U_s = Cons_s^{\omega_{Cons}} Gov_s^{\omega_{Gov}} Sav_s^{\omega_{Sav}} \qquad [A.IV.4]$$

Where U_s represents the utility of the representative household determining the demand side of the CGE model, obtained as the aggregate of private consumption ($Cons_s$); government consumption (Gov_s) and savings (Sav_s) in region s; and the parameters ω are the associated budget shares. Private and government consumption represent the aggregate demand for the commodities produced in the different sectors of the economy, where commodities can be produced either domestically or imported from other regions. Savings represent the resources available for investment needs.

A global bank collects regional savings and then allocates these resources as investments among regions. Investments are mobile at the international level and the difference between regional savings and investments determines the trade balance.

Trade is a central aspect in the CGE model. Commodities can be exchanged in the domestic, intra-national and inter-national markets. To model trade at these three levels, we consider an upper bundle between domestic and imported goods and a lower bundle to source imports from all sources. We keep the GTAP formulation assuming imperfect substitution (Armington, 1969) between the domestic demand ($dd_{j,s}$) and the aggregate demand for imported products ($dm_{j,s}$) in region s and sector j via a CES function. In each economic sector, the representative household, government or firm minimize the total expenditure under the CES constraint on domestic and imported goods.

$$\min_{dd_{j,s},\, dm_{j,s}} \left(pdd_{j,s} dd_{j,s} + pdm_{j,s} dm_{j,s} \right) \qquad \text{[A.IV.5]}$$

$$\text{s.t.:} \quad dtot_{j,s} = G_1\left(dd_{j,s}, dm_{j,s}, \sigma_j^{Up}\right) \; ; \qquad \sigma_j^{Up} > 0 \qquad \text{[A.IV.6]}$$

Where $dtot_{j,s}$ is the total demand and $pdd_{j,s}$ and $pdm_{j,s}$ are the prices associated with domestic and aggregate demand for imported goods, respectively.

Given the importance of the intra-national trade in this experiment and differently form GTAP which has no sub-country detail, in the lower level the aggregate amount of imports ($dm_{j,s}$) is sourced from the country or the sub-country region of origin through a Constant Ratio of Elasticities of Substitution and Homothetic (CRESH) constraint (Cai and Arora, 2015; Hanoch, 1971; Pant, 2007) which allows for more flexibility in the choice of product substitutability for each couple of spatial units.

$$\min_{imp_{j,s',s}} \textstyle\sum_{s'} pimp_{j,s',s} imp_{j,s',s} \qquad \text{[A.IV.7]}$$

$$\text{s.t.:} \quad dm_{j,s} = G_2\left(\mathbf{imp}_{j,s}, \boldsymbol{\sigma}_{j,s}^{Lo}\right) \quad ; \quad \mathbf{imp}_{j,s} \in R^S \; , \; \boldsymbol{\sigma}_{j,s}^{Lo} \in R^S \; , \; \sigma_{j,s',s}^{Lo} > 0 \qquad \text{[A.IV.8]}$$

Where $imp_{j,s',s}$ is the bi-lateral trade flow from region/country s′ to region/country s in sector j and $pimp_{j,s',s}$ is the associated price; $\mathbf{imp}_{j,s}$ and $\boldsymbol{\sigma}_{j,s}^{Lo}$ are two S-dimensional vectors (S being the number of country/regions in the CGE) representing respectively all the bi-lateral imports and elasticities of substitution of region/country s in sector j.