TALANOA

- water -

Deliverable 3.2: Intermediate database of simulations - sourcebook

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☐ CI = Classified, information as referred to in Commission Decision 2001/844/EC.

Executive summary

This sourcebook supplements the simulations obtained through the TALANOA-WATER multi-system modeling framework and reported in the Intermediate Database of simulations. The sourcebook is intended as a user-friendly interface that helps those interested in TALANOA-WATER results understand and navigate the simulation outputs obtained in the Intermediate Database of simulations for the relevant system models, namely, microeconomic, macroeconomic, hydrological, agronomic, or climate system models. The sourcebook is structured in three main parts that follow the Introduction (Section 1) and present the models used (Section 2.1), describe the variables assessed in models (2.2), and provide guidance on how to navigate the simulation results (2.3). The sourcebook is complemented with an Annex that expands the information contained in Section 2.1 with a more in-depth description of the models used.

The simulation results described in this sourcebook refer to the intermediate database of simulations as of month 24. A separate sourcebook for the final database of simulations will be produced in Deliverable 3.3 in month 35.

Acronym List

Acronym/Abbreviation	Definition
AUB	American University of Beirut
CMCC	Centro Euro-Mediterraneo sui Cambiamenti Climatici
DSS	Decision Support System
GPAI	Green Power for Agriculture and Irrigation
INAT	Institut National Agronomique de Tunisie
INRAE	National Research Institute for Agriculture, Food and the Environment
USAL	Universidad de Salamanca
WEAP	Water Evaluation and Planning
WP	Work Package
WiP	Work in Progress
PMP	Positive Mathematical Programming
PMAUP	Positive Multi-Attribute Utility Programming
WGP	Weighted Goal Programming

Contents

1. Introduction

The TALANOA-WATER project has the ambition of creating a multi-system modeling framework to simulate and assess the impacts of adopting transformational adaptation policies to water scarcity under climate change in 6 water labs. This multi-system framework builds on a protocol-based modular approach that is described in detail in D3.1. Simulation results obtained through this modeling framework are to be made publicly available in an open database following FAIR principles (Findability, Accessibility, Interoperability, and Reusability). The open database is to be produced in two steps: an intermediate database (presented in this deliverable), and the final database (which will be described in D3.3).

This deliverable offers a sourcebook to navigate the simulation results obtained across the 6 water labs of TALANOA-WATER as of month 24. The sourcebook presents a simple and standardized structure in which simulation results are reported for every lab using the same structure. The reader is first shown the models used and variables reported, and is then guided through the different simulation files to understand the main aspects of the experimental design of the simulation, the forcings and scenarios, and the outcomes. The Annex of this deliverable provides a more detailed description of each model used.

Table 1 presents the systems and labs for which simulation results are available. For some systems, the simulation results are pending (Work in Progress, WiP). In some labs, there are specific systems that were deemed not relevant by stakeholders in science-policy workshops and thus were not incorporated into the modeling framework (NA).

Table 1: Systems and labs for which intermediate simulation results are available. Legend AA: Already Available, WiP: Work in Progress, N/A: Not Available, *: validation pending.

Lab	*Agronomic system*	*Climate system*	*Hydrologic system*	*Macroeconomic system*	*Microeconomic system*
Egypt	AA	N/A	WiP	WiP	AA
France	AA*	WiP	AA	WiP	WiP
Italy	WiP	AA	AA	WiP	WiP
Lebanon	N/A	N/A	AA	WiP	AA
Spain	AA	N/A	AA	WiP	AA
Tunisia	AA	N/A	AA	WiP	AA

2. Simulation sourcebook

This section presents the sourcebook of the intermediate database of simulations. It is divided in three sub-sections in which we list the models used (2.1), describe the variables simulated in models (2.2), and present the simulation results (2.3).

2.1. Models Used

Below we briefly present the system models used on a system-by-system basis. A more detailed description of the models included in the multi-system modeling framework thus far is available in the Annex.

2.1.1. Agronomic system models

ALES-Arid (Agriculture Land Evaluation System for arid and semi-arid regions) is used for evaluating land suitability and capability for producing different crops based on physical and chemical properties of soil, in addition to irrigation water quality. It has been adopted in the Egyptian water lab.

SALTMED model is a generic model that can be used for a variety of irrigation systems, soil types, crops and trees, water application strategies, and different water qualities. It has been adopted in the Egyptian water lab.

SIMETAW#/R/GIS is a daily crop-soil-water balance model, used in the French water lab.

MABIA, based on FAO 56, is a model for crop growth and production integrated into the WEAP hydrological model (see below), used in the Tunisian water lab.

HSEB (Hybrid Surface Energy Balance) model, developed by AUB, uses satellite images to calculate the historical evapotranspiration (ET) of the study area. It has been adopted in the Spanish water lab.

We have also incorporated into the modeling framework the global gridded agronomic models of ISIMIP. These results are published by ISIMIP and are therefore neither produced by our modeling framework nor incorporated into our database. However, their outcomes are used to force the modeling framework of TALANOA-WATER to obtain simulation results. A description of ISIMIP models is available in the Annex.

2.1.2. Climate system models

COSMO CLM is a regional climate model that produces precipitation and temperature driven by (i) perfect boundary conditions given by the ERA40 Reanalysis and (ii) suboptimal boundary conditions from the global climate model (GCM) CMCC–CM used in the simulation of the Italian water lab.

We have also incorporated into the modeling framework the global climate models of ISIMIP.

2.1.3. Hydrologic system models

WaPOR (Water Productivity Open-access portal) uses remote sensing technologies to monitor and report on agricultural water productivity in Africa and the Near East. This model was used in the Lebanese water lab.

AQUATOOL is a Decision Support System (DSS) model used by Spanish River Basin Authorities to inform about water allocation between users, and it is used in the Spanish water lab.

WAEP-MODFLOW is a combined model whose components are used for solving the groundwater flow equation (MODFLOW) and for integrated water resources planning using the Water Evaluation and Planning (WEAP) code used in the Tunisian water lab.

The **French hydrologic modeling** is based on a semi-distributed rainfall-runoff hydrological model, used in the French water lab.

TOPKAPI (TOPographic Kinematic Approximation and Integration) is a physically-based and spatially-distributed hydrological model used to obtain the runoff that is the input to **RIBASIM** (RIver BAsin SIMulation), a water balance model at basin scale to simulate the average daily discharge at different sections of the river network used in the hydrologic simulation of the Italian water lab.

We have also incorporated into the modeling framework the global hydrological models of ISIMIP.

2.1.3. Macroeconomic system models

CGE (Computable General Equilibrium) models capture feedback in the economic system in terms of inter-sectoral production reallocation. The experimental design of the simulations using CGE modeling is being finalized. The CGE model will be applied in all labs.

2.1.3. Microeconomic system models

All the microeconomic models used in TALANOA-Water are mathematical optimization models, also known as mathematical programming models. These models are widely used in agroeconomics and water resources management, and different modeling techniques can be implemented depending on the data availability and the case study. Below we list the models used.

PMP (Positive Mathematical Programming): non-linear single-attribute programming model. **PMP_1:** calibrated following the technique of Howitt (1995) with a quadratic cost function. **PMP_2:** calibrated following the technique of Júdez et al. (2002) with a quadratic cost function.

PMAUP (Positive Multi-Attribute Utility Programming): non-linear multi-attribute programming model. **PMAUP_1:** calibrated following the technique of Gutiérrez-Martín and Gómez (2011). **PMAUP_2:** calibrated following the technique of Gómez-Limón et al. (2016).

WGP (Weighted Goal Programming): linear multi-attribute programming model, calibrated following the technique of Sumpsi et al. (1997).

2.2. Variables

All the variables simulated in the different system models are presented in the following tables, including a description of the short name used, the unit of measure, the relevant model, and their availability in the current database of simulations (some results are still being elaborated and will be incorporated to the final database of simulations in month 36). Table 2 presents the relevant output variables of the agronomic system, table 3 the relevant output variables of the climatic system, table 4 the relevant output variables of the hydrologic system, and finally table 5 and table 6 the relevant output variables of the macro- and micro-economic systems respectively.

Table 2: Relevant variables in agronomic system models

Variable	*Short name*	*Unit of measure*	*Model*	*Available*
Transpiration	T	mm/d	MABIA	Yes
Crop potential evapotranspiration	ETP	mm/d	MABIA	Yes
Crop water requirement	WR	m^3	MABIA	Yes
Crop yield	Yield	Kg	MABIA	Yes
Evapotranspiration	ET	mm	HSEB	Yes

Dry Matter	DM	t/ha	SALTMED	No
Grain Yield	GY	t/ha	SALTMED	No
Crop Suitability	CS	%	ALES-Arid	Yes
Predicted yield	Yp	t/ha	ALES-Arid	Yes
Reference Evapotranspiration	ET0	mm	SIMETAW#/R/GIS	Yes
Crop Coefficient	Kc	-	SIMETAW#/R/GIS	No
Crop Evapotranspiration	ETc	mm	SIMETAW#/R/GIS	Yes
Actual Evapotranspiration	ETa	mm	SIMETAW#/R/GIS, SALTMED	Yes
Net Application	NAc	m^3	SIMETAW#/R/GIS	Yes
Soil Salinity	Ss	dS/m	SALTMED	No
Soil Moisture Profiles	θs	m^3 water/m^3 soil	SALTMED	No
Salinity Leaching Requirements	Lr	%	SALTMED	No
Soil Nitrogen Dynamics	Ns	g N/kg	SALTMED	No
Nitrate Leaching	NO3	mg N/l	SALTMED	No
Soil Temperature	Ts	(ºC)	SALTMED	No
Land suitability	S	%	ALES-Arid	Yes
Land Capability	C	%	ALES-Arid	No

Table 3: Relevant variables in climatic system models

Variable	*Short name*	*Unit of measure*	*Model*	*Available*
Precipitation	P	mm	WEAP-MODFLOW	Yes
Max Temperature	Tmax	°C	WEAP-MODFLOW	Yes
Min Temperature	Tmin	°C	WEAP-MODFLOW	Yes
Wind speed	Ws	m/s	WEAP-MODFLOW	Yes
Relative humidity	RH	%	WEAP-MODFLOW	Yes
Evaporation	Evap	mm/d	WEAP-MODFLOW	Yes

Projected Gross inflow in CC downscaled daily	QgP1	m^3/s	COSMO CLM	Yes
Projected Gross inflow in CC downscaled_monthly	QgP2	m^3/s	COSMO CLM	Yes
Projected Frequency distribution in CCdownscaled	QgP3	m^3/s	COSMO CLM	Yes

Table 4: Relevant variables in hydrologic system models

Variable	*Short name*	*Unit of measure*	*Model*	*Available*
Rivers head flows	Hflow	CMS	WEAP-MODFLOW	Yes
Aquifers recharge	RECH	Mm^3	WEAP-MODFLOW	Yes
Drinking water demand	DWD	m^3	WEAP-MODFLOW	Yes
Irrigation water demand	IWD	m^3	WEAP-MODFLOW	Yes
Demand coverage	COV	%	WEAP-MODFLOW	Yes
Groundwater storage	GWS	Mm^3	WEAP-MODFLOW	Yes
Cell head (MODFLOW)	CHead	m	WEAP-MODFLOW	Yes
Deficit of irrigation water	Deficit	hm^3/month	AQUATOOL	Yes
Gross Inflow modeled (modeled values from ARPE/CMCC) - average daily	Qgm	m^3/s	TOPKAPI-RIBASIM	Yes
Natural inflow	Qnat	Mm^3/day	French hydrologic model	Yes
Transbasin inflow	Qintrans	Mm^3/day	French hydrologic model	Yes
Reservoir releases	Qrelease	Mm^3/day	French hydrologic model	Yes
Reservoir volumes	Vreservoir	m^3	French hydrologic model	Yes
Net abstraction	Qabstract	Mm^3/day	French hydrologic model	Yes

Canal flow	Qcanal	Mm^3/day	French hydrologic model	Yes
Influenced river flow	Qriver	Mm^3/day	French hydrologic model	Yes
Water Uptake	W	g/g	SALTMED	No
Storage Change	ΔS	Mm^3/y	WaPOR	Yes
Incremental ET	Etinc	Mm^3/y	WaPOR	Yes
Rainfall ET	Etg	Mm^3/y	WaPOR	Yes
Landscape ET	PLU, ULU, MLU, MWU	Mm^3/y	WaPOR	Yes
Consumed Water	Consumed Water	Mm^3/y	WaPOR	Yes
Non-Consumed Water	Non-Consumed Water	Mm^3/y	WaPOR	Yes
Net Inflow	Qnet	Mm^3/y	WaPOR	Yes
Gross Inflow	Qg	Mm^3/y	WaPOR	Yes
Exploitable Water	Exploitable Water	Mm^3/y	WaPOR	Yes
Outflow	Q	Mm^3/y	WaPOR	Yes

Table 5: Relevant variables in macroeconomic system models

Variable	*Short name*	*Unit of measure*	*Model*	*Available*
Sectoral output (crops)	qo	% change	CGE	No
Sectoral prices (crops)	pm	% change	CGE	No
GDP	qgdp	% change	CGE	No
Sectoral output (crops)	qo	% change	CGE	No

Table 6: Relevant variables in microeconomic system models

Variable	*Short name*	*Unit of measure*	*Model*	*Available*
Profit	GM	EUR/ha, USD/ha, TUD/ha, EGP/fed.	PMP_1, PMP_2, PMAUP_1, PMAUP_2, WGP	Yes
Hired labor	Hlab	Working days/ha	PMP_1, PMP_2, PMAUP_1, PMAUP_2, WGP	Yes
Total labor	Tlab	Working days/ha, EGP/fed.	PMP_1, PMP_2, PMAUP_1, PMAUP_2, WGP	Yes
Water use	Water	m^3/ha	PMP_1, PMP_2, PMAUP_1, PMAUP_2, WGP	Yes
Water price	Water price	EUR/m^3, USD/m^3, TUD/m^3, EGP/m^3	PMP_1, PMP_2, PMAUP_1, PMAUP_2, WGP	Yes
Monetized forgone utility	Pay	EUR/ha, USD/ha, TUD/ha, EGP/fed.	PMAUP_1, PMAUP_2, WGP	Yes
Crops	Name of the crop	%	PMP_1, PMP_2, PMAUP_1, PMAUP_2, WGP	Yes
Simulation index	p1, p2, …, pn	-	PMP_1, PMP_2, PMAUP_1, PMAUP_2, WGP	Yes

2.3. Results

The intermediate database of simulations is presented in a separate spreadsheet (publicly available at https://docs.google.com/spreadsheets/d/1Rspu3a5GZM4cNreat2HYyC_WyrJIuByq/edit?usp=share_link&ouid=114728377452086309212&rtpof=true&sd=true). The first sheet, “Index of variables”, contains a table with the variables listed in Section 2.2. The second sheet, “Index for database of sims”, presents in rows the simulations carried out in every water lab as of month 24. Each simulation is presented in an individual row, which contains the metadata for that simulation, including: simulation Code; Water lab; Country; System Model; Transformational adaptation strategy(ies) tested; other relevant Stressor; Nº sim in that lab; Output file (**link to the simulation file**); Climatic scenario; Socioeconomic scenario; Other scenarios; and some additional columns describing the stakeholder(s) involved; the relevant system(s); and the output variable(s) of the simulation as listed in Table 1 (note that a value of 0 means actor/system/variable not involved/simulated).

For example, if the readers are interested in learning about the effect of a pricing policy in the Litani Basin, they will find it in line 4. The information contained in this row indicates that this Transformational adaptation strategy was designed with the collaboration of the Academic community, the output of this simulation contains information on the impacts on the microeconomic and the hydrologic system, and the variables reported in this simulation are profit, total labor, water allocation, and crop allocation.

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Annex 1: Models

A1.1. Agronomic system

SIMETAW#/R/GIS are daily crop-soil-water balance models developed to compute the reference evapotranspiration (ETo), the crop evapotranspiration (ETc), the actual evapotranspiration (ETa), and the evapotranspiration of applied water (ETaw). The model includes revised crop coefficient (Kc) values to ETc, and stress coefficient (Ks) values to account for water deficit effects on evapotranspiration and yield. In addition, SIMETAW# corrects midseason Kc values for the effect of climate. SIMETAW# also addresses the impact of rising CO2 concentration on reference evapotranspiration (ETo), so it is useful for planning responses to climate change. The ETaw, or irrigation requirement, represents the portion of crop water requirement that is supplied by irrigation and not by water tables, effective precipitation, i.e., rainfall, dew, and fog, and the reduction in water storage in the crop root zone from pre- to post-season. Determining ETaw requires a daily water balance throughout the season to estimate effective precipitation, contributions from water tables, and the change in soil water content during the season. In SIMETAW#, the ETaw is calculated as the sum of the mean depth of water infiltrating into the low quarter of the irrigated field. For the irrigated crop, the mean depth of infiltrated water (IW) over the field is calculated as the quotient of ETaw and the Du. Then, the gross application (GA), or diverted irrigation water, is calculated as the sum of the IW and Roff, if any. Using this approach results in a net application (NA) depth that matches the mean infiltration of water into the lower quarter of the soil. When adequate water is available, the NA should return the soil water content in the low quarter back to near-field capacity. The remaining 75 % of the cropped soil infiltrates more water than needed to refill to field capacity, and the excess water mainly contributes to deep percolation of water below the rooting zone. For most crops, this approach to scheduling is likely to result in the highest productivity.

Available input data:

- Crop and Soil data: soil characteristics and crop-irrigation management practices are input to the model to calculate the soil water balance and determine hypothetical irrigation schedules. The potential crop rooting depth (mm), the allowable depletion (AD, %) of available water, and the volumetric available water holding capacity (θA, mm mm^{-1}) are input or selected and used to determine the plant available water (PAW, mm) within the soil rooting depth. Moreover, data about crop management and phenology are needed, such as the date of plantation, presence of cover crops, and irrigation system.
- Climate data: historical data (1976-2005) and future projections (2006-2100) of possible changes were used for the following variables on the scenarios RCP 2.6, 4.5, and 8.5: minimum and maximum temperature, wind speed, solar radiation, relative humidity, and precipitation.

The main model outputs are the reference evapotranspiration (ET0), the crop coefficient for each phenological stage of the crop (Kc), the crop evapotranspiration (ETc), and the real evapotranspiration (ETa), and the net application of water (NAc).

Spanish Agronomic model. In surface energy balance models, latent heat flux and consequently ET is usually estimated from the residual of the energy balance equation, where ET is partitioned between Evaporation (E) and transpiration (T). As in other models, HSEB performs the energy balance at the satellite overpass time (instantaneous) to obtain the latent heat flux as the residual of the surface energy equation, neglecting the change in heat storage in the canopy biomass and the energy fluxes for photosynthesis. For a more thorough explanation of HSEB model, the reader can refer to Jaafar et al., (2022).

ISIMIP global agronomic models

We explore forecasts from 4 Global Gridded agricultural Models, whose outputs are used as inputs for microeconomic models, where yields have been updated to account for climatic impacts.

- **GEPIC (The Erosion Productivity Impact Calculator)** is one of the models that form the basis of the simulations for the results of the agricultural sector for a complete technical description of the ISIMIP2b simulation data from the Agricultural Sector. The Integrated Environmental Climate Policy (EPIC) (was developed by USDA) is a model used and tested in the menu continuous since 1981, capable of simulating many agrosystem processes including plant growth, yields for many different crops in the field, where each crop has unique values for model parameters, tillage, wind erosion and water, runoff, soil density, and drainage. Since soil productivity is expressed in terms of crop yields, the model should be able to realistically simulate crop yields for soils with a wide range of erosion damage. *Climate Drivers:* IPSL-CM5A-LR, HadGEM2-ES, GFDL-ESM2M, MIROC5. *Date: 2017-10-16*

- **CLM4.5 (The Community Land Model)** is the land model for the Community Earth System Model (CESM). It examines the physical, chemical, and biological processes by which terrestrial ecosystems affect and are affected by climate across a variety of spatial and temporal scales. The central theme is that terrestrial ecosystems, through their cycling of energy, water, chemical elements, and trace gases, are important determinants of climate. Model components consist of: biogeophysics, hydrologic cycle, biogeochemistry, and dynamic vegetation. The land surface is represented by 5 primary sub-grid land cover types (glacier, lake, wetland, urban, vegetated) in each grid cell. The vegetated portion of a grid cell is further divided into patches of plant functional types, each with its own leaf and stem area index and canopy height. Each subgrid land cover type and PFT patch is a separate column for energy and water calculations. The current version of the Community Land Model is CLM4.5. Simulations for ISIMIP2b were conducted with CLM4.5, and include an interactive Carbon and Nitrogen cycle (CN) and an interactive crop model (CROP). ISIMIP2a simulations were conducted either with CLM4.0 (global water) or CLM4.5post. *Climate drivers*: IPSL-CM5A-LR, HadGEM2-ES, GFDL-ESM2M, MIROC5. *Date*: 2018-02-08.

- **LPJmL (The Lund-Potsdam-Jena Managed Land):** is a multi-sectoral Dynamic Global Vegetation Model, suited to address the water sector as it includes the full terrestrial water balance with irrigation modules. Among other changes, the current version features the differentiation of three irrigation system types and a more process-based representation of irrigation efficiencies. First, it addresses nonlinear biophysical and biogeochemical features of continuing large-scale replacement of natural vegetation by agroecosystems, under CO2 increase and climate change. Second, human societies worldwide make substantial economic and cultural use of ecosystem services (food, fiber, and energy crops, but also climate regulation, water purification, etc.) – but the assessment of their future provision is still in an early stage (Alcamo et al., 2005). LPJmL is designed for the consistent quantification of multiple drivers (climate, CO2, land management, land use change) on the future provision of these services (Bondeau et al., 2007). *Climate drivers*: IPSL-CM5A-LR, HadGEM2-ES, GFDL-ESM2M, MIROC5. *Date*: 2018-01-18.

- **PEPIC (Environmental Policy Integrated Climate):** is a Python-based Environmental Policy Integrated Climate (EPIC) model. PEPIC is one of the 14 models following the ISIMIP2a protocol which form the base of simulations for the ISIMIP2a agricultural sector outputs; for a full technical description of the ISIMIP2a (ISIMIP, 2023). *Climate Drivers:* IPSL-CM5A-LR, HadGEM2-ES, GFDL-ESM2M, MIROC5. *Date: 2017-10-16*

A1.2. Climate system

ISIMIP global climatic models

We explore forecasts from 4 GCMs, whose outputs are used as inputs for hydrological models. All model data has been bias-corrected by applying an updated version of the method used in the ISIMIP Fast Track, where a composite dataset EWEMBI was used as the target observational data set. Original GCM data have been extracted from the CMIP5 archive. The GCMs models used are:

- **GFDL-ESM2M (Geophysical Fluid Dynamics Laboratory):** GFDL has constructed NOAA's first Earth System Models (ESMs) (Dunne et al., 2013, 2012) to advance our understanding of how the Earth's biogeochemical cycles interact with the climate system. Like GFDL's physical climate models, these simulation tools are based on an atmospheric circulation model coupled with an oceanic circulation model, with representations of land, sea ice, and iceberg dynamics. ESMs incorporate interactive biogeochemistry, including the carbon cycle. The atmospheric component of the ESMs includes physical features such as aerosols (both natural and anthropogenic), cloud physics, and precipitation. The land component includes precipitation and evaporation, streams, lakes, rivers, and runoff as well as a terrestrial ecology component to simulate dynamic reservoirs of carbon and other tracers. The oceanic component includes features such as free surface to capture wave processes; water fluxes, or flow; currents; sea ice dynamics; iceberg transport of freshwater; and a state-of-the-art representation of ocean mixing as well as marine biogeochemistry and ecology. While carbon is necessarily included as the basic building block of ecosystems undergoing terrestrial and oceanic chemistry, associated chemical and ecological tracers which control nutrient limitation, plant biomass, productivity, and functional composition are also included. Chemical tracers are also tracked in the atmosphere. ESMs capture numerous types of emissions, variations of land surface albedo due to both natural vegetation changes and land use history such as agriculture and forestry, and aerosol chemistry. Adding these different components to the ESM represents a major step forward in simulating the Earth's ecological systems in a comprehensive and internally consistent context.

- **HadGEM2-ES (Hadley Centre Global Environment Model):** The HadGEM2 family of models comprises a range of specific model configurations incorporating different levels of complexity but with a common physical framework. The HadGEM2 family includes a coupled atmosphere-ocean configuration, with or without a vertical extension in the atmosphere to include a well-resolved stratosphere, and an Earth-System configuration which includes dynamic vegetation, ocean biology, and atmospheric chemistry.

- **IPSL-CM5A-LR:** This model is a full earth system model, with two different sets of physical models: the IPSL-CM5A is an extension of IPSL-CM4 with NEMO for the ocean. The IPSL-CM5 ESM platform allows for a large range of model configurations, which aim at addressing different scientific questions. These configurations may differ in various ways: physical parameterizations, horizontal resolution, vertical resolution, number of components (atmosphere and land surface only, ocean and sea ice only, coupled atmosphere–land surface–ocean–sea ice), and number of processes (physical, chemistry, aerosols, carbon cycle). The IPSL-CM5 model is built around a physical core that includes the atmosphere, land-surface, ocean, and sea-ice components. It also includes biogeochemical processes through different models: stratospheric and tropospheric chemistry, aerosols, terrestrial, and oceanic carbon cycle (Dufresne et al., 2013).

- **MIROC 5 (Model for Interdisciplinarity Research on Climate):** MIROC 5 was developed for better simulation of the mean climate, variability, and climate change due to anthropogenic radiative forcing. A century-long control experiment was performed using the new version (MIROC5) with the standard resolution of the T85 atmosphere and 1° ocean models. The climatological mean state and variability were then compared with observations and those from a previous version (MIROC3.2) with two different resolutions, coarser and finer than the resolution of MIROC5 (Watanabe et al., 2010).

A1.3. Hydrologic system

AQUATOOL is a DSS for the edition, operation, review, and analysis of hydrologic models for river basin management that produces information on the quantitative and qualitative status of water bodies. The AQUATOOL DSS features several modular blocks, each with its software/model suitable for alternative tasks: AQUATOOL is the general interface for editing data and managing the other blocks; SIMGES is the block for simulating watershed management, including conjunctive use; GESCAL is the block for simulating water quality at the basin scale; OPTIGES is the block for optimizing watershed management; SIMRISK is the block for risk assessment and management; EGRAF is the block for the graphical visualization of the results obtained through SIMGES, OPTIGES, GESCAL, and SIMRISK; and EXTOPO is the block for exporting spatial data to vector format (PUV, 2020). Our study in the Cega sub-catchment uses the AQUATOOL (setup) and SIMGES (simulation) blocks to conduct a longitudinal and spatial assessment of water allocations under climate change conditions.

The different elements of the water system that are incorporated into the AQUATOOL block include surface water bodies, groundwater bodies, discharge series under natural conditions, river-aquifer interaction, infrastructures (reservoirs, canals, irrigation systems), water demand units (including AWDUs—the agent in the microeconomic model, but also other agricultural uses, households, industry, fish farming, hydropower, cooling, and other minor uses), return flows, conveyance, distribution and application inefficiencies (a key input to obtain water consumption by economic agents), evaporation from reservoirs, environmental flows, water rights, and water operation rules. All the necessary data for the setup of AQUATOOL is accessible from online databases made available by the Douro River Basin Authority (DRBA, 2017, 2016a, 2016b), except for the discharge series under natural conditions, which need to be produced. Discharge series under natural conditions are derived by processing daily series of precipitation for the 1950-2015 period using the EVALHID tool, which integrates several rainfall-runoff models (Lerma et al., 2017). The resultant 1950-2015 series is further expanded using data from the SIMPA (Sistema Integrado para la Modelación del proceso Precipitación Aportación) rainfall-runoff model for the 1940-1950 and 2015-2018 periods (CEDEX, 2020). Data records from reservoirs and monitoring stations representative of the natural regime were used to address discrepant values. For all modeling exercises in this paper, we adopt the latest version of AQUATOOL which was set up and calibrated by the Douro River Basin Authority to inform its 2021 Douro River Basin Management Plan (DRBA, 2020).

Once the AQUATOOL block has been set up, the SIMGES block can be used to run longitudinal simulations that offer spatial information on the impacts of several exogenous shocks (e.g., climate change) on surface and subsurface water flows on a monthly basis. For surface water bodies, water flows are obtained by continuity or balance, while for groundwater bodies this is obtained through unicellular and multicellular models. Next, the management of the water system by the river basin authority that determines water allocations among alternative uses (including irrigators and the environment through environmental flows, but also other productive uses such as households or industry) is simulated using a network optimization algorithm. This algorithm determines water allocations across the basin conditional to the achievement of several objectives, including i) meeting environmental flow targets but also ii) minimizing water deficits among uses, iii) achieving a certain water stock in reservoirs, and iv) achieving hydropower generation targets. The management algorithm is calibrated using up-to-date data on water rights and observed water allocations among uses, to match simulation outputs with the historical discharge and water stock in reservoirs (PUV, 2020).

French Hydrologic model. The model is based on a semi-distributed rainfall-runoff hydrological model on which the water basin is subdivided into hydrological units delineated by gauging stations and points of interest in the river network (e.g., derivation to reservoir, navigation or irrigation canal, reservoir release point). Each hydrological unit uses daily mean precipitation, potential evaporation, and temperature of its area for simulating runoff. The conceptual model only depends on few parameters that are optimized to minimize the difference between simulated and observed flows. Human influences (reservoir release, derivation, and withdrawals) are added to the system and the integrated model routes all these flows in the river/canal network. Human influences because there are both model inputs and dependent on the model output would be modeled inside the integrated hydrological model:

- reservoir management models mimicking the current management rules provided by the stakeholders or deduced from observed flows.
- irrigation abstraction from the agronomic model coupled with economic models and calibrated on observations provided by abstraction database.
- industrial and drinking water abstraction from abstraction database.

Follow the input data used for the calibration of the model, listed per type of data.

Meteorology. Meteorological data are inputs for the hydrological model and agronomic model; they consist of 3 variables: total precipitation (solid + liquid), Potential Evaporation, and temperature (for the snow model). The data is distributed on a mesh of 8 by 8 km covering the study area at a daily time step.

Several meteorological sources are available:

- Historical (SAFRAN database 1958-2022)
- 11 GCM/RCM models forced by RCP2.6, RCP4.5, and RCP8.5 (1950-2100)

Hydrology. Observation of influenced flows at gauging stations for variable available periods.

Withdrawals

- Annual volumes declared at basin agency.
- Annual volumes declared by state authority with start and end month for irrigation.

The model would need to reconstitute missing years and desegregate the data at a daily time step with repartition keys extracted from the literature.

Reservoirs. Management rules and observation of stored volumes and releases

Calibration strategy. The calibration consists of running the model on the period 2000-2020 and optimizing the parameters of each hydrological unit with observed flows at gauging stations. In case no observed flows are available at downstream locations of the hydrological units, parameters are copied from a nearby unit. As data about human influences is difficult to obtain when exists or it does not exist, it is difficult to calibrate the model with all influences at once. Therefore, we suggest making several iterations of calibration as new information is integrated into the model.

Calibration iterations will focus on the following part of the model:

- Modeling of rainfall-runoff model only.
- Add observed abstraction.
- Add water transportation (navigation/irrigation) and canal regulation.
- Add reservoir regulation.

Once calibrated, the model can be forced by:

- GCM/RCM climate models.
- Coupling with the agronomic model.
- Regulation management models (reservoirs and canals).

Outputs of the model. The main outputs of this model are the simulated flows at different locations in rivers and canals, as well as volumes in reservoirs at daily time steps. We also have an indirect output which is the constraint on water availability for the agronomic model. Simulated flows in the river and restriction of uses will be used for computing synthetic indicators on water availability for irrigation and environment to assess the transformative scenarios proposed by the stakeholders.

MODFLOW 2000 was used to build the hydrodynamic model of the main aquifer in the Djeffara plain (Zeuss Koutine), whose domain covers an area of approximately 783 Km^2. It is rolled into a matrix of 57 columns and 48 rows. There is 2,736 square mesh and regular with 1 km per side, of which 783 were active. The model consists of a single aquifer. The MODFLOW model was calibrated both in a steady state (the year 1982) and a transient regime (1983 to 2009). Domestic, touristic, and agricultural demands were modeled in the **WEAP** schematic as "Demand site" nodes, mainly characterized by their "Annual Activity Level," "Annual Water Use Rate" and "Salinity Inflow." Each of the water sources was modeled as WEAP "Groundwater node," characterized by its "Storage Capacity," "Initial Storage," "Variable Operating Cost", and "Water Salinity Concentration." Pipes used for pumping and water supply were modeled as WEAP "Transmission Links," characterized by their "Maximal Flow" and "Variable Operating Cost." The linkage between WEAP nodes and MODFLOW cells was ensured by a linkage shape file which linked MODFLOW cells to catchments, groundwater nodes, and demand sites supplied from wells. The linkage shape file reflects the physical linking between wells and the supplied demand sites.

The groundwater model, hydraulic characteristics, and future water projects in the study area were taken into consideration in the WEAP Area schematic that contains 16 demand site nodes. In addition to the six domestic and touristic demand sites (Medenine, Tataouine, Jerba, Zarzis, Benguerdene, Other), demand site nodes were used to represent irrigation demand (Irrigation), recharge to Zeuss Koutine from the Trias aquifer (Rch_Trias1 and Rch_Trias2) and recharge from the Gabes aquifer (Rch_faille). Two 'Other supply' nodes (Inflow 1 and Inflow 2) were used to model this recharge. Demand site nodes were also used to model evaporation from the aquifer (Evaporation) and recharge of the rivers (Rch_Oued_Zigzaou, Rch_Oued_Zeuss, Rch_Oued_Oum_Zassar, Rch_Oued_Sidi_Makhlouf, and Rch_Oued_Morra). Groundwater resources and desalination plants were represented in the schematic by groundwater nodes. The Zeuss Koutine aquifer was represented by two groundwater nodes: 'GW_Natural_Recharge,' to model the natural recharge from rain, and 'GW_Sebkha,' to model the evaporation process. The desalination plants of Jerba were represented by two groundwater nodes to model the principal plant and the mobile unit separately. Twenty-four transmission links were used to supply the demand site by nine groundwater nodes. To simulate recharge, eight return flow links between the demand site and the natural recharge groundwater node were used. Two methods were used to compute water demand. The first uses annual activity level, annual water use rate, and monthly variation. This was used for Medenine, Jerba, Zarzis, and Benguerdene, and the Evaporation and Irrigation nodes. The second method is to introduce a monthly demand. It was applied to 'Other' and Tataouine and the demand site nodes used to model recharge. For the domestic and touristic demand site nodes, the official population statistics of 1984, 1994, and 2004 made up the observed data of the Annual Activity Levels. To compute future population growth, linear regression was used. For Jerba and Zarzis, the Annual Activity Levels were computed as the sum of the domestic and touristic values. Different Annual Water Use Rates were used to compute their water demand. To compute the monthly water demand of this set of demand site nodes, their observed average monthly variations were used. The Monthly Demand of Tataouine was defined by a constant flow (60 ls^{-1}). For 'Other', it was not possible to define either 'Annual Activity Level' or 'Annual Water Use Rate.' This is because this demand site node represents small agglomerations, a few industries, and ungrouped consumers supplied directly from the main pipes. The drinking water administration of the Medenine governorate grouped their demand in a monthly report under the heading 'Other demands.' To keep the same aggregation done by the water resource manager, the monthly demand measured between 1997 and 2010 was used for this site. To compute water demand for all time steps of the study period, a linear regression was used. The maximum aquifer withdrawal was considered unlimited. For groundwater nodes representing the desalination plants, the maximum monthly abstraction was equal to the plant capacity. Given the variability of energy pricing over time, it was decided that the specific consumption of energy would be taken as the variable operating cost of each of the groundwater nodes. It is assumed in this study that the loss from the supply network was 10 % of the flow passing through the pipes. More details of the conceptual model can be found in Hadded et al. (2013). Agriculture activities were modeled using a MABIA catchment, integrating crops and areas used in the microeconomic model. Their potential yields and market prices are used to assess the impact of water availability on crop yields and production value.

Italian Hydro-climatic modeling. These climate/hydrological simulations aim to investigate the impacts of climate change on extreme discharges and the adaptability to climate change of the Po River. The simulations are performed through a climate/hydrological modeling chain composed in a cascade by (a) a module for the climate, i.e., precipitation and 2-m temperature, and (b) a hydrological/hydraulic module to simulate the climate impacts at the soil. The hydrological/hydraulic part of the modeling chain is common to all the simulations, and it is composed of TOPKAPI (TOPographic Kinematic Approximation and Integration), a physically-based and spatially-distributed hydrological model used to obtain the runoff that is the input to RIBASIM (RIver BAsin SIMulation), a water balance model at basin scale to simulate the average daily discharge at different sections of the river network. The simulations over the period 1971–2000 are driven by different climate datasets: (a) high resolution observed data; precipitation was provided by ARPA SIMC based on Hydrological Yearbooks while the temperature is based on EOBS dataset, additional temperature information was available for the period 1991–2010 from ARPA SIMC; precipitation and temperature obtained from the regional climate model (RCM) COSMO–CLM driven by (b) perfect boundary conditions given by the ERA40 Reanalysis and (c) suboptimal boundary conditions from the global climate model (GCM) CMCC –CM. The nominal resolution of the ERA40 Reanalysis is 1.125° (about 128 km) and 0.75° (about 85 km) for CMCC–CM; both are dynamically downscaled to a nominal resolution of 0.0715° (about 8 km) through COSMO–CLM that is more suitable for hydrological studies. The first simulation, driven by climate observations, is used as the reference simulation; the second aims to evaluate how the uncertainties introduced by the RCM propagate in the simulated discharges; and the last is designed to evaluate the joint effects of the GCM and the RCM on the discharges. This point is relevant for the interpretation of climate change impacts when future scenarios are considered. The climate change impacts on the period 2001–2100 will be simulated under the IPCC Representative Concentration Pathways (RCP) 4.5 and 8.5.

ISIMIP global hydrologic models

Output from GCMs act as an input for GHMs. Outputs from GHMs can be used in turn to force regional hydrological models or the Decision Support Systems listed above. Noteworthy, not all GHMs are forced by all GCMs; below we indicate the climate drivers considered in each of the GHMs. All GHMs considered are spatially aggregated in regular grids of 0.5ºx0.5º. We used the following 8 GHMs:

- **CLM4.5:** The Community Land Model is the land model for the Community Earth System Model (CESM). It examines the physical, chemical, and biological processes by which terrestrial ecosystems affect and are affected by climate across a variety of spatial and temporal scales. The central theme is that terrestrial ecosystems, through their cycling of energy, water, chemical elements, and trace gases, are important determinants of climate. Model components consist of: bio-geophysics, hydrologic cycle, biogeochemistry, and dynamic vegetation. The land surface is represented by 5 land types (glacier, lake, wetland, urban, vegetated). The vegetated areas are further divided into patches of plant functional types (ISIMIP, 2023). *Climate drivers*: IPSL-CM5A-LR, HadGEM2-ES, GFDL-ESM2M, MIROC5. *Date*: 2018-02-08

- **H08**: H08 is a grid-cell-based global hydrological model. It consists of six sub-models, namely land surface hydrology, river routing, reservoir operation, crop growth, environmental flow, and water abstraction. The formulations of sub-models are described in detail by Hanasaki et al. (2017). The simulation period is typically for several decades, and the calculation interval is a day. The six sub-models exchange water fluxes and update water storage at each calculation interval with the complete closure of the water balance (the error is less than 0.01% of the total input precipitation). These characteristics enable H08 to explicitly simulate the major interactions between the natural water cycle and major human activities of the globe. In 2016, the water abstraction schemes of H08 has been substantially enhanced. In addition, a simple groundwater scheme was added to the land surface hydrology sub-model. It enabled H08 to estimate water abstraction from six major water sources, namely, streamflow regulated by global reservoirs (i.e., reservoirs regulating the flow of the main channel of the world's major rivers), aqueduct water transfer, local reservoirs, seawater desalination, renewable groundwater, and non-renewable groundwater (ISIMIP, 2023). *Climate drivers*: IPSL-CM5A-LR, HadGEM2-ES, GFDL-ESM2M, MIROC5. *Date*: 2017-10-10.

- **LPJmL**: LPJmL is a multi-sectoral Dynamic Global Vegetation Model, suited to address the water sector as it includes the full terrestrial water balance with irrigation modules. Among other changes, the current version features the differentiation of three irrigation system types and a more process-based representation of irrigation efficiencies. First, it addresses nonlinear biophysical and biogeochemical features of continuing large-scale replacement of natural vegetation by agroecosystems, under CO2 increase and climate change. Second, human societies worldwide make substantial economic and cultural use of ecosystem services (food, fiber, and energy crops, but also climate regulation, water purification, etc.) – but the assessment of their future provision is still in an early stage (Alcamo et al., 2005). LPJmL is designed for the consistent quantification of multiple drivers (climate, CO2, land management, land use change) on the future provision of these services (Bondeau et al., 2007). *Climate drivers*: IPSL-CM5A-LR, HadGEM2-ES, GFDL-ESM2M, MIROC5. *Date*: 2018-01-18.

- **MATSIRO**: The minimal advanced treatments of surface interaction and runoff (MATSIRO) has been developed to be coupled with the atmospheric general circulation model developed at the Center for Climate System Research, the University of Tokyo, and the National Institute for Environmental Studies. MATSIRO is projected to be used in climate studies at the time scales from a month to a few centuries and at resolutions larger than tens of kilometers. MATSIRO is intended to represent all the important processes for the water and energy exchange between land and atmosphere, at that time and spatial scales, in a physically based way, i.e., advanced, though in a simple manner, i.e., minimal (Takata et al., 2003). *Climate drivers*: IPSL-CM5A-LR, HadGEM2-ES, GFDL-ESM2M, MIROC5. *Date*: 2019-09-10-

- **MPI-HM**: The MPI-HM is a global hydrological model which solves the land surface water balance at a horizontal resolution of 0.5º with a time step of 1 day. It is restricted to the computation of water fluxes and does not consider any energy balance calculations. It is used to investigate hydrological research questions mostly related to high-resolution river routing. While hydrological processes are implemented in similar complexity as in full land surface models, the MPI-HM does not compute any energy-related fluxes (Stacke and Hagemann, 2012). *Climate drivers*: IPSL-CM5A-LR, GFDL-ESM2M, MIROC5. *Date*: 2017-09-08.

- **PCR-GLOBWB**: The PCR-GLOBWB model simulates for each grid cell and for each time step (daily) the water storage in two vertically stacked soil layers and an underlying groundwater layer, as well as the water exchange between the layers (infiltration, percolation, and capillary rise) and between the top layer and the atmosphere (rainfall, evapotranspiration, and snow melt). The model also calculates canopy interception and snow storage. Water use for agriculture, industry, and households is dynamically linked to hydrological simulation at a daily time step. The simulated local direct runoff, interflow, and baseflow are routed along the river network that is also linked to water allocation and reservoir operation scheme (ISIMIP, 2023). *Climate drivers*: IPSL-CM5A-LR, HadGEM2-ES, GFDL-ESM2M, MIROC5. *Date*: 2017-10-05.

- **WaterGAP2 & WaterGAP2-2C**: The global freshwater model WaterGAP (Water Global Assessment and Prognosis) calculates flows and storages of water on all continents of the globe (except Antarctica), taking into account the human influence on the natural freshwater system by water abstractions and dams. It supports understanding the freshwater situation across the world’s river basins during the 20th and the 21st centuries and is applied to assess water scarcity, droughts and floods and to quantify the impact of human actions on e.g., groundwater, wetlands, streamflow, and sea-level rise. Modeling results of WaterGAP have contributed to international assessments of the global environmental situation including the UN World Water Development Reports, the Millennium Ecosystem Assessment, the UN Global Environmental Outlooks as well as reports of the Intergovernmental Panel on Climate Change. *Climate drivers*: IPSL-CM5A-LR, HadGEM2-ES, GFDL-ESM2M, MIROC5. *Date*: WaterGAP2: 2013-12-17; WaterGAP2-2C: 2017-08-29.

A1.4. Microeconomic system

Economic calibrated models follow an inductive approach that aims to elicit the parameters of an objective/utility function capable of reproducing observed agents' choices within a domain/set of constraints, to accurately predict future responses to policy shocks through simulation. Noteworthy, each modeling family considered explores one specific functional form for the objective function: additive (WGP), Cobb-Douglas (PMAUP), and quadratic (PMP).

The **WGP** approach used in our ensemble framework relies on the calibration method developed by Sumpsi et al. (1997) to elicit the parameters of a multi-attribute, additive objective function. Note that due to the definition of the attributes above, our application includes a non-linear component in the additive objective function through the risk attribute. WGP allows for both single- and multi-attribute specifications, which makes the approach consistent with the Theory of Planned Behavior (TPB) (Ajzen, 1991). The TPB argues that decision-making is driven by "the multiple attributes of objects (including but not limited to profit) and farmers' beliefs regarding these attributes" (Pérez-Blanco et al., 2017). TPB's theoretical construct is substantiated by a large body of empirical research on the relevance that attributes other than profit, such as risk aversion or management complexity aversion, have in explaining agent's behavior and choices (see e.g., Gómez-Limón et al. (2016)). On the other hand, the use of an additive function may lead to over-specialized responses and even corner solutions: the agent sets the crop that delivers the highest utility at the maximum level until a binding constraint prevents further specialization, which often results in a characteristic "jumpy behavior" (Graveline, 2016).

PMP is possibly the most popular economic calibrated model to assess the behavior of agricultural agents, and irrigators in particular (Graveline, 2016). PMP relies on non-linear objective functions to calibrate and accurately reproduce observed agent behavior. Through the use of non-linear functions, PMP avoids unrealistic outcomes such as corner solutions or abrupt discontinuities in the agent's responses, yielding instead smooth calibration results (Howitt, 1995). Due to these obvious advantages, PMP has been consistently used to assess agricultural and water policies, including water pricing, in several regions worldwide (Graveline, 2016). PMP calibration uses "information contained in dual variables of calibration constraints, which bound the solution of the original linear programming 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). This is done in three steps: (i) an additional area constraint that bounds the model calibration results to observed choices is introduced in the domain and the dual values associated with the constraint for each crop are obtained; (ii) these dual values are used to add a non-linear component to the utility function (typically a quadratic cost function, or shadow cost); and (iii) the utility non-linear function obtained in (ii) is maximized subject to a similar set of constraints to those considered in the original problem, which perfectly reproduces the observed agent's behavior (Henry de Frahan et al., 2007). The main critique of PMP modeling regards the challenge of providing an "economic or technological rationale for the non-linear terms in the objective function" (Heckelei et al., 2012). As a result, a modeler needs to resort to ad-hoc arguments to elucidate the outcomes of PMP models following a policy shock (Graveline, 2016). Moreover, while PMP has modeled risk aversion in a single-attribute environment through the use of the mean-variance approach, its single-attribute approach struggles to explicitly measure and account for the utility relevance of alternative attributes such as management complexity aversion. The ensemble framework in this paper relies on the classic calibration method (PMP_1) (Howitt, 1995) and a variation proposed by Júdez et al. (2002), that skips the first step using the average rent of land as dual value (PMP_2).

PMAUP models "build on the axioms of revealed preference to construct a multi-attribute objective function that is both consistent with an observed (and finite) set of choices and prices and suitable as a basis for empirical analysis" (Parrado et al., 2019). PMAUP replaces the dual variables that would traditionally be added to the objective function to make calibration possible in PMP with the agent's preference parameters represented as shares of a non-linear (typically Cobb-Douglas) utility function, the arguments of which are competing attributes (e.g., profits v. avoided management complexity). PMAUP is a data and computationally intensive approach consistent with the TPB that has been used to empirically explore the relevance of attributes other than profit (Gómez-Limón et al., 2016; Gutiérrez-Martín and Gómez, 2011), particularly during the last decade, propelled by expanding frontiers in computational power and micro-data. Yet, since only observed behavior is used as an input and assumptions are limited (no engineering-based yield functions, no assumptions of fixed proportions, no limitation to profits as the sole relevant attribute of farmers), the calibration of PMAUP models is challenging where there is a large number of choice variables (several alternatives in the crop portfolio) and cross-sectional variation is low (time-series variation might be confounded with other trends), which may lead to some instability in the model calibration that is difficult to rationalize (e.g. abrupt changes in parameter values following the introduction of an additional attribute). The ensemble framework in this paper relies on two specific calibration methods: the projection method (Gutiérrez-Martín and Gómez, 2011) (PMAUP_1) and the iteration method (Gómez-Limón et al. 2016) (PMAUP_2).