Deliverable 2.1: BLUEPRINT FOR THE MODELLING SUITE

Author(s): Adria Rubio-Martin, Manuel Pulido-Velazquez & Hector Macian-Sorribes, *Universitat Politècnica de València*

With contributions from: Maggie Kossida (SEVEN), Klio Monokrousou (SEVEN), Panos Sourtzinos (SEVEN), Gustavo Ayala (SEI), Camilo Gonzalez (SEI), Tania Santos (SEI), Hadi Jaafar (AUB), Lara Sujud (AUB), Róbert Blaško (SAŽP)

Title	BLUEPRINT FOR THE MODELLING SUITE
Author(s)	ADRIA RUBIO-MARTIN, HECTOR MACIAN-SORRIBES, MANUEL PULIDO-VELAZQUEZ
Organization(s)	UNIVERSITAT POLITÈCNICA DE VALÈNCIA
Reviewer(s)	ALL
Deliverable number	D2.1
Submission date	30/10/2023

Prepared under contract from the European Commission

Grant Agreement no. 101084110

This publication reflects only the authors' views and the European Commission is not liable for any use that may be made of the information contained therein.

Start of the project:	01/01/2023
Duration:	48 months
Project coordinator organization:	Universidad de Salamanca
Related Work Package:	WP2
Type of Deliverable:	Report
Due date of deliverable:	Month 10
Actual submission date:	31 october 2023 (month 10)

Dissemination level

☒ PU = Public, fully open, e.g. web

☐ CO = Confidential, restricted under conditions set out in Model Grant Agreement

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

The TRANSCEND Project has received funding from the European Union's Horizon Europe Research and Innovation Programme under the Grant Agreement 101084110

Executive summary

The document aims to describe the blueprints of the modelling suite for each lab. Ultimately, this initial description of the existing modelling suite available in each lab will help to develop a modelling suite for each lab that can capture the interactions and dynamics of different systems relevant to climate change adaptation. This document is partially based on the reviewing the existing socio-ecological and ensemble modelling approaches in T3.1.

Table of contents

1. Introduction

Our goal in the TRANSCEND project is to explore strategies and pathways to achieve comprehensive and transformative change as a response to persistent water challenges, exacerbated by climate change. Modelling is an essential tool for this task. Models and chains of models can help predict the impacts of different scenarios, alternatives, and policies on the water system and its components. They can also help evaluate the trade-offs between different objectives, such as water supply, water quality, environmental goals, economy, and social aspects. Ultimately, models and modelling chains can support decision-making by providing quantitative information and insights that can complement qualitative information.

This document describes the blueprints of the modelling suite for each lab. This initial description of the existing modelling suite available in each lab will help to develop an improve modelling suite that can capture the interactions and dynamics of different systems relevant to climate change adaptation, enabling cross-fertilization across case studies and teams to achieve the best modelling suite possible within TRANSCEND. Relevant models do not only include water resource management, but also any hydrological, agricultural, climatic, and micro or macro-economics that can be relevant for decision-making and the integrated management of water resources.

2. Mapping the existing landscape of models

For many centuries, people and their economies have enjoyed the benefits of water resource systems. These systems provide various services, such as drinking water, sanitation, irrigation, hydropower, transportation, recreation, and habitat for wildlife. However, in many parts of the world, these systems are unable to meet the basic needs of people and nature. Many factors contribute to this problem, such as poor or damaged infrastructure, overuse of water, contamination from industry and agriculture, nutrient overload, salt accumulation, invasion of alien species, overfishing, land use change, and altered water and sediment flows. These challenges often stem from failures in planning, management, and decision-making at different levels beyond water. To ensure that water resources can provide equitable, affordable, and sustainable water quality and quantity for both humans and ecosystems, we need to address the underlying social and economic causes, such as limited access to education, energy and sanitation, corruption, inequality, and poverty.

Professionals in water resources have learned how to create and operate infrastructures that, along with non-structural measures, have the potential to enhance the benefits that people can get from the water resources in aquifers, lakes, rivers, and estuaries. However, these resources have a limit to the services they can provide. Rivers, estuaries, and coastal zones that are stressed by over development and overuse cannot meet the needs of those who depend on them reliably. How should these resources be used and managed in the best way? How can this be done in a situation of uncertain and changing supplies and demands, and increasing conflicts among people with different interests in their use and management? The main goal of water resources planning, management, and analysis activities is to deal with these questions and try to answer them. These questions involve scientific, technical, political (institutional), and social aspects. Therefore, water resources planning processes and products are essential.

Modelling approaches are useful tools for exploring and evaluating different options for water resources planning and management. This deliverable presents various modelling approaches to support water resources decision-making. It focuses on how to use models to address specific water resources issues and challenges. The aim of these type of models is to provide relevant, unbiased, transparent, timely and meaningful information to the decision-makers who are responsible for the development, management, and use of our water resources (Loucks et al., 2017).

Regarding the spatial scale, since decisions for water resource management mainly are confined within the watershed or basin, river basins are usually considered logical regions for water resources planning and management. The way land and water are used in one part of a river basin can affect the land and water in other parts of the basin. For instance, the release of pollutants or the removal of forests in the upstream part of the basin may worsen the quality and increase the variability of the flows and sedimentation downstream. The building of a dam or weir in the downstream part of a river may prevent vessels and fish from moving up- or downstream through the dam site. Planning and management on a basin scale is often done to: (i) optimize the economic and social benefits from the whole basin, and (ii) to ensure that benefits and costs are fairly distributed across multiple interests (e.g. agriculture and tourism) and social groups.

Regarding the temporal scales, water resources planning should be updated regularly and adapt to new information, new objectives, and updated projections of future needs, costs, and benefits (Loucks et al., 2017). Current decisions should not limit the options that future generations may want to consider, but rather current decisions should be responsive to current needs and opportunities, and have the flexibility to adjust in the future to possible changes in those needs and opportunities. The planning process should consider the number and length of time periods within a year that are relevant for water resources management. This will depend partly on the need to account for the variability of water supplies and demands, the available data and the purposes that water resources serve. Evaluating the impacts of alternatives for managing both surface and groundwater, or for managing both water quantity and quality, require attention to processes that occur on different spatial and temporal scales.

Finally, regarding approaches for the development of models, two general strategies are generally considered:

- *Bottom-up approaches* start from the local level, by identifying the water resources problems and needs of the communities and stakeholders. It then considers the potential future risks and opportunities, and evaluates the possible solutions and alternatives. These approaches aim to ensure cooperation and commitment from the stakeholders, and to align the goals and priorities with the laws and regulations. They often involve developing models that are tailored to the specific context and objectives of the water resources management as expressed by the stakeholders. The models can be used to assess the vulnerability and resilience of the water resources systems, and to support decision-making under uncertainty.
- *Top-down approaches* assume that one or more institutions have the ability and authority to develop and implement the water management plans. They have been used by water resources professionals to prepare integrated, multipurpose "master" development plans for many of the world's river basins (Loucks et al., 2017). In this context, models are developed by professionals, with little to no feedback from stakeholders in the watershed. The lack of participation of

interested stakeholders may lead to a lack of cooperation and commitment from the people who are affected by the decisions. The top-down approaches may also fail to account for the local context and needs, and the uncertainties and variabilities of water resources systems.

Integrated Water Resource Management (IWRM) is a process that aims to integrate the development and management of water, land and related resources, in order to achieve the best possible economic and social outcomes for all, without damaging the vital ecosystems and the environment (GWP, 2000). IWRM is focused on planning how to manage water policies in a better way, looking at how different sectors use water and how they affect each other. Far from top-down approaches, it also tries to find the most important issues for stakeholders, the best ways to organize and run the institutions involved, and how to improve the skills and knowledge of the people involved.

As identified by Loucks at el. (2017), not all water resources planning and management problems can be addressed by modelling. Modelling is most likely to be appropriate when:

- The planning and management objectives are reasonably well defined, and organizations and individuals can be identified who can benefit from obtaining and understanding the model results.
- There are many alternative decisions that may satisfy the stated objectives, and the best decision is not obvious.
- The water resources system and the objectives being analysed are describable by reasonably tractable mathematical representations.
- The information needed, such as the hydrological, economic, environmental, and ecological impacts resulting from any decision, can be better estimated with a combination of observations and models than using exclusively observations.
- The values of the model parameters are estimable from readily obtainable data.

Simulation and optimization models are the two main types of computer-based models that can be used for integrated water resource management. They have different purposes and characteristics.

Simulation models address “what if” questions. Given the assumptions for a system design and operation, a simulation model can predict how well it will perform. Simulation models can include various components of a water resource system, such as hydrology, ecology, economics, engineering, and social aspects. Simulation models are more flexible than optimization models, as they can handle complex and nonlinear relationships, discontinuous and stochastic variables, and multiple objectives. As such, simulation models do not aim to provide optimal solutions, but rather evaluate the performance of a given scenario or alternative.

Optimization models address “what should be” questions, what design and operating policy will best meet the specified objectives. Optimization models use mathematical techniques to find the best solution among a set of feasible alternatives, subject to some constraints. Optimization models can be useful for screening out unsatisfactory alternatives and identifying promising ones. However, optimization models often require simplifying assumptions and approximations to make the problem solvable by the available algorithms. These models may also have difficulties in dealing with multiple and conflicting objectives, uncertainty and risk, and spatial and temporal variability (Zeinalie et al., 2021).

Hence, simulation and optimization models have different strengths and limitations for integrated water resource management. Depending on the problem context and the available data, one type of model may be more suitable than the other, or a combination of both may be needed to achieve a comprehensive and robust analysis (Sing, 2014).

Models relevant for any other dimensions of the water resource system, such as climatic, hydrologic, agricultural, micro and macro-economics are also considered part of the IWR modelling suite.

3. Existing models in each lab

This section summarizes the models already existing in each lab, describing their capabilities and the results they are able to generate. It will be indicated when the models are used or accepted by relevant stakeholders in the basin, particularly if they are the result of a bottom-up or a co-creation process. Climatic, hydrologic, agricultural, micro and macro-economics, as well as any other relevant models for decision-making and the integrated management of water resources will be included in the summary of existing models. A summary of the current modelling suite per model type is provided in the next table.

Current TRANSCEND modelling suite.

	Reno River Basin	Jucar River Basin	Nitra River Basin	Tympaki River Basin	Caplina-Mauri-Desaguadero System	Mahanadi River Basin	Orontes River Basin
Climate change scenarios*		EUROCORDEX, CMIP6	EUROCORDEX, CMIP6			CMIP4, CMIP5	
Landuse scenarios*							
Agronomic models	CRITERIA-1D, Icolt, Irrinet	Aquacrop, Aquacitrus	DAISY, WOFOST				Aquacrop, Ecocrop
Hydrological models	Topkapi	TETIS	HBV, TUW, Bilan, Frier, MIKE, HEC-RAS	SACRAMENTO, HYMOS	WEAP	WEAP	WMS, HEC-HMS
Water resource management models		GAMS, Vensim		RIBASIM, MODFLOW			WEAP, MODFLOW
Hydro-economic models		GAMS					
Microeconomic models							
Macroeconomic models							

* Refers exclusively to scenarios explicitly mentioned in the deliverable

3.1. Reno River Basin

Agronomic model CRITERIA-1D

CRITERIA-1D is an agro-hydrological model developed by Arpae Emilia-Romagna, freely available at the following link: https://github.com/ARPA-SIMC/CRITERIA1D.

The model computes the crop development and the dynamics of soil water fluxes in agricultural soils, driven by daily weather data, namely minimum and maximum temperature, precipitation and, if available, hypodermic water table depth (Consoli et al., 2016).

Soil water flow can be simulated with two different approaches depending on the user's choice: a physically based numerical model or a layer-based conceptual model. Soil and crop parameters can be defined at different levels of detail. The model assumes a multi-layered soil and computes daily actual evaporation and transpiration, water flows among soil layers, deep drainage, surface and subsurface flows. The soil water retention and hydraulic conductivity are described by a modified version of van Genuchten–Mualem model (Bittelli et al., 2010).

Crop development and the dynamics of the related processes, such as the Leaf Area Index (LAI) and the rooting depth, are simulated in Criteria by means of empirical equations (Marletto et al., 2007) based on degree days sums.

Potential evapotranspiration is computed using the equation of Hargreaves and Samani (1985). The partitioning of the evapotranspiration into potential evaporation and transpiration is driven by LAI. Potential evaporation is assigned to the first soil layers, while potential transpiration is assigned to the rooting system, distributed based on root density. Actual evaporation and transpiration may be lower than potential, depending on actual soil water content and physiological parameters of the crop.

Every crop in the model has its own sensitivity to water stress, defined by the fraction of Readily Available Water (fRAW) for the rooting system. The model estimates the suggested irrigation volume and timing according to several triggers: the current soil moisture in the rooting system, the current fRAW, the minimum period of irrigation shift and the maximum volume for a single irrigation. In addition, a threshold of tolerated water stress can be defined (Villani et al., 2011).

The model can be used in geographical mode (CRITERIA GEO), by defining a computational unit map, where one computational unit is a polygon having the same weather, soil and crop data. This version is used in the iCOLT operational chain.

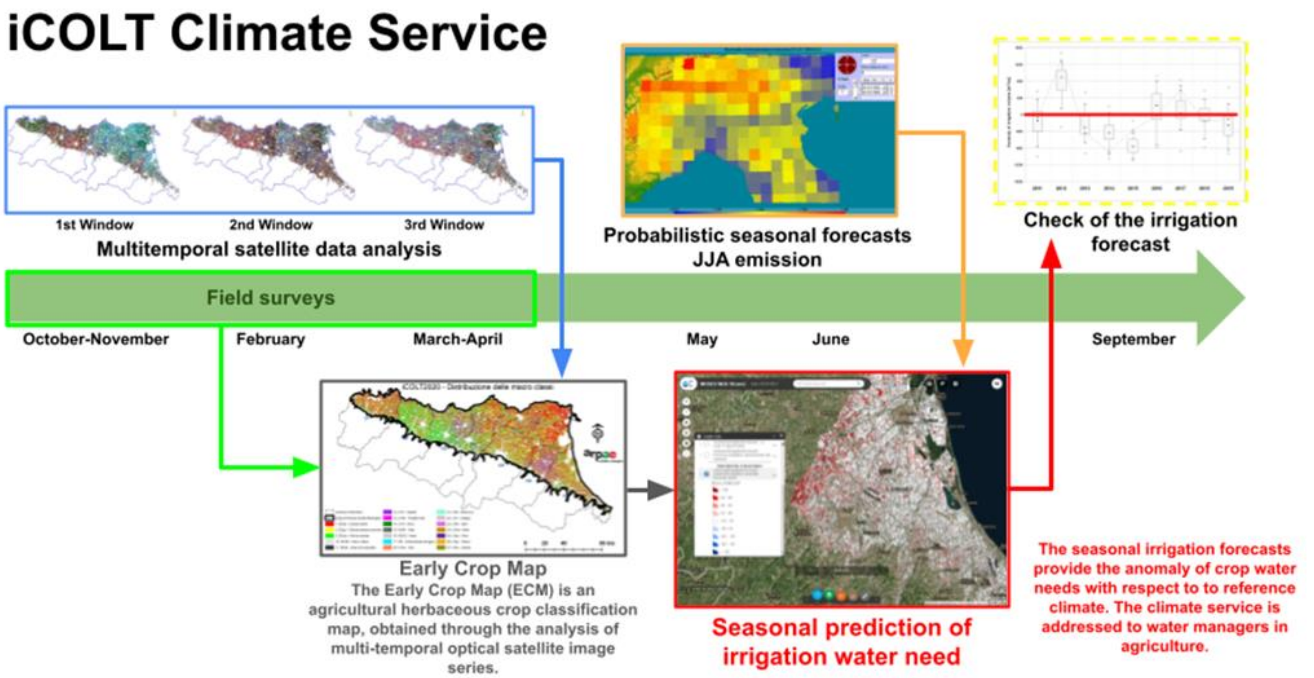
Icolt seasonal irrigation forecast

iCOLT is a climate service aimed at producing probabilistic forecasts of summer irrigation water demand before the start of irrigation season (i.e.: end of May for the JJA season) in the Emilia-Romagna region, including the Reno River basin (Villani et al., 2021).

The Emilia-Romagna Region, located in Northern Italy, is characterized by summer water shortages and recurrent drought conditions, therefore the iCOLT system has been developed, operating both at regional and at Land Reclamation and Irrigation Board level.

In this service, remote sensing crop detection, validated with field surveys, is used in combination with an agro-hydrological model (CRITERIA-1D). The meteorological input data for the service are the ERG5 analysis 5 × 5 km-grid as observed data until the forecast, and the operational calibrated probabilistic seasonal forecast products currently based on Copernicus Climate Services, converted by means of a weather generator in daily time series using the same 5 × 5 km-grid.

The timeline of the operational chain (next figure) starts from the previous winter and spring months in which an early crop map is produced by means of remote sensing analysis. During May, calibrated probabilistic seasonal predictions are issued. The early crop map, the seasonal predictions and observed weather data are the input of CRITERIA-1D model to produce the probabilistic predictions of June–July–August irrigation. In the following autumn, the observed daily weather data are used as input of the agro-hydrological model to validate the predictions. This climate service has been operational since 2011.



iCOLT climate service: operational chain

Irrinet irrigation system model

Irrinet is an irrigation information service developed by the Canale Emiliano Romagnolo (CER), aimed at advising farmers on the efficient management of water resources. Considering the growing need for efficient use of water and the impact of climate change on water availability, the National Association of Soil Reclamation Consortia (ANBI) has developed IRRIFRAME, a web service based on Irrinet. In 2014 the Ministry of Agricultural, Food and Forestry Policies identified IRRIFRAME as the most widespread and advanced information irrigation system for farmers in Italy.

Irrinet is available free of charge and currently provides more than 12,000 farms in the Emilia-Romagna Region, with irrigation programming daily via web interface and SMS. This information supports the efficient use of water resources in the agricultural sector, helping to address water scarcity due to climate change. The model processes data on meteorology (daily temperatures, rainfall and evapotranspiration), soil properties and crop parameters, the combination of which generates the water balance for individual crops, allowing the real demand for water to be defined and saving irrigation water without decreasing the quality and amount of agricultural production.

The main processes simulated by the model are:

- The dynamics of water in the soil, considering three different soil layers: soil surface, root layer and bottom layer.
- Crop development, guided by degree days; crop growth is calculated starting from sowing, transplanting or vegetative growth for fruit crops.
- The growth of the root system, based on a function that estimates the effect of daily temperature, soil water content and growth stage. For fruit trees a fixed and constant layer over time was used.

- The crop water requirement, calculated starting from the reference data of crop evapotranspiration (ET0) provided daily by ARPAE and then applying the FAO kc factor, specific for each crop and each growth phase and, in many cases, corrected with research carried out by the CER. Under conditions of low soil water content, crop water stress is calculated defining a specific level of soil moisture below which crops reduce their evapotranspiration rate.
- Water table contribution to crop water requirements, expressed in terms of percentage of crop evapotranspiration. The contribution is calculated using water table depth, soil particle size, crop soil water exploitation capacity and root system depth.

Once the water balance has been computed, the model sets the water to be supplied to the crop, i.e. the difference between the interval values of the two thresholds of water available in the soil. Thresholds are specific to each crop, growth stage and irrigation system (drip, sprinkler, flood). The model compares the soil water content with the daily lower threshold. When the minimum value is reached, the quantity of water for irrigation is calculated as the difference between the thresholds. The upper threshold can be equal to the field capacity, or, usually, lower than it, to avoid both the depletion of soil water not transformed into yield, and to have dry soil to store further precipitation.

Topkaki hydrological model

<u>Description of the model features</u>

The TOPKAPI (TOPographic Kinematic Approximation and Integration) model is a fully distributed physically based hydrologic model that can be used in real-time operational forecasting at the scales that are of primary interest to operational hydrology.

The present version of the TOPKAPI model is the result of an intense review that has transformed it from an academic model developed at University of Bologna in 1995 to a real-time operational model. The main features of TOPKAPI include:

- reduced execution times suitable for distributed model calibrations and real-time operational applications and flood forecasting.
- easy calibration due to physically meaningful parameters whose values can be retrieved from Digital elevation maps, soil maps, land use and vegetation maps in terms of measurable physical quantities such as slope, soil permeability, surface roughness, etc.
- track the spatial variability of runoff conditions in the catchment getting flow predictions at any point of the channel network (1D outputs).
- explicitly consider the spatial variability in precipitation fields, fully exploiting distributed rainfall estimates such as the ones produced by RADAR networks.
- resolve basin hydrologic response at very fine temporal (few minutes) and spatial (100-1000 m) scales in both small and large catchments.
- represent the behaviour of the main components of the hydrological cycle thus producing not only stream flow forecast but also distributed information on soil moisture, evapotranspiration, snow accumulation, etc. (2D output maps).
- run the model at different time scales, up to daily simulations.
- run event based and continuous simulations.
- couple with HEC-RAS hydraulic model (directly).

TOPKAPI model can provide high resolution information on the hydrological state of a catchment. The model can be used both as a stand-alone program and inside real-time operational flood forecasting systems. Fields of application include:

- Catchment hydrology
- Flood forecasting
- Water resources management
- Artificial reservoirs management
- Land use and climate change
- Irrigation and drought
- Landslides

Description of the model functioning

The TOPKAPI model is based on the idea of combining the Kinematic approach and the topography of the basin; the latter is described by a Digital Elevation Model (DEM), which subdivides the application domain by means of squared cells, whose size generally increases with the overall dimensions. Each cell of the DEM is assigned a value for each of the physical parameters represented in the model. The flow paths and slopes are evaluated starting from the DEM, according to a neighbourhood relationship based on the principle of the minimum energy cost, namely the maximum elevation difference. Due to the finite difference approach underpinning the model, TOPKAPI works with a four-direction scheme (N-S and W-E): the model takes into account the links between the active cell and the four surrounding cells connected along the edges; the active cell is assumed to be connected downstream with a sole cell, while it can receive upstream contributions up to three cells.

The integration in space of the non-linear Kinematic wave equations representing subsurface flow, overland flow and channel flow results in three ‘structurally similar’ zero-dimensional non-linear reservoir equations. The parameters of the model are shown to be scale independent and obtainable from digital elevation maps, soil maps and vegetation or land use maps in terms of slopes, soil permeability, channel and surface roughness. The integration of the fundamental equations is performed on the individual cell of the DEM.

Beside subsurface, overland and channel flow TOPKAPI includes components representing infiltration, percolation, evapotranspiration and snowmelt, plus a lake/reservoir component and a parabolic routing component. For the deep aquifer flow, the response time caused by the vertical transport of water through the thick soil above this aquifer is so large that horizontal flow in the aquifer can be assumed to be almost constant with no significant response on one specific storm event in a catchment. Nevertheless, the model accounts for water percolation towards the deeper subsoil layers even though it does not contribute to the discharge.

As precipitation falls on the catchment, the snow accumulation and melting component identifies the amount of water that actually reaches the soil surface. For reasons of limited data availability, the snow accumulation and melting (snowmelt) component is based on an energy budget method that is driven by a radiation estimate based upon air temperature measurements.

The amount of water that reaches the soil surface infiltrates unless the soil is already saturated or impervious.

The soil water component is affected by subsurface flow (or interflow) in a horizontal direction defined as drainage; drainage occurs in a surface soil layer, with limited thickness and with high hydraulic conductivity due to its macro porosity. The drainage mechanism plays a fundamental role in the model both as a direct contribution to the flow in the drainage network and most of all as a factor regulating the soil water balance, particularly in activating the production of overland flow. The surface water component is activated on the basis of an excess of infiltration mechanism. Lastly, both components contribute to feeding the drainage network.

Evapotranspiration is considered as water loss, subtracted from the soil's water balance. The most complex and physically realistic model for estimating actual evapotranspiration is the Penman-Monteith equation, which has been widely used in many distributed models. However, a simplified approach is generally necessary because almost nowhere is real-time data available for Penman-Monteith estimation in operative flood forecasting applications. Evapotranspiration plays a major role not in terms of its instantaneous impact, but in terms of its cumulative temporal effect on the soil moisture volume depletion; this reduces the need for an extremely accurate expression, provided that its integral effect is well preserved. TOPKAPI computes hourly evapotranspiration using a radiation method starting from air temperature and from other topographic, geographic and climatic information.

The channel network is assumed to be tree shaped with reaches having rectangular or triangular cross sections. Channel routing is performed using a Kinematic approach for steep cells. Where channel slope is too small to use a Kinematic approach TOPKAPI uses a parabolic routing component based on Muskingum-Cunge method.

At the smallest spatial scale, the pixel element, evolution of all the hydrological state variables can be obtained: rainfall, temperature, evapotranspiration, soil moisture conditions, snow accumulation and runoff generation. Analysis of these dynamics is extremely important for verifying the general physical soundness of the model performance as well as for calibrating parameters of certain hydrological processes.

For each cell of the model containing a channel reach the time-series of stream flow are provided. This offers the flexibility of tracking the spatial variability of runoff conditions in the catchment. As opposed to semi-distributed modelling approaches that pre-define points of interest by partitioning the main catchment into nested sub-basins, TOPKAPI provides hydrologic prediction at any point of the channel network (distributed 1D output).

The capability for reproducing Internal variation of hydrologic response is among the essential features offered by distributed models. TOPKAPI produces spatial maps of all the major hydrological state variables (soil moisture conditions, runoff generation, snow accumulation, evapotranspiration etc.) at a specified temporal resolution (2D output maps). In addition to instantaneous basin states, the model generates the catchment water balance.

Implementation of the model for the Reno River Basin

For the calibration of the TOPKAPI model, a 9-year data period is available, from January 2005 to January 2014. In consideration of the flood events that characterized the Rhine basin in January 2014, it was chosen to perform the calibration model using the 2005-2013 data period and to use the January 2014 events as a test for the calibration.

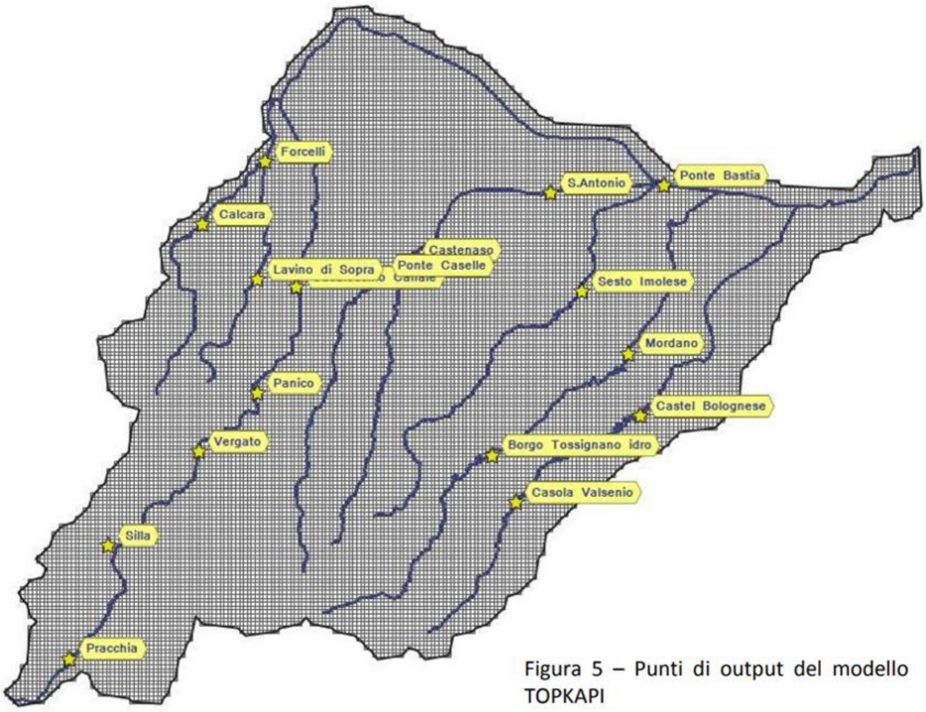
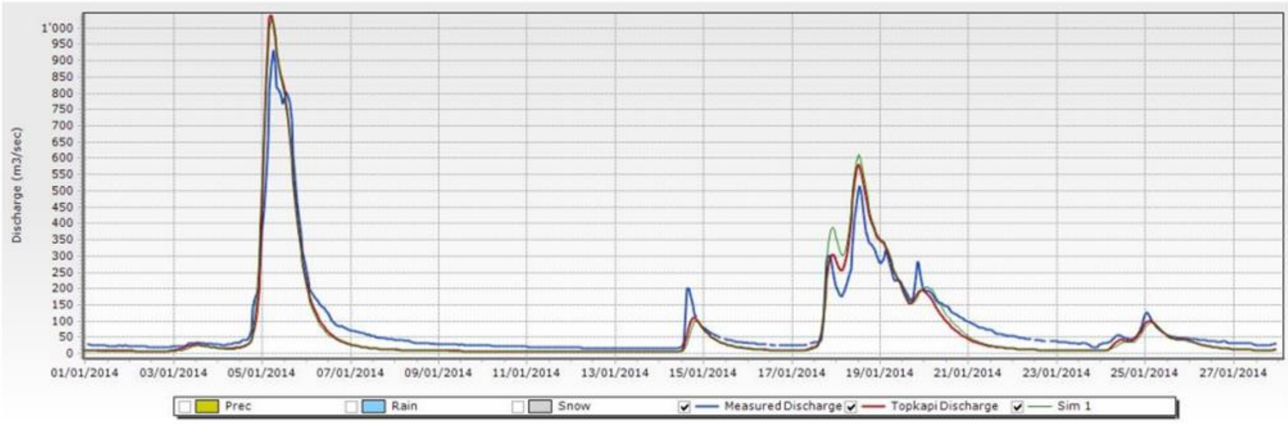


Figura 5 – Punti di output del modello TOPKAPI

Outlets of Topkapi model in the Reno river basin.

Given the long recalibration period, there are numerous significant flood events on which the model parameters have been recalibrated. The calibration obtained therefore takes into account the characteristics of numerous events and guarantees a more balanced behaviour of the model. Furthermore, calibration over a long period of time allows us to verify that the water balance within the basin is respected and that in the long term even the simulated low flow rates reflect the real behaviour of the basin. The model calibration review involved a total of 16 control points.



Comparison between hydrograms obtained with the calibration of Topkapi model (red line) and the 2006 calibration (green line) and observed data (blue line).

<u>The software for the operational use of TOPKAPI-based outputs in the Reno River Basin</u>

EFFORTS is a GIS-based software with user-friendly interface for the acquisition and display of hydro-meteorological information and real-time flood forecasting.

The platform is organized into different components that can be customized and extended. The modules allow managing hydrologic, hydraulic and statistical models for flood forecasting. Software modules and mathematical modules are combined in sequence according to operational forecasting needs and they provide forecasts with a lead time up to 48-60 hours.

The real-time engine is activated automatically upon the arrival of each new data, at fixed intervals or with manual activation of the user.

EFFORTS platform can include a large number of forecasting models which can operate at different spatial scales: a simple unit hydrograph convolution model; a hydrologic model, a hydraulic model and a reservoir management model. EFFORTS can include a module for artificial reservoir management for flood forecasting that provides EFFORTS Users a system to simulate effects of water release scenarios in real-time during flood events.

EFFORTS is a GIS package for environmental monitoring and flood forecasting in real time that works fully automatically, without user intervention: it connects to real-time data acquisition systems, validates and stores the data into the hydro-meteorological database, runs chains of flood forecasting models and displays results.

The system receives and displays real-time data from different types of sensors and models, such as rain gauges tele-metering network, weather stations, hydrometric stations, weather RADAR, satellite, data from high-resolution numerical weather prediction models, etc. The information display is updated automatically each time the system acquires new data.

Once real-time data have been received and processed, EFFORTS automatically runs forecasting models and displays results using a GIS based interface. Flood forecasts can be visualized as maps, time-series and animations.

The system shows warning thresholds and highlights alarm situations at gauges, river reaches or user defined areas to help users in taking decisions. Visualization options include real-time display of river cross-sections with water level indication and warning thresholds, water level profile on the main river reaches, multi-window visualization features and animations. Favorite windows and display configurations can be saved and recalled to create custom visualizations. Data can be exported at any time from the visual interface to Microsoft Excel files.

EFFORTS flood forecasting system is linked to the hydro-meteorological database containing information on the forecasting area and past hydro-meteorological data. At any time, the User can move the time reference of the flood forecasting system to any time in the past and analyse issued forecasts and recorded data.

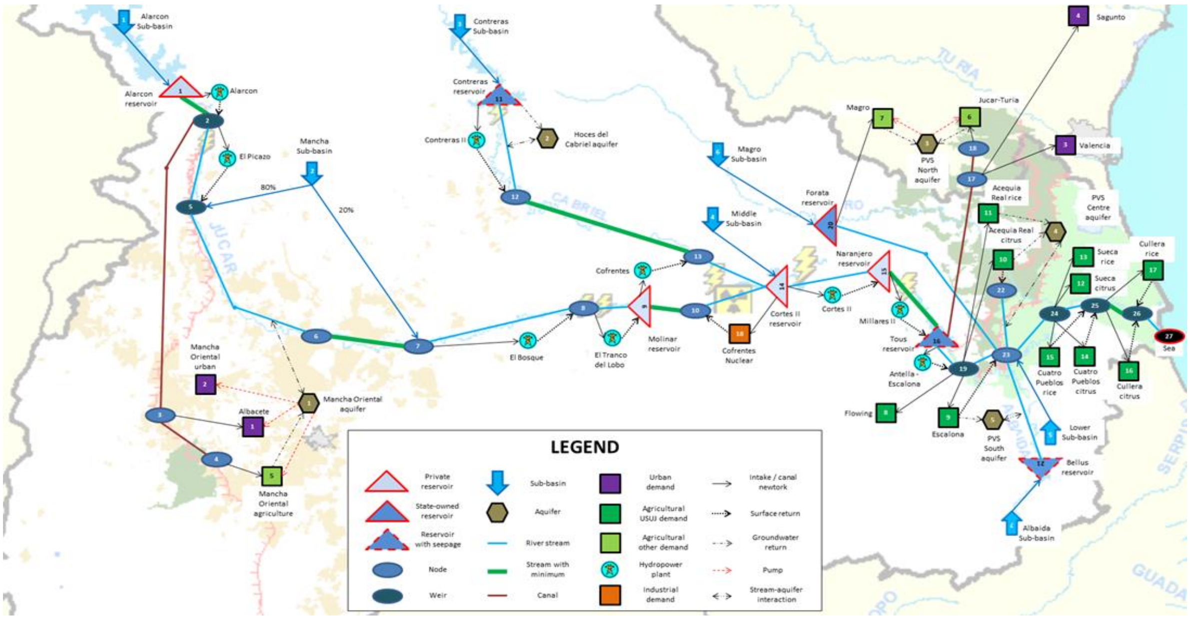
The data management and visualization software respond to the following basic functions:

- GIS-based visualization interface
- Visualization of real-time data
- Data processing, validation and transformation
- Management of models runs and display for flood forecasting
- Alarms and reports
- Historical events analysis

3.2. Jucar River Basin

Hydro-economic models of the Jucar system

Three hydro-economic models with the same system representation have been developed for the Jucar River using the Explicit Stochastic Programming Advanced Tool (ESPAT) developed by Macian-Sorribes et al., (2017). These models are operated at the monthly time scale and follow a simulation, stochastic optimization, and deterministic optimization approach respectively. The Jucar River system model includes 27 nodes, 8 surface reservoirs, 5 groundwater bodies modelled using the Embedded Multireservoir Model (Pulido-Velazquez et al., 2005), 7 sub-basins, 18 consumptive demands, 9 hydropower plants and 6 minimum environmental flows. Of these, 5 are set to adhere to habitat sustainability curves of native fish species, and 1 corresponds to the minimum discharge to the sea committed. All three models share the system representation (next figure).



Main view of the hydroeconomic model for the Jucar River basin.

The current version of the system represents the period between 1998 and 2020 and may be subject to future modifications.

The physical features of the model, such as hydrological sub-basins, reservoir capacity, storage-head and storage-surface curves, groundwater models, river reach and canal capacity, minimum streamflow prescribed, water demands and returns, and fish habitat curves, were obtained from the Jucar River Basin Agency. Meanwhile, the economic features of water uses, including urban demand curves, energy prices, and pumping costs, were obtained from CHJ (2013) and were updated from previous efforts (Pulido-Velázquez et al., 2006) in the context of the DMA implementation in the Jucar as part of the EU AQUAMONEY project. These features were successfully contrasted with other hydroeconomic models (Kahil et al., 2016). Urban demand was modelled using demand functions that link the amount of water supply to the marginal value of water for the user.

Citrus, orchards, and perennial crops benefit from agricultural demand, which is calculated using a revised version of the crop yield calculation included in the FAO33 methodologies (FAO, 2012). This modified methodology calculates the yearly crop yield as a function of the supply-demand ratio, and then estimates the total food production from the product between the crop yield and a reference production value extracted from historical statistics. The total benefits are calculated by multiplying the yearly total food production with the crop price. Rice crops are crucial for maintaining the l'Albufera Lake, a protected area in the region, and their supply is considered a constraint.

The Cofrentes Nuclear power plant is the only industrial demand using surface water, and its benefits per unit of water consumption are evaluated using the alternative cost method. The cost of providing the equivalent amount of energy by gas, minus the operation costs of the plant obtained from Pereira-Cardenal et al. (2014), is used to estimate the benefits.

Many-objective Robust Decision-Making model of the Jucar system

Initially developed by Macian-Sorribes (2017) as a hydro-economic model, the model was altered with new capabilities for performing Multi Objective Robust Decision Making.

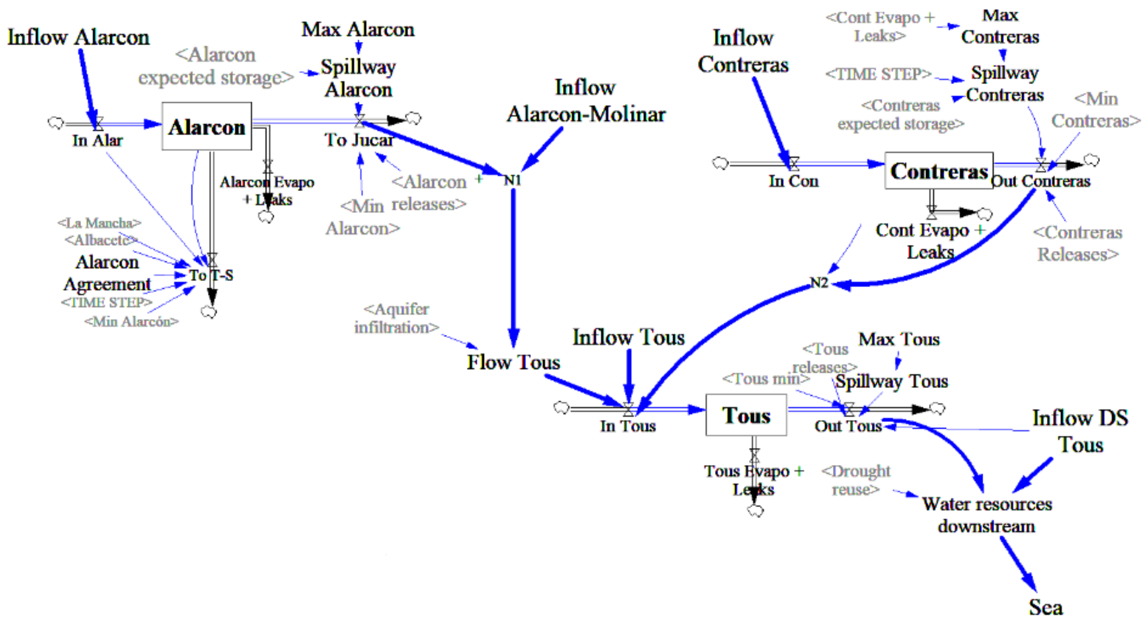
The model has two parts: an optimization component and a simulation module. The optimization component is a hydroeconomic conjunctive use model that aims to enhance the operation of the Jucar river system by exploring different strategies. It takes into account the interactions between streams and aquifers and aims to maximize the net total benefits. The optimization method used is called Combined Surface-Groundwater Stochastic Dual Dynamic Programming (CSG-SDDP), which can make optimal decisions even when there is hydrologic uncertainty and influential stream-aquifer interactions.

The simulation module was created to compare the CSG-SDDP optimization outcomes with the current operating rule'' simulation. Unlike the optimization component, in this scenario, water resources are not allocated based on economic benefits. Instead, they are distributed according to various priorities associated with different needs and uses, which are adjusted to replicate the system's historical operation.

For previous works, only the simulation component of the model was used to stress-test the system under various future scenarios, including both IPCC projections and synthetic scenarios.

System dynamics model of the Jucar system

A monthly time step system dynamics model has been created for the Jucar River system to manage its operations. The simulation is based on real operating rules of the reservoir and the drought management plan implemented in the basin, following the latest plan for hydrological planning cycle (CHJ, 2023). The model framework consists of 5 subsystems that interact with each other. The next figure displays the main view of the model, including the network definition.



Main view of the system dynamic model for the Jucar system.

This simulation model represents the interaction between the Mancha Oriental aquifer and the Jucar River. It uses a two-cell Embedded Multi-reservoir Model, which was developed by Pulido-Velazquez et al. in 2005. In addition, the model includes a state index subsystem that monitors the system's state during each time-step of the simulation. The equations used to define the relationship between past and present system states are based on the Jucar drought management plan (CHJ, 2023). The state index subsystem can activate drought management measures based on the current state of the system.

This model simulates the connection between irrigation return and the coastal lake of the Albufera in Valencia, a lake spanning 2320 hectares. Most of the water that flows into the Albufera comes from irrigation channels. Therefore, a reduction in inflows could occur as a result of reduced agricultural demand or irrigation modernisation, which could harm the ecosystem.

To simulate scenarios of land use change, irrigation demand for the main crops in the area (rice, citrus fruit, vegetables, persimmons) has been calculated based on data from the new basin hydrological plan (cycle 2022-2027). The model considers irrigation efficiency when calculating demand, which enables the acquisition of irrigation return values for different modernisation levels.

The operating rules subsystem decides the behaviour of the releases by defining monthly operating rules for the three main reservoirs of the Jucar River basin. The operating rules for the reservoirs were obtained using fuzzy rule-based systems (FRB), co-developed with the experts from the Operation Office of the Jucar River Basin Authority (Macian-Sorribes and Pulido-Velazquez, 2017), and adapted to the system dynamics model using piece-wise linear functions. The development of quantitative system dynamics models requires the use of a large volume of data coming from different fields (from hydrological to economic and reservoir data) as well as a deep understanding of the system structure and behaviour (Rubio-Martin et al., 2020). The water demands considered by the model are divided into urban and agricultural demands and were located and compiled from the public information provided by the CHJ (CHJ, 2022). The water demands are updated to the current Hydrological Plan for the Jucar Demarcation for the 2022-2027 period, approved on the 24th of January 2023.

Hydrological models of the Jucar system

A hydrological TETIS model is being developed for the whole Jucar River Basin. TETIS was developed by the Research Group of Hydrological and Environmental Modelling (GIMHA) of the Universitat Politècnica de València (UPV). It can solve problems of both floods and erosion, as well as water resources. It has been widely used in Spain and other countries of the world, covering a wide range of climates and sizes of watersheds. It also has a powerful automatic calibration algorithm and an interface for data input and output visualization (Francés et al., 2007).

Additionally, we have 7 hydrological models developed for each one of the sub-basins of the Jucar RB. The hydrological model of Temez (1977) is a distributed model that simulates the water balance of a watershed on a monthly basis, using precipitation, potential evapotranspiration, and hydrological parameters as inputs, and producing outputs such as soil moisture, aquifer volume, evapotranspiration, and total runoff. It is based on the concept of time of concentration, which is the time required for water to flow from the farthest point of the watershed to the outlet. The model has been applied to various watersheds in Spain and other countries and has been used for flood forecasting and water resources management.

Agronomic models AquaCrop and AquaCitrus

AquaCrop is a crop growth model developed by the Land and Water Division of FAO to assess the effect of environment and management on crop production (Steduto et al., 2009). It uses a relatively small number of parameters and input variables to simulate yield response to water of herbaceous crops. Conditions where water is a critical limiting factor in crop production are particularly suitable for this modelling approach. In this regard, AquaCrop has been used to analyse the effects of different irrigation strategies on crop yields in the upper basin of the Jucar River, providing practical information on how to apply full and deficit irrigation to improve irrigation water productivity in a barley crop (López-Urrea et al., 2019). Optimizing crop irrigation for other crops, such as oats and garlic, is another example of using the approach in the basin (Martínez-López et al., 2022).

A new model named AquaCitrus has recently been developed in the UPV, aiming to address the limitations of AquaCrop for specific woody crops that are particularly abounding in the lower Jucar River basin. AquaCitrus models the soil water balance for citrus trees, simulating water fluxes in the soil-plant-atmosphere on a daily time step (Boubakri et al., 2023). It combines various sub-models to compute the fluxes of effective precipitation, infiltration, runoff, soil evaporation, drainage, and crop transpiration. The model includes a rainfall interception routine by the canopy, and computes the soil evaporation and crop transpiration separately. AquaCitrus also considers the heterogeneity of the soil, given that localized irrigation keeps a small fraction of the soil frequently wet while the remaining area remains dry.

3.3. Nitra River Basin

Climate models

The Slovak Hydrometeorological Institute (SHMÚ) is preparing new climate scenarios for Slovakia, however, which should be available for the SAŽP within close future. SHMÚ uses EURO-CORDEX´s RCMs (15-20 models) and RCP2.6, 4.5, and 8.5, and the ERA-interim reanalysis. For the time horizons 2021-2050 or 2071-2100. RCMs were validated using regional meteorological observations (EOBS) and the model outputs were validated for the reference period 1961-1990, resp. 1981-2010.

SHMÚ has been also working on projections using their model ALARO_1 governed by the CNRM_CM6(ESM2-1) emissions scenarios SSP126, SSP245, and SSP585 at 4 x 4 km grid and their aim was to downscale to 1 x 1 km. According to the latest information, the projections for extreme weather events should be available for time horizons 2030 and 2050 even at a 0.5 x 0.5 km resolution.

Other authors prepared climate scenarios and prognosis of drought for selected river basins in Slovakia, including Nitra RB (Fendeková & Blaškovičová, 2018). They used outputs from the GCMs and Dutch KNMI (Meijgaard et al., 2008) and German MPI (Jacob 2001, Jacob et al. 2001) RCMs for downscaling to 25 x 25 km resolution, which translated to 19 x 10 grid points in Slovakia (Fendeková & Blaškovičová, 2018). Medium pessimistic scenario SRES A1B (IPCC 2007, 2014) and data (1951-2016) from 30 meteorological stations (SHMÚ) were used for these RCMs to prepare scenarios to 2100 for daily max and min air temperatures, daily total precipitation, and potential and actual evapotranspiration (Fendeková & Blaškovičová, 2018).

Hydrological models in the Nitra RB

HBV and TUW models

A rainfall-runoff bucket-type model TUW (Technische Universität Wien), which follows (model HBV model (Bergström & Forsman, 1973; Seibert & Bergström, 2022) was used to model the impacts of climate change on the runoff in eight selected river basins in Slovakia, including Horná Nitra RB (Sleziak et al., 2021). Temperature and precipitation scenarios (KNMI, MPI models at A1B scenario) were used to simulate the runoff for three time-horizons (2011-2040, 2041-2070, and 2071-2100) for the reference period 1981-2010 (Sleziak et al., 2021). The input data used were mean daily runoffs, precipitation totals, and air temperature for the period 1981-2019 provided by SHMÚ (Sleziak et al., 2021). The air temperature and precipitation projections were fed into the TUW model to produce the runoff simulations, the details can be found in (Sleziak et al., 2021).

HBV model (Bergström & Forsman, 1973; Seibert & Bergström, 2022) was also used to model hydrological drought occurrence and propagation in Nedožery subcatchment in Horná Nitra RB within the WATCH project (Oosterwijk et al., 2009). The data used for parametrization are shown in the next table, while the model is described in a great detail in (Oosterwijk et al., 2009).

Used and input data for the HBV model (Oosterwijk et al., 2009).

Action	Used data
Calculation of potential evapotranspiration (PE)	Min/max temperature Wind speed Cloudiness Air humidity %
HBV input	Precipitation PE Air temperature
HBV results validation	Snow cover

The modelling outputs of HBV model were compared to results from the Bilan and FRIER models used by Comenius University in Bratislava (Oosterwijk et al., 2009).

Bilan and FRIER models were also used to model the water balance in selected river basins in Slovakia, including Nitra RB (Fendeková & Blaškovičová, 2018).

Bilan

Bilan model, developed by T.G. Masaryk Water Research Institute in Prague (Kašpárek & Novický, 2004), simulates water-balance components in catchment/river basins. Model is not spatially distributed and the structure is based on equations describing water-balance principles on surface, in soil, and in groundwater (Fendeková & Blaškovičová, 2018). The model can operate on monthly or daily time series. Inputs for the model are mean catchment´s precipitation totals, air temperature, and relative humidity (Fendeková & Blaškovičová, 2018; Oosterwijk et al., 2009). Potential evapotranspiration can be calculated using various methods. Bilan simulates daily PE, ground evaporation, soil infiltration, and groundwater recharge, as well as quantity of water in snow, soil, and groundwater storage for each time step (Fendeková & Blaškovičová, 2018). Simulation of total discharge consists of direct runoff, interflow, and base flow (Fendeková & Blaškovičová, 2018, Oosterwijk et al., 2009). Direct runoff has no effect on the soil water balance, likewise is not available for evaporation, which differs compared to HBV where surface runoff is not included (Fendeková & Blaškovičová, 2018; Oosterwijk et al., 2009).

FRIER

FRIER is a rainfall-runoff model with distributed parameters (Horvát, 2008; Oosterwijk et al., 2009). FRIER stands for Flow, Routing, IUH (instantaneous unit hydrograph) model with accent to Evapotranspiration and Radiation methods. The model consists of three components: the first one is a GIS interface displaying the input data fed in the second component, while the third component determines IUH, water balance, and simulates runoff (Horvát, 2008). The input data include discharge time-series, precipitation, and climate data; the type o climate data depend on the method used to set the global parameters (Horvát, 2008). Snow cover-height can be either computed or measurements can be fed into the model (Horvát, 2008). The spatial inputs include digital elevation model, soil texture, and land-use maps of the catchment (Horvát, 2008; Oosterwijk et al., 2009). The methods for spatial distribution of the input data in the model are arithmetic mean, Thiessen polygons, lapse rate, or kriging (Horvát, 2008).

Mike, HEC-RAS

SVP uses MIKE and HEC-RAS for water flows and flood protection. The focus of the modelling was on floods, where very good models have been developed. SVP is running a map portal, where inundation areas and areas prone to floods can be shown.

Water resource management

There is no systemic modelling focused on water scarcity or climate change impacts on hydrology in place. Likewise, water resources management models are not used. VÚVH prepares water balance overview, from a water management and not hydrological perspective, for the different river basins based on the water permits and SHMÚ´s abstraction registry. They also prepare water balance outlooks.

Agronomical models DAISY

DAISY is a mechanistic simulation model of agricultural fields developed by the Agrohydrology group at the University of Copenhagen. Model has been used by the VÚPOP for simulation of crop growth, water regime, temperature regime, organic matter balance, and nitrogen dynamics in agricultural soils. IT was used in, e.g., PHARE project in Danubian lowland (https://www.osti.gov/etdeweb/servlets/purl/668552). Climatological data are used as input.

WOFROST is a mechanistic dynamic model used to predict crop production, water use, etc. Developed by WURL. VÚPOP uses the model to predict the crop production and climatological input data are used (SHMÚ).

Other models include **RothC-26.3** (Coleman & Jenkinson, 1996) for simulating the turnover of organic carbon. This model uses the effects of soil type, temperature, moisture content and plant cover on the turnover process. In Slovakia, model is mostly used for modelling organic C stocks in soil for the periods 1970-2020, 2000-2020, or for predicting organic C stocks in soil for time horizon 2020 – 2100 (Bielek & Jurčová, 2010, Skalský et al. 2017). The model uses monthly precipitation totals, mean monthly temperature (soil temperature is used most often), and mean monthly evapotranspiration.

3.4. Tympaki River Basin

Hydrological models SACRAMENTO, HYMOS DB

SACRAMENTO model: This is a continuous rainfall-runoff model used to generate daily stream flow from daily rainfall and potential evapotranspiration data. It uses soil moisture accounting to simulate the water balance within the catchment (i.e. functional unit). The input data are from existing monitoring stations. The model is run at catchment spatial scale and daily timestep. The following output parameters are provided by the model: daily surface and base flow (m^3/sec), soil moisture depletion by evapotranspiration and soil moisture redistribution, soil moisture replenishment by rainfall and percolation. The existing model needs to be updated and run for the most recent years. The SACRAMENTO model for Tympaki is managed by the Region of Crete.

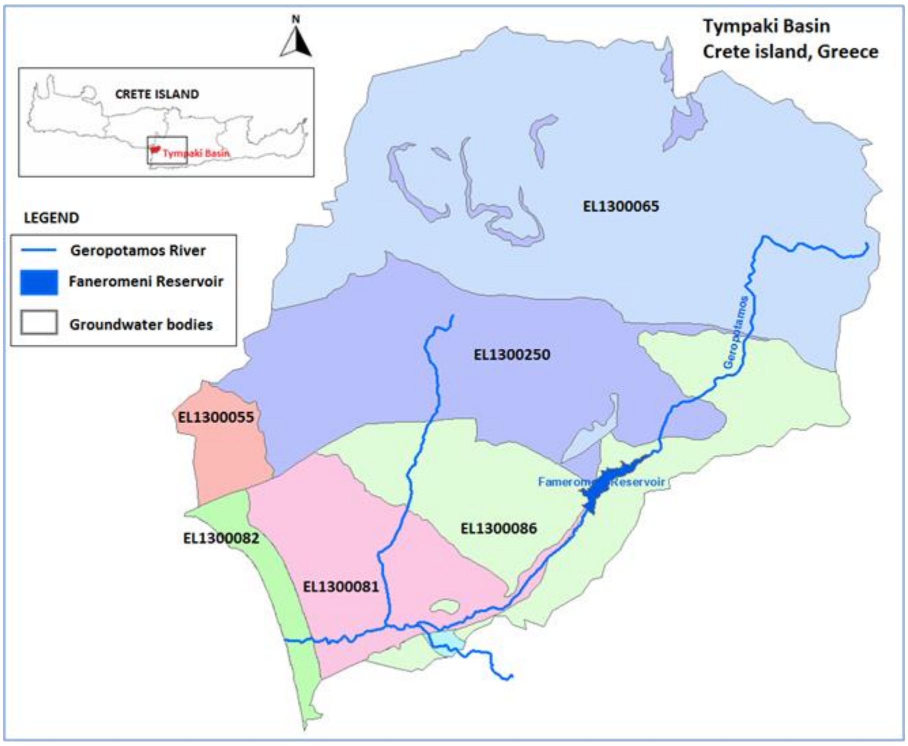
HYMOS Database: This is an information system for storage, processing and presentation of hydrological and environmental data. It follows a database structure with additional tolls for Database structure with tools for data entry, validation, completion, analysis, retrieval and presentation. As an output of specific tools we can obtain validated and completed hydrometeorological timeseries and PET calculations. The existing database is not up to date. Other databases are being used by the different entities that collect the data, based on their data storage and analysis needs.

Water resources management RIBASIM and MODFLOW models

RIBASIM model: This is a water management/water allocation model and has been used for high level basin planning as a Decision Support System (DSS). It allows for the estimation of water demands under different scenarios that have been incorporated in the modes, for distributed water resource allocation (demand nodes-based) where prioritisation is user-defined (within water districts and on distribution network level), as well as for impact analysis (WADIS module: crop production, costs and yields; DELWAQ module: water quality, flow composition on distribution network level). The spatial resolution of the mode is per node and per catchment, while it runs at a monthly timestep. The following output parameters are provided by the model:

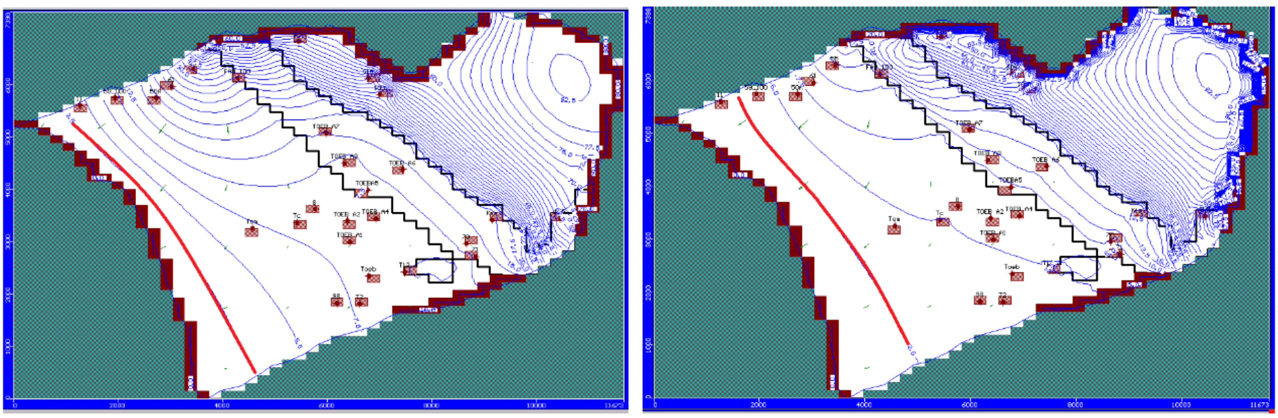
- Per water use/demand node: available water (m^3/s), water demand (m^3/s), ratio (%) of water availability/demand, flow to downstream (m^3/s), water deficit, % of time with water deficit.
- Per hydrological node: storage capacity (Mcm), water level (m), produced and consumed energy (GWh), filling rate (%), available surface and groundwater (m^3/s), streamflow (m^3/s), downstream flow (m^3/s), total surface water availability and demand (m^3/s), total groundwater availability and demand (m^3/s), return flow (m^3/s), groundwater storage (Mcm).
- Per environmental requirement node: % requirement met.

The existing RIBASIM model is managed by the Region of Crete. The model presents a couple of shortcomings. As it has been developed for the entire island of Crete, it may require further discretization and disaggregation to capture more detailed specificities of the Tympaki basin. It also needs to be updated and run for the most recent years, and to incorporate new and updated scenarios on future climate and socio-economic changes. Specific side elements could also be improved, like the surface-groundwater interaction and the definition of environmental flows.



Schematic representation of the Tympaki basin in Crete, Greece

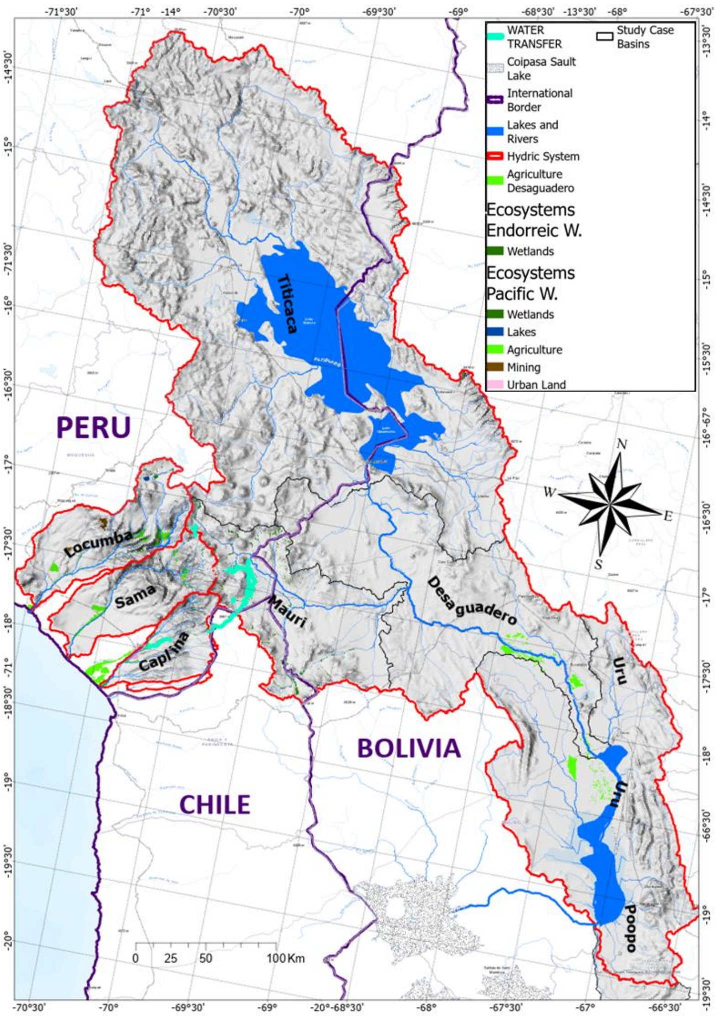
MODFLOW model: This is a groundwater model simulating and predicting groundwater conditions and groundwater/surface-water interactions. The model is grid-based including the different aquifers, and runs at an annual timestep. The existing MODFLOW model is managed by the Region of Crete and the Technical University of Crete. The average annual aquifer recharge from rainfall infiltration and irrigation return amounts to 11 Mm^3, while 0.5 Mm^3 flow into the aquifer from the neighbouring Messara basin. About 1.2 Mm^3 of seawater enters on average, the aquifer every year along its coastal front. Discharge to the sea, of mostly fresh water with a relative small proportion of saline water, amounts, on average, to 7 Mm^3 per year. Rainfall in the area is low (less than 500 mm per year). Despite these unfavorable climatic conditions intense agricultural activity occurs. The model needs to be updated and run for the most recent years and could also benefit from a monthly temporal resolution.



Groundwater levels and seawater-freshwater interface (red line) in the main Tympaki aquifer (left: during the wet period October-March; right: during the dry period April-September). Source: Agioutanti E. (2016).

3.5. Caplina-Mauri-Desaguadero System

The basins of the Caplina, Mauri and Desaguadero are part of two of the most relevant water systems in the Andean region of South America. The first is the hydrographic region of the Pacific to the west of the continent on the coasts of Peru (Caplina), and the second is the endorheic hydrographic region between Peru and Bolivia (Mauri and Desaguadero). Both are not hydrologically linked as they are independent systems, however, there is a relationship in the use of water resources since there is a process of water transfer from the endorheic basin (Maure-- Mauri River Basin) to the Pacific region (Caplina, Locumba Sama Basins), that implies considering both systems when studying the water uses in any of these watersheds. Hydrologically, the endorheic region has an area of 143,900 km² [Bengtsson, 2012], and constitutes its own system called Titicaca-Desaguadero-Salar de Coipasa (TDPS) in correspondence to their main water bodies. On the other hand, the Pacific basin system with a series of individual basins that drain towards the Pacific Ocean throughout Peru, those that are specifically part of the water system of the study area are the corresponding of Caplina [4,303 km²], Locumba [6,400 km²] and Sama [4,845 km²] river basins in the Tacna region in Peru that accumulate an area of 15,548 km² [PET – Perú, 2019]. The study area constitutes a surface of 121,833 km², composed of the Caplina, Locumba, Sama, Maure-Mauri, Desaguadero basins and areas surrounding lakes Titicaca and Poopo, shown in next figure.



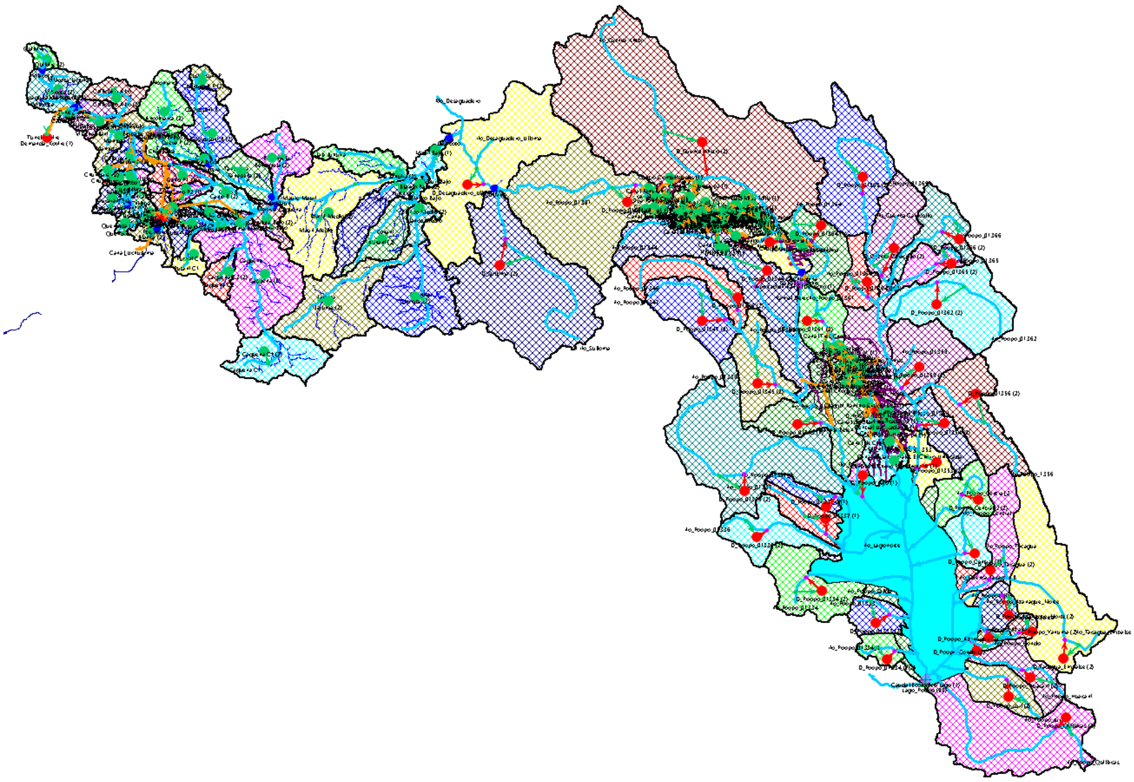
Main view of the hydric system of Caplina – Mauri -Desaguadero rivers

At these latitudes and elevations, the water resources located in the Andean Mountains are extended beyond the local scale, considering that this runoff provides water to adjacent regions, usually drier with less water availability (Viviroli et al., 2007). Under the context of non-integrated local management for water distribution throughout the study area, the system has a diversity of tools and management models that have been produced by academic entities, non-governmental [NGOs], as well as local water authorities in Bolivia, Peru, and Chile.

Water resources management WEAP model for planning and management

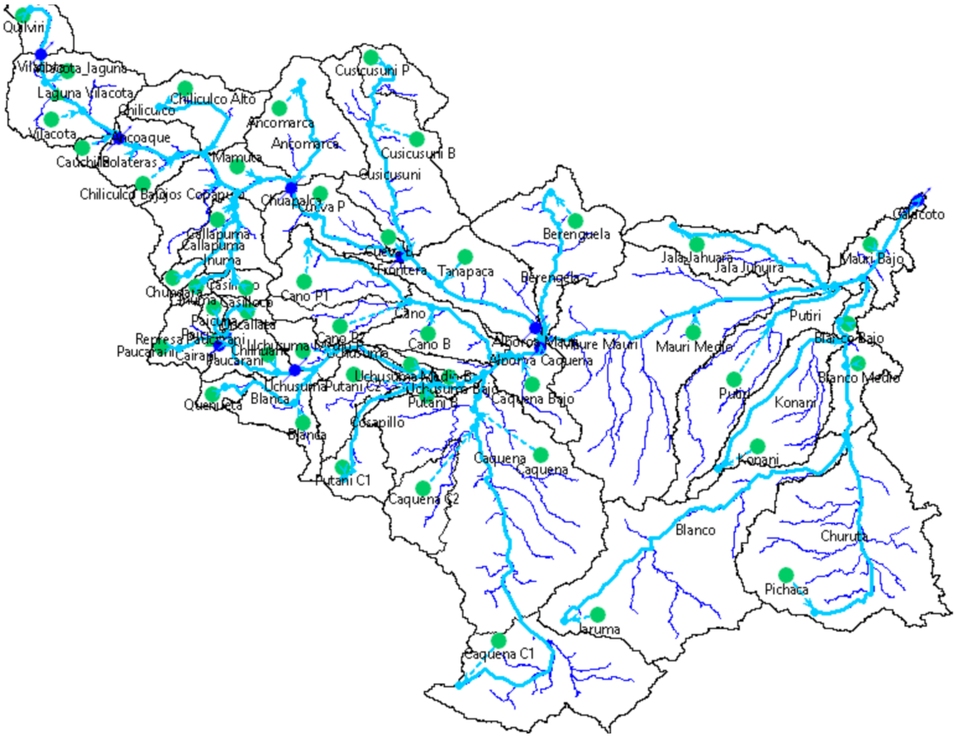
SEI developed a supply and demand model [WEAP platform] for the basin system of Lake Titicaca, Desaguadero, Mauri, and Lake Poopo (Lima N., et al., 2021), to evaluate the effects of increasing agriculture irrigation and the influence of climate variability. According to the analysis of Lima N., et al., (2021), 80% of the changes in the volume of Lake Titicaca (the largest lake in South America) are related to climatic variability and the remaining 20% related to regulation and consumption for agricultural production. In the case of Lake Poopo 65% is attributed to climate variability while 35% has its source in the regulation of productive systems in the Lak's contribution areas. In this case, the model allowed establishing representation of water use, as well as the fluctuation in the supply of both the water system, as well as the two lakes of the system. However, the model has been used in academic and scientific development and not with management purposes without a co-creation process.

In a binational coordination, both governments Peru and Bolivia have developed hydrological studies in the water system under study. In the case of the area surrounding Lake Titicaca, the National Service of Meteorology and Hydrology of Peru (SENAMHI, Peru) developed a hydrological model of the system of basins contributing to the lake (SENAMHI-Perú, 2020). The study allows for a hydrological characterization of the Ramis, Coata, Ilave and Huancane river basins in a period from 1981 to 2016 using SWAT. Likewise, the Ministry of Environment and Water of Bolivia (MMAyA) developed an analogous study for the basins with the same period (MMAyA, 2020). In this study, the Desaguadero River basin, Mauri, the area surrounding basins to Lake Poopo, as well as the regulation in both lakes, Titicaca and Poopo, were modeled through the SWAT platform. A specific case of management models, MMAyA in 2019 developed a vulnerability study of the Desaguadero and Mauri rivers (MMAyA, 2019), considering water use scenarios in both basins, with agricultural use represented in detail due to the influence and scale of this use in both river basins [see next figure].



WEAP model for the vulnerability analysis of water use in Desaguadero and Mauri river basins [Source: MMAyA, 2019]

The trinational Maure Mauri River Basin is the convergence point for transboundary management on which the project focuses. This basin has a technical commission between Bolivia and Peru whose main objective is the development of a binational management model between both countries for the operational management of water resources from the basin. In 2019, this commission published the initial report of the hydrological modeling of the basin generated with agreed data, as well as flow reports at the different points of interest for the binational distribution of these resources (Technical Commission Maure – Mauri River Basin, 2019). This basin model has a description of the hydrological balance of the Uchusuma, Maure, Caquena, Jaruma, Blanco rivers basins, all these tributaries of the Mauri River [see next figure]. The hydrological description presents a detail of the monitoring network throughout the basin for climatology, hydrology, and water quality, considering that the Maure River has traces of water contribution of volcanic origin with loads of boron and arsenic, which restrains the use of water in specific sections of the rivers. Likewise, the upper area of the Uchusuma River has a high influence of groundwater contributors that are highly influential in the lower area at its confluence with the Caquena River and subsequent join with the Mauri River. The study describes these influences on the generation of runoff. An important aspect of the model is the quantification of natural water availability considering the non-altered flows. Both countries that manage water use have provided water extraction data, which allows the model to report flows without effects of extraction in a period from 1964 to 2015.

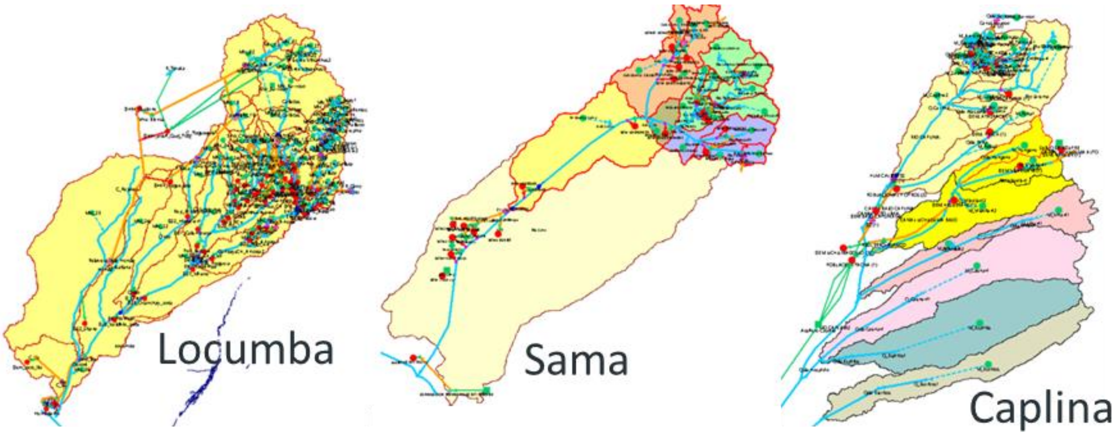


WEAP model of the binational technical commission of Maure-Mauri river Basin [Source: CTB Maure Mauri River Basin, 2019]

Finally, the Technical Secretariat of the Caplina, Locumba and Sama basin, has developed the management plan for these three basins in 2012, as part of the implementation of the Water Resources Management Plan, by The National Water Authority in Peru (ANA), and it was updated in 2021 [see **¡Error! No se encuentra el origen de la referencia.**ext figure. The update included the different allocation components in coordination with the requirements and operational characteristics provided by the different water users in the basins (ANA, 2021), among the most important, Tacna Special Project [PET].

The basin management plan has three WEAP models for the representation of the supply and demand balance, as well as the water deficit for which the plan defines strategies to cover this deficit in the following years. The three WEAP models have information that systematizes the water uses of domestic, industrial, agriculture, and mining, which implies a complexity in the connectivity and dependencies of the three watersheds if any changes under different distribution strategies are proposed. Additionally, it considers the influence of different sources, such as the water transfers from the Puno region from the Maure and Uchusuma river basins. It also considers the representation of the Yarada Aquifer in the lower area, as well as the desalination pilots on the Pacific coast for the supply of demands in the lower area of the Caplina river basin [see next figure].

The models in Tacna have been used to make decisions about water management for the Peru National and Local Authorities. The international models are not used yet for planning purposes, but it is a need to have a model to integrate the decisions at this scale. All the previous models have been developed in a top-down approach, but in this project, we are going to build an integrated model for the whole system using a bottom-up approach through co-creation.



WEAP models for Caplina, Locumba and Sama river basins from Water Resources Master Plans in Tacna Region [ANA, 2022]

Hydrological models using WEAP

From the previous described models, four hydrological models are used to analyse the Caplina-Mauri-Desaguadero basins in this project using the Water Evaluation and Planning (WEAP) software (Yates, Sieber, Purkey & Huber-Lee, 2005). One of the main advantages of WEAP compared to purely "hydrological" models is the possibility of representing the different components of a water resource system, such as structures e.g., regulation, diversion, and allocation; users and demands e.g., domestic, industrial, agricultural, hydropower, and environmental flows. This allows modelling and analysing how specific infrastructure configurations, operating rules and water allocation priorities to different users transform the hydrological regime and the components of interest for a properly water resource management, such as water supply, demands, water quality and vulnerability in a river basin.

In WEAP the basin is represented as a set of hydrological analysis units or "catchments". Water balances are executed at the level of each unit and are subsequently integrated through the drainage network. Therefore, it is possible to establish the cumulative effects of interventions located upstream at any point in the basin. The spatial and temporal scale of the model can be adjusted to satisfy the information requirements.

These models are operated at the monthly time scale and represent sub-basins of the whole system: Locumba (1968–- 2020), Sama (1964–- 2019), Caplina (1964–- 2020) and Mauri-Maure Desaguadero (1964–- 2014).

The Locumba model is depicted by 55 catchments, 43 rivers, 50 demand sites (water use: drinking water (6), agriculture (41), and mining (3)), 17 reservoirs or lakes, 2 hydropower plants, 13 springs, 36 diversions links (irrigation canals, transfers), 6 groundwater nodes that represents the potential and available volume of groundwater, 8 streamflow gauges used to calibrate the model and 20 flow requirements. The Sama model is depicted by 16 catchments, 24 rivers, 21 demand sites (drinking water (3), agriculture (18)), 1 reservoir, 5 springs, 16 diversion links, 2 groundwater nodes, 2 streamflow gauges and 5 flow requirements. The Caplina model is depicted by 24 catchments, 43 rivers, 20 demand sites (drinking water (5), agriculture (14) and mining (1)), 1 reservoir, 3 springs, 11 diversion links, 2 groundwater nodes, 1 streamflow gauge and 6 flow requirements.

To simulate the catchment processes such as evapotranspiration, runoff, infiltration, and irrigation demands for the water balance, these three models use the Soil Moisture Method. This method represents the catchment with two soil layers, as well as the potential for snow accumulation. In the upper soil layer, it simulates evapotranspiration considering rainfall and irrigation on agricultural and non-agricultural land, runoff and shallow interflow, and changes in soil moisture. This method allows for the characterization of land use and/or soil type impacts to these processes. Baseflow routing to the river and soil moisture changes are simulated in the lower soil layer. Correspondingly, the Soil Moisture Method requires more extensive soil and climate parameterization to simulate these processes.

The Mauri-Maure Model simulates the water balance with the Irrigation Demands Only method. It uses crop coefficients to calculate the potential evapotranspiration in the catchment, then determines any irrigation demand that may be required to fulfill that portion of the evapotranspiration requirement that rainfall cannot meet. It does not simulate runoff or infiltration processes, or track changes in soil moisture. (Any water that would have runoff or infiltrated is lost from the system). This model is depicted by 122 catchments, 47 demand sites representing the agriculture water use, 4 reservoirs, 59 diversion links, 16 streamflow gauges and 3 flow requirements.

The four models are being coupled into a unique model that represents the whole system using the Soil Moisture Method, at a monthly scale for the period 1970 – 2020. Climate data is being updated for Sama and Mauri-Maure Desaguadero WEAP models.

3.6. Mahanadi River Basin

Hydrological rainfall-runoff based model.

A rainfall-runoff model was built for various hydraulically independent catchments within the Chhattisgarh part of Mahanadi River basin and the total yield from the basin area was estimated in a report by Kumar and Bassi in 2017. For this, the historical data of stream flows of various (gauged) catchments was collected from Central Water Commission. The available data on impoundments and effective water diversions upstream of the gauging sites were obtained and added to the observed stream flow to arrive at the virgin flows for the catchment, which is the runoff that would occur from the catchment in the event of no artificial impoundments.

Based on the estimated stream flow series, and the weighted average of the annual rainfall of the catchment, the rainfall-runoff relationships were established for the catchments using regression analysis. The regression equation which gives the best fit was chosen as the rainfall-runoff relationship for the catchment/basin. However, under ideal conditions, for semi-arid and arid regions with low to medium rainfall, the non-linear curves (exponential and power functions) are preferred and linear relationships for sub-humid and humid regions with high rainfall.

According to the study, average annual rainfall varies from 888 mm to 1988 mm in upper and 861 mm to 1739 mm in middle sub-basin. The inter-annual variability in rainfall in both upper (CV=17%) and middle sub-basin (CV=16%) was found out to be not very high. In contrast, it was found that there is high inter-annual variability in stream-flows. Further, for the same amount of rainfall, runoff generated per unit of catchment area in upper sub-basin is higher for Parthardi; and in middle sub-basin it is for Kurubhata. Overall higher variability in stream-flows was observed in upper sub-basin in comparison to the middle sub-basin. The rainfall-runoff modelling shows linear relationship.

Frequency analysis was carried out for the estimated values of standard precipitation index (SPI) for select locations in the basin, and probability of non-exceedance was estimated for rainfalls corresponding to different SPI values. The probability of occurrence of rainfall below the mean value was in the range of 55-58 per cent. This means, there is greater probability of occurrence of a year being a drought year than being a wet year.

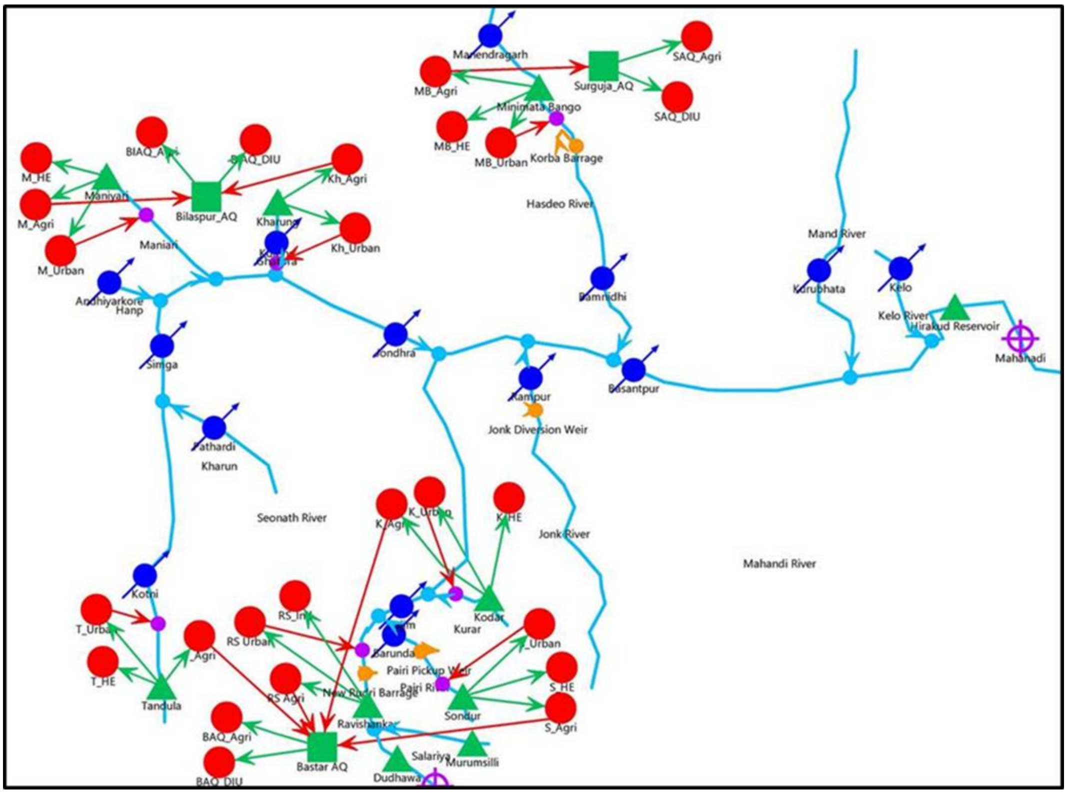
Analysis of long-term trends in rainfall of seven locations in the basin for a 41-year period (1975-2015) showed increase in rainfall in four locations and decrease in rainfall for others. As per the trend analysis of historical data, average annual rainfall change is expected to be in the range of -6.2 mm to 7.1 mm. The corresponding change in average annual runoff will be in the range of -4.3E-05 to 0.000114 m^3/sq. km in future in different catchments. In the case of rainy days, six locations showed decrease in number of rainy days, and one showed increase. Further analysis showed a linear relationship between the magnitude of annual rainfall and number of rainy days.

The estimated average annual increase in runoff owing to expected long-term change in rainfall (as predicted by Indian Institute of Tropical Meteorology under A2 B2 scenario) of 6mm per year in Chhattisgarh part of the basin is 0.003 MCM per sq. km. In a span of 40 years, this would add up to contribute a runoff increase of 0.12 MCM per sq. km per annum.

The rainfall-runoff models so constructed were used to generate the annual runoff data for the previous years for which stream gauging data are not available. The estimated stream flow series and the observed flows were used to estimate the (75%) dependable flows by estimating the 'probability of exceedance' (or the minimum amount of flows that would occur with 75% dependability). This was treated as the dependable yield of the respective catchments. These models were used to predict future changes in the runoff (in the sub-basins which the catchment represented), that would be caused by likely changes in climate, using the predicted values of rainfall for different points of time in the future.

Water resources management using a Water Evaluation and Planning System

In a study by Kumar and Bassi (2021), a Water Evaluation and Planning (WEAP) model was set up (beginning June 2009 and ending May 2050) to analyse the future water balance of upper and middle parts of the Mahanadi basin for the expected changes in socio-economic conditions. The WEAP configuration is shown in figure below. The model was also run for future scenarios that considered different water management interventions, and hydrological consequences of climate variability and change. The model results showed that there would be a water deficit, about 2,182 million cubic meters (MCM) by 2050 (20%of the demand) even under the business-as-usual scenario. The gap was found to widen to 5,005 MCM (25% of the demand) under a high growth scenario. Further, the study found that the water demand management interventions in agriculture would be able to reduce the overall demand for water in the basin to some extent, while it would also reduce the supplies slightly due to a reduction in return flows occurring as a result of irrigation efficiency improvement. The water deficit under this scenario would reduce to about 2,773 MCM in 2050. Under the predicted changes in climate, it was found that the water deficit is expected to reduce further by 1,684–2,373 MCM in 2050 due to an increase in supplies owing to an increase in the catchment yields resulting from higher rainfall. It was found that there will be a significant amount of outflow from the two sub-basins in all the scenarios in most future years (ranging from 25,286 MCM to 28,697 MCM in 2050), during drought years, the water deficit in the upper basin areas was found to increase slightly, but with a significant reduction in the outflows to the lower sub-basin areas by 2046–47 (will be about 11,311 MCM). The results of the study indicated that there would be a need for building more water storage/diversion infrastructure to detain floodwaters during wet years that can provide buffer storage for the dry years.



Schematic of the WEAP model for the Mahanadi River Basin

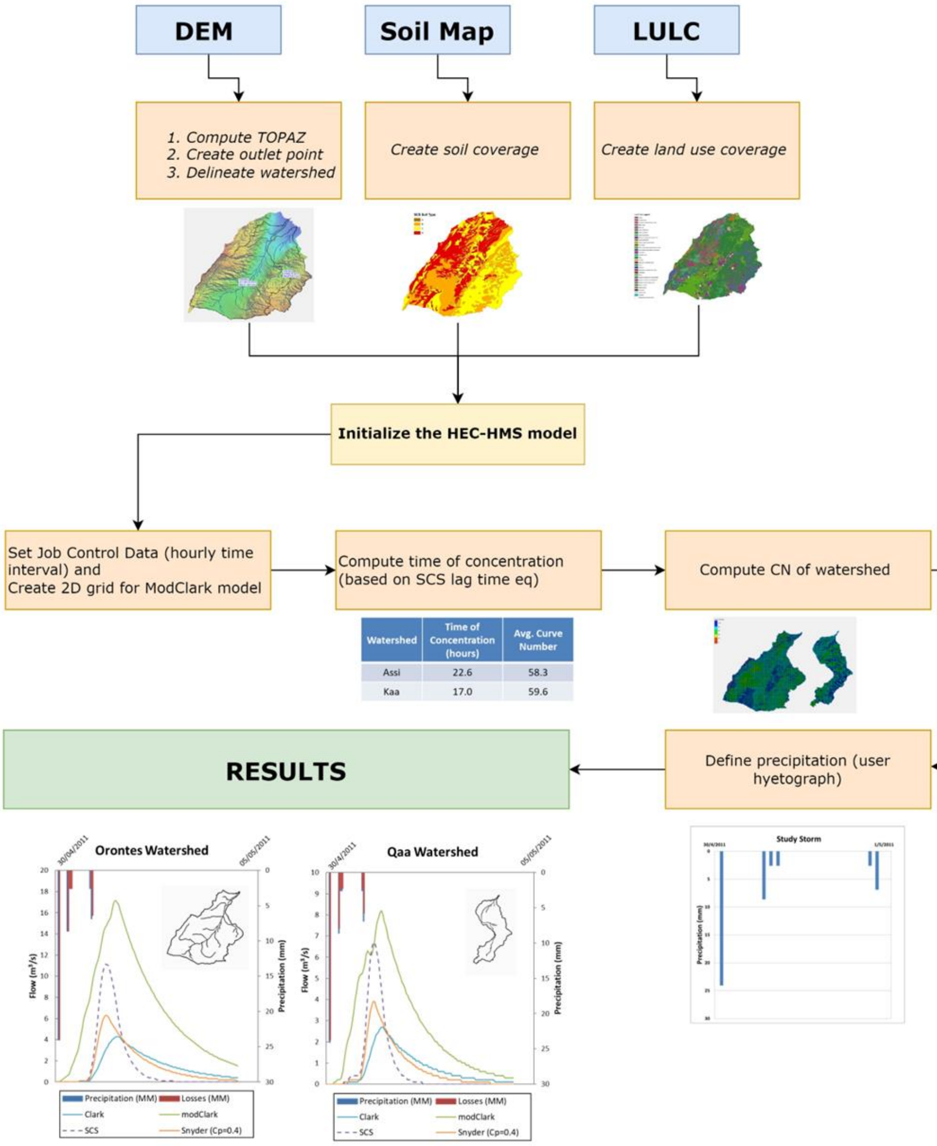
3.7. Orontes River Basin

Hydrological model based on WMS, HMS, AUB

Two hydrologic models have been developed to two sub basins of the Orontes watershed in Lebanon (Orontes and Qaa watersheds): WMS 9.1 (Watershed Modeling System)(Erturk, Gurel et al. 2006) and HEC-HMS 3.5 (Hydrologic Engineering Center–- Hydrologic Modeling System)(Chu and Steinman 2009). WMS was used for automatic watershed delineation, basin parameters computation, and acts as a graphical user interface for hydrological models. It was used to set up the modelling framework and prepare the necessary input data. HEC-HMS, on the other hand, was used for hydrologic modelling process and conducting hydrological computations. HEC-HMS accounts for rainfall, runoff, and routing when analysing and simulating the hydrologic processes within the watershed. Hence, WMS and HEC-HMS were used together to integrate the hydrologic components of the modelling process.

WMS 9.1, developed by the Environmental Modeling Research Laboratory of Brigham Young University in cooperation with the U.S. Army Corps of Engineers Waterways Experiment Station and is currently maintained by Aquaveo LLC, is a tool that automates watershed delineation and calculates basin parameters, including area, slope, and runoff distances. It acts as a graphical user interface for various hydraulic and hydrologic models, such as HEC-HMS. A WMS model was created for the two sub basin watersheds of the Orontes in Lebanon through importing the Digital Elevation Model (DEM) of Lebanon, estimating the Time of Concentration, identifying an outlet point, delineating the watersheds, creating soil coverage (using the soil map of Lebanon), and generating land use coverage map. WMS is adjusted to set hourly time intervals for modelling and analysis (temporal resolution) to capture variations in rainfall, runoff, and hydrological parameters on hourly basis, allowing for accurate representation of the hydrological conditions changes during the day.

HEC-HMS 3.5, a version of HEC-1, provides an improved user interface, graphics, and reporting competencies. It is widely used in hydrologic computations and incorporates multiple hydrologic functionalities. HEC-HMS model has three components: the basin model, meteorological data, and control specifications. For the two sub basins of the Orontes watershed, hydrologic information was imported from WMS to be used in HEC-HMS model. Total runoff areas were estimated using precipitation and land surface data to produce hydrographs. Losses methods, including the Soil Conservation Service (SCS) Curve Number (CN) model and others, were applied. To analyse runoff processes, several transfer methods were considered – including: SCS, Clark, ModClark, Snyder, and Kinematic wave.



Creating WMS model of Orontes and Qaa watersheds.

Hydrological model based on MODFLOW and WEAP, ACTED, WeWorld-GVC, & BTD

For groundwater assessment, MODFLOW (McDonald & Harbaugh, 2003) (Modular Finite Difference Groundwater Flow Model) was recently applied to construct a three-dimensional finite-difference groundwater flow model of the aquifers in the Upper Orontes River Basin (Lebanese section of the basin) (ACTED, WeWorld-GVC, & BTD, 2023). MODFLOW is one of the standard tools for groundwater modelling, developed and maintained by the U.S. Geological Survey (USGS), and it can simulate groundwater flow using multiple hydrogeologic settings. Additionally, a 3D lithological model was created to visualize the distribution of different lithologies (geological formations) and represent the hydrogeological layers of the basin.

Due to the challenges and complexities associated with karstic aquifers, hydraulic conductivity, conductance of General Head Boundary (GHB), and recharge rates were treated as unknown parameters. To address the complexity of subsurface geology and account for spatial variability within the aquifers, a zonal parameterization approach was implemented. Later, an inversion method was employed using historical observational spring discharge data to estimate the unknown values. PEST, an independent parameter optimization tool, was used to calibrate and optimize model parameters.

For future scenarios, the CMIP6 model complications (adopted from the World Bank CCKP) climate projection data was adopted. Two Shared Socioeconomic Pathways (SSPs) were considered – SSP2-4.5 (Intermediate stabilization) and SSP-8.5 (High Baseline). Additionally, various water management scenarios/assumptions were incorporated into the study – accounting for increased irrigation demand and the implementation of NWSS (National Water Sector Strategy) measures.

The Water Evaluation and Planning (WEAP) model (Sieber, 2006), developed by the Stockholm Environment Institute (SEI), was used to assess water resource management in the Upper Orontes Watershed (ACTED, WeWorld-GVC, & BTD, 2023). WEAP is used to simulate river flow, water demand, and supply of a watershed over time, incorporating technical and socioeconomic aspects. WEAP supports studying the impact of various scenarios on water resources, such as land use, climate, and population change.

In this report, a simplified hydrologic model was developed for the Upper Orontes Basin, where runoff was generated through an iterative calibration process and results were compared with observational streamflow measurements from the Hermel hydrometric station. In WEAP software, a semi distributed (node-based) water resources management model was developed at the monthly timestep (2000-2018 and 2020-2035). Various scenarios were modelled to evaluate domestic water demand, irrigation demand, ground water abstraction, and pollution.

Agronomic model–- AquaCrop

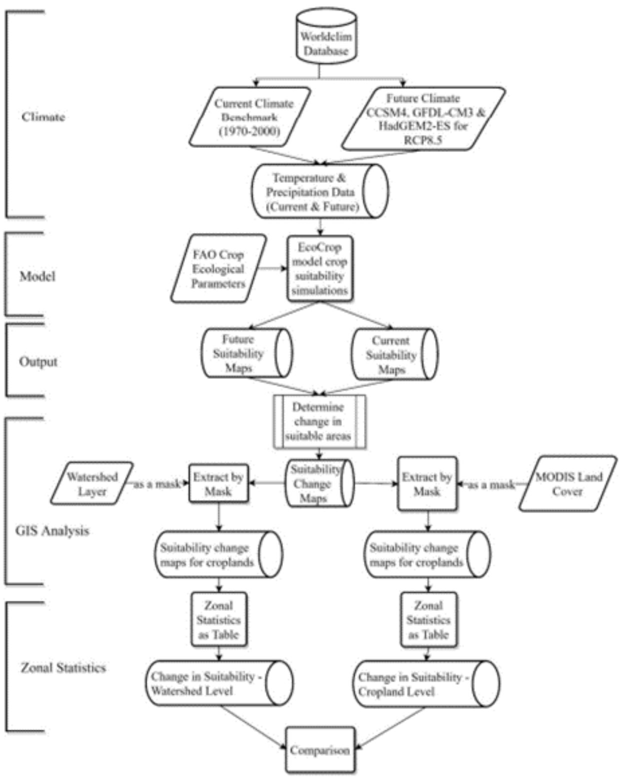
Two agronomic models have been developed for the Orontes River Basin using AquaCrop (Steduto, Hsiao et al. 2009) and EcoCrop (Ramirez-Villegas, Jarvis et al. 2013) by (Abdallah 2018). The EcoCrop model was used for crop suitability analysis, while the AquaCrop model was used for evaluating evapotranspiration, biomass, yield, and water productivity using climate data from 1970-2000 as baseline and a future scenario (2050) under high emissions (i.e., the RCP 8.8) for assessing of the impact of climate change on crop suitability and agricultural production.

AquaCrop, developed by the FA''s Land and Water Division, is a widely used crop growth model that focuses on crop responses to climate change, irrigation methods, and fertilizer applications. When calculating evapotranspiration, AquaCrop separates between transpiration and evaporation – it links transpiration to canopy cover, and evaporation to uncovered soil. The model includes stress coefficients such as stomata closure, canopy senescence, leaf expansion, and harvest index variability. Using a normalized water productivity constant and taking into consideration CO2 concentrations and climatic conditions, AquaCrop converts transpiration directly to daily biomass. AquaCrop allows for simulations in various locations under several climate scenarios. Hence, it has been used in assessing the impact of future climate change projections on major crops in the Orontes River Basin, including apple, barely, cabbage, chickpeas, cotton, cucumber, eggplant, olives, onion, soybean, sugar beet, tomato, watermelon, and wheat.

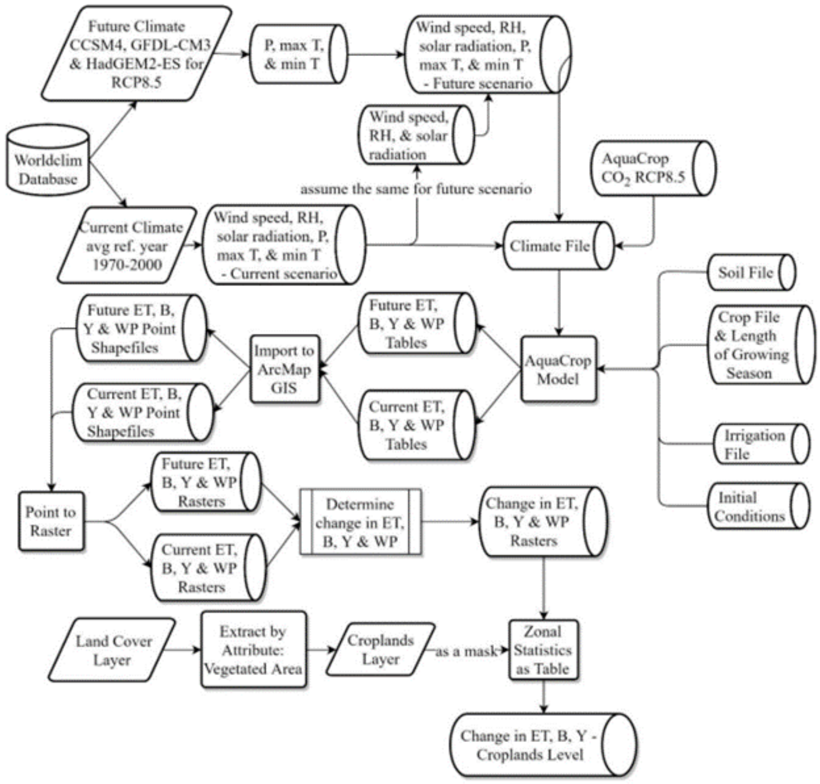
EcoCrop, developed by the Food and Agriculture Organization of the United Nations (FAO), is an initiative used to assess crop suitability and ecological niches based on environmental conditions. It was developed to help determine the suitability of specific regions for growing different crops considering climate change. EcoCrop generates a suitability index as an output which are computed based on whether precipitation and temperature conditions are in agreement with predefined thresholds. Here, it has been used for crop suitability analysis in the Orontes River Basin along with the AquaCrop model.

The current baseline of the agronomic models represents the period between 1970 and 2000 and will be subject to future modifications.

The overall methodology is shown in the below figures.



Flowchart of the steps performed for crop suitability analysis.



Flowchart of the steps performed for the evapotranspiration, yield, biomass and water productivity simulations for the two climate datasets: current benchmark (1970-2000) and future climate (2050) with RCP 8.5 emission scenario.

4. Gaps in the existing modelling landscape

The gaps identified in the different case studies show some common points in which TRANSCEND would need to focus, taking also into account the synergies and the cross-fertilization opportunities between labs that are enabled by this situation. The common issues identified among the labs (involving at least two of them) are:

- Lack or limited inclusion of groundwater modelling nor stream-aquifer interaction.
- Need of expanding the current modelling suite to enable economic assessments.
- Lack of evaluation of ecological flows or environmental needs or services
- Need to incorporate climate change projections from the last family of scenarios (CMIP6)

The gaps identified in each lab are stated below.

<u>Reno River Basin:</u>

Some of the current models of the Reno River Basin will need to be updated to account for new datasets and to incorporate some new developments that could have a positive impact in the assessment of water resources. In particular, the agronomic modelling would need some improvement. Furthermore, a socio-economic model for the Reno River Basin would be adequate to characterize water uses and adaptation measures under an economic point of view. Besides these modelling improvements, the Reno River Basin modelling suite would benefit from adopting CMIP6 scenarios over 2021-2050 and

2071-2100 to better inform climate change impact assessments and define tipping points triggering the need of adaptation measures.

Jucar River Basin:

Both the hydro-economic and the system dynamics water resource management models would need to be improved to enable an efficient assessment of climate change impacts. The current hydro-economic model is based on demand curves, for which representing variations in crop water demands (e.g. changes in crop ET, change of crops, irrigation techniques, area) is challenging. This model would need to be updated to represent such modifications in an agile way. Similarly, the system dynamics model does not take into account ecosystem services in its current version, so it will need to be updated to take them into consideration. In addition to water resource management models, the crop responses to climate change conditions in the main crop of the lower Jucar (citrus) is challenging to be modelled using standard crop models. In this regard, a new agronomic model designed for woody crops, in particular citrus trees, is under development at UPV and would be applied to address the impacts of climate change on citrus areas. Finally, current climate change projections available rely on CMIP5 and CMIP5-related EUROCORDEX models, which would need to be updated to the new family of climate models, CMIP6.

Nitra River Basin:

The integrated information and data system is missing; the various information and data collected by the different institutions within the sector are not well linked. Often, the institutions do not have their own data/information system. Sometimes, even the institution with the same Ministry (of Environment) have to pay for the data from the other institutions. Institutional and financial capacities for systemic use of modelling in water-resources management are insufficient.

Up to 80% of the drinking water comes from the groundwater, yet there is no systemic modelling of the groundwater in place and how will the climate change impact on the aquifers given also the hydrogeological situation in the region. As well, a model for simulation of the mining water and flooding of the mines is missing. The mining water had been drained during the mines operations in order to make it possible to mine the coal deposits. The mining company did not have enough resources to maintain the drainage system, hence, some of the mines started to be filled up with water. The company still wants to maintain the drainage in 16 km, because of the geothermal potential of the water for heating of greenhouses where they grow tomatoes, catfish farm, and for heating of the buildings. It thus uncertain how fast the mines will fill up, especially in the interplay with groundwater. It is uncertain what will be the consequences for the water levels in the wetlands and rivers. For instance, Handlovka, the left-side tributary of the Nitra river was donated 200 $l\ s^{-1}$ by the mining water. Ťakov wetland is also still fed by the mining water.

Tympaki River Basin:

The existing RIBASIM model presents a couple of shortcomings. As it has been developed for the entire island of Crete, it requires further discretization and disaggregation to capture more detailed specificities of the Tympaki basin. It also needs to be updated and run for the most recent years, and to incorporate new and updated scenarios on future climate and socio-economic changes. Specific side elements could also be improved, like the surface-groundwater interaction and the definition of environmental flows. The Tympaki basin is heavily dependent on groundwater sources. About 7.5 million m^3 are annually abstracted from groundwater for irrigation purposes in the central plain of Tympaki (to irrigate about 40 km^2). It is thus evident that the surface-groundwater interactions need to be well captured, and thus coupling of the water resources management model (e.g. RIBASIM, WEAP, etc.) with a groundwater model (like e.g. MODFLOW) is an important element to be added.

Caplina-Mauri-Desaguadero System:

The issues of the Caplina-Mauri-Desaguadero System mainly refer to the fact that it a large basin covering several countries with different socioeconomic, political and governance features. Climatic information and projections are not homogeneous in the basin and, in particular, none of them employ CMIP6 scenarios. Furthermore, several catchments of the basin have WEAP models developed, but a single and homogeneous model does not exist yet, which would be crucial for basinwide analyses and climate change adaptation. Besides water quantity, water quality is also an issue in the basin, but currently there is no water quality model developed in the basin. Similarly, ecological streamflows are currently not addressed in a comprehensive and homogeneous way in the basin.

Mahanadi River Basin:

The current WEAP model of the Mahanadi River Basin will need to be distinctly improved to properly address climate change impacts. One of the main points is to include groundwater flow modelling to adequately represent the impacts of changes in groundwater use. Another issue is lack of coverage of the Odisha rea. Similarly, economic analyses at the basin scale are not possible with the current WEAP model configuration. Finally, environmental flow requirements for the delta are not set yet.

Orontes River Basin:

WMS model Karst Hydrology remains a challenge; difficult to model the processes in the Orontes due to the complex hydrology of karst systems (spring flow is from a karst aquifer); snow-depth data is lacking in the basin as well; we have some snow duration data; well data is also lacking so no data on pumping for non-ag uses; many illegal wells; need to update the agricultural land crop types due to reports on recent mono-cropping; no economic model currently available.

5. Blueprints of the proposed modelling suite

The blueprints are described per lab in the following sub-chapters. A table summarizing the requested modelling suite is provided below.

TRANSCEND requested modelling suite.

	Reno River Basin	Jucar River Basin	Nitra River Basin	Tympaki River Basin	Caplina-Mauri-Desaguadero System	Mahanadi River Basin	Orontes River Basin
Climate change scenarios*	CMIP6	EUROCORDEX, CMIP6	EUROCORDEX, CMIP6		CMIP6	CMIP4, CMIP5	
Landuse scenarios*					Agricultural areas and water demands		Water account using remote sensing
Agronomic models	CRITERIA-1D, Icolt, Irrinet	Aquacrop, Aquacitrus	DAISY, WOFOST				To be decided
Hydrological models	Topkapi, new model to be decided	TETIS	HBV, TUW, Bilan, Frier, MIKE, HEC-RAS	SACRAMENTO, HYMOS	WEAP, TBD (water quality, ecological flows)	WEAP extended and integrated with groundwater flow model and environmental flows	WMS, HEC-HMS, snowmelt model
Water resource management models		GAMS, Vensim	To be decided	WEAP			WEAP extended, MODFLOW
Hydro-economic models		GAMS	To be decided		To be decided	To be integrated with WEAP	
Microeconomic models	To be decided						To be decided
Macroeconomic models			To be decided				

Existing model

Updated model

New model

5.1. Reno River Basin

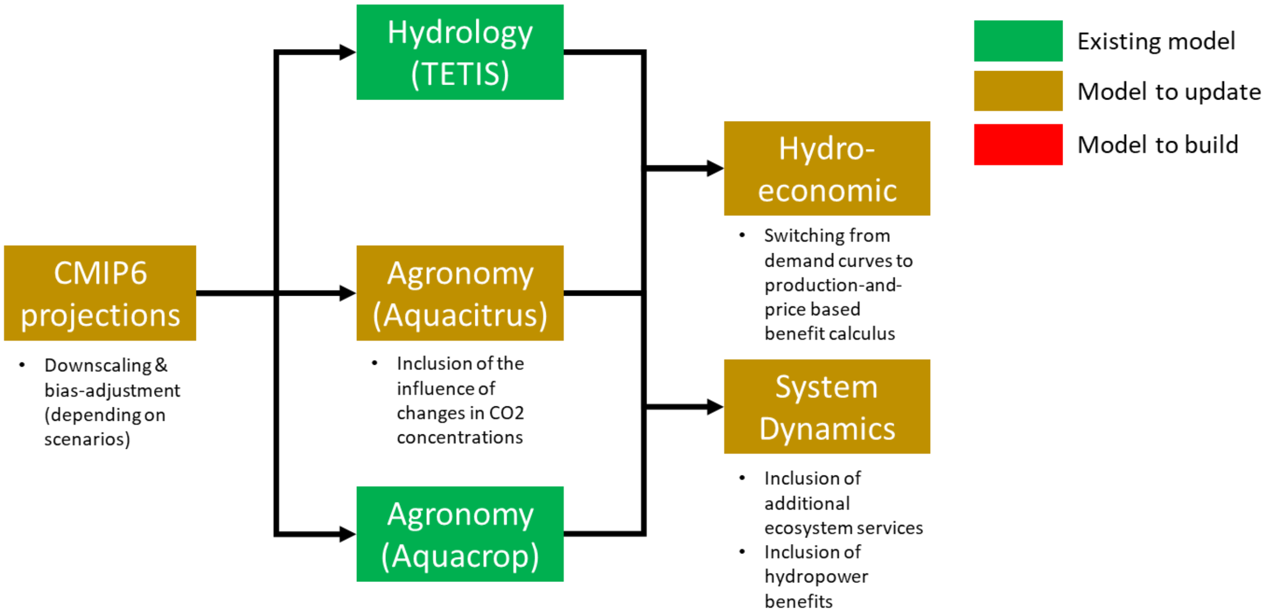
The improvements requested for the Reno River Basin modelling suite are:

1. Hydrological projections tailored to the Reno River Basin based on CMIP6 emission scenario (SSPs available) over 2021-2050 and 2071-2100.
2. Improvement/generation of the water resources management model for the Reno River Basin with updated data framework, statistics, and modelling suite.
3. Improvement of the agronomic model for the Reno River Basin.
4. Implementation of the socio-economic model for the Reno River Basin.

5.2. Jucar River Basin

The improvements requested for the Jucar River Basin modelling suite are:

1. Generation of additional CMIP6 scenarios tailored to the particular features of the Jucar River Basin by applying novel downscaling and bias correction methods (artificial intelligence), in addition to the current CMIP6 scenario available for the basin (5 climate models for the SSP1_2.6, SSP3_7.0 and SSP5_8.5 scenarios).
2. Improvement of the agronomic model Aquacitrus, designed for being applied to woody citrus crops, by including on its formulation the influence of raising CO2 concentrations in the plant processes.
3. Transformation of the current benefit estimation mechanism for agricultural demands in the hydro-economic model into a benefit computation based on estimated crop production (depending on water allocation) and crop prices.
4. Expansion of the system dynamics models by including additional ecosystem services (e.g. fish habitat curves in selected streams) and hydropower production and benefits.

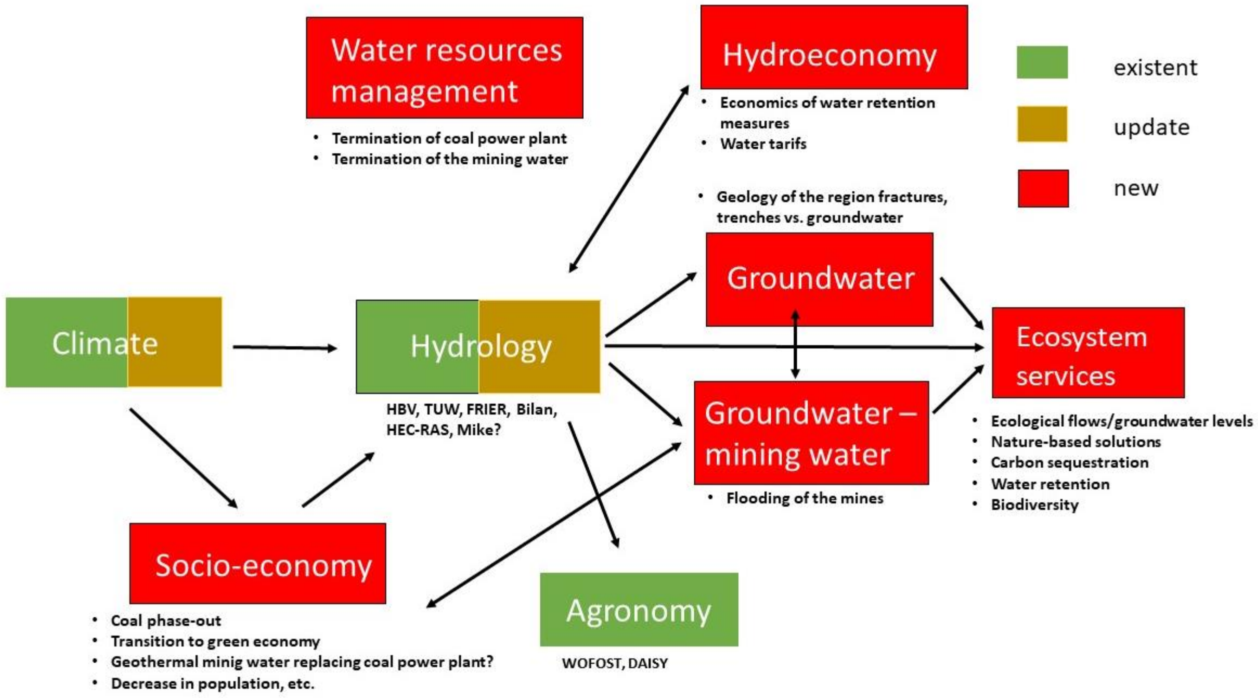


5.3. Nitra River Basin

The improvements requested for the Nitra River Basin modelling suite are:

1. Improved climate projections developed by SHMÚ, plus additional scenarios in case of further gaps were identified.
2. Hydrological projections based on the previous scenarios (e.g. using HBV, TUW, Bilan, Frier)
3. Development of a water resource management model to analyse the impacts of termination of mining water in the Handlovka and Nitra rivers.
4. A new hydroeconomic model to support the Horná Nitra River Basin in estimating the cost-efficiency of water retention solutions and extending the use of geothermal water for heating.
5. A macro-economic model, in combination with the hydroeconomic model, to estimate the socio-economic impacts of shifting from coal mining to green economy.
6. Update of the existing WOFOST and DAISY agronomic models to be fed by new scenarios.
7. Incorporate adequate models to estimate climate change impacts on aquifers and stream-aquifer interaction.
8. Inclusion of a model to describe the flooding of the mines and how their dynamics might affect wetlands and groundwater bodies.

The hydrology of the surface and groundwater affect consequently the wetland ecosystems and, but also the water levels in tributaries and Nitra River (ecosystem services, Fig. 1). In addition, mining company (HBP) has been developing water-retention projects. HBP has projects for three lakes, two of them are former sedimentary ponds and would be fed by the mining water. The third one would be created in the former surface mining pit in rather technologically simple way.



5.4. Tympaki River Basin

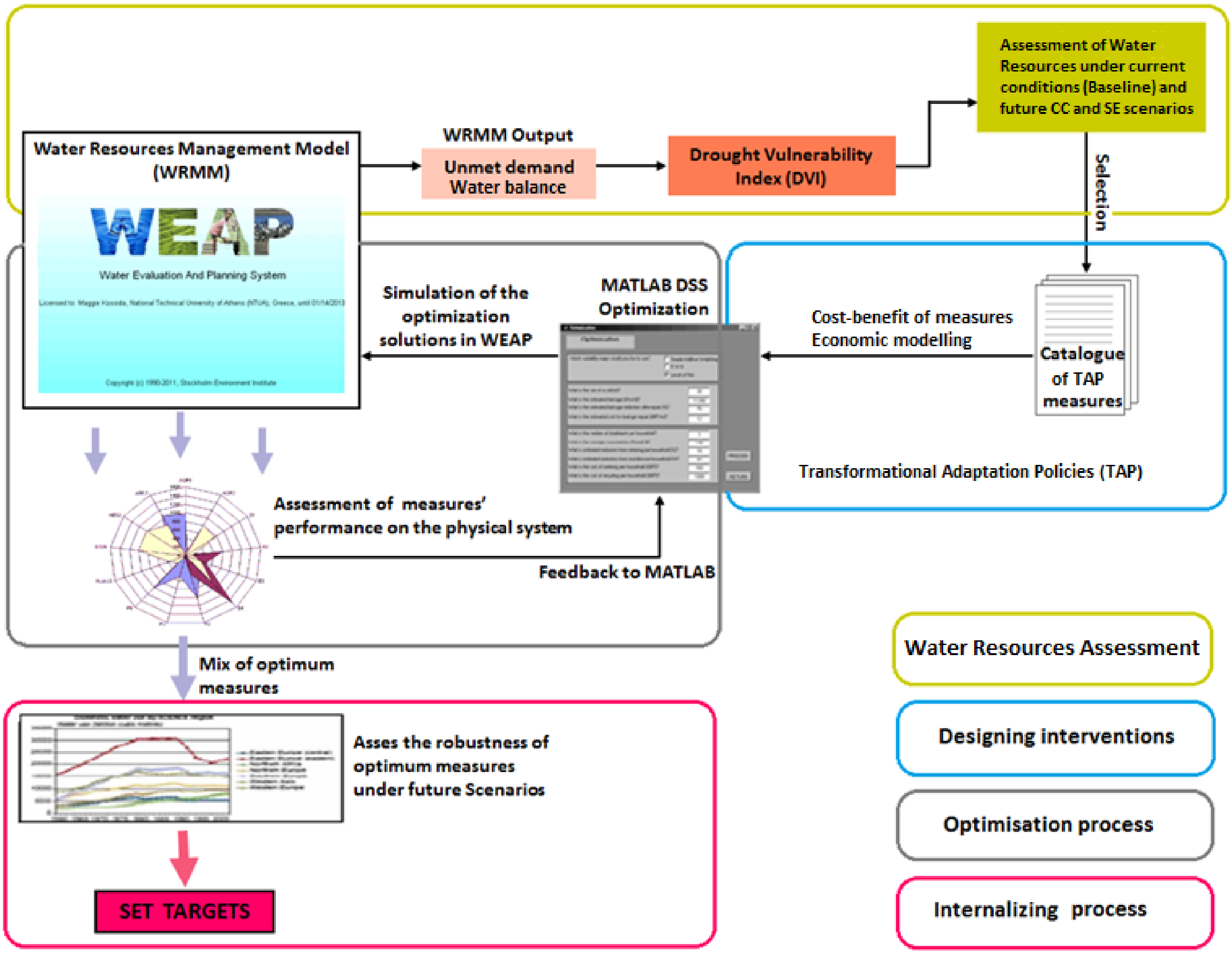
The modelling suite of the Tympaki River Basin would request the following improvements:

1. Development of a detailed water resource management model, at monthly scale and sub-catchment level, to represent the water balance in the basin using physical-based hydrological modelling in WEAP.

The baseline (current account in WEAP) will opt to cover at last 10 years of the most recent period, e.g. 2013-2023. The accurateness of the water balance will be subject to local stakeholders' expert knowledge and discussed with them. The detailed water balance will represent the salient feature of the river basin in their actual spatial orientation. The application will include all major surface water and groundwater resources, distributed representations of water demands, returns, losses, transfers, etc. and objects that represent the major water management infrastructure (reservoirs, WWTPs, desalination plants, etc.). The model will be built by the based on a detailed assessment of the river basin and in consultation with the local stakeholders and water managers as previously mentioned.

WEAP can be applied to municipal and agricultural systems encountered in Tympaki Moreover, WEAP can simulate a broad range of natural and engineered components of these systems, including rainfall, runoff, baseflow, and groundwater recharge from precipitation; sectoral demand analyses; water conservation; water rights and allocation priorities, reservoir operations; hydropower generation; pollution tracking and water quality; ecosystem requirements. Regarding the spatial resolution of the model, the Tympaki WEAP model will be built at sub-catchment level, with the maximum possible disaggregation of urban, agricultural and industrial water demand nodes. Of course, some aggregation of water users might be meaningful (e.g. aggregating domestic water use from neighbouring villages which use the same water supply source, or individual farmers who abstract from the same groundwater aquifer/ strata). These cases will be evaluated, and a distributed model will be developed at the optimal disaggregation level, given the data availability constraints and the policy and decision-making scope of the model (i.e. a model that can serve policy relevant assessments and can be used to support decision-making also for future applications). The suggested temporal resolution of the model is a monthly timestep, while the simulation period will be based on data availability, yet it is suggested that a minimum of 10 years are simulated. The model will be fully documented (key assumptions used, proxies, equations, routines, etc.), flexible and expandable so that additional components could be added in the future for other purposes by other modelers.

With regard to the TAPs, a bundle of measures/ interventions will be identified jointly with the stakeholders. These will be then tested/simulated to assess (ex-post evaluation) their impact and effectiveness in the Tympaki RB, against specific criteria (e.g. water saving, water use reduction per economic activity, cost, environmental benefits, etc.), within the WEAP model. Furthermore, optimization algorithms will be applied in order to optimize water allocation and meet demand in the Tympaki RB model while maximizing the selected objective function. The WEAP model, while it constitutes the core part of the overall analytical framework, is not individually sufficient to support the sort of this ex-ante policy analysis as described. The model will need to be nested within a larger decision-support structure (modelling suite) which is presented in the following figure.

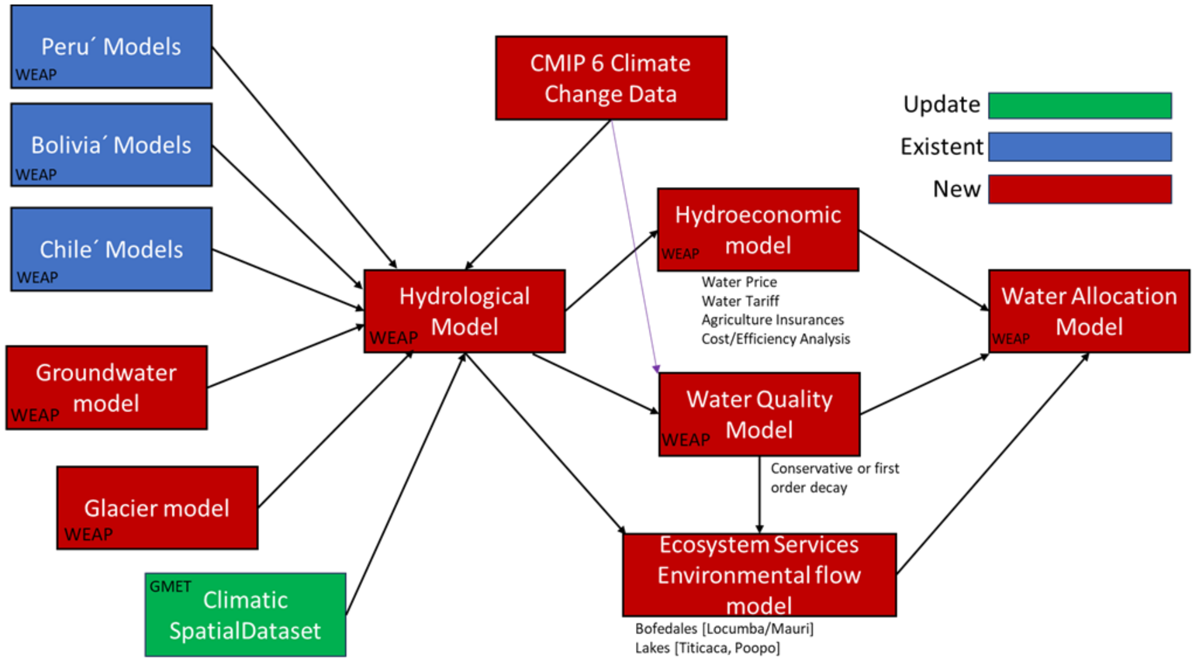


5.5. Caplina-Mauri-Desaguadero System

The Caplina-Mauri-Desaguadero System would request the following improvements:

1. Development of new climate change scenarios using CMIP6 climate models.
2. Generation of a single WEAP model combining and updating the existing models of the Caplina/Locumba/Sama, Mauri and Desaguadero catchments.
3. Development of a water quality model coupled to WEAP, including organic loads and heavy metals.
4. Creation of a hydroeconomic model, in combination with WEAP, to analyse the influence of water prices and operational costs.
5. Set up of an estimation of agricultural areas and water demand for agriculture using remote sensing.
6. Development of ecological flows and inclusion of them in WEAP, especially in the lower area of the Desaguadero River, related to the environmental and socioeconomic functions of the Lakes Uru Uru and Poopo

Furthermore, the climatic and hydrological information must be homogenized for the entire study area and for a period between 1960 and 2020. For this, the data available in the reports and water resource plans of each of the catchments will be used. This information will allow us to analyze climate patterns over extended periods, as well as climate anomalies related to water deficit, their recurrence, level of impact, and severity on the economic systems.
An integrated WEAP model will allow us to evaluate the influence of the actions on the entire system. This aspect is vital since the catchments are interconnected from the perspective of water use and therefore a change in either water use pattern, as well as in water availability in any of the catchments implies changes in the others. Additionally, the complexity of having the influence of Lake Titicaca is added. As a conclusion of the start-up workshop in the living lab, it was recommended that it should be integrated into the modeling area, considering the implications from the perspective of actions and influence on water availability on Desaguadero River.



The water resources plans, as well as the appendices of their productive studies in the basins from Peru, establish information baselines for the development of economic models, which can analyze influences related to water prices and operational costs. Water use systems, such as reservoirs, canals, irrigation systems, groundwater pumping, in the case of basins in Bolivia will be coordinated with NGOs as well as ALT which can generate this data or contact the entities that can be a link to the water users. Preliminarily, the use of satellite information has been projected for the general estimation of agricultural areas as well as their water demand, these based on the conversion of the light spectrum captured by satellite images into vegetation indices such as NDVI and others (O., Beri., et al 2019, H., Jaafar., et al., 2022). The methodological scheme for the development of the economic component is also subject to consensus and development with the project partners; however, SEI's experience in the region allows us to identify that the initial approach for the economic analysis could be based on a Cost/Efficiency approach.

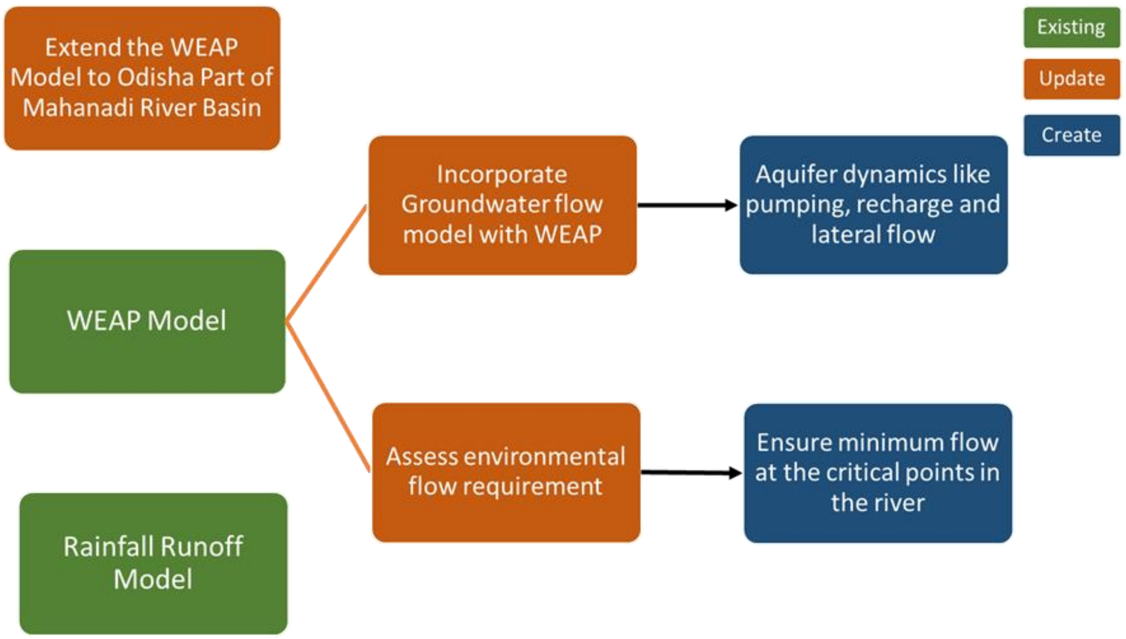
In this system, water availability is limited to quantity and quality. Considering the natural presence of Arsenic and Boron in the rivers, the small quantity of water will be affected by the higher concentrations of heavy metals due to climate change effects in flow and less dilution. The organic loads also affect water availability, and its impact could be exacerbated due to temperature and precipitation change patterns. The proposed water quality model in WEAP would use first-order decay and/or conservative equations to model selected pollutants.

Lastly, contrasting the water requirements of the agricultural area in Desaguadero with the minimum acceptable levels of water discharge necessary in both lakes, established by the developed ecological flows, is an urgent necessity to support the regularization of rights, licenses, as well as sustainable water use schemes by agricultural systems. In the case of Peru, the focus can be on the efficient use of resources under current distribution schemes and possible changes in the productive schemes.

5.6. Mahanadi River Basin

The Mahanadi River Basin will request the following improvements:

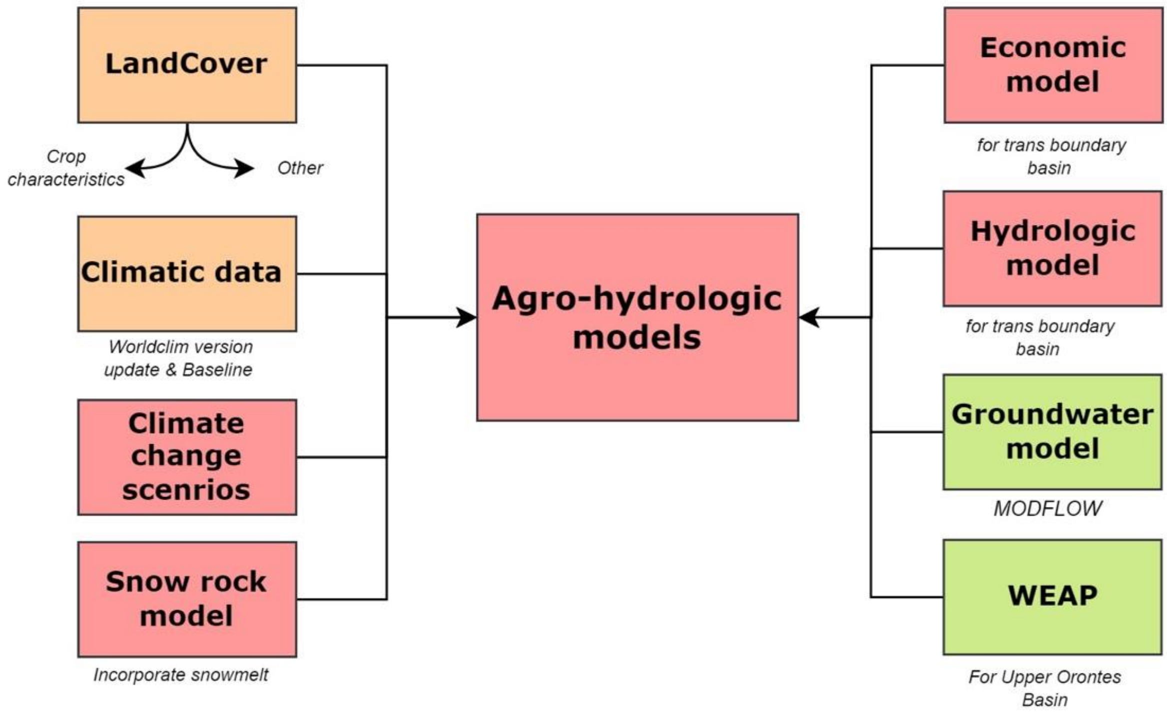
1. Integrate the current WEAP model with a sound groundwater flow model to understand the impacts of intensive or modified groundwater use on the lean season flows in the streams that results from groundwater discharge; and to simulate the groundwater dynamics (water level fluctuations annually and seasonally) induced by pumping, natural recharge, and lateral flows.
2. Extend the WEAP model for the entire basin area, covering Odisha.
3. Update of WEAP to incorporate a hydroeconomic component able to evaluate the water management alternatives identified, in particular for Chhattisgarh and Odisha, to deal with floods and droughts choose cost-effective water management alternatives.
4. Include in WEAP an assessment of environmental flow requirements for the delta area, and also other critical points in the trunk river and tributaries, to ensure that the minimum flow is maintained at critical points in the river system in all future scenarios.



5.7. Orontes River Basin

The modelling suite of the Orontes would request the following improvements:

1. Extension of the current WEAP model of the Orontes (and maybe MODFLOW) to the Upper Orontes (Lebanese part).
2. Development of a microeconomic model to evaluate the cost-effectiveness of water resource management strategies.
3. Creation of an agro-hydrological model to study the impact of climate change on streamflows downstream (from Lebanon to Syria).
4. Setting a methodology to perform a water account on the entire basin using remote sensing.
5. Incorporation of a snowmelt model
6. Development of appropriate interconnections between existing, updated and new models.



Furthermore, agricultural land crop types would be updated using reports on recent mono-cropping.

References

Abdallah, C. G. (2018). Crop suitability modeling under climate change scenarios in the Near East.

ACTED, WeWorld-GVC, & BTD. (2023). Consultancy Services for River Basin Management: Al Assi River Basin Final Report, Beirut Lebanon.

Agarwal, A., de los Angeles, M. S., Bhatia, R., Chéret, I., Davila-Poblete, S., Falkenmark, M., ... & Wright, A. (2000). Integrated water resources management (pp. 1-67). Stockholm: Global water partnership.

Agioutanti, E. (2016). Study of the current state of water resources in the Tympaki basin using the Visual Modflow model and electrical conductivity measurements. Thesis, Technical University of Crete. http://purl.tuc.gr/dl/dias/6DF708DB-FAEA-4F6F-9265-5ECC7889808B

Autoridad Nacional del Agua [ANA] - Peru, (2022). Plan de Gestion de los recursos hídricos de la cuenca Caplina Locumba.

Bengtsson, L. (2012). Poopó Lake, Bolivia. In: Bengtsson, L., Herschy, R.W., Fairbridge, R.W. (eds) Encyclopedia of Lakes and Reservoirs. Encyclopedia of Earth Sciences Series. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-4410-6_137

Bergström, S., & Forsman, A. (1973). Development of a conceptual deterministic rainfall-runoff mode. Nord. Hydrol, 4, 240–253.

Bielek, P., Jurčová, O. 2010. Metodika bilancie pôdnej organickej hmoty a stanovenie potreby organického hnojenia poľnohospodárskych pôd. Výskumný ústav pôdoznalectva a ochrany pôdy, Bratislava. 145 s.

Boubakri, N., Garcia-Prats, A., and Pulido-Velázquez, M.: AquaCitrus: Soil water balance model for irrigation management in citrus orchards, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-13408, https://doi.org/10.5194/egusphere-egu23-13408, 2023.

Chu, X. and A. Steinman (2009). "Event and continuous hydrologic modeling with HEC-HMS." Journal of Irrigation and Drainage Engineering 135(1): 119-124.

Coleman, K., & Jenkinson, D. S. (1996). RothC-26.3—A Model for the turnover of carbon in soil. In D. S. Powlson, P. Smith, & J. U. Smith (Eds.), Evaluation of Soil Organic Matter Models (pp. 237–246). Springer. https://doi.org/10.1007/978-3-642-61094-3_17.

Confederación Hidrográfica del Júcar (CHJ). (2023). Plan hidrológico de Cuenca. Ciclo 2022-2027. Ministerio para la Transición Ecológica y el Reto Demográfico, Dirección General del Agua.

CTB Maure Mauri River Basin, (2019). Informe técnico binacional Modelación hidrológica de la cuenca del rio Maure - Mauri. Republica de Perú, Estado Plurinacional de Bolivia.

Erturk, A., et al. (2006). "Application of watershed modeling system (WMS) for integrated management of a watershed in Turkey." Journal of Environmental Science and Health Part A 41(9): 2045-2056.

Francés, F., Vélez, J. I., & Vélez, J. J. (2007). Split-parameter structure for the automatic calibration of distributed hydrological models. Journal of Hydrology, 332(1-2), 226-240.

Fendeková , M. & Blaškovičová, L. (Ed.) (2018). Prognosis of hydrological drought development in Slovakia. Comenius University. http://europeandroughtcentre.com/2020/04/03/open-access-book-on-prognosis-of-hydrological-drought-development-in-slovakia/.

Horvát, O. (2008). Description of the rainfall-runoff model FRIER. Podzemná Voda, XIV(1), 37–45.

Jacob, D. (2001). A note to the simulation of the annual and inter-annual variability of the water budget over the Baltic Sea drainage basin. Meteorology and Atmospheric Physics, 77(1), 61–73. https://doi.org/10.1007/s007030170017.

Jacob, D., Van den Hurk, B. J. J. M., Andræ, U., Elgered, G., Fortelius, C., Graham, L. P., Jackson, S. D., Karstens, U., Köpken, Chr., Lindau, R., Podzun, R., Rockel, B., Rubel, F., Sass, B. H., Smith, R. N. B., & Yang, X.

(2001). A comprehensive model inter-comparison study investigating the water budget during the BALTEX-PIDCAP period. Meteorology and Atmospheric Physics, 77(1), 19–43. https://doi.org/10.1007/s007030170015

Kahil, M. T., Ward, F. A., Albiac, J., Eggleston, J., & Sanz, D. (2016). Hydro-economic modeling with aquifer–river interactions to guide sustainable basin management. Journal of Hydrology, 539, 510–524.

Kašpárek, L., Novický, O., 2004, Background information BILAN, available on CD as attachment to: Tallaksen, L.M., Van Lanen, H.A.J. (eds.), 2004a, Hydrological drought: Processes and Estimation Methods for Streamflow and Groundwater, Developments in Water Science, 48, Elsevier Science BV, The Netherlands.

Kossida, M. (2015). Methods and tools supporting operational drought risk management in water stressed areas. PhD Dissertation. National Technical University of Athens. https://dspace.lib.ntua.gr/xmlui/handle/123456789/42014?show=full

Lima-Quispe, N., Escobar, M., Wickel, A. J., von Kaenel, M., & Purkey, D. (2021). Untangling the effects of climate variability and irrigation management on water levels in Lakes Titicaca and Poopó. Journal of Hydrology: Regional Studies, 37, 100927.

López-Urrea, R., Domínguez, A., Pardo, J. J., Montoya, F., García-Vila, M., & Martínez-Romero, A. (2020). Parameterization and comparison of the AquaCrop and MOPECO models for a high-yielding barley cultivar under different irrigation levels. Agricultural Water Management, 230, 105931.

Loucks, D. P., van Beek, E., Loucks, D. P., & van Beek, E. (2017). Water resources planning and management: An overview. Water resource systems planning and management: an introduction to methods, models, and applications, 1-49.

Macian-Sorribes, H., Tilmant, A., & Pulido-Velazquez, M. (2017). Improving operating policies of large-scale surface-groundwater systems through stochastic programming. Water Resources Research, 53(2), 1407–1423.

Martínez-López, J. A., López-Urrea, R., Martínez-Romero, Á., Pardo, J. J., Montoya, F., & Domínguez, A. (2022). Improving the Sustainability and Profitability of Oat and Garlic Crops in a Mediterranean Agro-Ecosystem under Water-Scarce Conditions. Agronomy, 12(8), 1950.

McDonald, M. G., & Harbaugh, A. W. (2003). The history of MODFLOW. Ground water, 41(2), 280.

MMAyA, (2019). Analisis Tecnico de Vulnerabilidad e Impacto del Sistema Mauri – Desaguadero – Poopo, a Obras en la cuenca del rio Mauri.

MMAyA, (2020). Actualización hidroclimática y modelación hidrológica en la vertiente del lago Titicaca, Bolivia.

Oosterwijk, J., Van Loon, A., Machlica, A., Horvát, O., Van Lanen, H., & Fendekova, M. (2009). Hydrological drought characteristics of the Nedozery sub catchment, Upper Nitra, Slovakia, based on HBV Modeling, WATCH Technical.

PET-Perú, 2019. Proyecto Especial Tacna (2019). Extension of the Reservation Period for Water Resources in favor of the PET. PET, Peru, june 2021.

Pulido-Velázquez, M., Andreu, J., & Sahuquillo, A. (2006). Economic Optimization of Conjunctive Use of Surface Water and Groundwater at the Basin Scale. Journal of Water Resources Planning and Management, 132(6), 454–467.

Ramirez-Villegas, J., et al. (2013). "Empirical approaches for assessing impacts of climate change on agriculture: The EcoCrop model and a case study with grain sorghum." Agricultural and Forest Meteorology 170: 67-78.

Rubio-Martin, A.; Pulido-Velazquez, M.; Macian-Sorribes, H.; Garcia-Prats, A. (2020). System Dynamics Modeling for Supporting Drought-Oriented Management of the Jucar River System, Spain. Water 2020, 12, 1407. https://doi.org/10.3390/w12051407

SENAMHI-Peru, (2020). Actualización hidroclimática y modelación hidrológica en la vertiente del lago Titicaca, Perú

Seibert, J., & Bergström, S. (2022). A retrospective on hydrological catchment modelling based on half a century with the HBV model. Hydrology and Earth System Sciences, 26(5), 1371–1388. https://doi.org/10.5194/hess-26-1371-2022.

Sieber, J. (2006). WEAP water evaluation and planning system.

Singh, A. (2014). Simulation–optimization modeling for conjunctive water use management. Agricultural Water Management, 141, 23-29.

Skalský, R., Pavlenda, P., Barančíková, G., Koco, Š., Barka, I., Tarasovičová, Z., Makovníková, J. 2017. Odhad zásoby organického uhlíka v povrchovej vrstve pôd Slovenska. Vedecké práce VÚPOP, (ed. Sobocká, J.). 39, 87-94.

Sleziak, P., Výleta, R., Hlavčová, K., Danáčová, M., Aleksić, M., Szolgay, J., & Kohnová, S. (2021). A Hydrological Modeling Approach for Assessing the Impacts of Climate Change on Runoff Regimes in Slovakia. Water, 13(23), Article 23. https://doi.org/10.3390/w13233358.

Steduto, P., Hsiao, T. C., Raes, D., & Fereres, E. (2009). AquaCrop—The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agronomy Journal, 101(3), 426-437.

Témez, J. R. (1977). Modelo matemático de transformación precipitación-aportación. Comisión E. Explotación y Garantía. Grupo de Trabajo de Predicciones de Precipitación y Relación entre Precipitaciones y Caudales, Madrid.

van Meijgaard, E., Van Ulft, L., Van de Berg, W., Bosveld, F., Van den Hurk, B., Lenderink, G., & Siebesma, A. (2008). The KNMI regional atmospheric climate model RACMO, version 2.1. KNMI De Bilt, The Netherlands.

Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M., & Weingartner, R. (2007). Mountains of the world, water towers for humanity: Typology, mapping, and global significance. Water resources research, 43(7).

Yates, D., Sieber, J., Pukey, D., & Huber-Lee, A. (2005). WEAP21—A demand-, priority-, and preference-driven water planning model: part 1: model characteristics. Water International, 30(4), 487-500. doi:https://doi.org/10.1080/02508060508691893

Zeinalie, M., Bozorg-Haddad, O., & Azamathulla, H. M. (2021). Optimization in water resources management. In Essential tools for water resources analysis, planning, and management (pp. 33-58). Singapore: Springer Singapore.