SOS-Water deliverable report

D2.3: Setup and outcome of historical and business as usual simulations

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Authors

Authors	Partner no	Partner organization	Name of author
Main author	3	Universitat Politècnica de València (UPV)	Hector Macian-Sorribes, Manuel Pulido-Velazquez
Contributing author(s)	1	Internationales Institut Fuer Angewandte Systemanalyse (IIASA)	Emilio Politti, Silvia Artuso, Peter Burek, Sylvia Tramberend, Taher Kahil
	2	Universiteit Utrecht (UU)	Jen Steyaert, Niko Wanders
	4	Politecnico di Milano (POLIMI)	Bruno Invernizzi, Carola Calisi, Matteo Giuliani, Andrea Castelletti
	8	Southern Institute of Water Resources Planning (SIWRP)	Dang Thanh Lam

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Document history

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28/01/2026	2.1	Summary, model outcomes	Expansion of the summary to also report on the performance achieved by the business-as-usual simulations in the case studies, provided link to datasets hosted in the Zenodo repository	Hector Macian-Sorribes, Silvia Artuso, Taher Kahil	FINAL
19/03/2026	2.2	All	Updated doi link to the YODA repository	Silvia Artuso	FINAL

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Publishable Executive Summary

This deliverable describes the setup of the modelling chain used per case study and facilitates access to the business-as-usual simulations by providing the links to the YODA (for the raw output data) and Zenodo (for the postprocessed output data) repositories. Its purpose is to provide access to the datasets that are its core, plus some context information so that potential users of those datasets have proper knowledge of the models used to generate them, as well as their performance levels.

The datasets referred to each case study are tailored to its specific needs and modelling chain. The Danube, Mekong, and Rhine use modelling chains driven by a common set of CMIP6 climate change scenarios to produce homogeneous assessments. The Jucar case study, in addition to its top-down approach, also conducts bottom-up experiments in which climate forcing is derived from a weather generator driven by different perturbations of temperature and precipitation.

This deliverable provides a description of the model and its calibration, a description of the datasets included in the YODA and Zenodo repositories, and a summary of the performance of those datasets. The business-as-usual simulations show that all case studies face some challenges today, although for most variables the performance level achieved could be deemed acceptable. However, all of them experience a decrease in their performance level that, in most cases, is proportional to the severity of the climate change scenario. For the Danube, the current challenges concentrate in its Northern part and refer to an imbalance between pumping rates and aquifer recharge. This situation is maintained for the most optimistic scenario (SSP1-2.6), slightly degrades for the SSP3-7.0 scenario due to deficits in industrial demands in its Northern reaches, and extends to deficits in agriculture and to the whole basin under SSP5-8.5. For the Jucar river basin, performance levels are adequate for most variables but for some fish species and reaches. Nevertheless, results show that even a small reduction in precipitation (10%), or a mild increase in temperature (2 degrees) could quickly cause a drop in performance for most variables. The Mekong case study offers an adequate performance but for hydropower for the current situation. Although future scenarios point to an increase in hydropower production and an improved water supply for irrigation, it will also cause a significant reduction in fish catches, sediment transport, and CO2 emissions. The Rhine is expected to experience an increase in streamflow variability in the future, aligned with the severity of the scenario considered (SSP1-2.6, SSP3-7.0 and SSP5-8.5). Although navigation is expected to improve for those scenarios, drought exposure will also show in a more prominent way than today.

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Table of Contents

Description of deliverable

This document is the recipient of D2.3, including the links to the datasets corresponding to the setup and outcome of the historical and business-as-usual simulations developed in SOS-WATER.

Introduction

In order to guarantee that the datasets provided by the business-as-usual model runs developed in WP2 of the SOS-WATER project are FAIR (findable, accessible, interoperable and reproducible), it is necessary to provide adequate information to contextualise them, enabling their adequate understanding and thus their conscious use in any downstream application desired.

Model setup

The setup of the models used in each case study is described in D2.2, delivered by month 24. Given that the purpose of the modelling teams involved, as of SOS-WATER, is to continuously improve them, this section focuses on the changes made to the model setup of each case study between the delivery of D2.2 and the due date of D2.3.

Danube

Model description

The model used to simulate the Danube case study is CWatM (Burek et al., 2020). CWatM and the settings applied to run the simulations are described in D2.2.

Calibration

The three components of the hydrological cycle validated in CWatM are: river discharge, reservoir storage and evapotranspiration. No further calibration was performed since the last model version described in D2.2.

Jucar

Model description

The Jucar River model setup used in the simulations is the same as in D2.2.

Calibration

The current version of the Jucar model was calibrated for the 1998-2012 period, which represents a time frame with a homogeneous system setup, demands and operational policies. Training involved storages and releases from its three main reservoirs (Alarcon, Contreras and Tous), streamflows in eight gauges along the Jucar River (including one in its tributary Cabriel river), deliveries to surface demands, and inflows to the Albufera lake. The model performance, detailed in D2.2, was mostly positive, with KGE values above 0.60 in the majority of the locations and variables compared.

Mekong

Given the necessity of modelling different parts of the Mekong River system with distinct approaches, we divide the Mekong system into two regions: the Upper Basin (Upper and Lower Mekong) and the Mekong Delta, each with its own characteristics, criticalities, and tailored models.

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Upper Basin

Model description

The Upstream Mekong River model setup is based on the one presented in D2.2, where the hydrological – water management model VICRes and the sediment connectivity model D-CASCADE are thoroughly explained. In addition to these two modules, a fish catch predictor has been developed, designed to estimate the annual fish catches of the Dai Fishery in the Tonle Sap. The predictors include bioclimatic variables derived from temperature and precipitation data downscaled from global projections, a connectivity index that represents river connectivity based on the number of dams present in the basin, and flow alteration indices at Stung Treng, calculated directly from discharge data produced by VIC-Res. Using these drivers, the model estimates the annual fish catches of the Dai Fishery, which is one of the largest fisheries in the world. This model thus captures the crucial fishery dimension within the Mekong basin.

Furthermore, we introduced a module to estimate greenhouse gas (GHG) emissions from reservoirs, thereby incorporating their sustainability into the SOS assessment for the Mekong River basin. Currently, an empirical formula based on the work of Tangi et al. (2024) has been applied to a subset of reservoirs for which all necessary data were available.

Finally, using discharge data at Stung Treng from VICRes simulations along with monthly potential irrigation water withdrawal data coming from CWatM (Burek et al., 2020), we also calculated the agricultural water deficit in the area south of Stung Treng.

Calibration

All modules included in the IWSM of the upstream Mekong River have been calibrated. The VICRes module was calibrated using a multi-objective optimisation algorithm to optimise four different hydrograph metrics at Stung Treng, namely the Nash–Sutcliffe efficiency (NSE), the transformed root mean square error (TRMSE), the mean squared derivative error (MSDE), and the runoff coefficient error (ROCE), using the period 1996–2005 for calibration. Details on parameter calibration and performance in both calibration and validation phases are reported in Eldardiry et al. (2025).

The D-CASCADE module was calibrated by identifying, for each river reach, the available input values of sediment yield and grain size distribution, ensuring that the model could reproduce the annual mean sediment loads for different sediment classes at five stations along the Mekong River Basin, namely: Chiang Saen, Luan Prabang, Nong Khai, Pakse, and Stung Treng. Sediment load data for the different sediment classes at these stations refer to the period 2009–2013 and are presented in Koehnken, 2014.

The linear regression used as the fish catch predictor for the Dai Fishery follows the approach presented in Yu et al. 2024. In our work, however, the predictor drivers were replaced with variables including bioclimatic indices derived from temperature and precipitation, as well as flow alteration indices at Stung Treng and a connectivity index of the whole basin, in order to better capture the dynamics of fish catches in the fishery. The regression parameters were recalibrated (due to the change in input variables) using the same 15 years of historical annual fish catch data employed in this study.

Finally, the GHG emissions estimation module is based on the methodology of Tangi et al. (2024), which in turn draws on GHG flux data reported in Deemer et al. (2016).

Mekong Delta

Model description

The model setup of the Mekong Delta is the same as described in D2.2.

Calibration

The Mekong Delta model was calibrated against water level, discharge, salinity and sediment load records obtained at permanent gauging stations and additional survey sites. The calibration involved one dry flow period and one flood period. The performance level achieved, summarised in D2.2, is overall very good for the entire model domain.

Rhine

Model description

To evaluate global climate impacts, we use PCR-GLOBWB 2 for the Rhine Basin at the 30 arc second spatial resolution. Our model setup does not change drastically from the setup described in D2.2. We did opt to run our model simulations on the 30 arcsecond resolution using a model setup described in Hoch et al., 2023. This allows us to have a finer resolution for climate evaluations. We also incorporated the updated data derived reservoir operations in PCR-GLOBWB 2 and the updated number of dams described in D2.2

Calibration

To calibrate our 30 second PCR-GLOBWB2 model on the 30 arc seconds we used the results of model validation described in D2.2 for both the reservoirs and the discharge locations.

Model outcomes of historical and business as usual simulations

Danube

Simulation results of key indicators postprocessed at relevant spatial units for historical and business as usual scenarios for the Danube basin are freely available in the SOS-Water community on Zenodo (“Indicator_value_hist_BAU_Danube.xlsx”, DOI: 10.5281/zenodo.18400522). Complete list of indicators and their postprocessing (calculation and normalization) methods are available in Deliverable 5.2. Raw data (model outputs) used to calculate those indicators for the Danube basin is hosted in the YODA repository by Utrecht University (DOI: 10.24416/UU01-DY4F1I) at this link. Different subfolders contain data for simulations run using CWAatM 5 arcminutes resolution, CWatM 1 arcminutes resolution, and fish species distribution data.

The CWatM_1_minute folder is further organized into five subfolders, one for each scenario considered in the study: *Historical*, *ssp126*, *ssp370*, and *ssp585*. Additionally, the repository includes a yoda-metadata.json file that provides a detailed description of all files contained within the dataset.

The *Historical* scenario covers the period 1981–2010, while the three future scenarios (*ssp126*, *ssp370*, and *ssp585*) cover the period 2041-2100. Within each of the scenario folders, there are five further subfolders, each corresponding to one of the Global Circulation Models (GCMs) used as climate forcing. Each GCM-specific folder contains the following post-processed variables (including two indices) derived from CWatM 1 arcminutes raw outputs:

- annual_mean_streamflow
- baseflow_index
- hydrological_variability_index
- mean_discharge_driest_month
- mean_discharge_driest_quarter
- mean_discharge_hottest_month
- mean_discharge_wettest_quarter
- mean_discharge_wettest_month
- monthly_standard_deviation
- streamflow_season_index

All above variables are stored as NETCDF files for the years 2041–2070 and 2071-2100.

The folder CWatM_5_minutes contains two subfolders with simulations under natural conditions (barriers and human influence on the water cycle removed) and non-natural (considering human component as well). As above, each folder contains simulations for the historical period (1981–2010) and the three scenarios (2041-2100) under five different GCMs. Simulations in the natural folder contain outputs only for discharge and runoff, given as monthly averages (discharge_monthavg, runoff_monthavg, respectively). The nonnatural simulations contain the following outputs, all in NETCDF format but one, being in all cases monthly or annual variables computed from the raw CWatM otuputs:

- act_domWithdrawal_monthtot.nc - actual domestic water withdrawals, expressed as monthly totals
- act_indWithdrawal_monthtot.nc - actual industrial water withdrawals, expressed as monthly totals
- act_totalIrrConsumption_monthtot.nc - actual water consumption for irrigation, expressed as monthly totals
- act_totalWaterWithdrawal_monthtot.nc - actual total water withdrawals, expressed as monthly totals
- discharge_daily_critical_navigation.csv - daily discharges for critical navigation water levels
- discharge_daily.nc - daily discharges
- discharge_monthavg.nc - monthly average discharges
- domesticDemand_monthtot.nc - monthly total domestic water demand
- gw_recharge_rate_annual.nc - groundwater recharge rate
- industryDemand_monthtot.nc - monthly total industry water demand
- livestockDemand_monthtot.nc - monthly total livestock water demand
- nonFossilGroundwaterAbs_monthtot.nc - monthly total nonfossil groundwater abstraction
- runoff_monthavg.nc - monthly average runoff
- sum_gwRecharge_monthtot.nc - monthly sum of groundwater recharges
- totalIrrDemand_monthtot.nc - total monthly irrigation water demand
- unmetDemand_monthtot.nc - total monthly unmet water demand

Finally, the fish folder contains historical and scenario simulations of species distribution for the following 37 key fish species in the Danube:

- *Abramis brama*
- *Acipenser gueldenstaedtii*
- *Acipenser naccarii*
- *Acipenser ruthenus*
- *Acipenser stellatus*
- *Alburnoides bipunctatus*
- *Alburnus alburnus*
- *Alosa immaculata*
- *Alosa tanaica*
- *Ameiurus melas*
- *Babka gymnotrachelus*
- *Barbus barbus*
- *Blicca bjoerkna*
- *Carassius gibelio*
- *Chondrostoma nasus*
- *Cobitis elongata*
- *Cottus gobio*
- *Cyprinus carpio*

- *Esox lucius*
- *Gymnocephalus schraetser*
- *Hucho hucho*
- *Huso huso*
- *Hypophthalmichthys molitrix*
- *Lepomis gibbosus*
- *Micropterus salmoides*
- *Neogobius fluviatilis*
- *Neogobius melanostomus*
- *Oncorhynchus mykiss*
- *Perca fluviatilis*
- *Pseudorasbora parva*
- *Romanogobio uranoscopus*
- *Romanogobio vladykovi*
- *Rutilus rutilus*
- *Rutilus virgo*
- *Sander lucioperca*
- *Scardinius erythrophthalmus*
- *Silurus glanis*

The habitat suitability for each species was modelled based on three GCMs (i.e., ipsl, ukesm, mpi). The results of the models are therefore created for each circulation model. For each species there is a folder with a list of files related to the following aspects:

- The random forest model output, as provided from the calculation of the *ranger* package in R, which can be used to create the prediction given a set of scenarios (e.g., *randomForestmodel_ipsl.RData*)
- Model evaluation measures:
    - Area Under the Receiver Operating Characteristic Curve (AUC) for each of the circulation models (e.g., *auc_ipsl.txt*)
    - List of thresholds–dependent evaluation measures given in the files *th_metrics*:
        - Sensitivity
        - Specificity
        - Omission
        - Commission
        - sTSS (True Skill Statistics)
    - Threshold to convert the predicted probability values to a binary response (Suitable Habitat / No Suitable Habitat) (e.g., *th_sens_spec_ipsl.txt*)

Additionally, there is a folder called “predictions” within each species folder, that contains the habitat suitability prediction files in tabular and raster (tif) formats for the historical and future periods (period_2041-2070 and period_2071-2100) for each of the three GCMs (IPSL-CM6A-LR, MPI-ESM1-2-HR and UKESM1-0-LL) and three scenarios (ssp1, ssp3 and ssp5).

The tabular predictions (e.g., *Abramis_brama_prediction_2041-2070_ipsl_ssp1.txt*) consist of a three-column file, where the first column is the ID of each of the sub-catchments of the Danube basin, and columns two and three are the habitat suitability probability values given as decimal (range between 0 and 1) and integer (column 2 multiplied by 100; range between 0 and 100).

In addition, each prediction is provided in raster format (i.e., tif file) for further spatial analysis and GIS visualization. There are two .tif files, one with the habitat suitability probability values (range 0 to 100) (e.g., Abramis_brama_prediction_2041-2070_ipsl_ssp1_prob.tif) and the second one where the threshold (available in the file *th_sens_spec_ipsl.txt*) has been applied to create a binary response (0 for unsuitable habitat and 1 for suitable habitat) (e.g., Abramis_brama_prediction_2041-2070_ipsl_ssp1_bin.tif).

In summary, the contents of the folders in the YODA repository for the Danube case study are:

- CWatM_1_minute: hydrological model outputs, 1 minute spatial resolution
- CWatM_5_minutes: hydrological model outputs, 5 minutes spatial resolution
- fish: fish habitat modeling outputs
- SOSEvaluation: values of the indicators for the reference period and baseline (i.e. without adaptations) climate change scenarios

Figure 1 shows a summary of the indicators from the SOS evaluation for the Northern, Central and Southern Danube sub basins. The columns State, Productive, Transport, Supply and Regulatory represent the water functions used to evaluate the SOS. For each function, the worst score of the indicators belonging to the function has been used to determine the score of the function. The evaluation shows that the SOS is not completely achieved in the whole basin even in the reference period (1981-2010) and that the SSP5-8.5 is the scenario with the worst outlook.

Sub-basin	Scenario	State	Productive	Transport	Supply	Regulatory	Safe
Northern	Reference	ARRL-Nor	HLR	NPL	Ind-Nor	MMFA-Nor.	No
Central		ARRL-Nor	HLR	NPL	Ind-Nor	MMFA-Nor.	Yes
Southern		ARRL-Nor	HLR	NPL	Ind-Nor	MMFA-Nor.	Yes
Northern	SSP1-2.6	ARRL-Nor	HLR	NPL	DmD-Nor	MMFA-Nor.	No
Central		ARRL-Nor	NND-Nor	NPL	Ind-Nor	MMFA-Nor.	Yes
Southern		ARRL-Nor	HLR	NPL	Ind-Nor	MMFA-Nor.	Yes
Northern	SSP3-7.0	ARRL-Nor	NND-Nor	NPL	Ind-Nor	MMFA-Nor.	No
Central		ARRL-Nor	NND-Nor	NPL	DmD-Nor	MMFA-Nor.	Yes
Southern		ARRL-Nor	HLR	NPL	Ind-Nor	MMFA-Nor.	No
Northern	SSP5-8.5	ARRL-Nor	NND-Nor	NPL	Ird-Nor	MMFA-Nor.	No
Central		ARRL-Norm.	NND-Nor	NPL	Ird-Nor	MMFA-Nor.	No
Southern		ARRL-Norm.	HLR	NPL	Ird-Nor	MMFA-Nor.	No

Figure 1. Summary of SOS indicators for the Danube case study

Jucar

Simulation results of key indicators postprocessed at relevant spatial units for historical and business as usual scenarios for the Jucar basin are freely available in the SOS-Water community on Zenodo ("Indicator_value_hist_BAU_Jucar.xlsx", DOI: 10.5281/zenodo.18400522). Complete list of indicators and their postprocessing (calculation and normalization) methods are available in Deliverable 5.2. Raw

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data (model outputs) used to calculate those indicators for the Jucar river basin is freely accessible on the YODA repository hosted by Universiteit Utrecht (DOI: 10.24416/UU01-DY4F1I) at this link. Instead of a traditional top-down modelling chain, the *status quo* runs of the Jucar, as will happen with runs including adaptation measures, follow a bottom-up approach, in which climate change scenarios are defined based on climate alterations (P and T changes), as done by Brown et al (2012) and Solans et al (2024). Bottom-up runs are stored in the "Jucar_bottomup_runs_statu_quo" folder. Within this folder, 18 subfolders appear, corresponding to each parallel run of the weather generator, containing a certain number of realisations. Each run folder includes a single "Results" subfolder in which a large set of Matlab data files (.mat) is provided. Although the size of each dataset depends on the variable or indicator to which it refers and on the number of realisations; the number of files, format and data organisation are the same.

The P and T scenarios analysed include changes in precipitation of -30%, -15%, 0%, 15% and 30% with respect to the current average value; and changes in temperature of 0, 1, 2, 3, 4, 5 and 6 degrees of increase. Both changes are combined together into 35 P and T combinations (including the current climate). For each combination, 531 stochastic time series of 65 years each (totalling the realisations from the 18 run folders) were generated and used to force the rest of the modelling chain: hydrological models, water resource management models, and fish habitat models.

For each .mat file, the dimensions of the .mat file are:

- Number of runs included inside each file. Variable per file, with a total number of 531 (adding the runs of all subfolders).
- Number of P and T combination (35 in total)
- Number of years (65)
- Number of months (12)
- Dimensions related to the variable (e.g. number of demands, number of aquifers and aquifer cells, number of reservoirs, number of demands and types of crop)

Each subset corresponds to the following variables. Since the weather generator and the modelling chain works at the monthly scale, monthly variables correspond to direct outputs of the model, while annual ones are post-proccesed outputs aggregated to the annual scale.

- ETp_ files: these correspond to the monthly time series of reference evapotranspiration (mm), to be used by the hydrological model and the water resource management model. They are divided by subbasins. The subbasins considered are:
    - Alarcon: ALCN
    - Contreras: CONT
    - Mancha: MANCH
    - Middle: MIDDL
    - Lower: LOWR
    - Magro: MAGR
    - Albaida: ALBD

For each subbasin, two files are provided: one with the actual data in mm and one with the relative change compared to the historical average (_rel). The former is used as direct input by hydrological models, while the latter is employed to adjust the agricultural demands.

- P_ files: these correspond to the monthly time series of precipitation (mm) to be used by the hydrological model, divided by subbasin.
- Q_ files: these are the monthly hydrological discharges (Mm^3) per subbasin, obtained from the hydrological models forced by the meteorological time series, and then used by the water resource management model.
- T files: these correspond to the monthly time series of temperature (degrees Celsius) to be used in the computation of the ETp time series to force the hydrological models, per subbasin.
- RR_files: these files are the results of the water resources management model. In particular, there are the following:
  - RR_Aq_Storages: monthly storage levels in aquifers (Mm3) with respect to the natural storage
  - RR_benefit_demands: monthly benefits (M€) per consumptive demand
  - RR_benefit_hydro: monthly benefits (M€) per hydropower plant
  - RR_crop_productions: annual yield (tons) per demand and crop type
  - RR_Deficits: monthly deficits (Mm3) per consumptive demand
  - RR_Deliveries: monthly allocation (Mm3) per consumptive demand
  - RR_Flow: six files with the monthly streamflow (m3/s) for the reaches of the Jucar model with habitat models (Alarcon, Antella, Contreras, DosAguas, Madrigueras and Molinar), and one file with the monthly inflow to the Albufera wetland in Mm3 (Albufera)
  - RR_hydropower: monthly energy production (Gwh) per hydropower plant
  - RR_Qhydro: monthly turbinated flow (Mm3) per hydropower plant
  - RR_Storages: monthly storage (Mm3) per reservoir

An example of the Jucar River dataset visualisation of the agricultural demand datasets (crop water stress index, CWSI) is shown in Figure 2. Results agree with the expected response sensitivity to precipitation changes and, to a lesser extent, to temperature increases. Given the current climate, the system's performance is adequate for most variables, except for some fish habitat concerns. However, the simulations highlight a significant drop in performance for even small reductions in precipitation (around 10%) in most variables. For temperature, the system's response to increases below 2 degrees remains stable. However, most variables show a decrease in performance levels above 2 degrees. The steepness of this decrease depends on the seniority of water rights or the priority level, with ecosystems and surface water demands (traditional agricultural areas, right plot) showing a less sensitive response.

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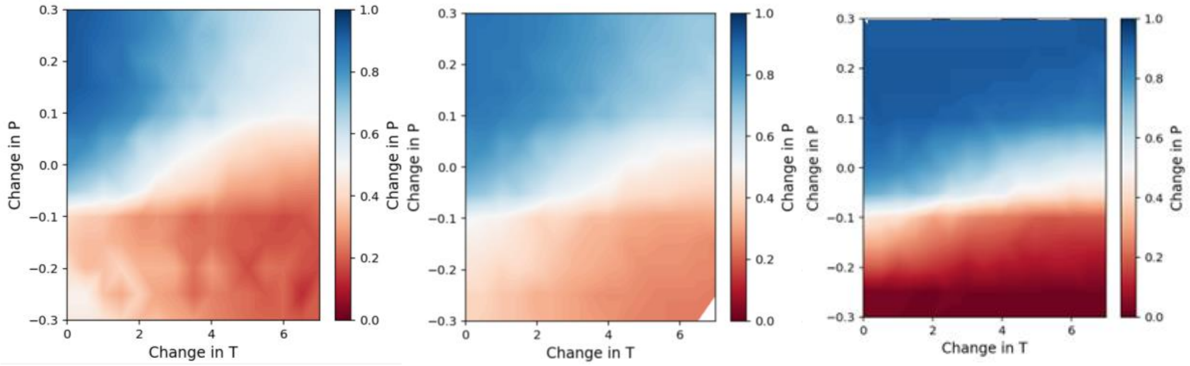


Figure 2. Summary of Jucar river basin bottom-up run datasets for Crop Water Stress Index (CWSI) for the Mancha Oriental (left), Jucar-Turia canal (centre) and Traditional (right) demands

Mekong

Upper Basin

Simulation results of key indicators postprocessed at relevant spatial units for historical and business as usual scenarios for the upstream Mekong basin are freely available in the SOS-Water community on Zenodo ("Indicator_value_hist_BAU_Upper_Mekong.xlsx", DOI: 10.5281/zenodo.18400522). Complete list of indicators and their postprocessing (calculation and normalization) methods are available in Deliverable 5.2. Raw data (model outputs) used to calculate those indicators for the Upper Mekong is freely accessible on the YODA repository hosted by Universiteit Utrecht (DOI: 10.24416/UU01-DY4F1I) at this link. Within the UpstreamMekong folder, there are five subfolders, one for each scenario considered in the study: *Historical*, *ssp126*, *ssp245*, *ssp370*, and *ssp585*. Additionally, the repository includes a yoda-metadata.json file that provides a detailed description of all files contained within the dataset.

The *Historical* scenario covers the period 1981–2014, while the four future scenarios (*ssp126*, *ssp245*, *ssp370*, and *ssp585*) cover the period 2031–2100. Within each of the five scenario folders, there are five further subfolders, each corresponding to one of the Global Circulation Models (GCMs) used as climate forcing. These GCMs represent the long-term average climatology and are part of the ISIMIP project, used in agreement with the other case studies.

Inside each GCM-specific folder, both the raw model output variables produced by the IWMS (mainly the VIC-Res model) and the post-processed indicators derived from those outputs are stored. This structure ensures that all data necessary for reproducibility within the SOS-Water framework are available in a transparent and well-documented format. The data are organized as follows:

- **Baseflow_and_Runoff**, **Discharges**, and **Reservoirs** folders contain the raw output variables directly produced by the VIC-Res model. These files include gridded and time-series data such as runoff, baseflow, river discharge, and reservoir storage and release. They represent the core physical outputs of the model and form the basis for subsequent analysis. From these raw outputs, indicators can be calculated through post-processing or used as input for other impact models (e.g., D-CASCADE for sediment transport or models estimating hydropower, fisheries, agriculture, and GHG emissions).

- The **Indicators** folder contains the post-processed output variables, i.e. the final impact-model results or aggregated indicators derived from the VIC-Res outputs. These indicators summarize the results of the full modelling chain and quantify basin-scale impacts and performance metrics relevant to the SOS-Water framework. The full list of files included in this folder is:
    - **AnnualHydropowerProduction.txt** – containing annual values of hydropower production for the entire basin, normalised by the total installed capacity of the basin
    - **ChinaAnnualHydropowerProduction.txt** – containing annual values of hydropower production in China, normalised by the total installed capacity of Chinese reservoirs
    - **MyanmarAnnualHydropowerProduction.txt** – containing annual values of hydropower production in Myanmar, normalised by the total installed capacity of Myanmar reservoirs
    - **LaosAnnualHydropowerProduction.txt** – containing annual values of hydropower production in Laos, normalised by the total installed capacity of Laos reservoirs
    - **ThaiAnnualHydropowerProduction.txt** – containing annual values of hydropower production in Thailand, normalised by the total installed capacity in Thai reservoirs
    - **CambodiaAnnualHydropowerProduction.txt** – containing annual values of hydropower production in Cambodia, normalised by the total installed capacity of Cambodian reservoirs
    - **VietnamAnnualHydropowerProduction.txt** – containing annual values of hydropower production in Vietnam, normalised by the total installed capacity of Vietnamese reservoirs
    - **StungTrengSediment.csv** – containing the annual sediment loads reaching Stung Treng (in Mt/year)
    - **DaiFisheryFishCatch.txt** – containing the annual values of fish catches predicted in the Dai Fishery (in kg/year)
    - **AgriculturalWaterDeficit.csv** – containing the annual values of agricultural water deficit in the area south of Stung Treng calculated as the sum of the monthly deficits for each year (in m^3/year)
    - **AnnualGHGemissions.txt** - containing annual values of GHG emissions for the entire basin, divided by the total installed capacity of the basin (in kg CO_2eq/MW)
    - **ChinaAnnualGHGemissions.txt** - containing annual values of GHG emissions of Chinese reservoirs, divided by the total installed capacity in China (in kg CO_2eq/MW)
    - **LaosAnnualGHGemissions.txt** - containing annual values GHG emissions of Laos reservoirs, divided by the total installed capacity in Laos (in kg CO_2eq/MW)
    - **ThaiAnnualGHGemissions.txt** - containing annual values of GHG emissions of Thai reservoirs, divided by the total installed capacity in Thailand (in kg CO_2eq/MW)
    - **CambodiaAnnualGHGemissions.txt** - containing annual values of GHG emissions of Cambodian reservoirs, divided by the total installed capacity in Cambodia (in kg CO_2eq/MW)
    - **VietnamAnnualGHGemissions.txt** - containing annual values of annual GHG emissions of Vietnamese reservoirs, divided by the total installed capacity in Vietnam (in kg CO_2eq/MW)

At present, the Indicators folder is available only for the GFDL-ESM4 model. Indicator data for the remaining GCMs will be added at a later stage, following the same structure, and will be used in the uncertainty analysis once calculations are completed.

A summary of the computed indicators—aggregated at the basin scale—is presented in Figure 3 and Figure 4, which illustrate the main results for the historical and future scenarios.

ORIGINAL INDICATOR MATRIX (BASELINE MANAGEMENT PATHWAYS): UPSTREAM MEKONG BASIN

Scenarios	Mean Annual hydropower production over total installed capacity	Mean Annual Dai Fishery fish catches	Mean Stung Treng Annual Sediment load	Mean Annual agricultural water deficit	Mean Annual CO2 equivalent emitted by reservoirs over total installed capacity
Historical - (1981 - 2022)	0.42	37647.98	83.58	58698253.54	7.98
Historical - (2001 - 2014)	0.47	38322.37	83.87	63825520.90	4.55
Historical - GFDL-ESM4 (2001 -2014)	0.36	25223.22	76.24	479034724.11	4.25
SSP1-2.6 - GFDL-ESM4 (2035 - 2050)	0.61	23601.06	75.67	0.00	19.25
SSP1-2.6 - GFDL-ESM4 (2041 - 2050)	0.61	22743.93	77.13	0.00	19.25
SSP1-2.6 - GFDL-ESM4 (2091 - 2100)	0.63	25637.77	81.83	0.00	19.35
SSP1-2.6 - GFDL-ESM4 (2031 - 2100)	0.61	23970.48	80.68	0.00	19.16
SSP2-4.5 - GFDL-ESM4 (2035 - 2050)	0.61	25640.44	78.33	No data	19.29
SSP2-4.5 - GFDL-ESM4 (2041 - 2050)	0.61	25160.41	77.83	No data	19.29
SSP2-4.5 - GFDL-ESM4 (2091 - 2100)	0.63	26421.31	85.86	No data	19.38
SSP2-4.5 - GFDL-ESM4 (2031 - 2100)	0.61	25203.64	80.56	No data	19.05
SSP3-7.0 - GFDL-ESM4 (2035 - 2050)	0.60	27106.18	78.39	0.00	19.27
SSP3-7.0 - GFDL-ESM4 (2041 - 2050)	0.60	31136.99	78.48	0.00	19.26
SSP3-7.0 - GFDL-ESM4 (2091 - 2100)	0.61	19846.92	81.52	0.00	19.28
SSP3-7.0 - GFDL-ESM4 (2031 - 2100)	0.60	20737.63	79.01	0.00	19.05
SSP5-8.5 - GFDL-ESM4 (2035 - 2050)	0.61	24166.57	78.88	0.00	19.29
SSP5-8.5 - GFDL-ESM4 (2041 - 2050)	0.61	24749.15	81.09	0.00	19.34
SSP5-8.5 - GFDL-ESM4 (2091 - 2100)	0.62	21717.17	85.58	0.00	19.33
SSP5-8.5 - GFDL-ESM4 (2031 - 2100)	0.61	22592.81	80.45	0.00	19.08

Figure 3. Upstream Mekong indicator matrix showing the mean values of the basin-wide indicators, calculated over specific time windows for both historical and future periods and under different climate change scenarios.

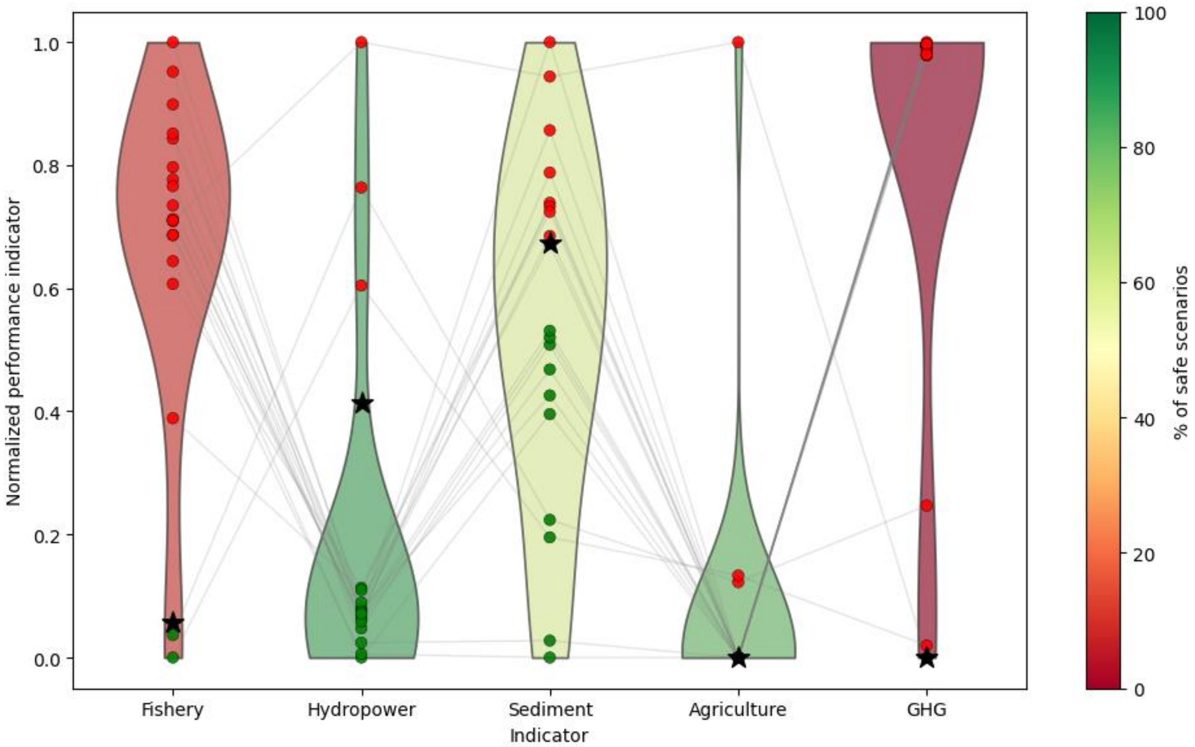


Figure 4. Violin plots representing Upstream Mekong normalized indicators' performance across scenarios.

Mekong Delta

Simulation results of key indicators postprocessed at relevant spatial units for historical and business as usual scenarios for the Mekong Delta are freely available in the SOS-Water community on Zenodo ("Indicator_value_hist_BAU_Delta_Mekong.xlsx", DOI: [10.5281/zenodo.18400522](https://doi.org/10.5281/zenodo.18400522)). Complete list of indicators and their postprocessing (calculation and normalization) methods are available in Deliverable 5.2. Raw data (model outputs) used to calculate those indicators for the Mekong Delta is freely accessible on the YODA repository hosted by Universiteit Utrecht (DOI: 10.24416/UU01-DY4F1I) at this link.

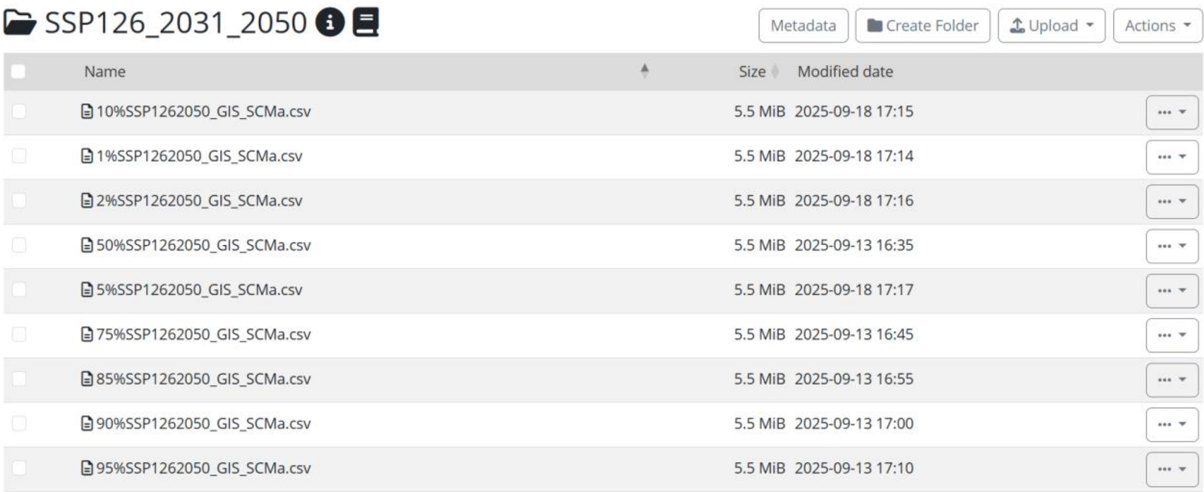
The VRSAP_Output_Mekongdelta folder contains two subfolders with data on salinity in the dry season (DrySalinity_Mekongdelta) and water level in the flood season (Flood_Mekongdelta). Each subfolder contains subfolders divided by historical data (1981-2014), and SSPs-RCPs (ssp126, ssp245, ssp370, ssp585) for the period 2031-2050 and 2051-2100.

Inside each folder there are the data files of the VRSAP hydrodynamic model in CSV format. In the DrySalinity folder there are salinity data files and in the Flood folder there are water level data files.

Each data file is the simulation result for one year of data with frequency P%, scenario, target year, available GIS linkage, maximum SC salinity (e.g. file name: 1%SSP1262050_GIS_SCMa.csv).

The first column of the data file is the hydraulic nodes (from 1 to 4279) and the row of salinity data by time step number of hours and last day of the year (SCMax1%SSP1262050_8761_8784).

Other data files of the model such as water level in the floodplain cells, flow velocity and flow discharge in the river sections, GIS layer for hydraulic nodes and sections will be updated.


SSP126_2031_2050

Name	Size	Modified date
10%SSP1262050_GIS_SCMa.csv	5.5 MiB	2025-09-18 17:15
1%SSP1262050_GIS_SCMa.csv	5.5 MiB	2025-09-18 17:14
2%SSP1262050_GIS_SCMa.csv	5.5 MiB	2025-09-18 17:16
50%SSP1262050_GIS_SCMa.csv	5.5 MiB	2025-09-13 16:35
5%SSP1262050_GIS_SCMa.csv	5.5 MiB	2025-09-18 17:17
75%SSP1262050_GIS_SCMa.csv	5.5 MiB	2025-09-13 16:45
85%SSP1262050_GIS_SCMa.csv	5.5 MiB	2025-09-13 16:55
90%SSP1262050_GIS_SCMa.csv	5.5 MiB	2025-09-13 17:00
95%SSP1262050_GIS_SCMa.csv	5.5 MiB	2025-09-13 17:10

Sample list of salinity data file for water year P% of ssp126 for period 2031-2050

Rhine

Simulation results of key indicators postprocessed at relevant spatial units for historical and business as usual scenarios for the Rhine basin are freely available in the SOS-Water community on Zenodo ("Indicator_value_hist_BAU_Rhine.xlsx", DOI: [10.5281/zenodo.18400522](https://doi.org/10.5281/zenodo.18400522)). Complete list of indicators and their postprocessing (calculation and normalization) methods are available in Deliverable 5.2. Raw data (model outputs) used to calculate those indicators for the Rhine river basin is freely accessible on the YODA repository hosted by Universiteit Utrecht (DOI: 10.24416/UU01-DY4F1I) at this link. Each of the scenarios is separated into folders related to the scenario they include. The historical scenario runs from 1979 – 2014 and the three future scenarios (SSP1, SSP3 and SSP5) run from 2015 – 2100. Within the three scenario folders, there are fourteen folders related to the indicators we decided to calculate for the Rhine basin. These fourteen folders are better described in the following table:

Indicator	Name
Bio 1	Annual mean streamflow
Bio 4	Monthly Streamflow standard deviation
Bio 4a	Streamflow seasonality index
Bio 5	Mean flow of the hottest month
Bio 6	Mean flow of wettest quarter
Bio 13	Mean flow of the wettest month
Bio 14	Mean flow of the driest month
Bio 17	Mean flow of the driest quarter
Q-bfi	Baseflow Index
Q-hvi	Hydrologic variability index
Q-si	Snowmelt Index
Q-rb	Baseflow Runoff Ratio
WT	Water temperature

Within each folder, we have files with endings related to the 5 global circulation models we used as climatic forcings. The five GCMs represent the long-term average climatology and are used within the ISIMIP project to evaluate climate impacts. The only model output that does not use the same model setup is the Water Temperatures, which we downscaled from Jones et al., 2023. Since this data is on the 5 arcminute resolution, we first had to downscale the water temperatures. We did this by identifying the river pixels on the 5 arcminute resolution and aligning those with the 30 arcsecond grid. Once we had this map of linked pixels (i.e. one 5 arcminute pixel to 10 30 arcsecond pixels), we could use this to map the water temperature data from Jones et al., 2023 to the correct 30 arcsecond pixel. We assume that any pixel that has water on the 30 arcsecond resolution but does not fall within the river pixels in the 5 arcminute domain are "small" rivers, and their temperature is closely related to air temperature. Therefore, we fill the rest of the domain with the ambient air temperature given in the input data to PCR-GLOBWB~2. We repeat this workflow for each GCM and SSP combo to create temporal and spatial maps of water temperature changes in the Rhine basin.

Five folders are related to the global circulation models (GCMs) we used. These GCMs are linked to the ISIMIP3b project, which uses five global circulation models that are fit to the long-term average climatology to assess climate impacts. Therefore, we have a total of 15 runs.

In the following figures (Figure 5, 6, and 7, we depict the average indicator for each time period in our analysis (Figure 5 and 6) and across multiple SSPs (Figure 7, 8). The line plots of the standard deviation of streamflow (Figure 5) depict the changes in seasonality across the future scenario with periods of increased deviation corresponding to more variability. The maps in Figure 6 of Bio14 demonstrate an increase in magnitude of low flows during the driest month when moving further into the future. Finally, the indicators plotted in Figure 7 demonstrate significant shifts across the different SSP with SSP5 showing the highest shifts. The lower mean flows, drought index value, Bio14 and Bio13 which both correspond to mean flows of the wettest (bio13) and driest (bio14) months. SSP3 has the lowest value for mean discharge suggesting there is some variability between the indicators at our key location. This suggests that our indicators will show strong changes in the overall basin level SOS upon aggregation by water functions as described in D5.2

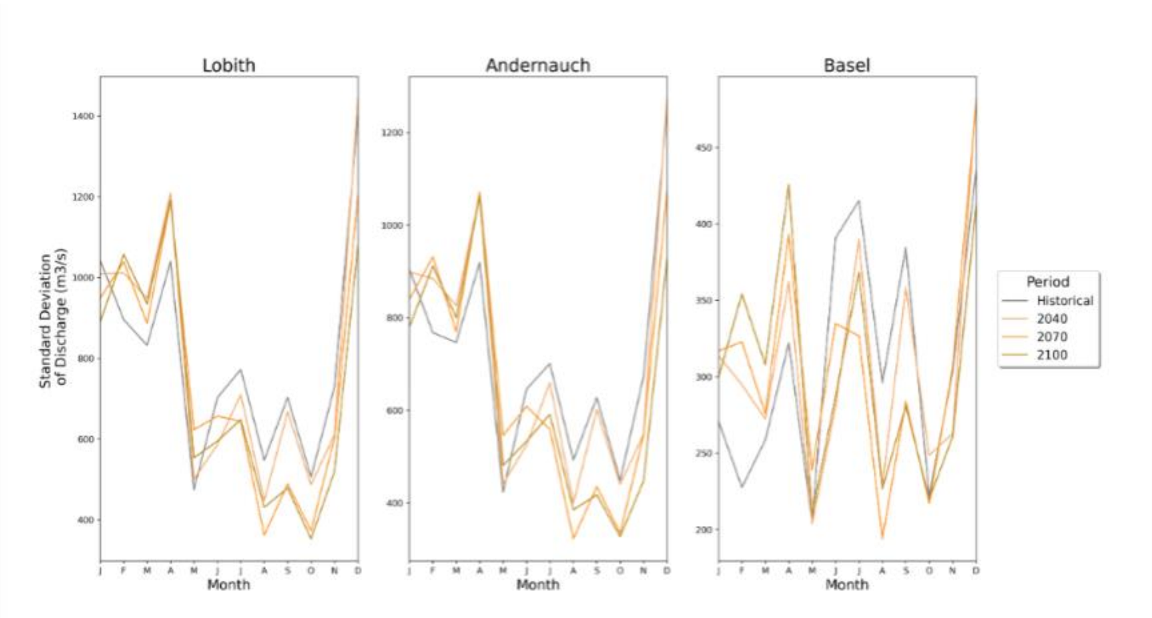


Figure 5. Line plot of Bio4a at the three main streamgage measurement points along the Rhine. We have averaged Bio4a for all the GCMs at each time point and plot the results for SSP3-RCP7.0.

Funded by the European Union

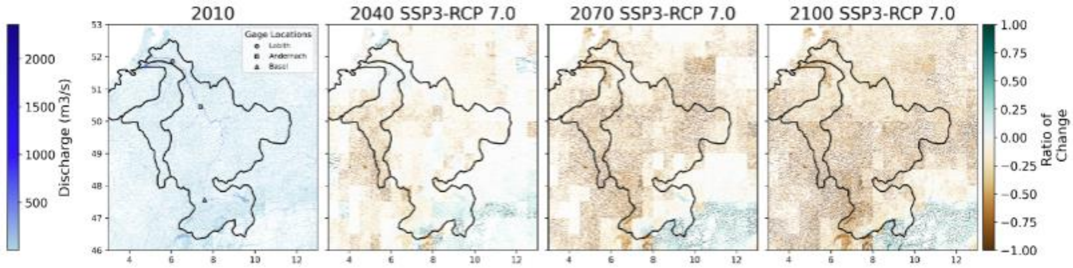


Figure 6. Spatial maps of Bio14 streamflow during the driest month for the four different time current and future time periods. We average the results of Bio14 across all five GCMs and calculate the percent difference between the future time period and the historic (2010).

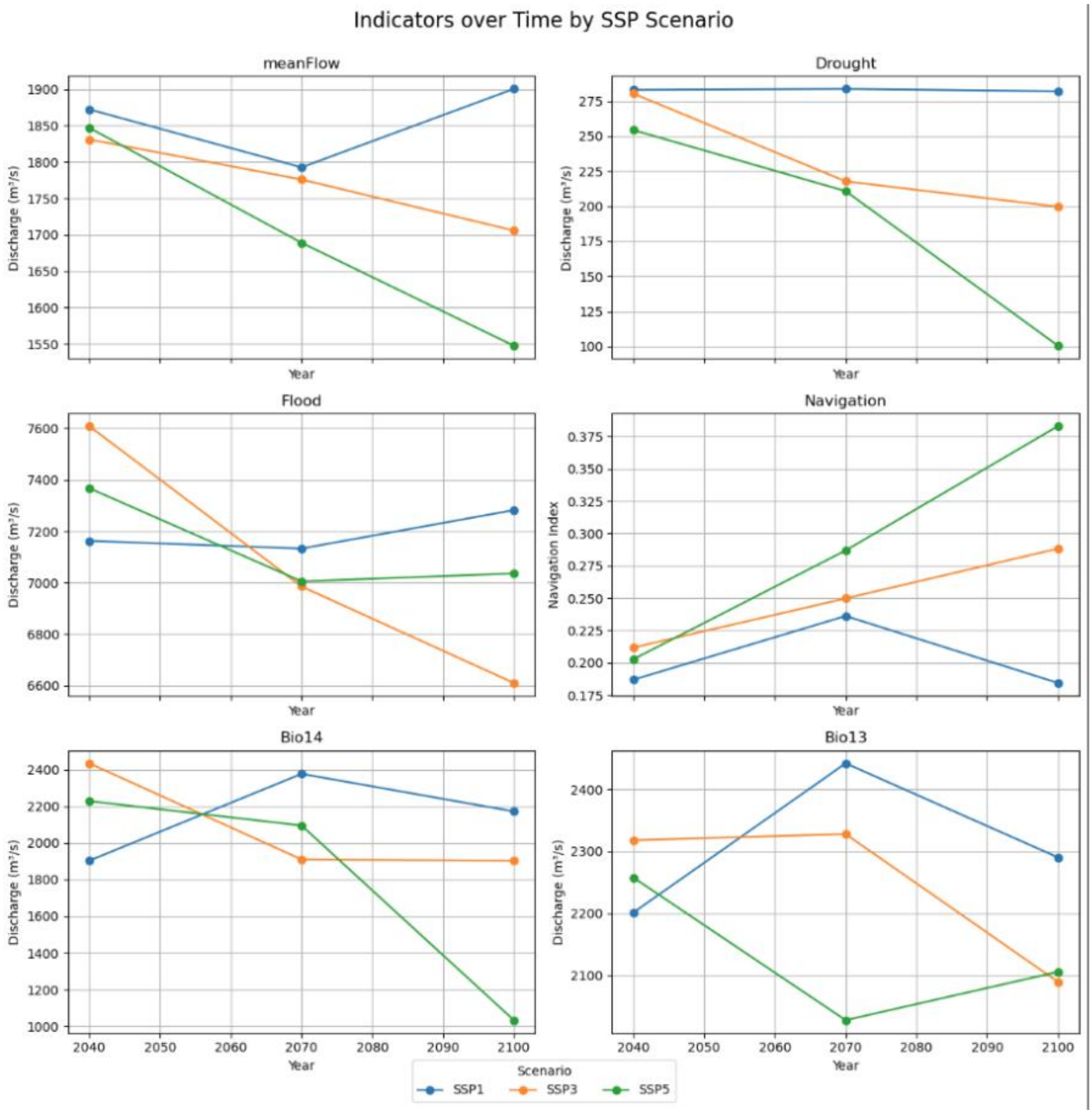


Figure 7. Depicts a selection of indicators and how they change over time with respect to the different SSPs. Each point corresponds to an average indicator value across all GCMs.

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Disclaimer

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