Project co-funded by European Union funds (ERDF, I
Project number: DTP3-308-2.3- lifeline M

Deliverable D.T1.2.4

Climate Change Study
Hydrological Assessment Report

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Date: January, 2022

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List of Abbreviations

ARSO	Agencija republike Slovenije za okolje (Slovenian Environment Agency)
ASTER GDEM	Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model
CC	Climate Change
CCM2	Catchment Characterisation Model 2
CLC	Corine Land Cover
CORDEX	Coordinated Regional Downscaling Experiment
DEM	Digital Elevation Model
DHMZ	Državni hidrometeorološki zavod (Croatian Meteorological and Hydrological Service)
ECA&D	European Climate Assessment & Dataset
EEA	European Environment Agency
eHYD	Hydrographischer Dienst Österreichs (Austrian Hydrographic Service)
ESDAC	European Soil Data Centre
ESDB	European Soil Database
EU	European Union
EU-DEM	European Digital Elevation Model
EURO-CORDEX	European Coordinated Regional Downscaling Experiment
GCM	Global Climate Model
GRDB	Global Runoff Database
GRDC	Global Runoff Data Centre
HEC-HMS	Hydrologic Engineering Center Hydrologic Modeling System
ICPDR	International Commission for the Protection of the Danube River
JRC	Joint Research Centre
LU	Land Use
NMHS	National Meteorological and Hydrological Services
NRCS	National Resources Conservation Service
NSE	Nash-Sutcliffe efficiency
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
RHMZ	Republički hidrometeorološki zavod (Republic Hydrometeorological Service of Serbia)
SCS	Soil Conservation Service
SRTM	Shuttle Radar Topography Mission
SWIM	Soil and Water Integrated Model
TBR-MDD	Transboundary Biosphere Reserve Mura-Drava-Danube
UNESCO	United Nations Educational, Scientific and Cultural Organization
USACE	United States Army Corps of Engineers
WCRP	World Climate Research Programme
WD	Water Demand
WMO	World Meteorological Organization
WWF	World Wide Fund

I. Introduction

• General introduction

The present report is the result of a study conducted within the DTP3-308-2.3 lifeline MDD, financed by the European Union´s Interreg Danube Transnational Programme. The area analysed and targeted by the present study (hereinafter called "target area") comprises river sections in the 5-country Biosphere Reserve Mura-Drava-Danube (TBR MDD, Figure 2), shared between Austria, Slovenia, Hungary, Croatia and Serbia. Lower courses of the Drava and Mura Rivers and related sections of the Danube are among Europe's most ecologically important riverine areas. The three rivers form a "green belt" 700 kilometres long, connecting almost 1.000,000 hectares of highly valuable natural and cultural landscapes, including a chain of 13 individual protected areas and 3.000 km2 of Natura 2000 sites. This is the reason why, in 2009, the Prime Ministers of Croatia and Hungary signed a joint agreement to establish the Mura-Drava-Danube Transboundary Biosphere Reserve across both countries. Two years later, in 2011, Austria, Serbia and Slovenia joined this initiative. Together with Croatia and Hungary, the five respective ministers of environment agreed to establish the world´s first five-country Biosphere reserve and Europe´s largest river protected area. Step by step the TBR MDD was realized: Hungary and Croatia (in 2012), Serbia (in 2017), Slovenia (in 2018) and Austria (2019) achieved UNESCO designation. The pentalateral designation was submitted in 2020 and designation finally achieved in September 2021.

The project´s work package for *Establishing the scientific knowledge base* (Work Package T1) has proposed as its aim to establish, as a first, a scientific knowledge base regarding vertical, lateral and longitudinal connectivity within the Mura-Drava-Danube bio-corridor. All studies' results and the overlaid GIS data collected therefore build the basis for a synthesis report on biotic indicators and abiotic framework conditions. This builds the basis for long-term conservation and restoration goals within the 5-country Biosphere Reserve Mura-Drava-Danube (TBR MDD) as well as for formulation of a TBR MDD River Restoration Strategy, elaborated in the framework of the same project (Output OT2.4). The facts and results presented in this project therefore come from a first ever such scientific assessment, harmonized on 5-country scale, setting the ground for future decision-making on 5-country level on river management and restoration. Whereas such activities and knowledge in each of the countries involved in the TBR MDD partly exist, this was the first time methods and area were harmonized for monitoring and studies of the biotic elements and the abiotic framework conditions for the Mura-Drava-Danube river corridor.

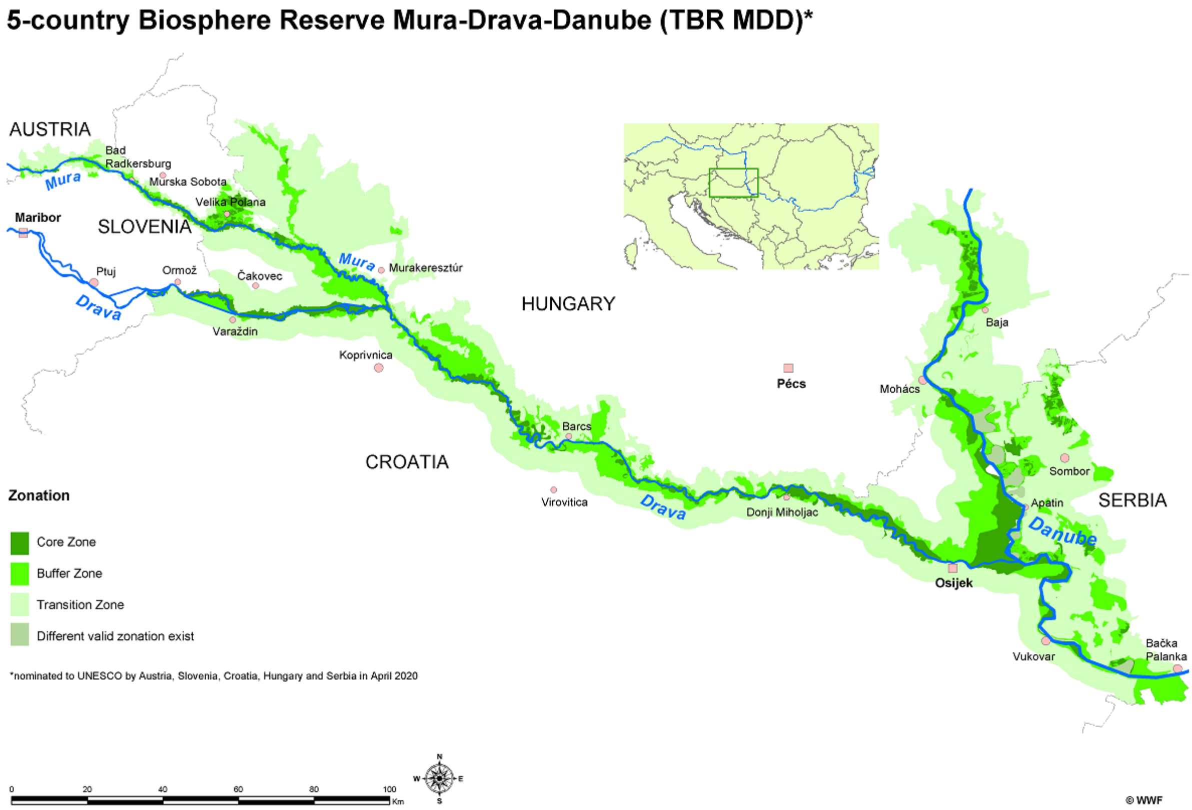


Figure 2. Map of the 5-country Biosphere Reserve Mura-Drava-Danube according to UNESCO designation in September 2021 (WWF Austria)

• Problem statement

The lives of almost a million people, as well as the survival of many species, are linked to the conservation of the Mura, Drava and Danube rivers. At a time of significant environmental change, such as climate change and biodiversity loss, this conservation area is crucial for flood protection, climate change mitigation, and the provision of drinking water and fertile land, and is increasingly recognised as a recreation and leisure area, as well as the driving force behind sustainable development.

As an integral part of the Climate Change Study together with the Climate Assessment, this Hydrologic Assessment report is meant to serve as a starting point in quantifying the possible effects of climate change on the hydrological regime of the Mura, Drava and Danube rivers within the TBR-MDD, by developing a model to simulate hydrological processes and provide hydrological projections.

• State of knowledge

The Danube River, as one of the most important rivers in Europe, and Drava together with Mura as one of its larger transboundary tributaries, have been studied extensively throughout the years. Numerous studies have been authored in recent years on both the observed hydrological regime throughout the basin and possible effects of climate change (Šraj et al, 2007; Brilly, 2012; ICPDR, 2014; Lóczy et al, 2017; Bisselink et al, 2018; Tadić and Brleković, 2019; Lóczy, 2019). The majority of studies have noted that many changes in the climate have already begun, including the rise in annual mean temperature, higher precipitation in mountains and lower in the lowland, duration of snow cover reduced in the lowland, etc. and the impacts of climate change on the hydrological regime are most often cited as: increasing summer drought (notably in the main Danube river), higher flood risk, deteriorating water quality, increase in water scarcity duration, etc.

A literature search for work on projected climate change impacts on runoff in this region found virtually no published studies which used catchment-scale modelling and analyses to assess local hydrological impacts in the region. The available projections for climate change impacts on runoff in the Danube and Drava basins were the result of applications of global and continental macroscale hydrological models. These models project a decrease in annual runoff of up to 20-30% in the region and an increase in the coefficient of variation in annual runoff (Arnell, 2003). Although these models can give a gross indication as to expected trends, they lack local detail and are not calibrated for use at a particular location. Hence, results from continental to global scale hydrological models provide a useful regional overview, but results at the level of a daily time step and for smaller areas are considered unreliable (Haddeland et al, 2013).

• Study aims

This report provides a description of the development and application of a hydrologic model for the Drava River basin (including Mura as its largest tributary), as well as an assessment for the Danube River, that is one of the main components of the Climate Change Study. Development of a hydrologic model that will be used to assess the hydrologic response of the Drava River basin to future climate scenarios is one of the key steps in establishing recommendations regarding adaptation to climate change for this basin. Predicting hydrologic response over a different range of climate scenarios will be of crucial importance for the future development of the basin.

II. Methodology

• Overview

In this study, hydrological modelling of climate change impacts on runoff in the Drava River basin has been performed. The scope of work included the following tasks:

- collect and analyse data needed for the model (meteorological, hydrological, digital terrain model, land use, soil maps, etc)
- perform an analysis and make the selection of the meteorological and hydrological stations from which the data will be collected and used for the modelling;
- set up the model, including calibration to observed data;
- using the observed and modelled hydrologic and meteorological data, create simulation forecasts for future scenarios.

Four time periods are considered, namely 1976-2005 (base period), 2021-2050 (near future), 2036-2065 (mid-future) and 2071-2100 (far future). Observations of hydrometeorological data have been used for hydrological model calibration and for bias correction of climate projection data.

The assessment of climate change impacts for the reach of the Danube river covered by the TBR-MDD are provided through literature review of relevant publications.

• Input data

All data used in this study are publicly available, and an overview of the datasets is given below.

Meteorological data

Meteorological data, namely observed mean daily precipitation and air temperature, was obtained from the E-OBS dataset. E-OBS is a daily gridded observational dataset for precipitation, temperature and sea level pressure in Europe. The blended time series from the station network of the European Climate Assessment & Dataset (ECA&D) (Klein Tank et al. 2002) forms the basis for the E-OBS gridded dataset, where all station data are sourced directly from the European National Meteorological and Hydrological Services (NMHSs) or other data holding institutes. For a considerable number of countries the number of stations used is the complete national network and therefore much more dense than the station network that is routinely shared among NMHSs (which is the basis of other gridded datasets).

E-OBS consists of daily mean, minimum, and maximum, temperature values, daily precipitation totals gridded and sea level pressure at a resolution of approximately 10 km. The dataset spans the period 1 January 1950 to the present, and is updated frequently. E-OBS is widely used for monitoring extremes across Europe and for the validation of numerical models (van der Schrier, 2019).

The reason the E-OBS gridded dataset was selected over observed data from meteorological stations was primarily due to data availability, as the meteo stations are operated by meteo services in corresponding member countries.

Table 1. Basic characteristics of the E-OBS dataset

DATA DESCRIPTION	
Data type	Gridded
Projection	Regular latitude-longitude grid
Horizontal coverage	Europe
Horizontal resolution	0.1° x 0.1° and 0.25° x 0.25°
Vertical coverage	Near surface
Vertical resolution	Single level
Temporal coverage	January 1950 to present
Temporal resolution	Day
File format	NetCDF-4
Conventions	Climate and Forecast Metadata Convention v1.4 (CF-v1.4)
Versions	v19.0e, v20.0e, v21.0e, v22.0e and the latest version v23.1e
Update frequency	New versions added every 6 months

Table 2. Main variables of the E-OBS dataset

MAIN VARIABLES		
Name	Units	Description
Land surface elevation	m	Earth's surface height above sea level derived from the Global 30 Arc-Second Elevation Data Set (GTOPO30) developed by the United States Geological Survey.
Maximum temperature	°C	Daily maximum air temperature measured near the surface, usually at height of 2 meters.
Mean temperature	°C	Daily mean air temperature measured near the surface, usually at height of 2 meters.
Minimum temperature	°C	Daily minimum air temperature measured near the surface, usually at height of 2 meters.
Precipitation amount	mm	Total daily amount of rain, snow and hail measured as the height of the equivalent liquid water in a square meter The data sources for the precipitation are rain gauge data which do not have a uniform way of defining the 24-hour period over which precipitation measurements are made. Therefore, there is no uniform time period (for instance, 06 UTC previous day to 06 UTC today) which could be attached to the daily precipitation.
Relative humidity	%	Daily mean relative humidity measured near the surface usually at a height of 2 meters. Relative humidity values relate to actual humidity and saturation humidity. Values are in the interval [0,100]. 0% means that the air in the grid cell is totally dry whereas 100% indicates that the air in the cell is saturated with water vapour.
Sea level pressure	hPa	Daily mean air pressure at sea level. In regions where the Earth's surface is above sea level the surface pressure is used to compute the air pressure that would exist at sea level directly below given a constant air temperature from the surface to the sea level point.
Surface shortwave downwelling radiation	W m-2	The flux of shortwave radiation (also known as solar radiation) measured at the Earth's surface.

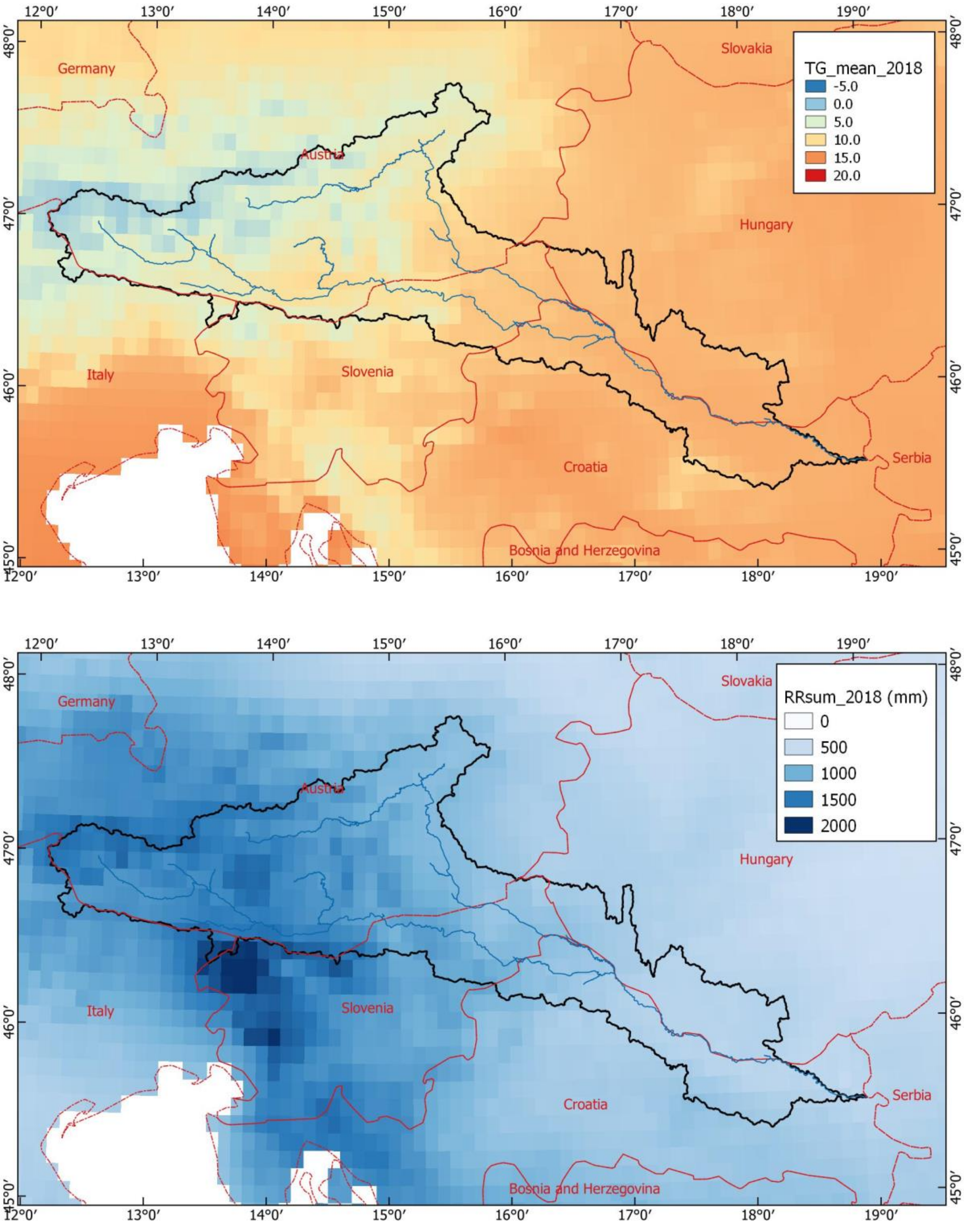


Figure 2. Examples of E-OBS gridded dataset for the Drava River basin: mean annual temperature in 2018 (above) and annual precipitation in 2018 (below)

Observed Hydrological Data

Daily discharge time series for hydrological stations on the Danube, Drava, Mura and their tributaries were obtained from the Global Runoff Database (GRDB). The Global Runoff Database of quality controlled historical mean daily and monthly discharge data , operated by GRDC (Global Runoff Data Centre) at the German Federal Institute of Hydrology (BfG) in Koblenz, under the auspices of the World Meteorological Organization (WMO), supports climate-related programs and projects of the United Nations and their special organizations and the scientific and research communities at large.

Data from GRDB was supplemented with discharge data available online from hydrometeorological services of member countries, namely:

- Austria: Hydrographischer Dienst Österreichs – eHYD (ehyd.gv.at)
- Slovenia: Agencija republike Slovenije za okolje – ARSO (arso.gov.si)
- Croatia: Državni hidrometeorološki zavod – DHMZ (meteo.hr)
- Serbia: Republički hidrometeorološki zavod – RHMZ (hidmet.gov.rs)

A total of 55 stations were included in the study (Fig. 3): 32 in Austria, 12 in Slovenia, 10 in Croatia, 2 in Serbia and 1 in Hungary

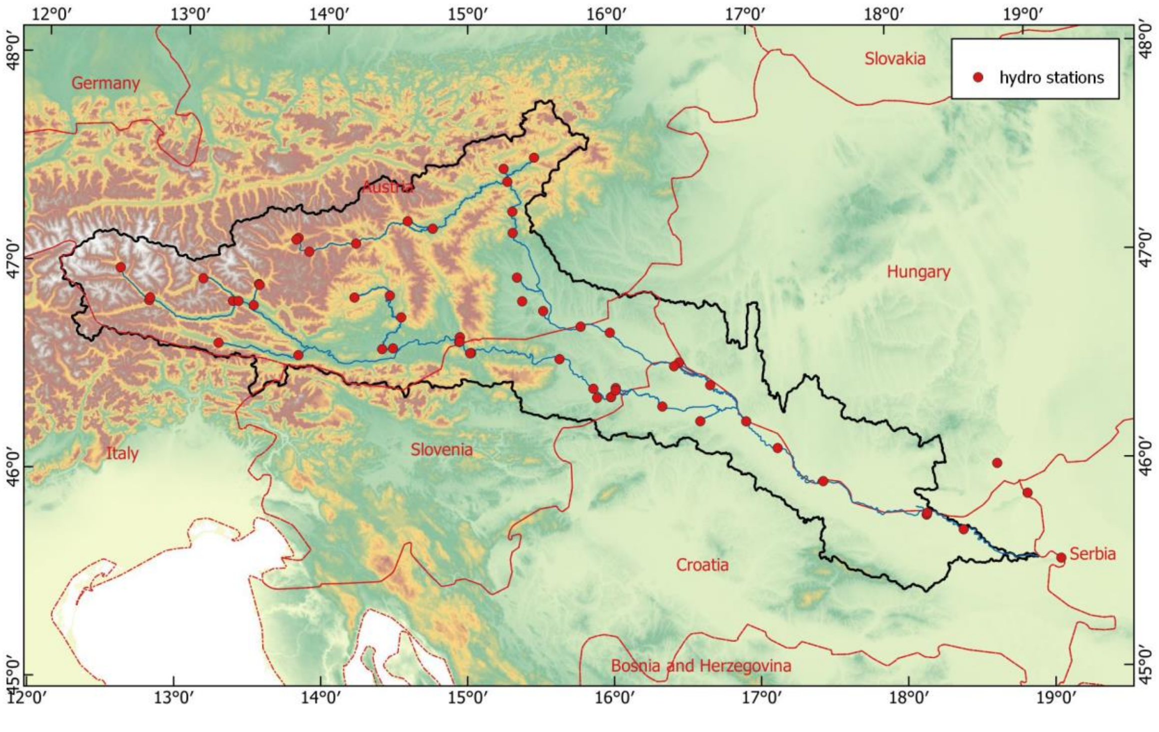


Figure 3. Locations of all included hydrological stations

Table 3. Complete list of available hydrological gauging stations

River	Station	Country	Lat	Lon	data_start	data_end
Gail	Rattendorf	AT	46.62	13.25	1951	2017
Lieser	Spittal - Fasan	AT	46.81	13.50	1951	2017
Isel	Bruehl	AT	46.97	12.55	1951	2017
Mura	Mureck	AT	46.71	15.79	1974	2017
Mura	Spielfeld	AT	46.71	15.64	1968	2001
Mura	Frohnleiten	AT	47.27	15.32	1951	1986
Mura	Friesach	AT	47.16	15.32	1987	2017
Mura	Bruck A. D. Mur, Below Muerz	AT	47.41	15.28	1967	2017
Taurachbach	Tamsweg (Taurach)	AT	47.14	13.80	1961	2017
Mura	Moertelsdorf	AT	47.13	13.79	1971	2017
Murz	Kindtal	AT	47.53	15.47	1966	2017
Thorlbach	Hansenhuette	AT	47.47	15.26	1951	2017
Mur	Gestüthof	AT	47.11	14.21	1961	2018
Pöls	Pölsfluß	AT	47.22	14.57	1951	2018
Mur	Zeltweg	AT	47.19	14.75	1966	2018
Kainach	Lieboch	AT	46.95	15.35	1951	2018
Sulm	Leibnitz	AT	46.79	15.53	1951	2018
Isel	Lienz	AT	46.83	12.77	1951	2018
Drau	Sachsenburg Süd	AT	46.83	13.35	1951	2018
Lieser	Gmünd-Ort	AT	46.91	13.53	1961	2018
Malta	Sandriesen	AT	46.91	13.53	1951	2018
Gail	Federaun	AT	46.57	13.81	1951	2018
Gurk	Weitensfeld-Ost	AT	46.85	14.20	1951	2018
Görtschitz	Brückl	AT	46.75	14.53	1951	2018
Glan	Zell	AT	46.60	14.40	1967	2018
Gurk	Gumisch	AT	46.61	14.48	1951	2018
Lavant	Krottendorf	AT	46.66	14.94	1951	2018
Möll	Flattach	AT	46.93	13.14	1972	2018
Drau	Lavamünd Ort	AT	46.64	14.94	2009	2018
Drau	Drauhofen	AT	46.83	13.39	1974	2018
Gurk	Mölbling	AT	46.86	14.45	1993	2018
Drau	Lienz-Falkensteinsteg	AT	46.82	12.76	1991	2018
Bednja	Ludbreg	HR	46.25	16.62	1974	2020
Drava	Belisce	HR	45.69	18.42	1962	2020
Drava	Botovo	HR	46.24	16.94	1926	2020
Drava	Donja Dubrava	HR	46.31	16.82	1986	2020
Drava	Donji Miholjac	HR	45.78	18.17	1994	2020
Drava	Novo Virje	HR	46.11	17.15	1977	2020
Drava	Terezino Polje	HR	45.94	17.46	1961	2020
Drava	Varazdin	HR	46.32	16.36	1957	1981
Mura	Gorican	HR	46.42	16.69	1926	2020
Mura	Mursko Sredisce	HR	46.51	16.44	1926	2020
Drava	HE Dravograd	SI	46.59	15.02	1965	2019
Drava	Maribor	SI	46.56	15.64	1926	1965
Drava	Ptuj	SI	46.41	15.88	1953	2019
Drava	HE Formin	SI	46.40	16.03	1990	2019
Mura	Gornja Radgona 1	SI	46.68	16.00	1946	2019
Drava River	Borl 1	SI	46.37	16.00	1961	2019
Pesnica	Zamušani 1	SI	46.41	16.03	1961	2019
Ledava	Čentiba	SI	46.53	16.48	1969	2019
Drava	Borl	SI	46.37	16.00	1954	1981
Meža	Otiški Vrh 1	SI	46.59	15.02	1953	2019
Dravinja	Videm 1	SI	46.37	15.90	1972	2000
Dravinja	Videm	SI	46.37	15.90	1946	2019
Danube	Bezdan	RS	45.85	18.87	1946	2006
Danube	Bogojevo	RS	45.53	19.08	1946	2006
Danube	Mohacs	HU	46.00	18.67	1930	1999

Digital Elevation Model

A digital elevation model (DEM) was used for obtaining topographic and morphologic characteristics of river reaches and basins. The European Digital Elevation Model (EU-DEM v1.1) was used, which was published by the European Environment Agency (EEA) in 2016, and provides a contiguous dataset at 25m spatial resolution. It is a hybrid product based on SRTM (Shuttle Radar Topography Mission) and ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) data fused by a weighted averaging approach.

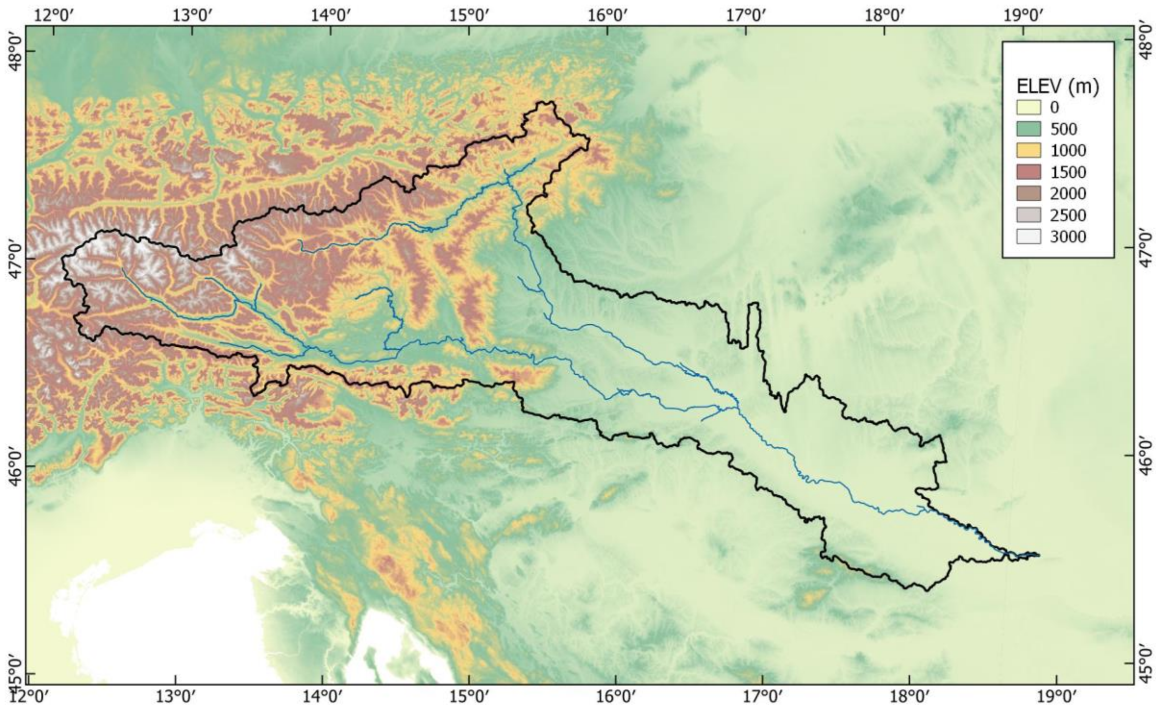


Figure 4. EU-DEM values

River Network

To ease the identification of river reaches and delineate watersheds (basins), the Catchment Characterisation Model (CCM2) database was used. The Catchment Characterisation Model (CCM2) database covers the entire European continent, and includes a hierarchical set of river segments and catchments based on the Strahler order (Strahler, 1952), a lake layer and structured hydrological feature codes based on the Pfafstetter system (De Jager, 2007). It allows for analysis from the regional to the continental scale, corresponding to traditional mapping scales of up to 1:500,000. CCM2 covers an area of about 12,000,000 square kilometres and includes more than 2,000,000 primary catchments. These can be aggregated to drainage basins at different hierarchical levels, forming, for example, about 650 river basins of more than 1000 square kilometers. CCM2 further includes a coastline, fully congruent with the river basins, and some 70,000 lakes. The layers are generated from a 100 meters resolution digital terrestrial elevation model.

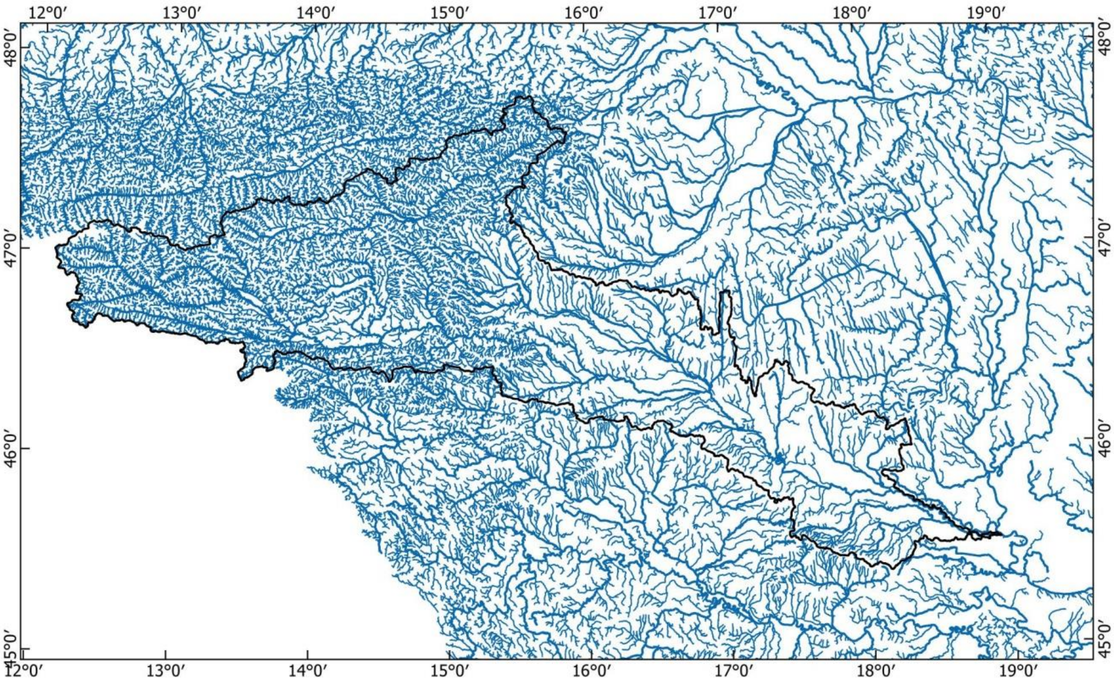


Figure 5. Example of river network from the Catchment Characterisation Model (CCM2) for the Danube river basin (Drava River basin is outlined)

Soil Data

For the soil map the "European Soil Database v2 Raster Library" was used, with resolution of 1000x1000 m (Panagos, 2004). This database was created by European Soil Data Centre (ESDAC) and can be accessed through the web service.

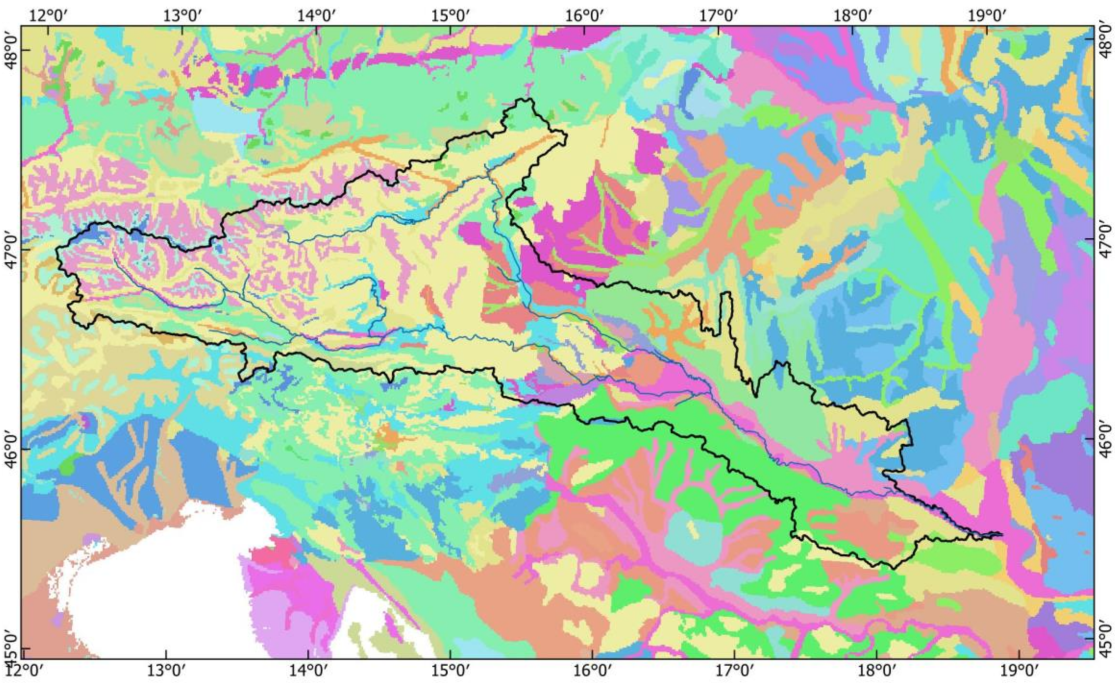


Figure 6. Soil map of the Drava River basin, based on the European Soil Database (ESDB)

Land Cover

For analysis of land cover properties of the Drava River Basin, the Corine Land Cover 2018 (CLC 2018) raster dataset with 100x100m resolution has been selected, as there is no freely available alternative. This dataset is free-to-use and can be downloaded from the Copernicus Land Monitoring Service website. It consists of an inventory of land cover in 44 classes, included in three levels of thematic detail in five major groups (Heymann et al., 1993).

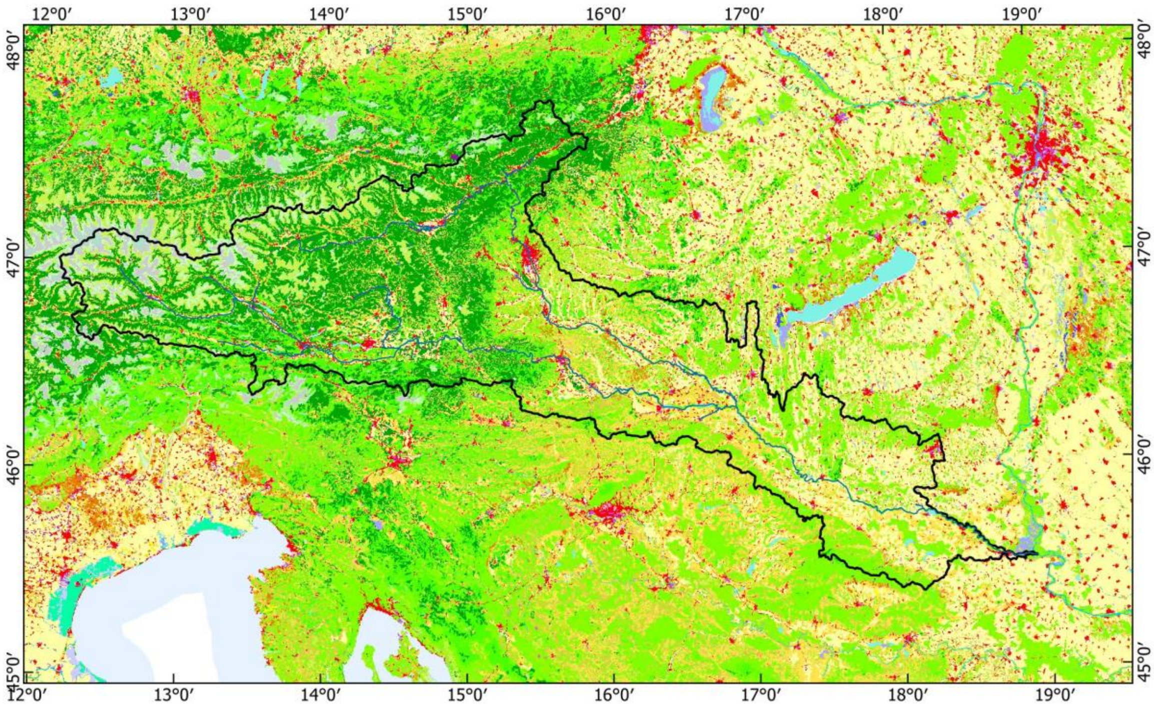


Figure 7. Corine Land Cover dataset for the Drava River basin

Climate Model Data

To assess the range of potential future climate change in Transboundary Biosphere Reserve Mura-Drava-Danube (TBR-MDD), the data of several regional climate models (RCMs) from the latest set of the World Climate Research Programme (WCRP) Coordinated Regional Downscaling Experiment (CORDEX) were analyzed. The CORDEX provides an internationally coordinated framework to improve regional climate scenarios. This includes harmonization of model evaluation activities and the generation of multi-model ensembles of regional climate projections for the land-regions worldwide. As part of the global CORDEX framework the EURO-CORDEX initiative (www.euro-cordex.net) provides regional climate projections for Europe at 12.5 km (EUR-11) resolution, thereby complementing coarser-resolution data sets of former activities like EU Projects PRUDENCE and ENSEMBLES.

Out of a total of 46 models, 5 were selected for each future scenario (Representative Concentration Pathways RCP-4.5 and RCP-8.5) representing the full spectrum of climate change and bias corrected against the gridded observation dataset E-OBS 0.1°.

The model selection was based on detailed analysis to select scenarios related to heat waves/droughts and heavy precipitation/floods for the Transboundary Biosphere Reserve Mura-Drava-Danube (TBR-MDD) up to year 2100 using the above mentioned two future emission scenarios.

Table 4. List of climate models used

No.	Driving Global Climate Model (GCM)	Regional Climate Model (RCM)	Short-Name
1	CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8-17_v1	CNRM-CM5_CLMcom-CCLM4
2	IPSL-IPSL-CM5A-MR	SMHI-RCA4_v1	IPSL-CM5A-MR_SMHI-RCA4
3	MOHC-HadGEM2-ES	KNMI-RACMO22E_v2	HadGEM2-ES_KNMI-RACMO22E
4	MPI-M-MPI-ESM-LR	MPI-CSC-REMO2009_v1	MPI-ESM-LR_MPI-CSC
5	CNRM-CERFACS-CNRM-CM5	SMHI-RCA4_v1	CNRM-CM5_SMHI-RCA4

• Assessment of hydrological regime

To evaluate the hydrological regime of the characteristic reaches of the study area, basic indicators of the hydrologic regime were calculated based on observed data, including mean flow, flood flows and low flows.

Mean flows are presented with the following indices:

- **Mean monthly discharge.** Period of record mean gauged flows at gauging stations are calculated by the average, weighted to account for the different number of days per month, of the mean monthly flows for the period of record.
- **Mean annual discharge.** The mean annual discharge as measured at the gauging station for the period of record.
- **Flow percentiles.**
    - Q10 (the 90-percentile flow): The flow in cubic metres per second which was equalled or exceeded for 10% of the specified term – a high flow parameter which, when compared with the Q90 flow can provide a measure of the variability, or 'flashiness', of the flow regime.
    - Q50 (the 50-percentile flow): The flow in cubic metres per second which was equalled or exceeded for 50% of the flow record.
    - Q75 (the 25-percentile flow): The flow in cubic metres per second which was equalled or exceeded for 75% of the flow record.
    - Q90 (the 10-percentile flow): The flow in cubic metres per second which was equalled or exceeded for 90% of the flow record. The Q90 flow is a significant low flow parameter particularly relevant in the assessment of river water quality consent conditions.
- **Mean annual flood.** The mean annual flood Q is determined as the mean of the annual maximum flow series at the gauging station.
- **Low flow.** Low flow conditions at a specific location are characterized by the 95% exceedance probability flow, obtained by statistical analysis of the minimum mean monthly discharge in every year.

• Considerations for model development

The Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS), developed by the United States Army Corps of Engineers (USACE, 2010), was chosen for the development of the hydrological model of the Drava River basin.

HEC-HMS models runoff in 5 steps. It calculates (1) interception, (2) surface detention, (3) infiltration, (4) direct runoff, and (5) baseflow. For a basin divided into sub-basins, routing the outflow hydrograph from a sub-basin toward downstream nodes of the river network is also necessary. Different methods can be applied in each step, but not all the methods are applicable for continuous simulation.

Two main decisions related to the model have to be made before actual modelling and corresponding data collection can begin. These are:

- definition of sub-basins within the basin, and
- choice of computational time step.

These two problems are interrelated. Basin subdivision into sub-basins should be made in such a manner to include all locations at which description of the water regime is needed, but also to include locations of hydrologic gauging stations where reliable observed data is available for model calibration and verification. On the other hand, computational time step should be chosen so that it enables good temporal representation of hydrologic processes in the basin, but it is generally related to the size of the sub-basin (smaller basin size requires shorter time step and vice versa). Finally, choice of the computational time step dictates temporal resolution of the model input data.

In the case of the Drava River basin, the computational time step of 1 day was chosen for modelling primarily due to the daily time step of all available data (precipitation, temperatures and discharge).

Basin subdivision was made with respect to the daily time step (sub-basin sizes approximately 500-2000 km^2) and to data availability and quality (reliable measurements with long record periods without gaps).

• Hydrological model setup

Model Structure

For the modelling purposes, the complete Drava River basin was divided into sub-basins. Two levels of subdivision were made, on the first level, three major sub-basins were selected:

- the upper Drava, upstream of the confluence with the Mura River
- the Mura River basin
- the lower Drava, downstream of the Mura River

Second-level subdivision resulted in a total of 57 sub-basins throughout the basin.

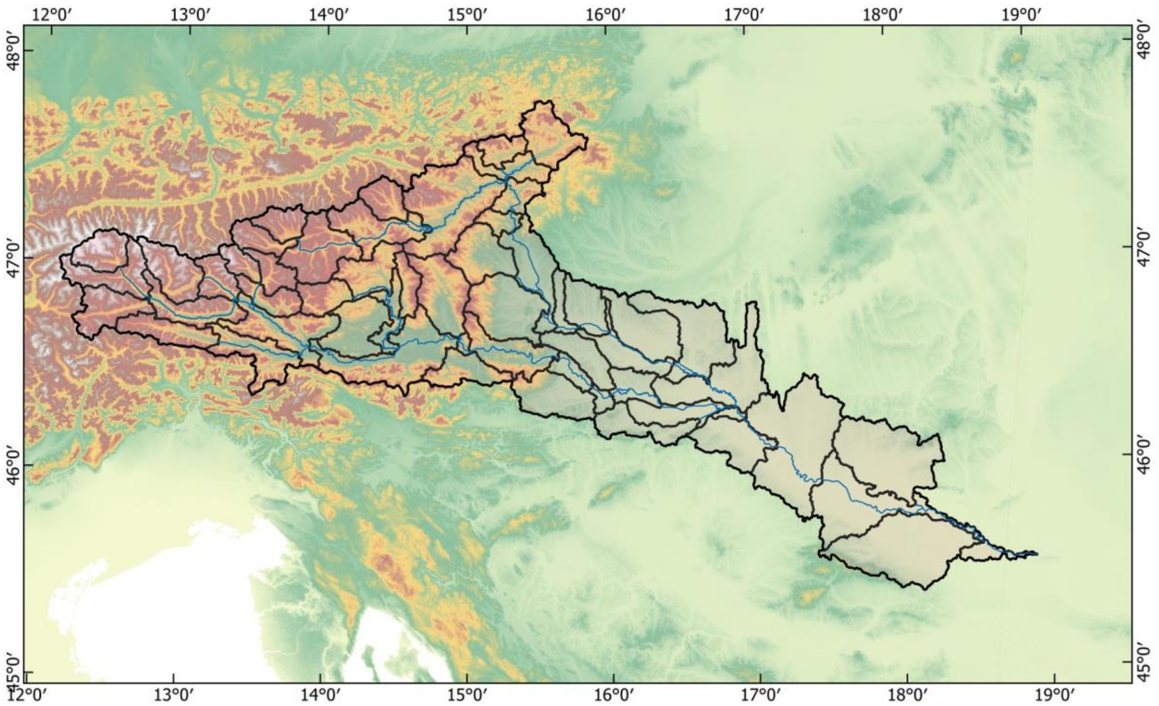


Figure 8. Subdivision of the Drava River basin into 57 sub-basins for the hydrologic model

The primary river network is represented as river reach segments, consisting of the Mura and Drava rivers, along with some larger tributaries such as Pöls, Murz, Thorlbach, Kainach, Sulm and Ledava in the Mura basin, and Isel, Möll, Lieser, Gail, Gurk, Pesnica and Bednja in the Upper Drava basin. A total of 55 river reaches were included in the model.

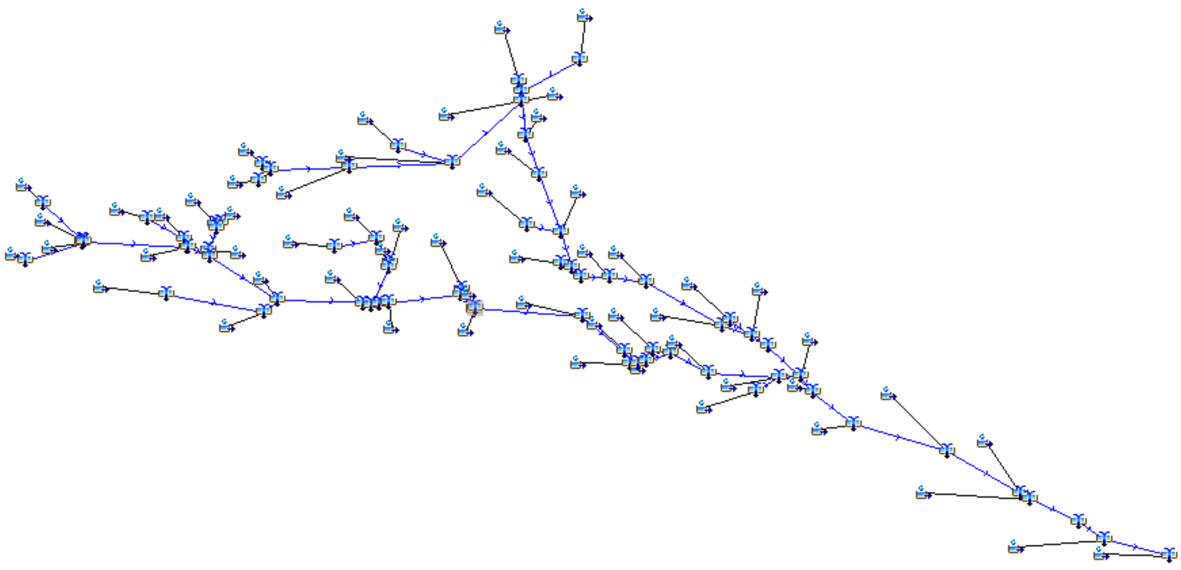


Figure 9. Hydrologic model structure (HEC-HMS)

Basin modelling methodology

An overview is given of the methods selected to model specific processes within the hydrological model.

Each sub-basin element conceptually represents infiltration, surface runoff, and subsurface processes interacting together, but the actual infiltration calculations are performed by a loss method contained within the sub-basin. The deficit constant loss method was implemented, which uses a single soil layer to account for continuous changes in moisture content, thus allowing for continuous simulation. The method implemented assumes that all precipitation is intercepted until the canopy storage capacity is filled. Once the storage is filled, all further precipitation falls to the surface, or directly to the soil if no representation of the surface is included. All potential evapotranspiration will be used to empty the canopy storage until the water in the storage has been eliminated.

The canopy component of the sub-basin represents the presence of plants in the landscape. Plants intercept precipitation, reducing the amount of precipitation that arrives at the ground surface. Intercepted water evaporates between storm events.

Transformation of excess runoff was performed using the SCS Unit Hydrograph, which defines a curvilinear unit hydrograph by first setting the percentage of the unit runoff that occurs before the peak flow (NRCS, 2007). A triangular unit hydrograph is then fitted to the curvilinear unit hydrograph so that the total time base of the unit hydrograph is calculated. The percentage of unit runoff occurring before the peak flow is not uniform across all watersheds because it depends on flow length, ground slope, and other properties of the watershed.

Calculations of subsurface processes are performed by a baseflow method contained within the sub-basin. The recession baseflow method was implemented, which is designed to approximate the typical behavior observed in watersheds when channel flow recedes exponentially after an event. This method has the ability to automatically reset after each storm event and consequently is useful for continuous simulations. The recession constant describes the rate at which baseflow recedes between storm events and is defined as the ratio of baseflow at the current time, to the baseflow one day earlier.

Evapotranspiration is the combination of evaporation from the ground surface and transpiration by vegetation. It includes both evaporation of free water from the surface of vegetation and the land surface. It also includes transpiration which is the process of vegetation extracting it from the soil through the plant root system. Whether by evaporation or transpiration, water is returned from the land surface or subsurface to the atmosphere. Even though evaporation and transpiration are taken together, transpiration is responsible for the movement of much more water than evaporation. Combined evapotranspiration is often responsible for returning 50 or even 60% of precipitation back to the atmosphere. The Hamon method (Hamon, 1963) was implemented, which is based on an empirical relationship where saturated water vapor concentration, at the mean daily air temperature, adjusted by a day length factor, is proportional to potential evapotranspiration. The day length factor accounts for plant response, duration of turbulence, and net radiation. The method has proven effective for estimating potential evapotranspiration in data-limited situations, and calculates daily potential evapotranspiration given daily average temperature.

Snowmelt was simulated using the temperature index method, which is an extension of the degree-day approach to modeling a snowpack. A typical approach to the degree day is to have a fixed amount of snowmelt for each degree above freezing. This method includes a conceptual representation of the cold energy stored in the pack along with a limited memory of past conditions and other factors to compute the amount of melt for each degree above freezing. As the snowpack internal conditions and atmospheric conditions change, the melt coefficient also changes.

Routing flow through river segments (reaches) is performed using hydrologic routing, as opposed to a hydraulic approach that implements full unsteady flow equations. The Normal Depth Routing method was implemented, which uses a Modified Puls routing approach where storage-discharge relationships are developed using a normal depth assumption for the reach, based on geometric data for the channel and Manning's equation.

• Hydrological model calibration

Model performance criteria

Evaluation of the model performance is typically based on specific statistics and ratings developed to evaluate (or penalize) various performance criteria, such as accuracy of predicting peak flows, total hydrograph volume, peak flow, time to peak etc., depending on project goals. For this project and the model intended to perform long-term simulations of present and future hydrologic regime, the goal is to predict the long-term mean flows on monthly and annual scale with reasonable accuracy. The Nash-Sutcliffe efficiency (NSE) was used to assess performance of the Drava River basin model.

Nash-Sutcliffe efficiency (NSE) coefficient:

$$NSE = 1 - \frac{\sum \left(Q_i^{sim} - Q_i^{obs}\right)^2}{\sum \left(Q_i^{obs} - \overline{Q}_i^{obs}\right)^2}$$

where Q_i^{sim} and Q_i^{obs} are simulated and observed flows at time step *i*, respectively, and $\overline{Q}_i^{obs}$ is observed mean flow. The NSE coefficient determines the relative magnitude of the error variance compared to the observed data variance, and essentially represents the percentage of observed data variance explained by the model. NSE takes values in range between −∞ and 1; value of 1 indicates a perfect agreement, while negative values indicate very poor agreement. The NSE coefficient is evaluated for daily time steps.

Although there are no generally accepted criteria for model evaluation in terms of the accuracy of simulated flow compared to measured data, the performance ratings given by Moriasi et al. (2007), based on the ratings and corresponding values reported from individual studies, are used here to evaluate quality of the fit. In general, a model simulation can be judged as very good if NSE > 0.75, good when NSE > 0.65 and satisfactory when NSE > 0.50.

• Model application with future climate scenarios

Investigation of the climate change impacts on the hydrological regime in the Drava River basin starts with the simulations of the future hydrologic regime in the basin using the hydrologic model and the projected climate from the Global Climate Models (GCMs) as the input. To assess the change in runoff under climate change, the runoff simulated with future climate scenarios should be compared to the runoff from some reference period, called baseline runoff.

Due to uncertainties that are attributed to the observed record extension and both climate and hydrologic modelling, the baseline runoff in this study is not the historically observed runoff, but the runoff simulated with baseline climate scenarios from the GCMs. Runoff simulations with the hydrologic model using the baseline and future scenarios provide the means to estimate the relative change rather than the absolute runoff values. The results therefore offer an insight into the range of potential consequences of climate change on water resources at the basin scale.

The results of the hydrologic simulations with baseline and future climate scenarios are used to describe changes in the hydrologic regime of the Drava and Mura rivers. The following indicators of the hydrologic regime are considered to assess the change:

- distribution of mean monthly discharge, defined as the long-term average flow for each month across years in a given 30-year period,
- distribution of the mean annual flood, defined as the mean of the annual maximum flow for the period of the time series,
- change in projected mean annual flood, defined as the percentual increase or decrease of the mean annual flood compared to the base period, and
- change in projected Q95% low flows, defined as the percentual increase or decrease of the low flow of 95% exceedance probability compared to the base period.

III. Results

● Locations

As already stated, the study area is defined by the extents of the TBR-MDD, which covers the following river reaches:

– The Mura River from Spielfeld (Austria) to the confluence with the Drava River;
– The Drava River from Ormož (Slovenia) to the confluence with the Danube, and
– The Danube River from Baja (Hungary) to Bačka Palanka (Serbia).

When taking into account hydrological conditions and similarities, four distinct river reaches can be identified:

- The Mura River flowing through the TBR-MDD, from Spielfeld to the confluence with the Drava river,
- The Upper Drava, from Ormož to the confluence with the Mura,
- The Lower Drava, from the confluence with the Mura river all the way to the confluence with the Danube, and
- The Danube flowing through the TBR-MDD, from Baja at the upstream to Bačka Palanka on the downstream end.

Based on these characteristic reaches, results will be presented at selected locations for each reach: Goričan on the Mura, Donja Dubrava for Upper Drava, Terezino polje for Lower Drava and Bezdan on the Danube.

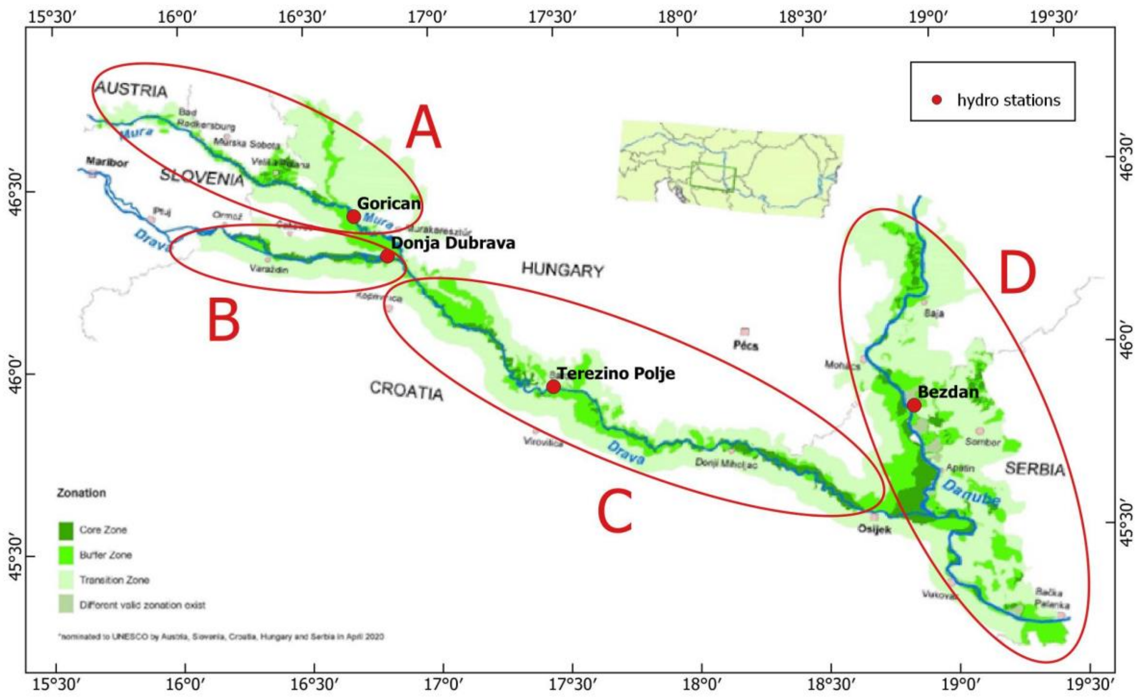


Figure 10. Selected river reaches and characteristic locations for model output: Mura (A), Upper Drava (B), Lower Drava (C) and Danube (D)

- ## Basic Characteristics of Hydrological Regime

Results of the assessment of hydrological regime are presented visually for the four characteristic hydrologic stations: Goričan (Mura), Donja Dubrava (Upper Drava), Terezino polje (Lower Drava) and Bezdan (Danube).

Observed mean monthly discharges are presented on a color-coded graph for the entire period of observation, where green shows lower mean monthly values, orange corresponds to mid to high mean monthly discharge and purple shows extreme values. This type of graph shows data from the entire observation period, and both seasonality and periods of higher of lower flow can be observed.

Mean monthly discharges, calculated as the mean discharge for each month and averaged for all years on record, are presented as a line graph, which clearly shows the seasonality of monthly flows. Shaded areas are included to show the 50, 75 and 90-percentile flows.

Mura - Goričan

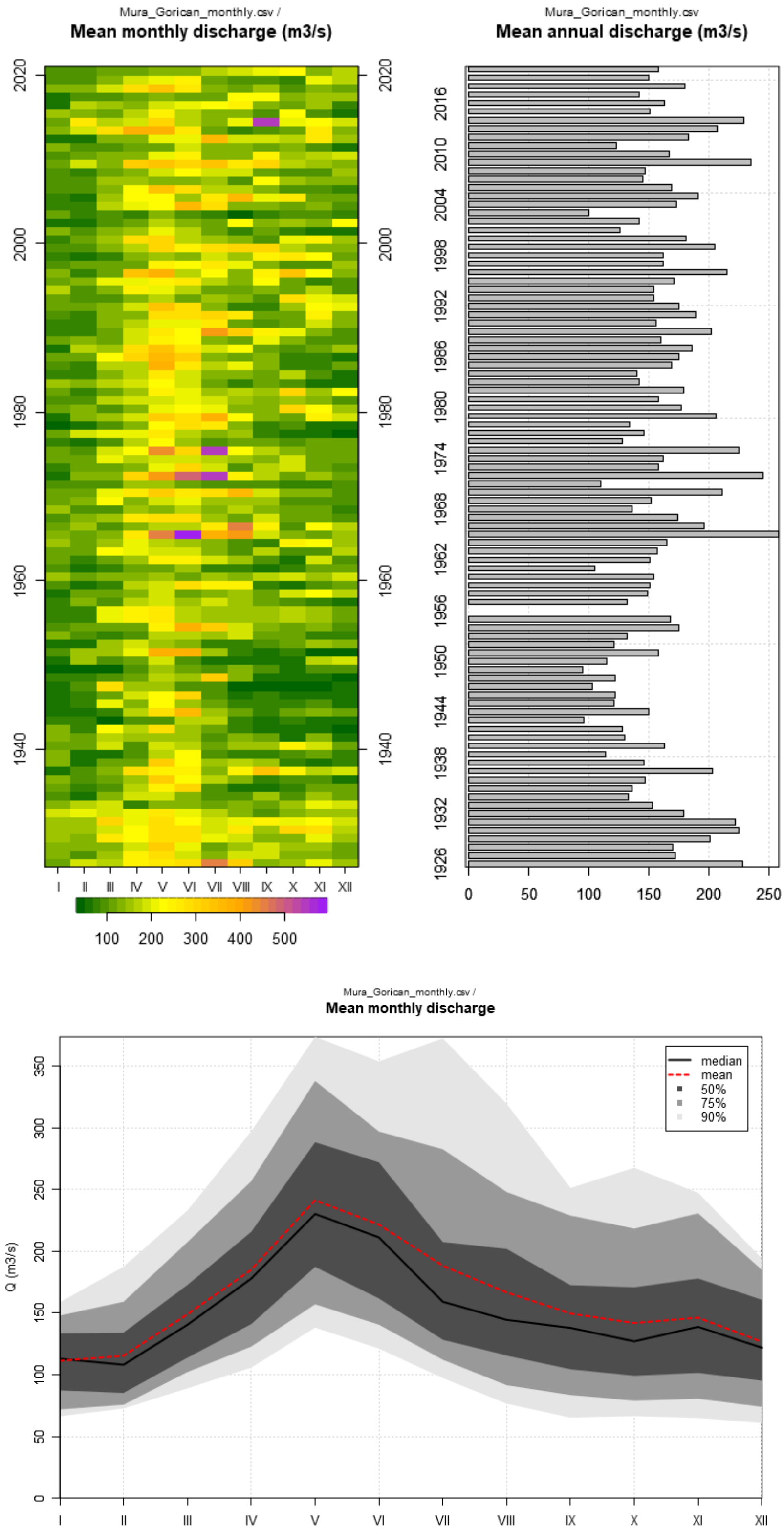


Figure 11. Basic characteristics of the hydrological regime: Mura / Goričan

Upper Drava – Donja Dubrava

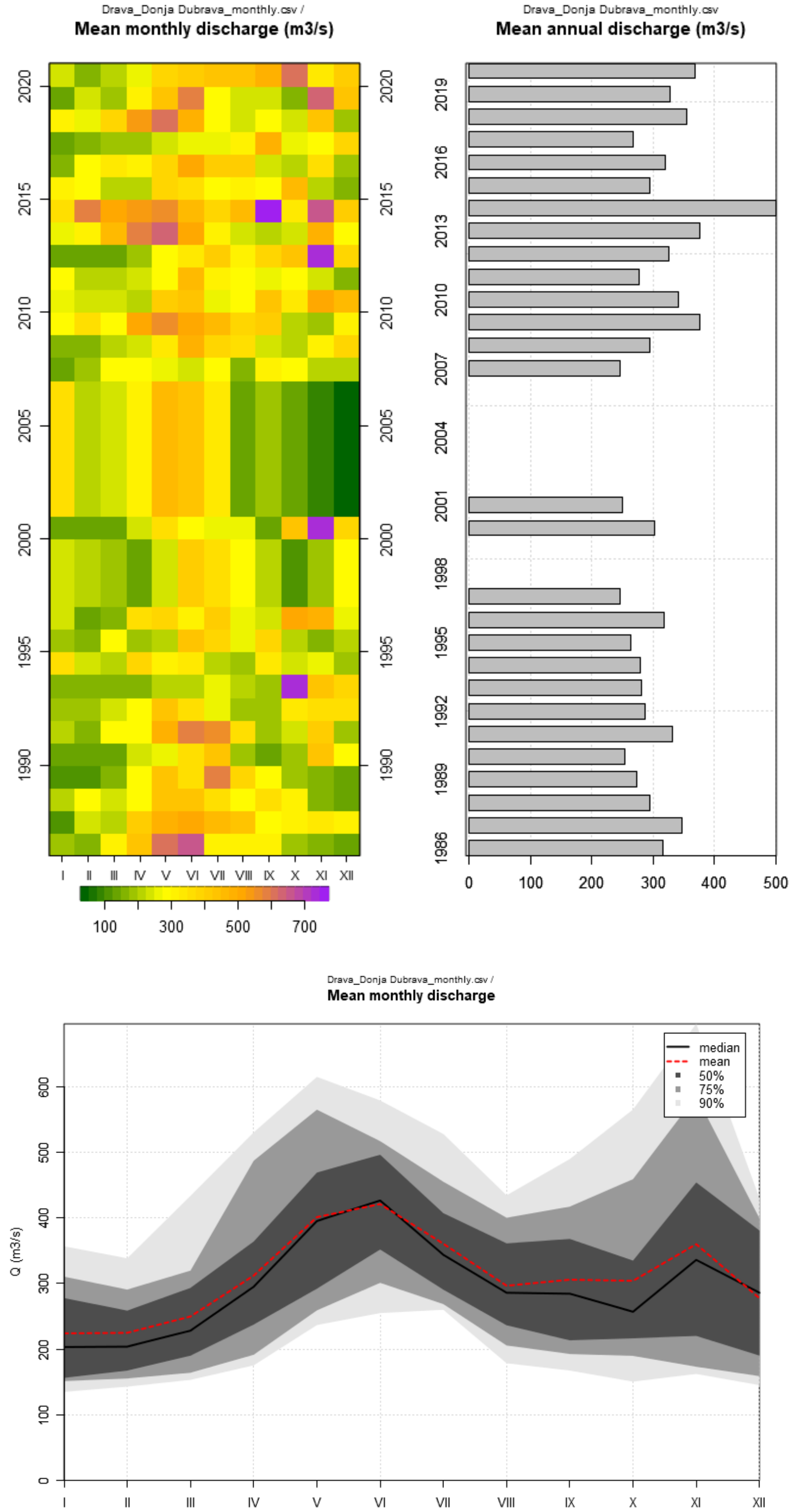


Figure 12. Basic characteristics of the hydrological regime: Drava / Donja Dubrava

Lower Drava - Terezino polje

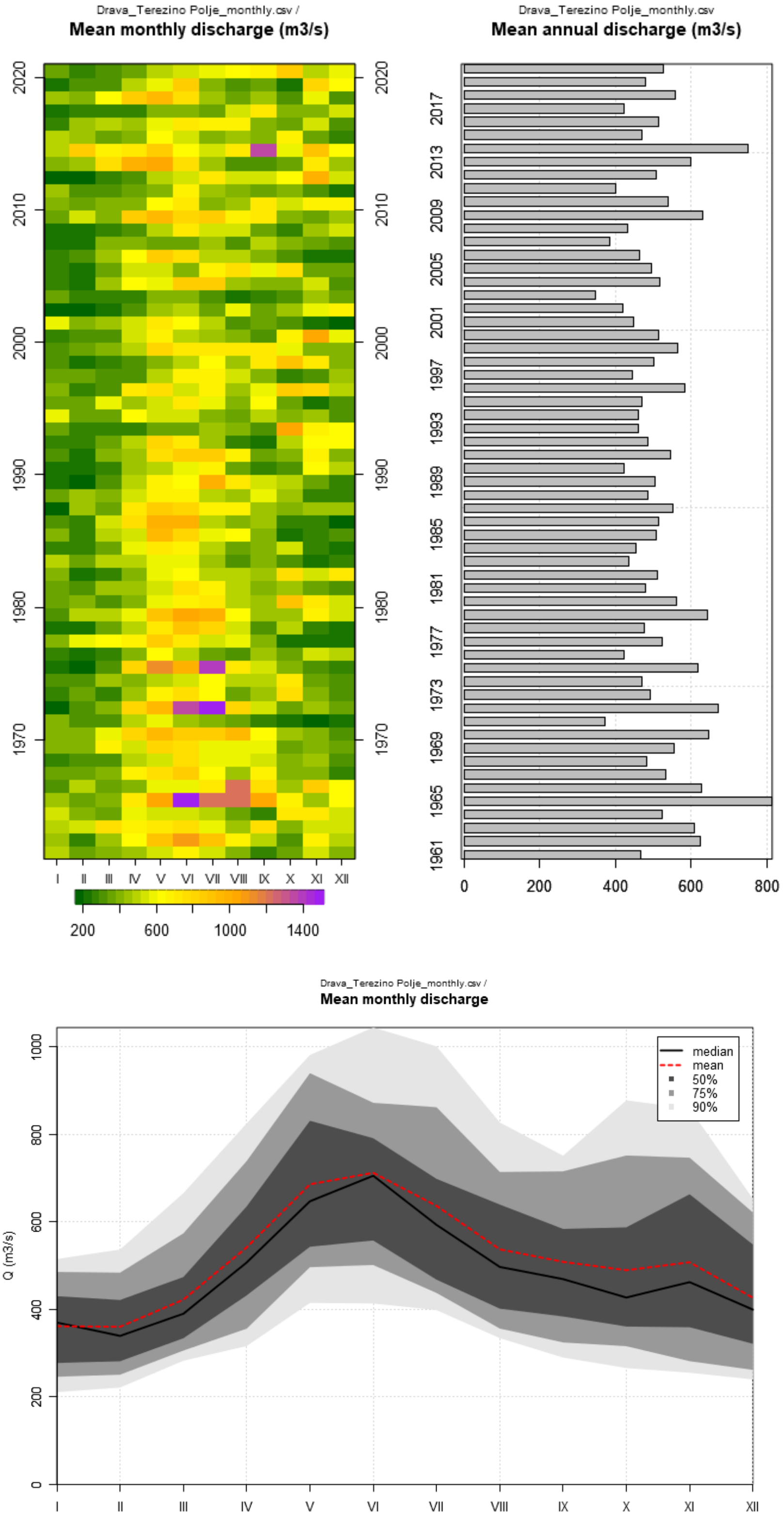


Figure 13. Basic characteristics of the hydrological regime: Drava - Terezino polje

Danube - Bezdan

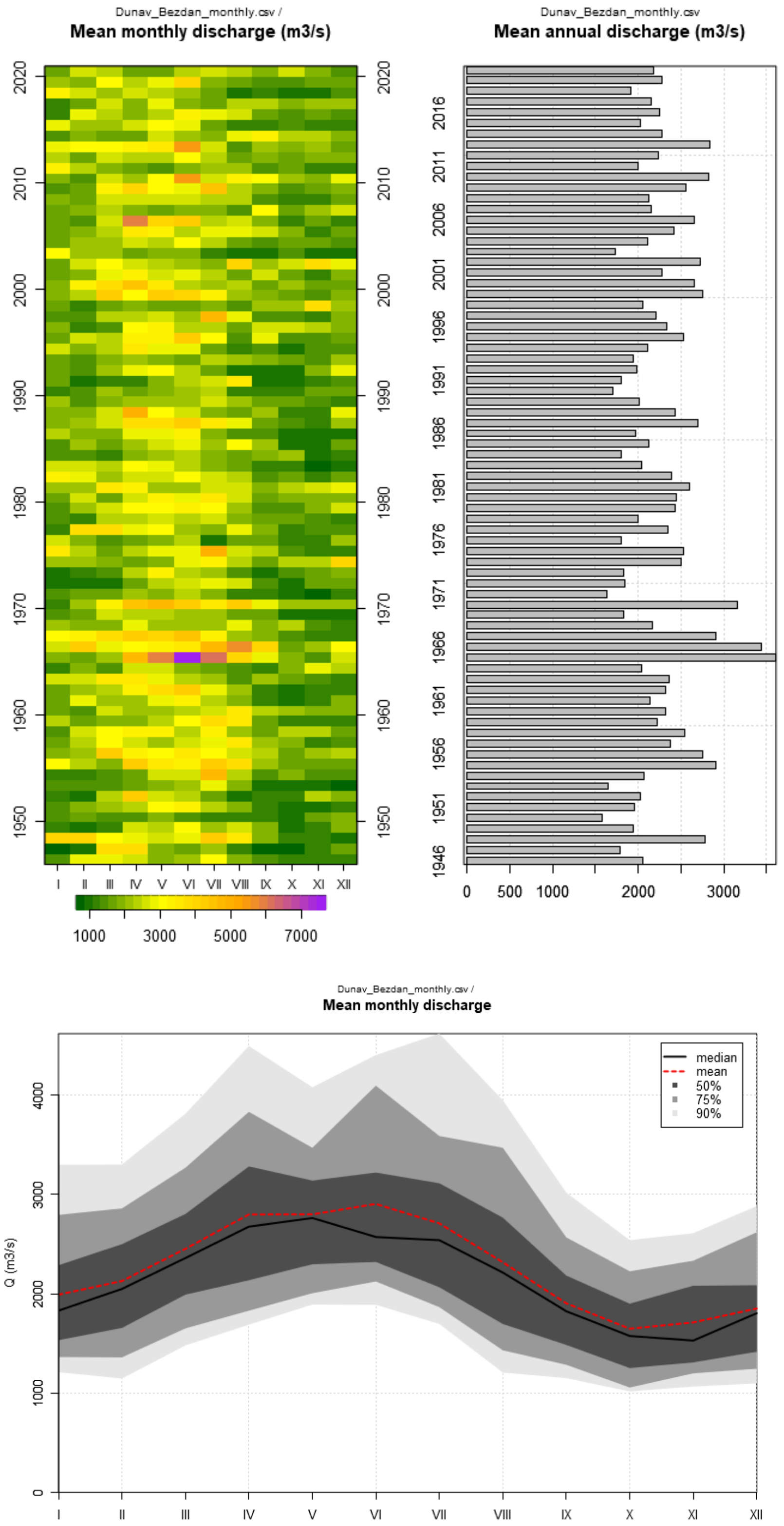


Figure 14. Basic characteristics of the hydrological regime: Danube - Bezdan

Model calibration results

The hydrologic model was calibrated using available daily discharge series from all gauging stations with sufficient length of time series, mainly on the Drava and Mura rivers but on some major tributaries as well.

Nash Sutcliffe Efficiency values of around 0.5 indicate a satisfactory fit of simulated results compared to observed values.

Table 5. Calibration results for stations within the extent of TBR-MDD

River	Station	NSE
Isel	Bruehl	0.703
Mura	Mureck	0.500
Mura	Bruck A. D. Mur	0.512
Mur	Gestüthof	0.467
Mur	Zeltweg	0.588
Isel	Lienz	0.670
Drau	Sachsenburg Süd	0.674
Gail	Federaun	0.486
Drau	Drauhofen	0.550
Drava	Belisce	0.457
Drava	Botovo	0.461
Drava	Donja Dubrava	0.447
Drava	Donji Miholjac	0.504
Drava	Novo Virje	0.500
Drava	Terezino Polje	0.530
Mura	Gorican	0.516
Mura	Mursko Sredisce	0.521
Drava	HE Dravograd	0.466
Mura	Gornja Radgona 1	0.475

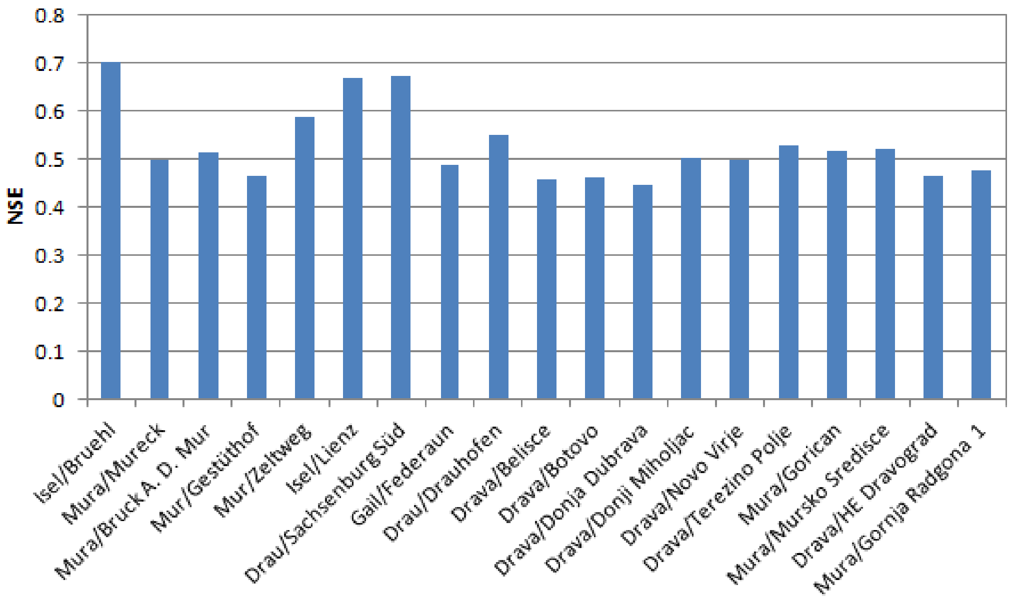


Figure 15. Nash Sutcliffe efficiency (NSE) coefficient for daily flows in the calibration period

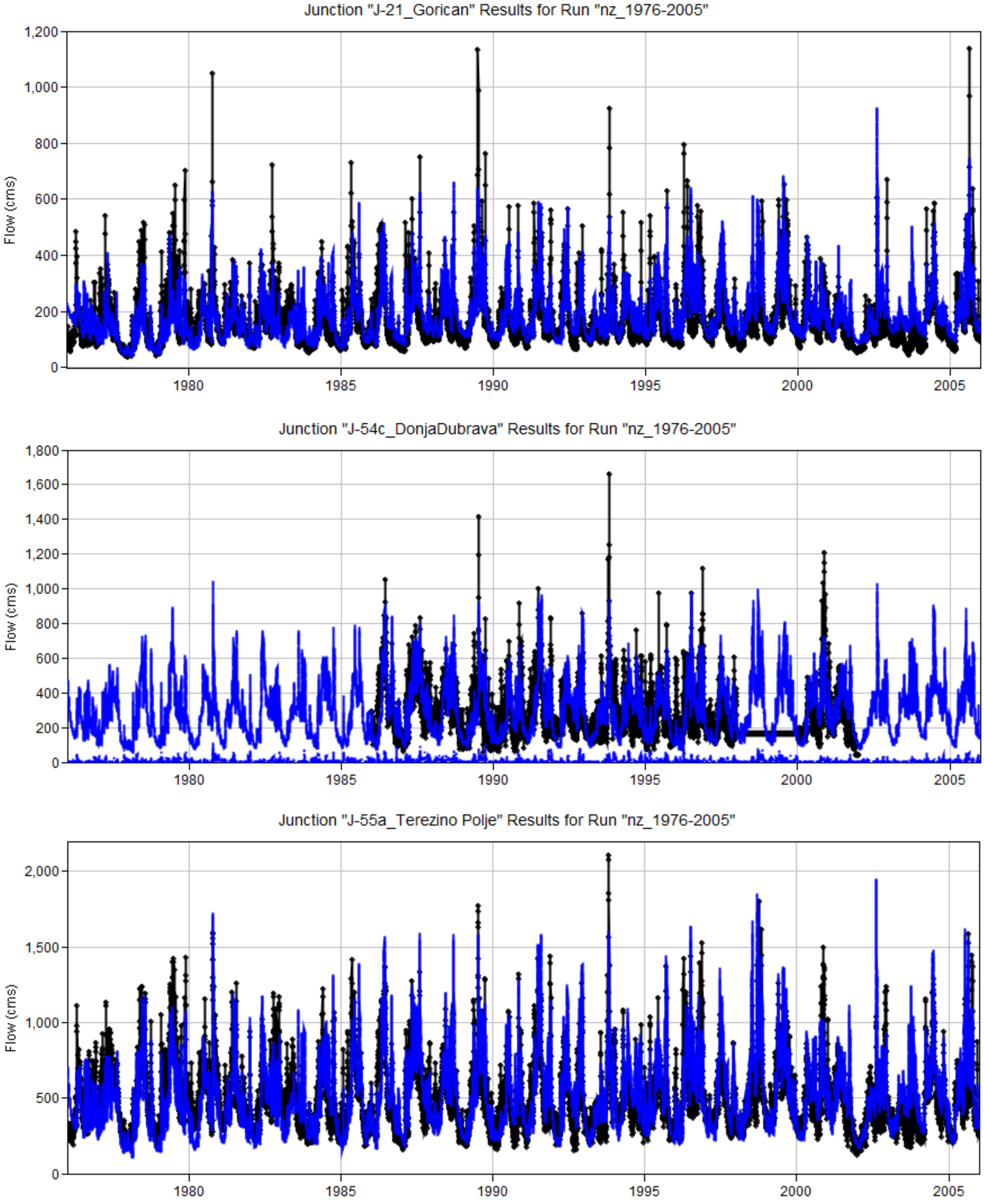


Figure 16. Examples of modelled (blue) and observed (black) time series, for the time period 1976-2005, for stations Mura/Goričan (top), Drava/Donja Dubrava (middle) and Drava/Terezino polje (lower)

• Hydrological projections – Drava and Mura

Projected changes in runoff

Changes in patterns of seasonal runoff, calculated in terms of average daily discharge by month, are illustrated in Figures 17-19 for the characteristic stations: Mura at Goričan, Drava at Donja Dubrava and Drava at Terezino polje. The projections in general indicate an increase in runoff in winter months (Dec to Feb), and a decrease in summer (May to Sep), with much less change expected in spring and autumn months (Mar-Apr and Oct).

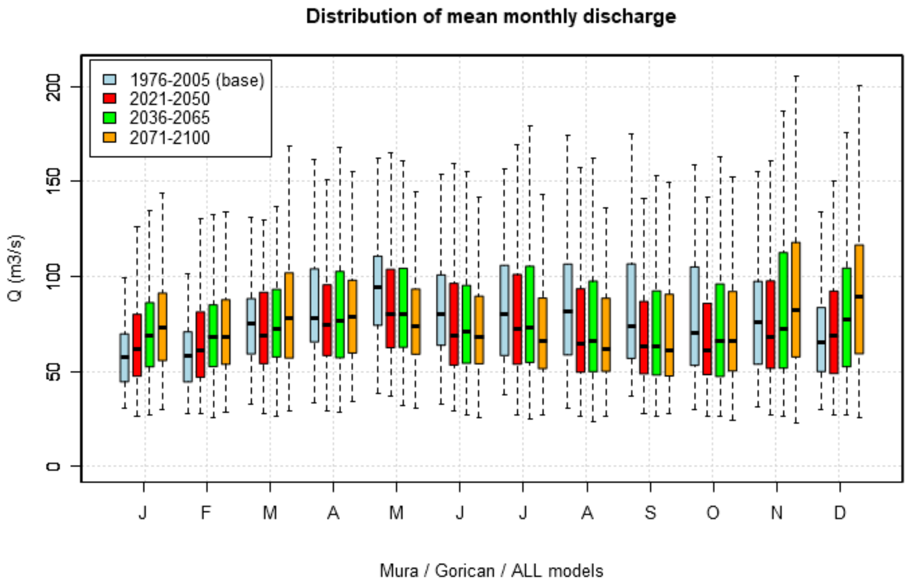


Figure 17. Distribution of mean monthly discharge for all model combinations at Mura/Goričan

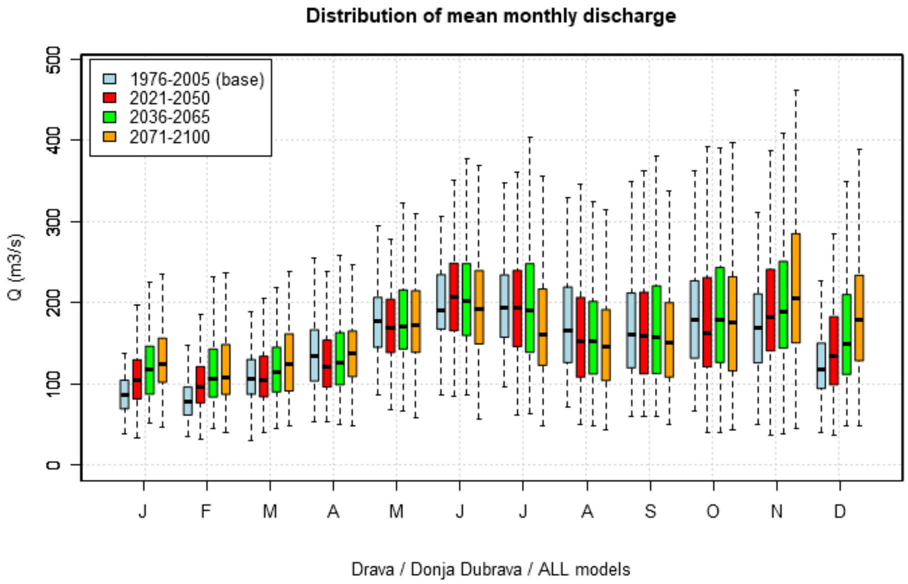


Figure 18. Distribution of mean monthly discharge for all model combinations at Drava/Donja Dubrava

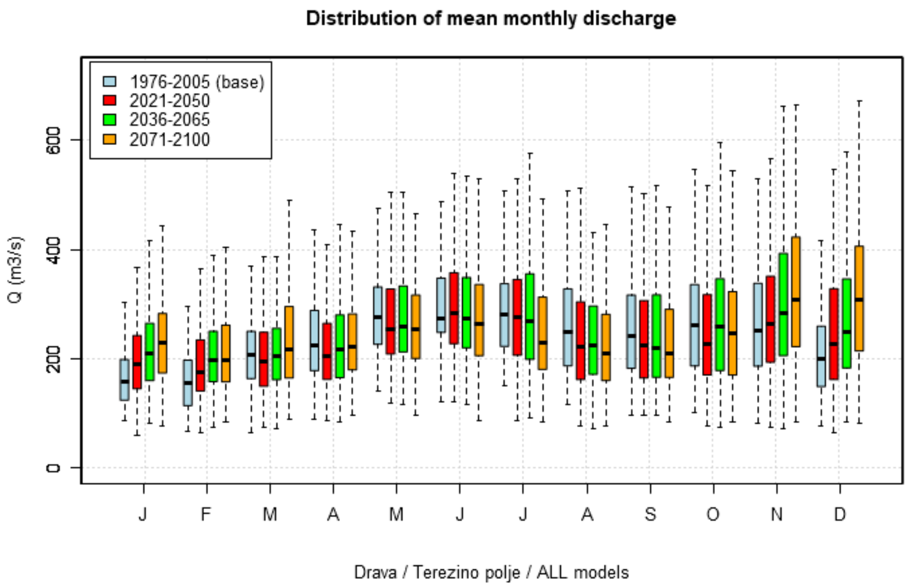


Figure 19. Distribution of mean monthly discharge for all model combinations at Drava/Terezino polje

Projected changes in flood flows

The annual maximum flow series were calculated for each of the three characteristic locations for the four time periods: 1976-2005 (base period), 2021-2050, 2036-2065, and 2071-2100, for each of the eight climate projections (model no.3 was omitted from this analysis), and their distribution is illustrated in Figures 20-22. The annual flood series is used for the estimation of floods of given return periods. The series for all three locations show a significant spread of results, with only the Upper Drava (as indicated at Donja Dubrava) showing a clear trend in the possible increase of mean annual floods. However, all models show an evident expected increase in mean annual floods by the end of the 21st century.

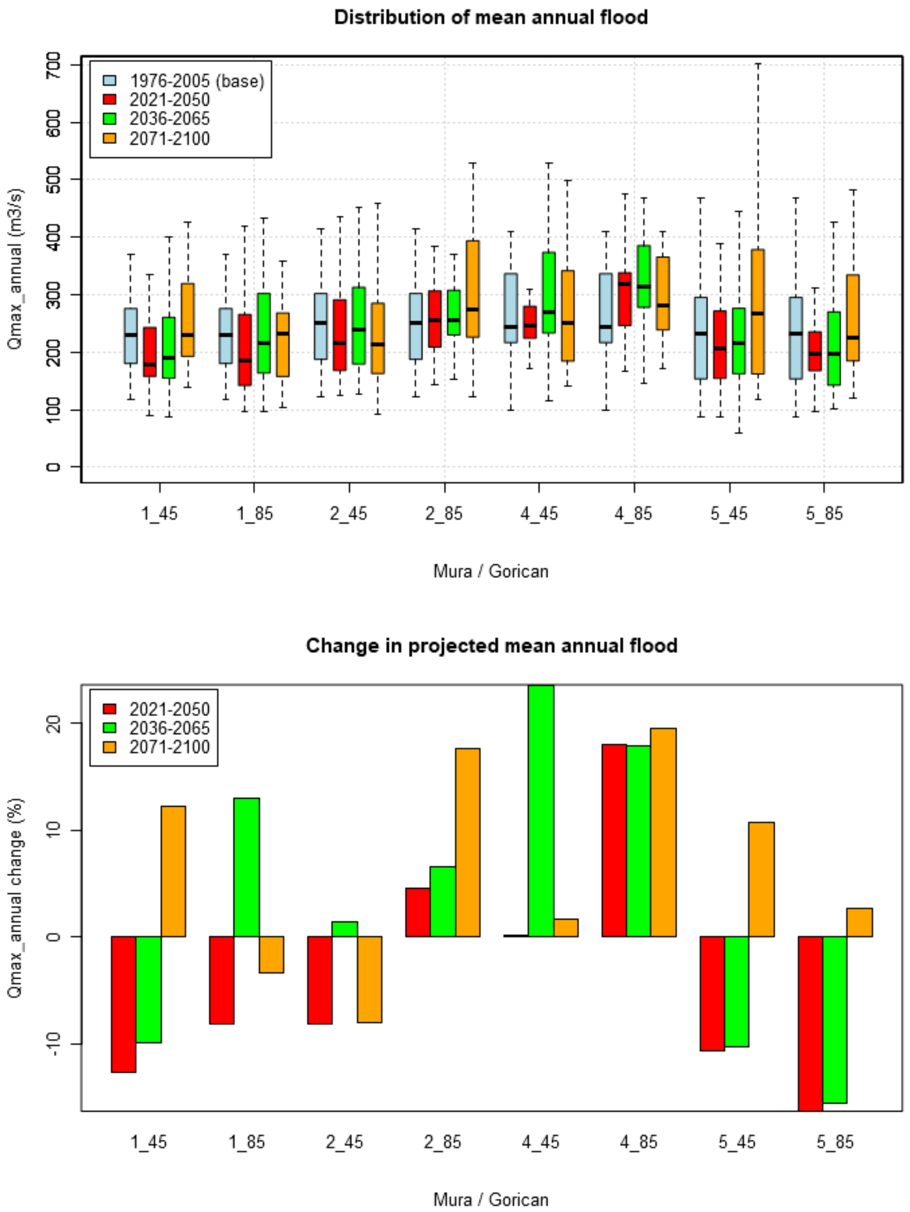
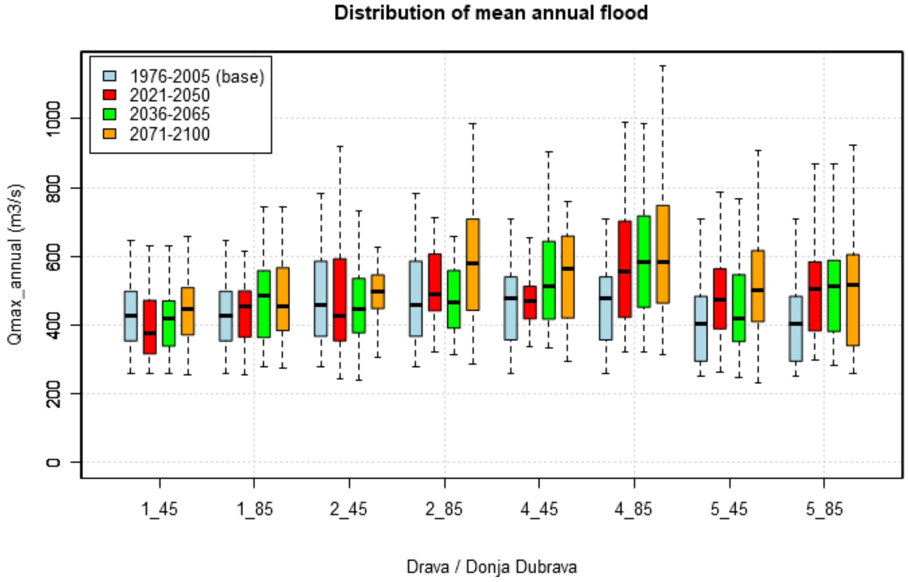


Figure 20. Distribution of projected mean annual flood for all model combinations at Mura/Goričan, in absolute values (above) and relative to the base period (below)



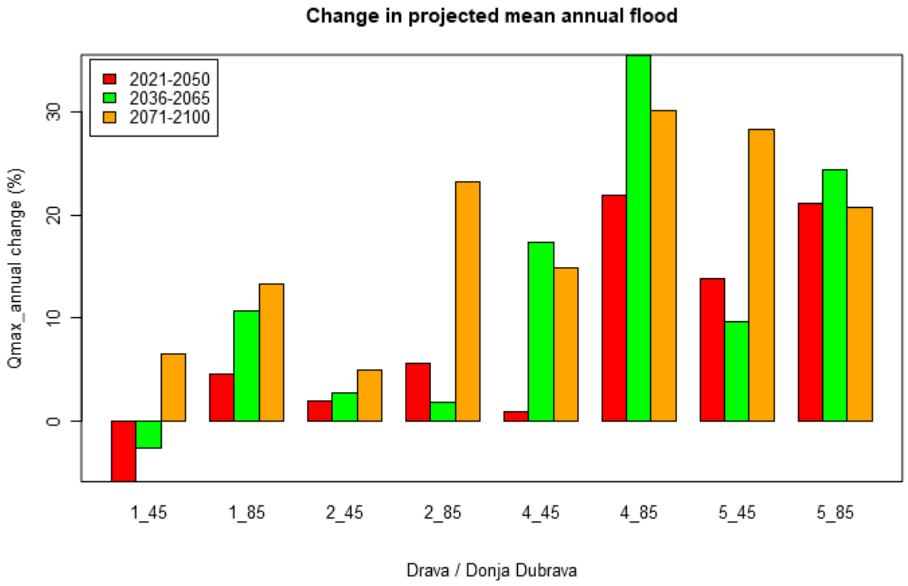
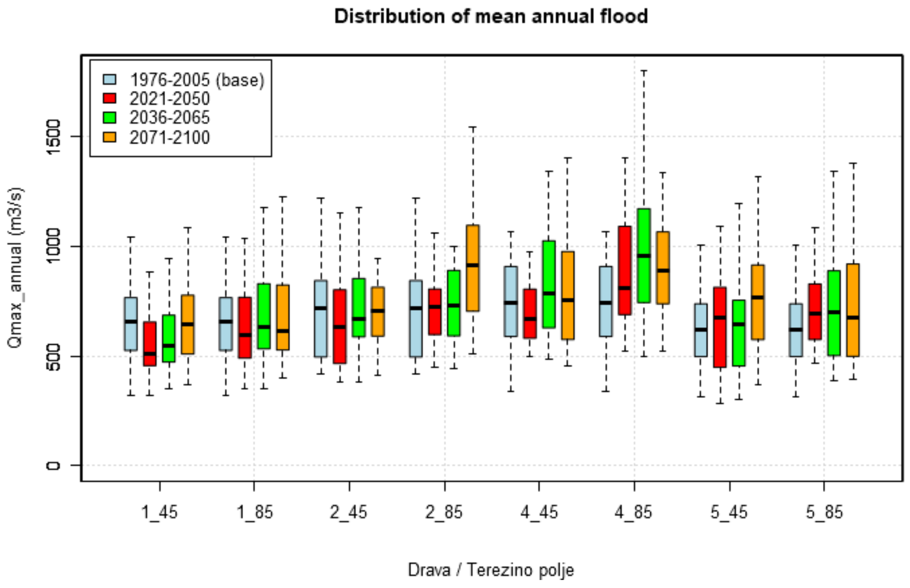


Figure 21. Distribution of projected mean annual flood for all model combinations at Drava/Donja Dubrava, in absolute values (above) and relative to the base period (below)



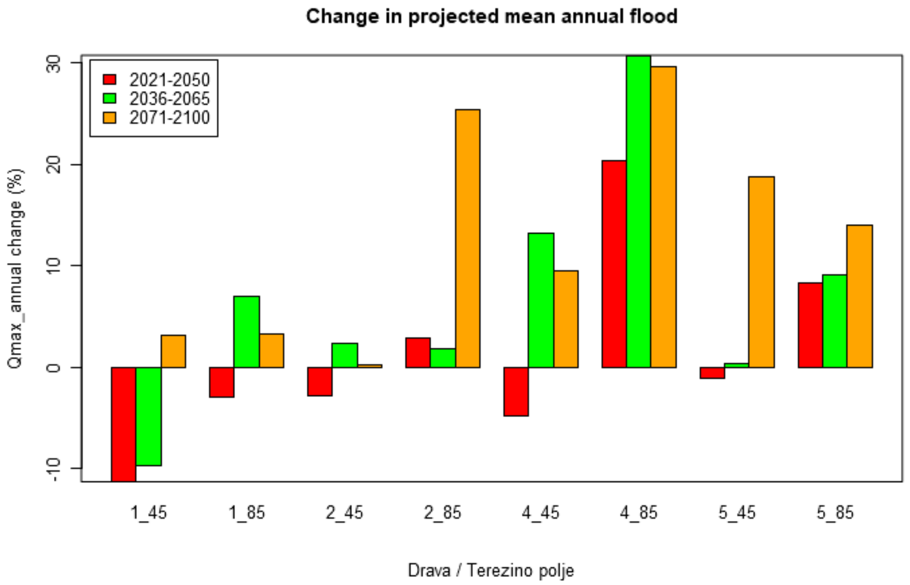


Figure 22. Distribution of projected mean annual flood for all model combinations at Drava/Terezino polje, in absolute values (above) and relative to the base period (below)

Projected changes in low flows

The discharge values of 95% probability of exceedance (Q95) were calculated for each of the three characteristic locations for the four time periods: 1976-2005 (base period), 2021-2050, 2036-2065, and 2071-2100, for each of the eight climate projections (model no.3 was omitted from this analysis), and the relative changes of the three future periods compared to the base period are illustrated in Figures 23-25. Results show significant scatter for the Mura basin (at Goričan), unable to distinguish a clear trend. The Drava, however, while also showing significant scatter, has most climate projections yield an increase in low flows.

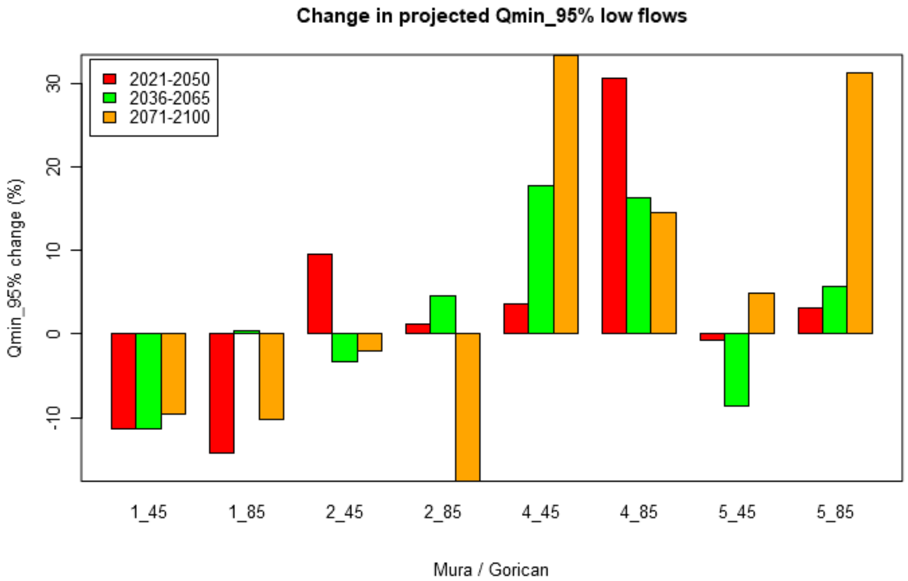


Figure 23. Projected changes in the 95% exceedance probability of low flow (Q95%), relative to the base period, at Mura/Goričan

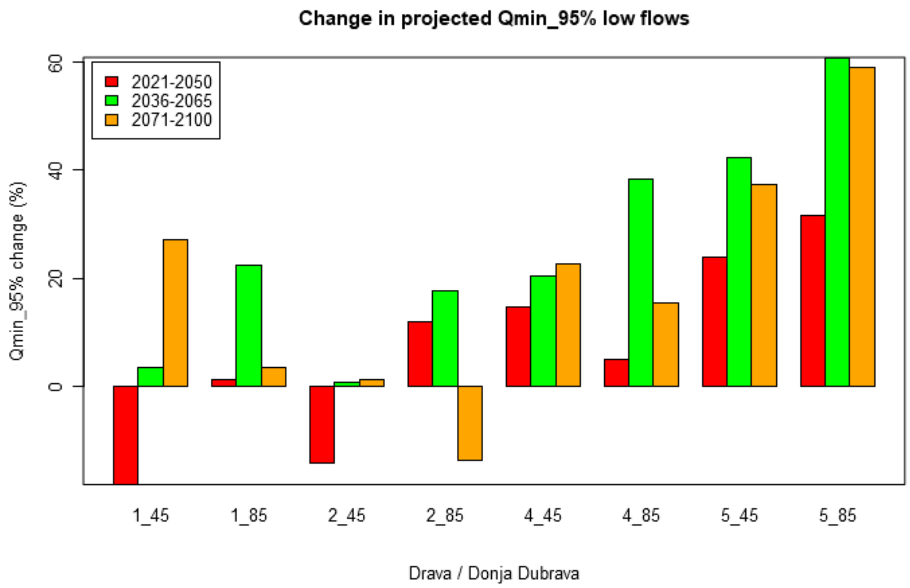


Figure 24. Projected changes in the 95% exceedance probability of low flow (Q95%), relative to the base period, at Drava/Donja Dubrava

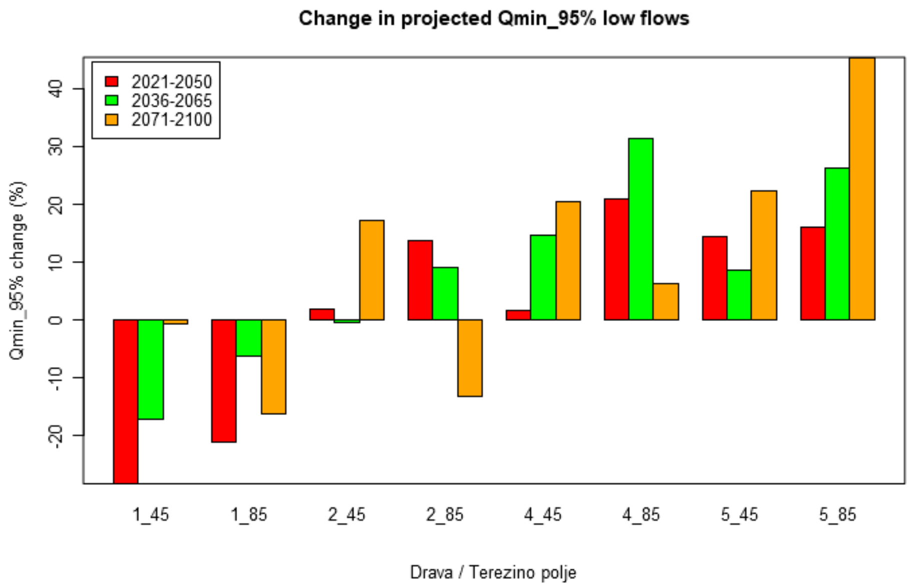


Figure 25. Projected changes in the 95% exceedance probability of low flow (Q95%), relative to the base period, at Drava/Terezino polje

• Hydrological projections – Danube

Modelling the Danube River basin in its entirety was out of the scope of this hydrologic study, therefore hydrological projections for the reach of the Danube river covered by the TBR-MDD are provided through literature review. The results of two relevant publications are shortly reviewed.

The first technical report, published by the Joint Research Centre (JRC) – the European Commission's science and knowledge service, describes an assessment of the projected future impacts of climate change, land use change and changes in water consumption on water resources in the Danube river basin, as obtained using JRC's LISFLOOD water resources model (Bisselink et al, 2018)

The summer months in the 30-year window around the year that global warming reaches 2°C at global scale are projected to be 15% drier than compared to the 1981-2010 baseline climate. Especially the southern Danube river basin area may experience up to 20% drier summers. For the end of the century 2070-2099 RCP8.5 climate the projected precipitation decrease for the southern Danube countries is locally even larger than 30% for the summer months June-July-August.

Projections for the Danube river basin under a 2-degree changed climate indicate in general wetter conditions and higher flooding risks, but drier summer months, especially in the southern regions of the Danube basin. For the main Danube river, increased peak river flows are projected that are 10-20% larger than peak flows under current climate. Combined with the projected urban expansion of some of the countries' capital cities (Vienna, Budapest, Belgrade) which are all situated along the main Danube or its main tributaries (Zagreb), the risk of flood damages is substantially increasing.

Projections for the Danube river basin under a more extreme changed climate (RCP8.5 at 2070-2099, corresponding to around 3.5-4 degree temperature increase) show a more extreme impact on water resources, with especially for the summer months drier conditions in the southern part of the Danube basin. For the upper and middle parts of the main Danube river, increased peak river flows are projected that are 10-30% larger than peak flows under the current climate.

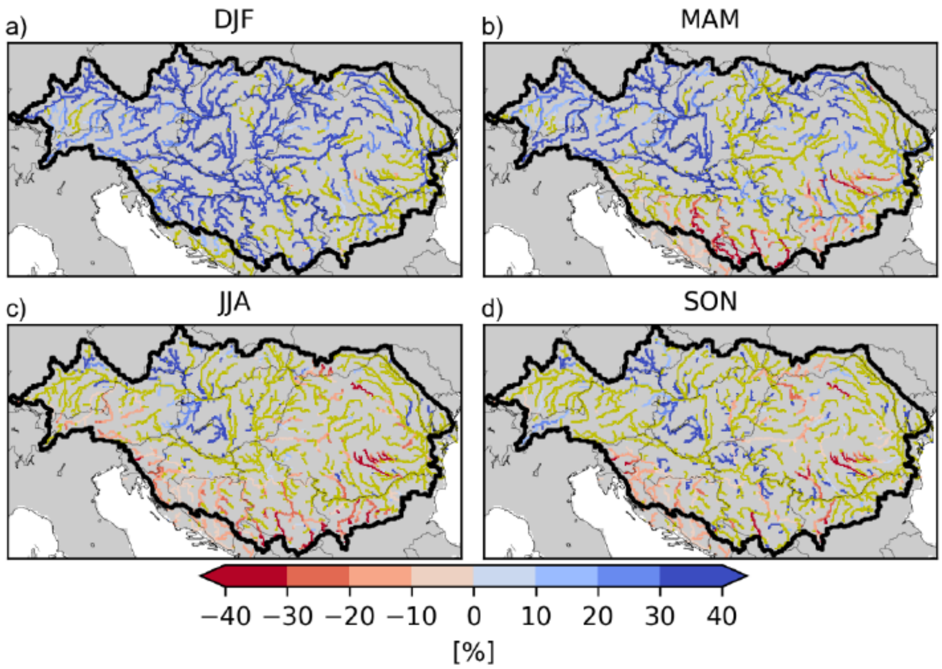


Figure 26. The impact of climate change (CC),land use (LU) change and changes in water demand (WD) for the 2070-2099 RCP8.5 climate on low flows, here indicated with the Q5: the 5 percentile of river discharge, which corresponds to flows reached on average around two weeks of the year. Note: the green colour indicates rivers where the uncertainty in the results is large; with at least 3 out of 11 models indicate opposite results. (source: Bisselink et al, 2018)

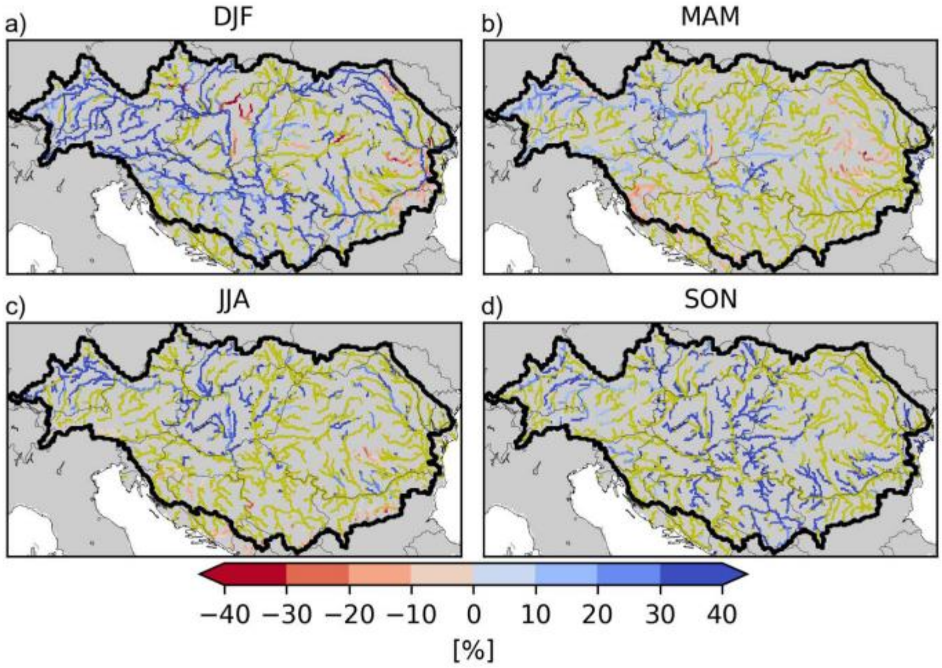


Figure 27. The impact of climate change (CC),land use (LU) change and changes in water demand (WD) in an RCP8.5-2070-2099 climate on floods, here indicated with the Q99.5: the 99.5 percentile of river discharge, which is close to a 1-year return period flow. Note: the green colour indicates rivers where the uncertainty in the results is large; with at least 3 out of 11 models indicate opposite results. (source: Bisselink et al, 2018)

The second study that is reviewed is from the Potsdam Institute for Climate Impact Research in Germany, titled "Impacts of Climate Change on the Hydrological Regime of the Danube River and Its Tributaries Using an Ensemble of Climate Scenarios" and published in Water (Stagl and Hattermann, 2015). The authors applied the eco-hydrological watershed model Soil and Water Integrated Model (SWIM) for the entire Danube River catchment, considering 1224 sub-basins, to create scenario projections for the future hydrological runoff regime in the Danube River Basin. After calibration and validation of the model, a set of high-resolution climate projections (bias-corrected and non-bias-corrected) served as meteorological drivers with which future daily river discharge under different climate warming scenario conditions was simulated.

Despite existing uncertainties, robust trends were identified. In the next 30 years, the seasonal stream-flow regime of the Danube and its tributaries is projected to change considerably. The results of this study show a general trend towards a decrease in summer runoff for the whole Danube basin and, additionally, in autumn runoff for the Middle and Lower Danube basin, aggravating the existing low flow periods. For the winter and early spring seasons, mainly January–March, an increase in river runoff is projected. Greater uncertainties show up in particular for winter runoff in the Dinaric Alps and the Lower Danube basin. The existing trends become very distinct until the end of the 21st century, especially for snow-influenced river regimes.

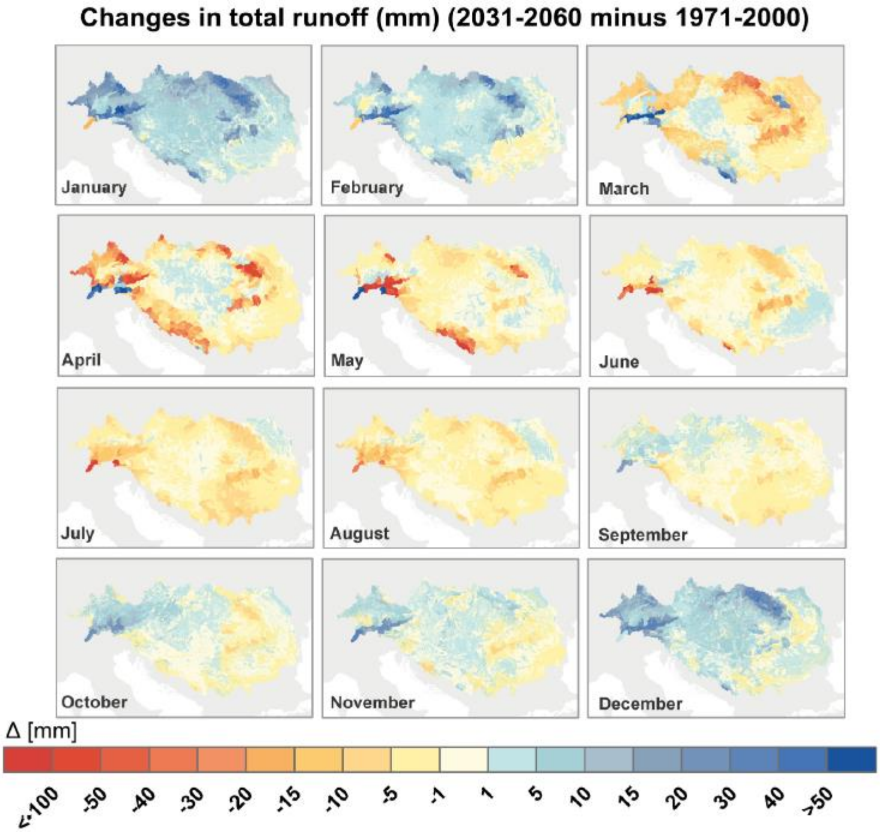


Figure 28. Changes in total runoff (mm/month) as the multi-model mean with ENSEMBLES climate data as the input; compared are the periods 1971–2000 and 2031–2060 (source: Stagl and Hattermann, 2015)

IV. Conclusions & actions recommendations

• Conclusions

The hydrologic projections for both Mura and Drava basins in general indicate decreases in snow storage and substantial decreases in runoff during the summer months, and increases in winter months. The decreases in summer runoff are particularly noticeable by the end of the century and reflect expected increases in evapotranspiration and decreases in precipitation, while increased winter runoff is linked with rising temperatures and increased snowmelt.

The flood series, based on daily time steps, show much scatter but clearly indicate a potential rise in the mean annual flood especially in the Upper Drava. All models show an evident expected increase in mean annual floods by the end of the 21st century.

Projections of the change of low flows, characterised by the discharge values of 95% probability of exceedance (Q95), also show much scatter, while most climate projections used show an increase in the second half of the 21st century. The scatter in projected changes in drought characteristics are most likely a result of increased temperature and reduction of summer precipitation in the future climate on one side (increasing drought) and increased snowmelt on the other (decreasing drought). It should be noted the hydrologic model did not take into account the total amount of snow in the basin, and more specifically glaciers in the Upper Drava, thus results of increased low flows should be taken with caution, as it clearly indicates a decrease in total snow storage and glacier volume and implying unsustainability.

The results of reviewed hydrologic climate change studies for the Danube are unanimous in identifying the general trend of considerable decrease of summer and autumn runoff, aggravating the existing low flow periods. For the winter and early spring seasons, mainly January–March, an increase in river runoff is projected.

• Recommendations

While the hydrological model that was developed in this study for the Drava river basin was successfully calibrated and deemed sufficient for simulating the most dominant hydrologic processes, there are still sources of uncertainty. One significant source of uncertainty, as already noted, is the reduction of the total snow and glacier storage in the basin which implies the unsustainability of projected increases in low flows. To include this in the hydrological model is a significant effort, due to the research and data required to estimate the total snow and glacier storage in the basin.

Further improvements to the assessment of the hydrological projections would need to include impacts of pressures other than climate change, such as land use changes, changes in water consumption, population increase/decrease, existing and planned river control structures, etc.

To successfully recommend climate change adaptation and restoration measures would require significant interdisciplinary approaches (including conservation and restoration practitioners and researchers, policy and decision makers, NGOs, other stakeholders, etc.) to address all of the impacts (Pletterbauer et al, 2018). Broad suggestions for adapting rivers to climate change impacts are similar to those for other ecosystems, including the enhancement of resilience, connectivity, and legal protection while reducing stressors, such as habitat degradation or fragmentation (Palmer et al. 2008).

Some examples would include a closer examination of the following aspects:

- impact of riparian vegetation on various important functions in relation to aquatic habitats, including moderation of water and ambient air temperature via evapotranspiration and reduction of solar energy input by shading, i.e. using riparian vegetation to buffer warming effects of climate change (Bond et al., 2015);
- maintaining habitat heterogeneity and morphological integrity through habitat connectivity, as species tend to follow their preferred thermal niche in the river network, thus the spatial connection between different river reaches, as well as surrounding habitats like deep pools with high groundwater exchange, is highly important, especially for cold-water taxa (Palmer et al. 2008);
- utilizing the existing infrastructure of flow control structures (dams, weirs, sluice gates, embankments, etc.), which have the potential to at least partially mitigate the possible negative hydrological effects of climate change through thoughtful operation. A total of 22 hydropower plants in the Drava basin are operated by different countries (Austria, Slovenia and Croatia), and the issues are not only technical in nature but also economic, social and political, and would require the understanding and willingness of operators to come to an agreement on operation and cooperation for mutual benefits.

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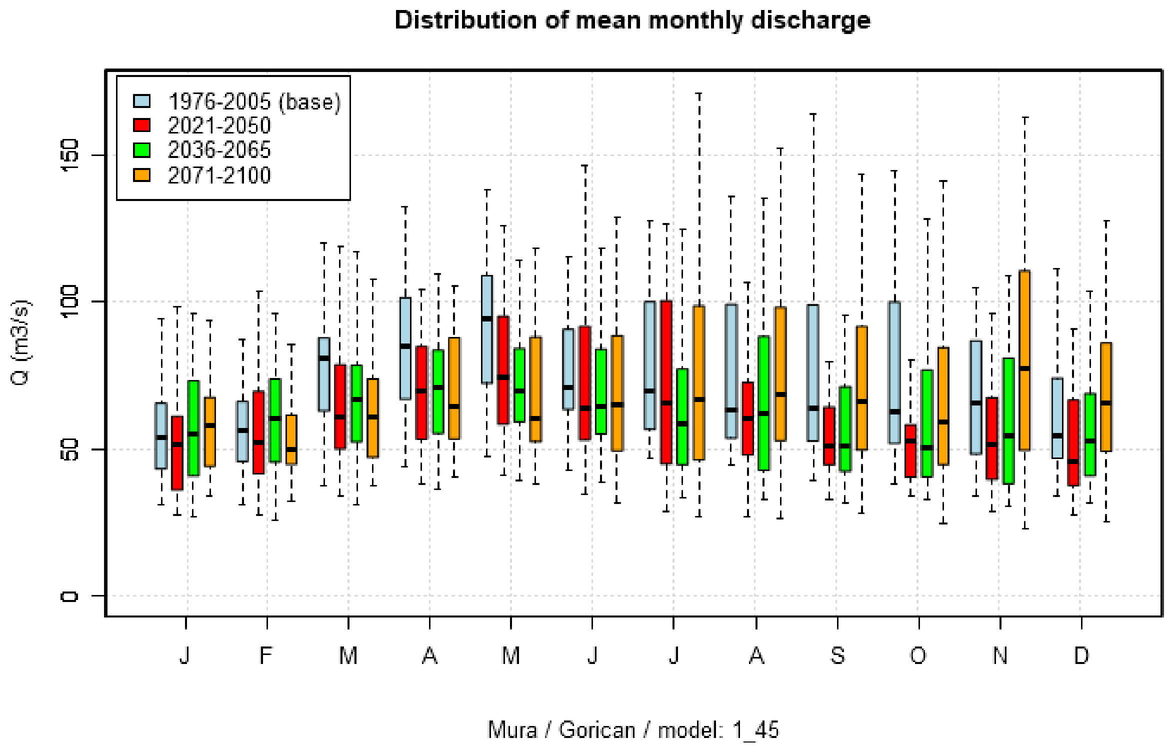
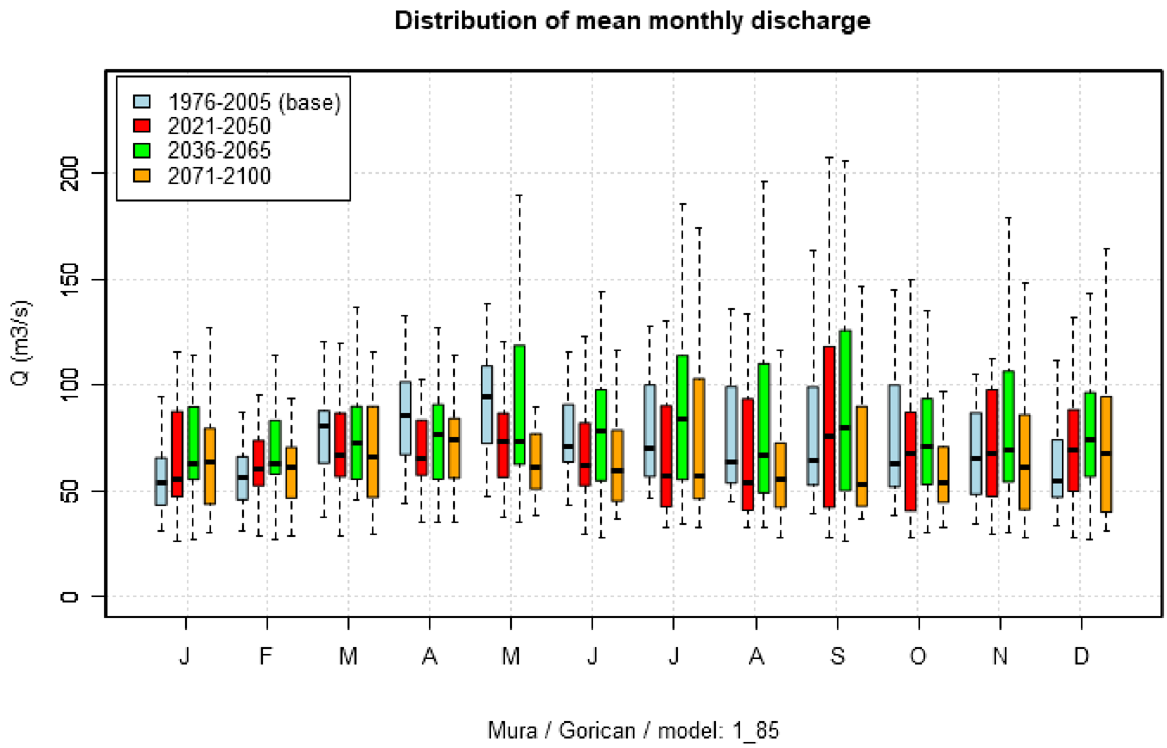
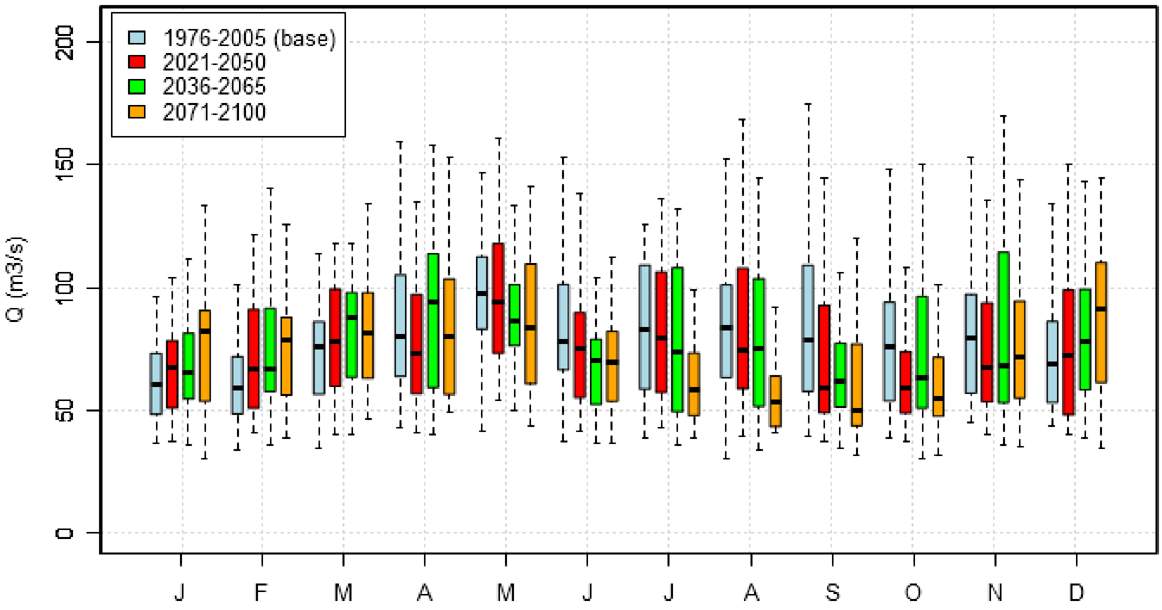
VI. APPENDIX A

- **Distribution of mean monthly discharge for all models and scenarios**



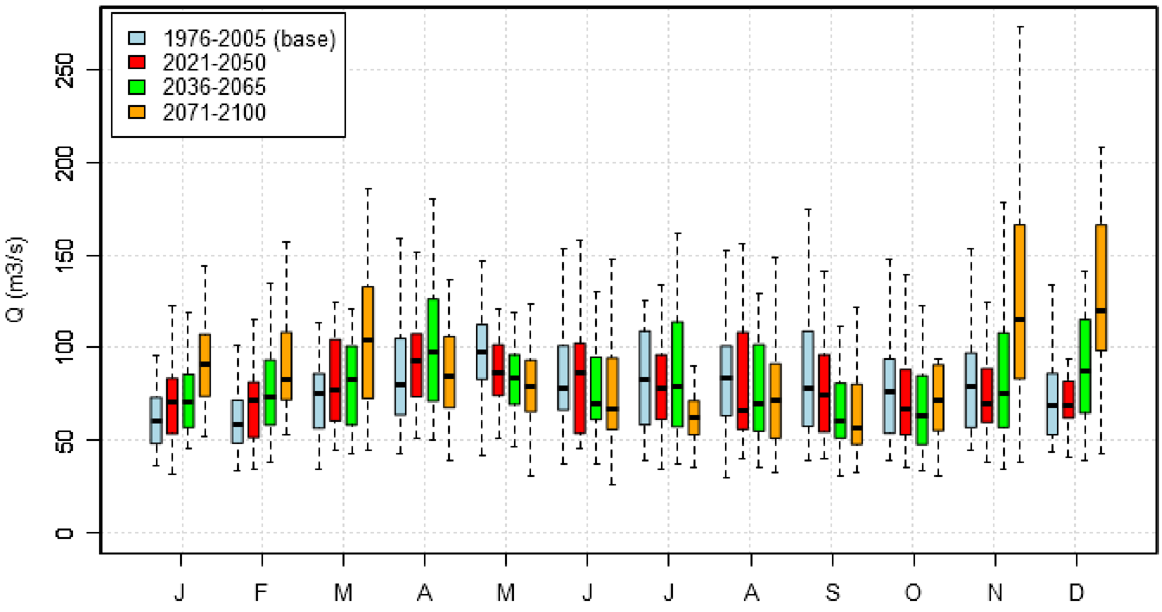


Distribution of mean monthly discharge

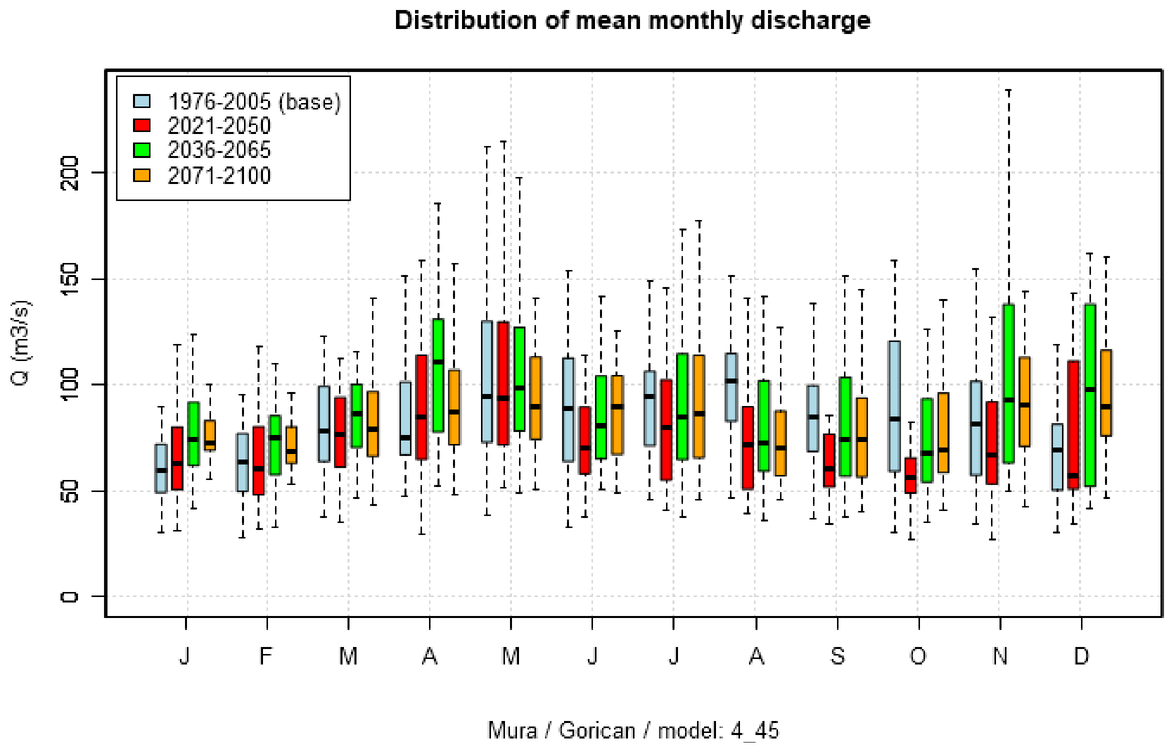


Mura / Gorican / model: 2_45

Distribution of mean monthly discharge



Mura / Gorican / model: 2_85


Distribution of mean monthly discharge
1976-2005 (base)
2021-2050
2036-2065
2071-2100
Q (m3/s)
0
50
100
150
200
J
F
M
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M
J
J
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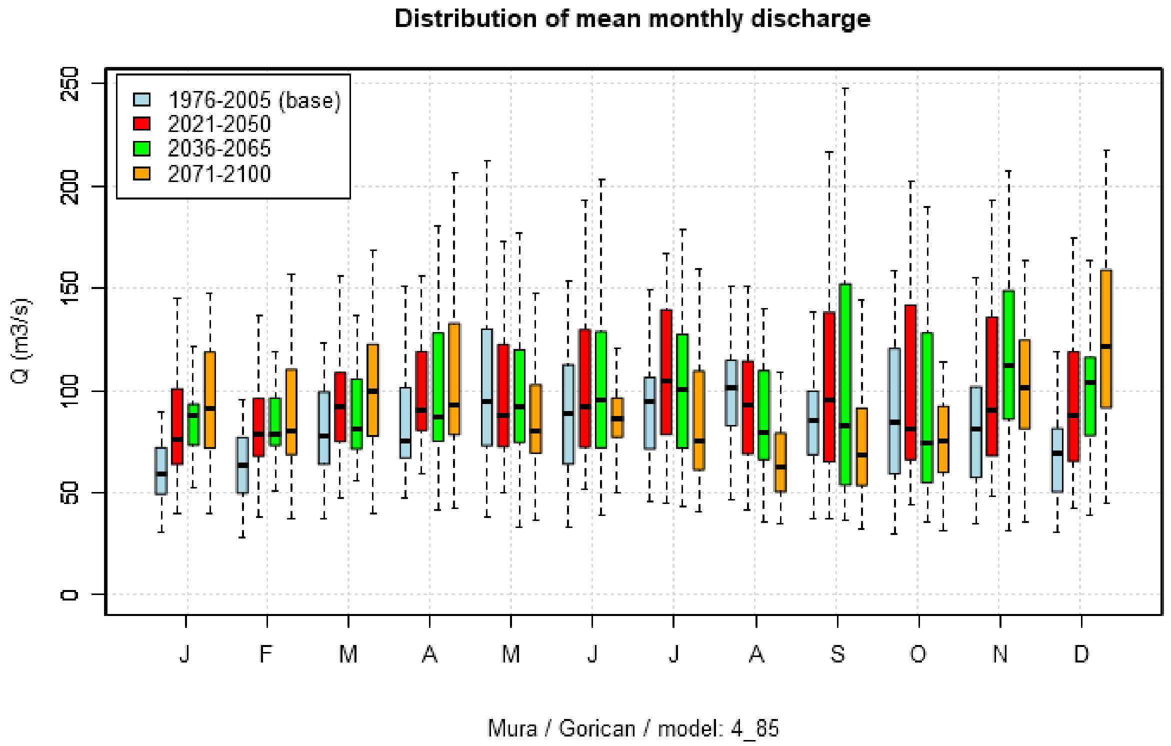
N
D
Mura / Gorican / model: 4_45


Distribution of mean monthly discharge
1976-2005 (base)
2021-2050
2036-2065
2071-2100
Q (m3/s)
0
50
100
150
200
250
J
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M
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J
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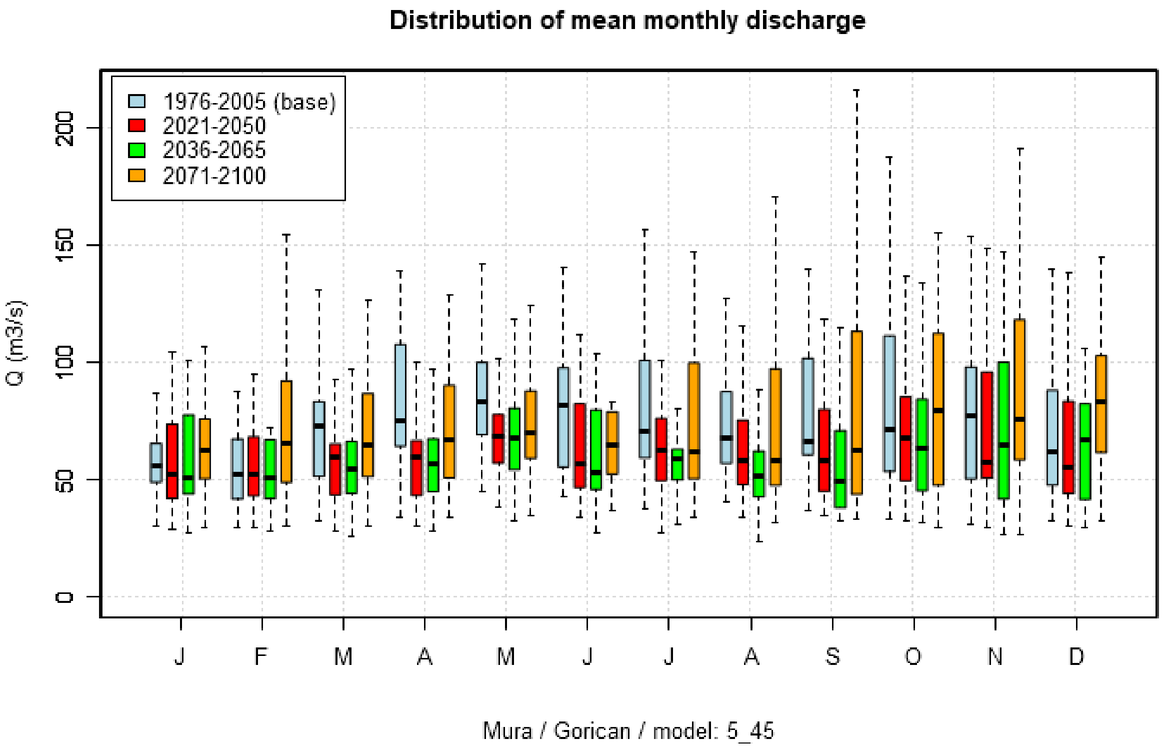
Mura / Gorican / model: 4_85


Distribution of mean monthly discharge
1976-2005 (base)
2021-2050
2036-2065
2071-2100
Q (m3/s)
0
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150
200
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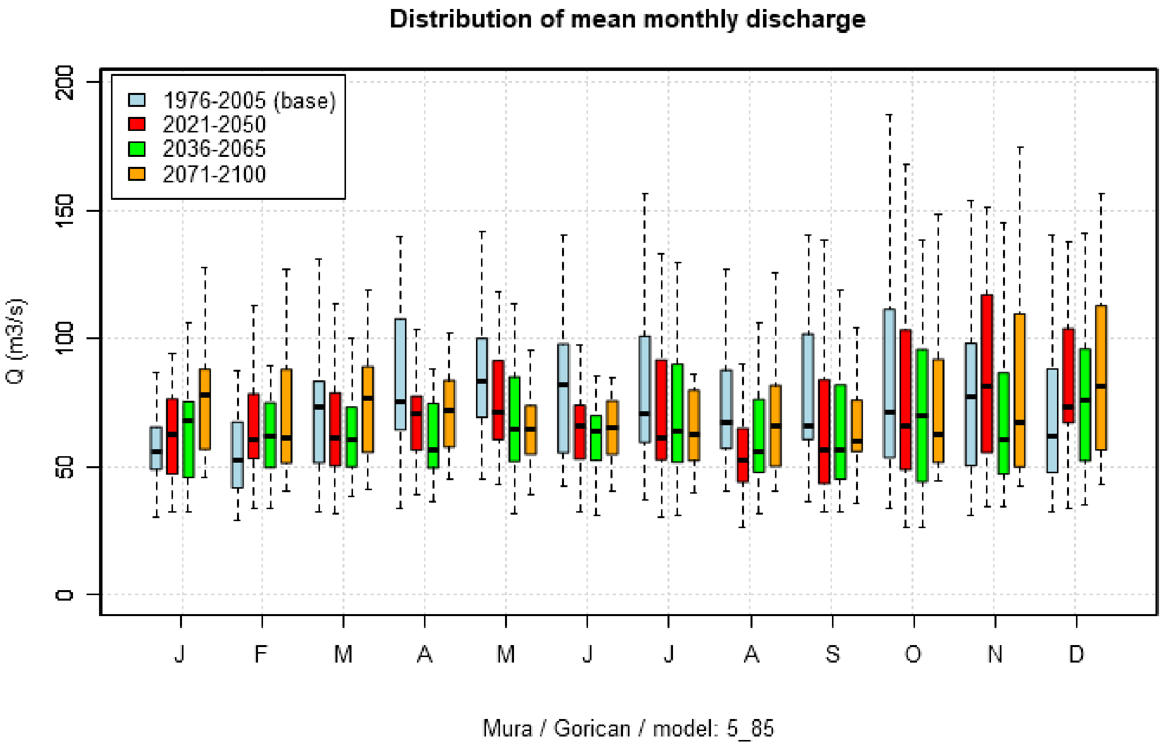
Mura / Gorican / model: 5_45


Distribution of mean monthly discharge
1976-2005 (base)
2021-2050
2036-2065
2071-2100
Q (m3/s)
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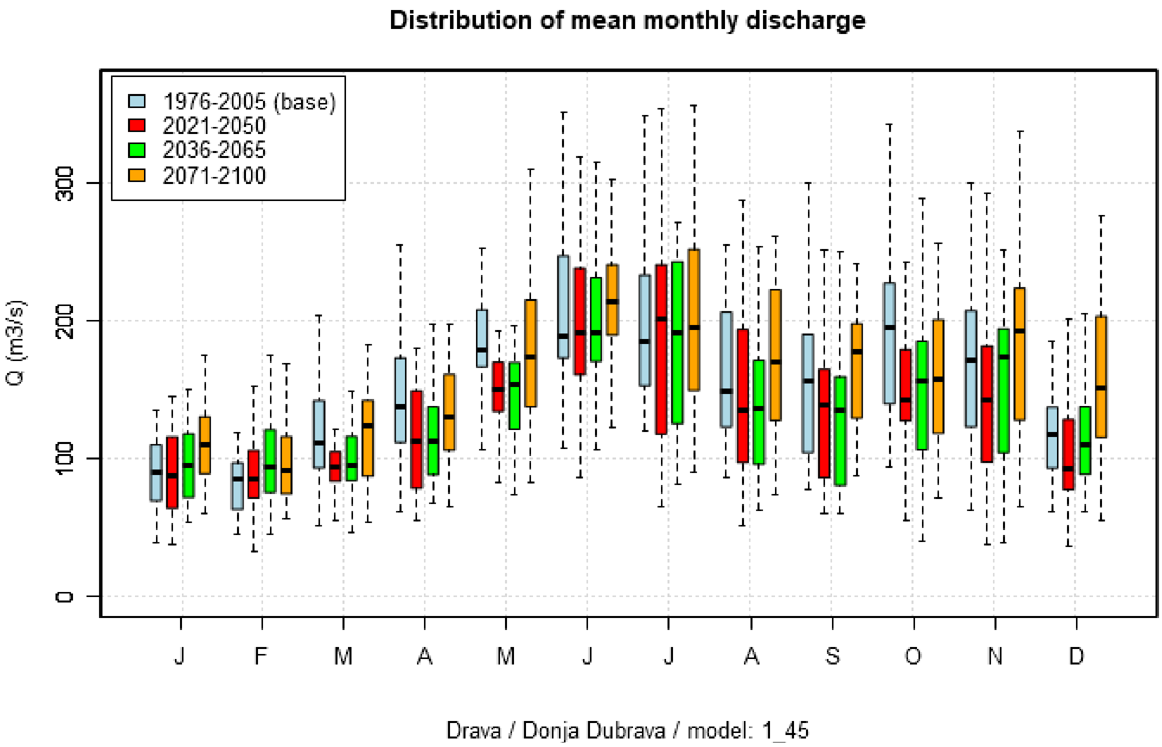
Mura / Gorican / model: 5_85


Distribution of mean monthly discharge
1976-2005 (base)
2021-2050
2036-2065
2071-2100
Q (m3/s)
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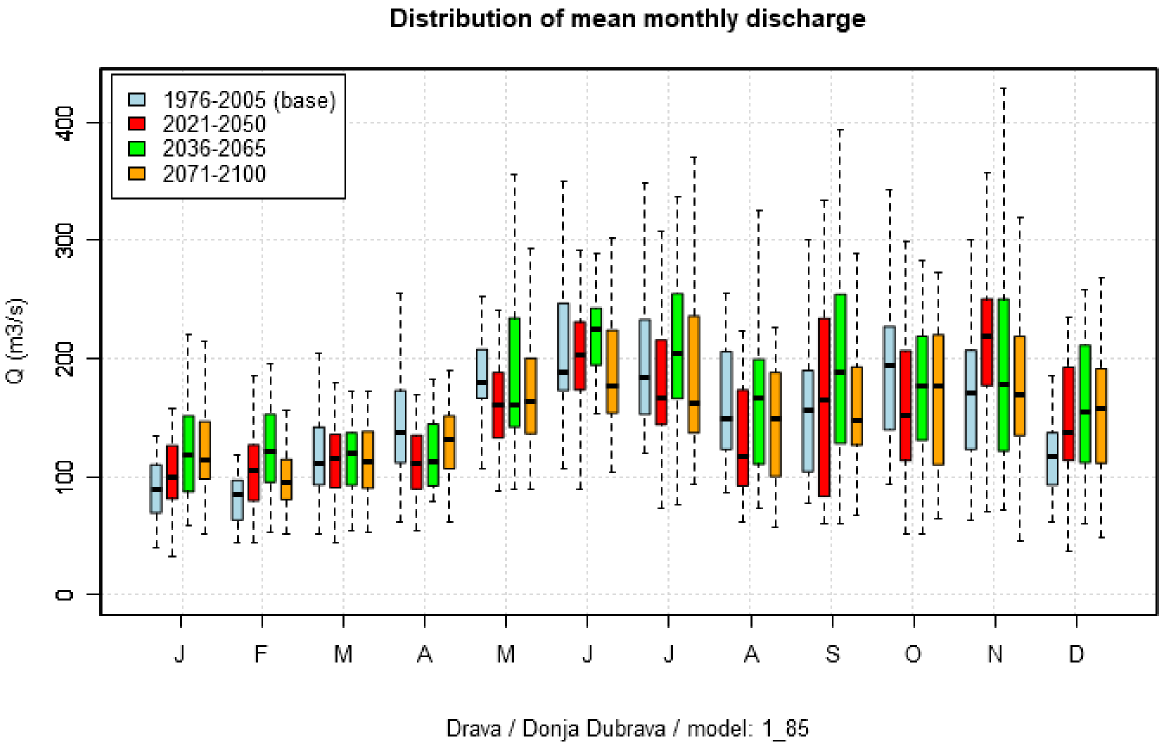
Drava / Donja Dubrava / model: 1_45


Distribution of mean monthly discharge
1976-2005 (base)
2021-2050
2036-2065
2071-2100
Q (m3/s)
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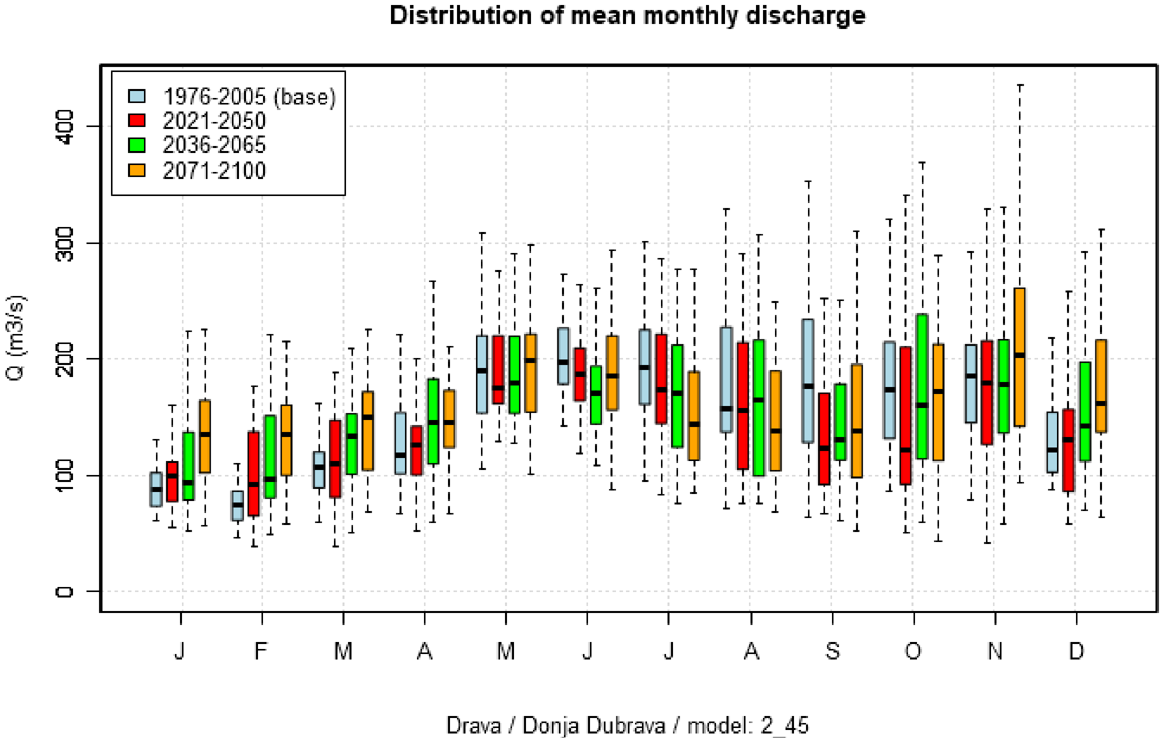
Drava / Donja Dubrava / model: 1_85


Distribution of mean monthly discharge
1976-2005 (base)
2021-2050
2036-2065
2071-2100
Q (m3/s)
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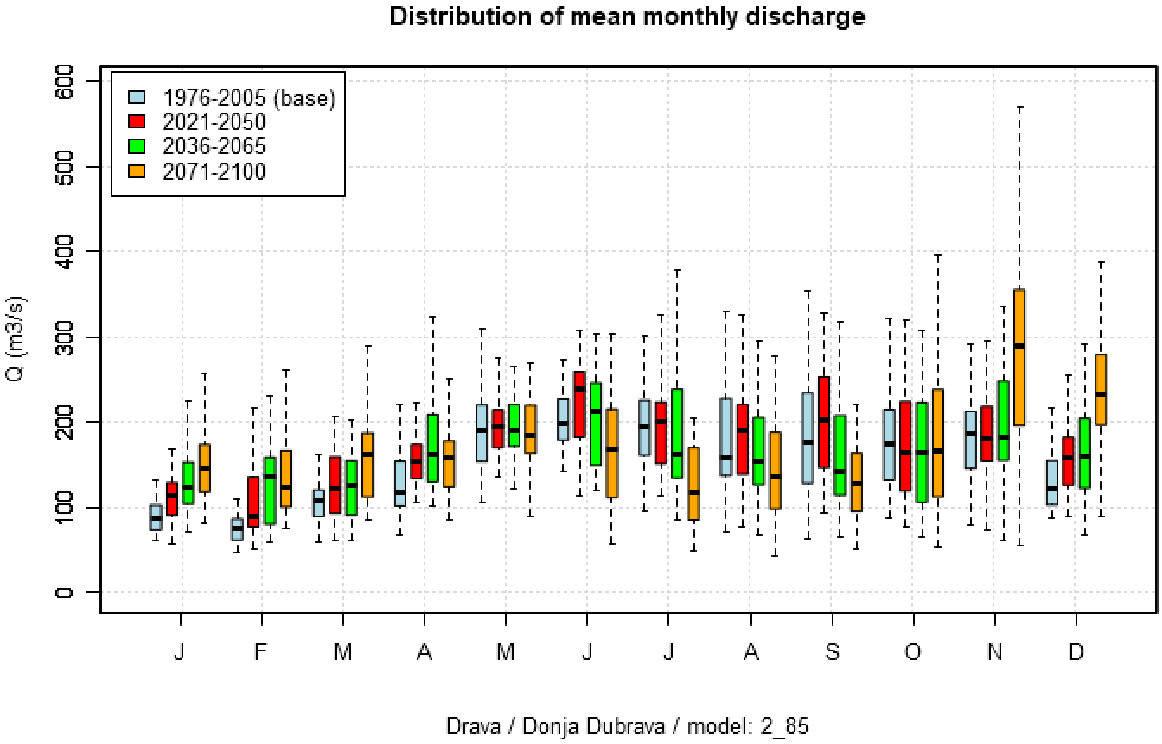
Drava / Donja Dubrava / model: 2_45


Distribution of mean monthly discharge
1976-2005 (base)
2021-2050
2036-2065
2071-2100
Q (m3/s)
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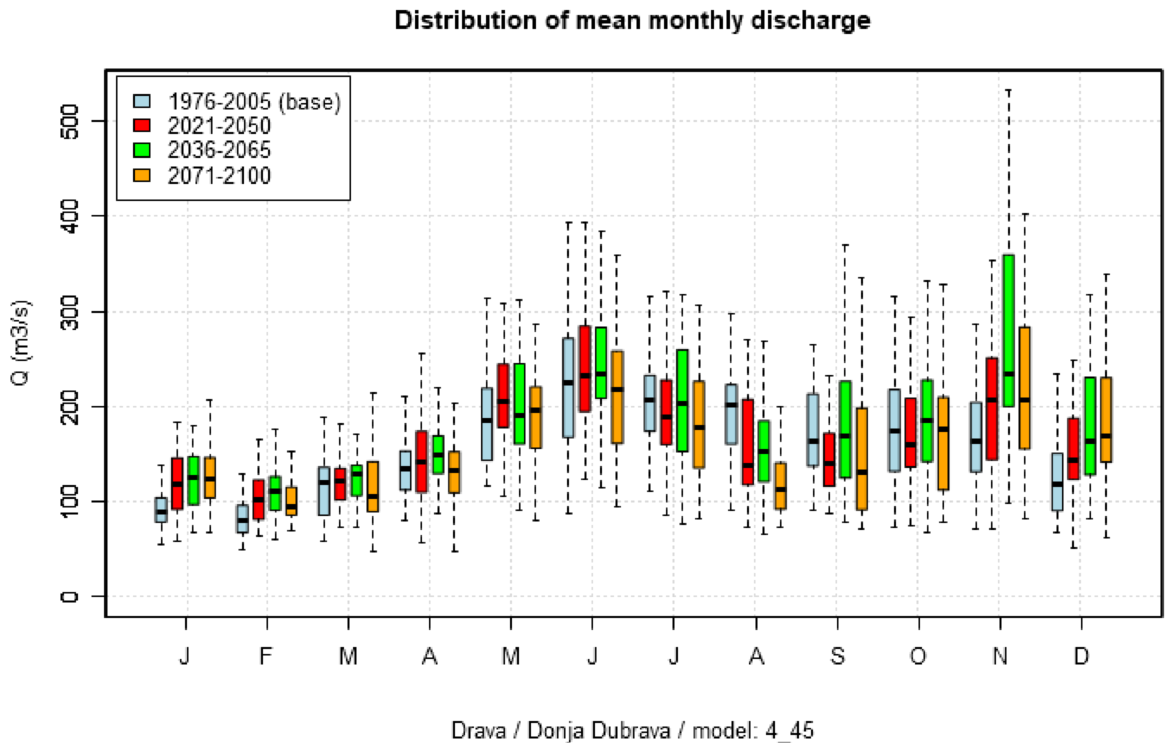
Drava / Donja Dubrava / model: 2_85


Distribution of mean monthly discharge
1976-2005 (base)
2021-2050
2036-2065
2071-2100
Q (m3/s)
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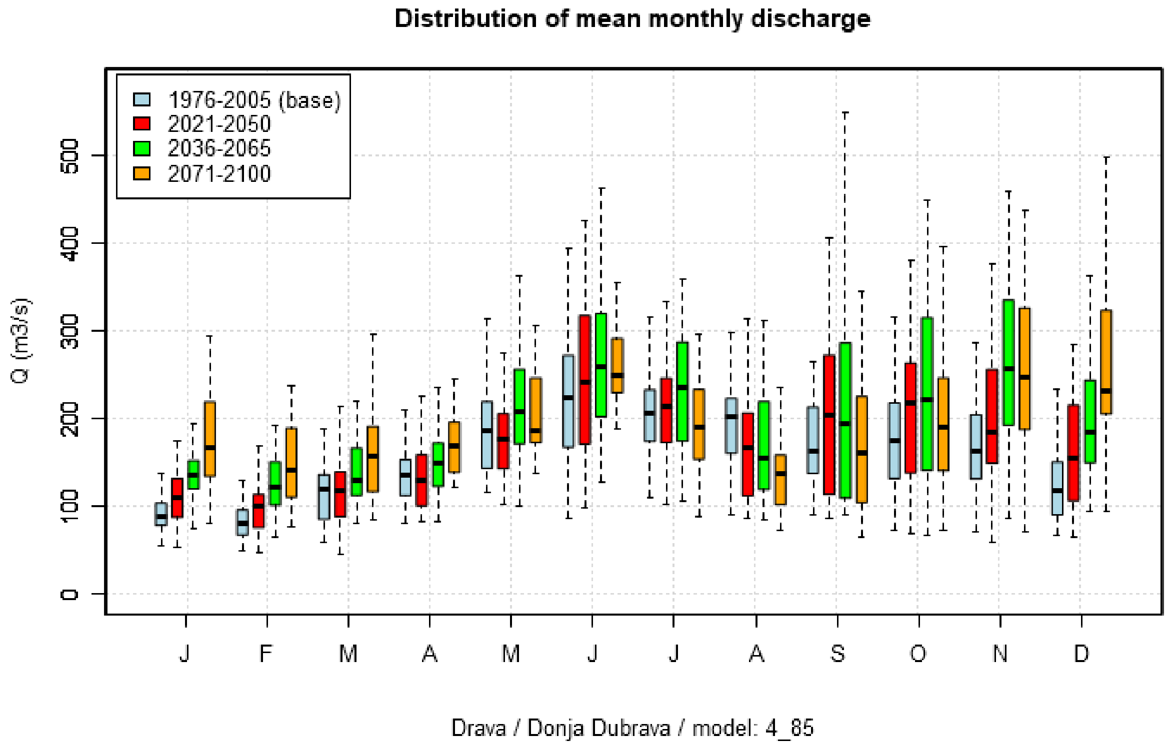
Drava / Donja Dubrava / model: 4_45


Distribution of mean monthly discharge
1976-2005 (base)
2021-2050
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2071-2100
Q (m3/s)
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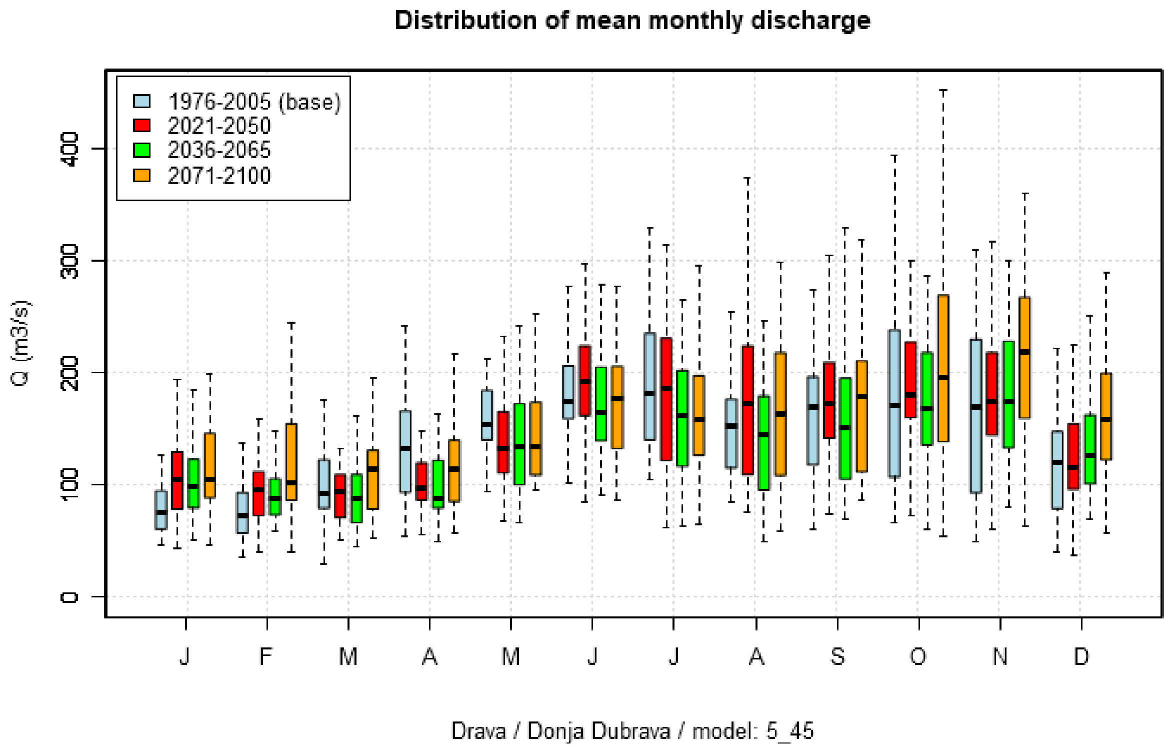
Drava / Donja Dubrava / model: 4_85


Distribution of mean monthly discharge
1976-2005 (base)
2021-2050
2036-2065
2071-2100
Q (m3/s)
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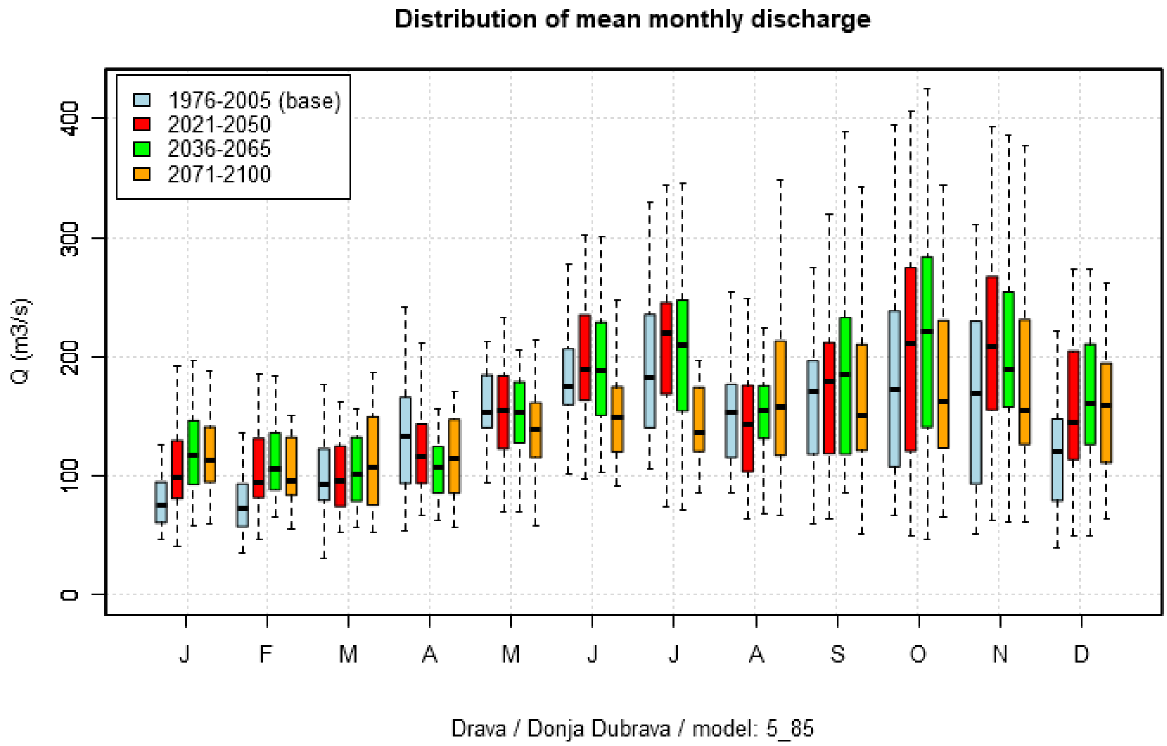
Drava / Donja Dubrava / model: 5_45


Distribution of mean monthly discharge
1976-2005 (base)
2021-2050
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2071-2100
Q (m3/s)
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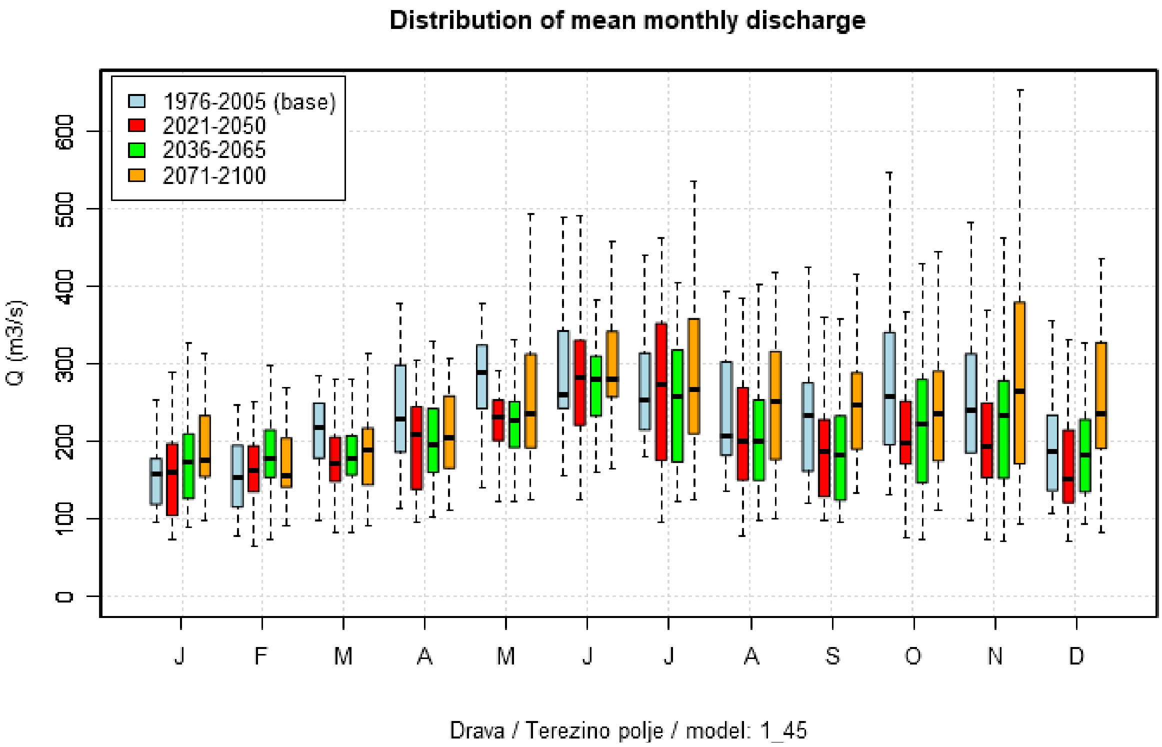
Drava / Donja Dubrava / model: 5_85


Distribution of mean monthly discharge
1976-2005 (base)
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Q (m3/s)
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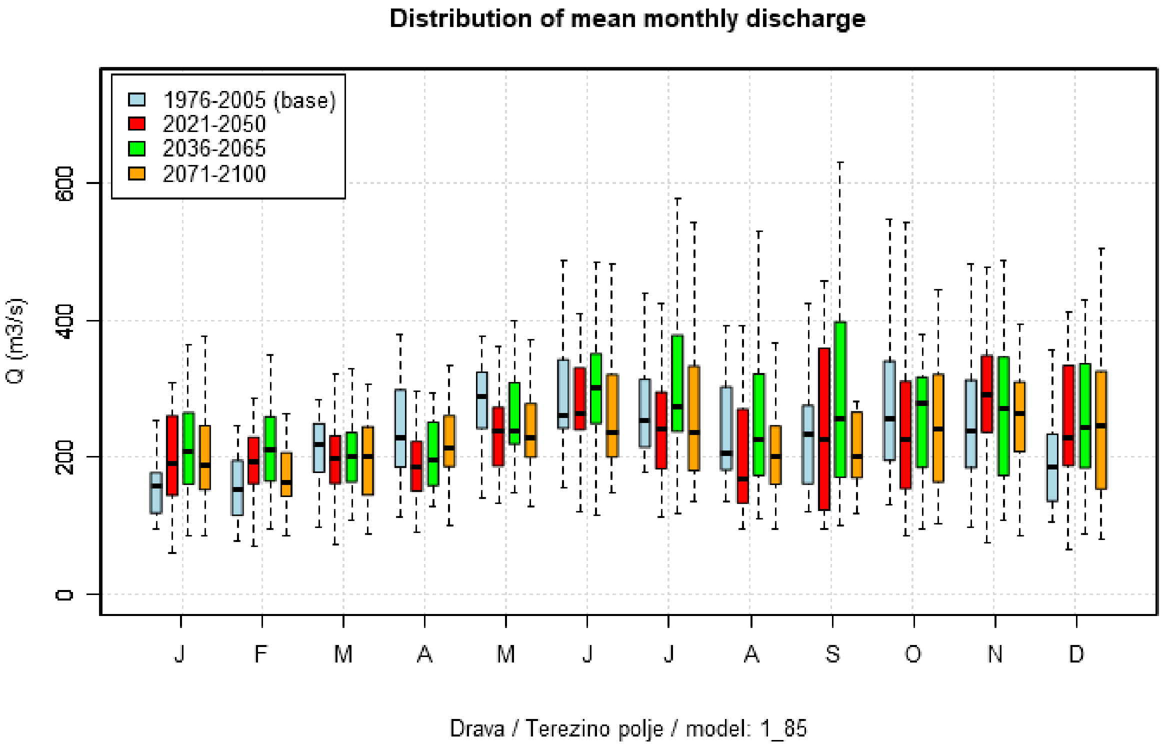
Drava / Terezino polje / model: 1_45


Distribution of mean monthly discharge
1976-2005 (base)
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Q (m3/s)
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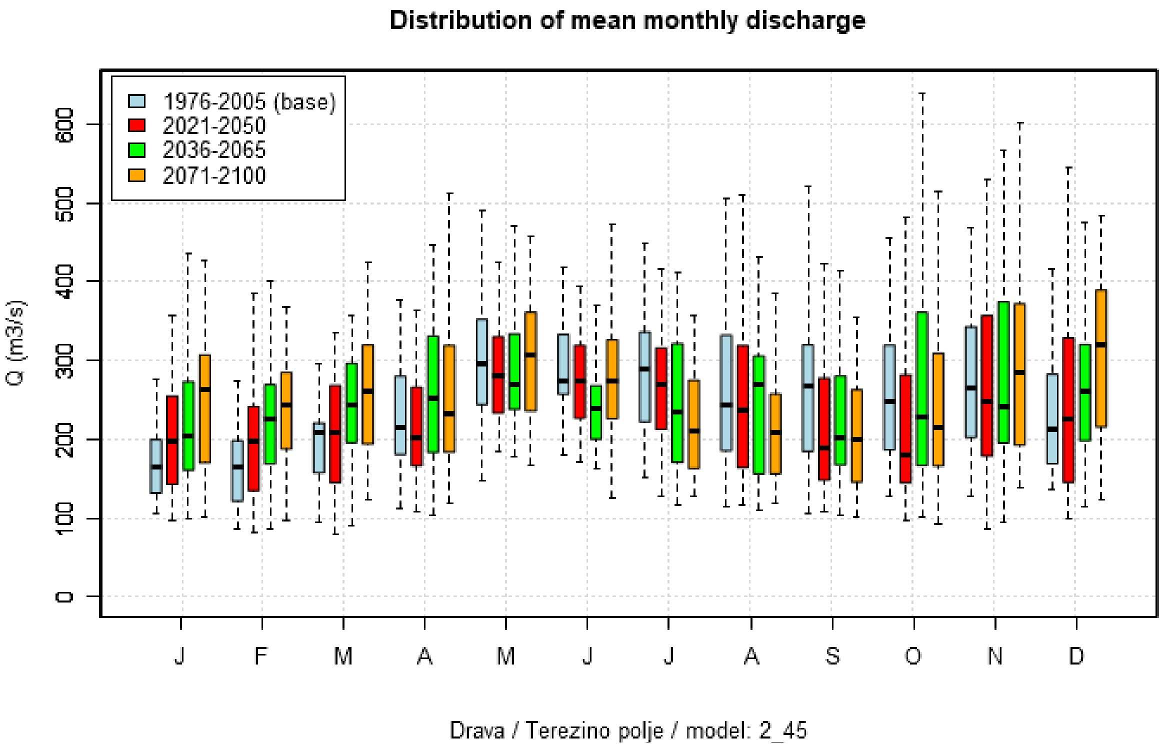
Drava / Terezino polje / model: 1_85


Distribution of mean monthly discharge
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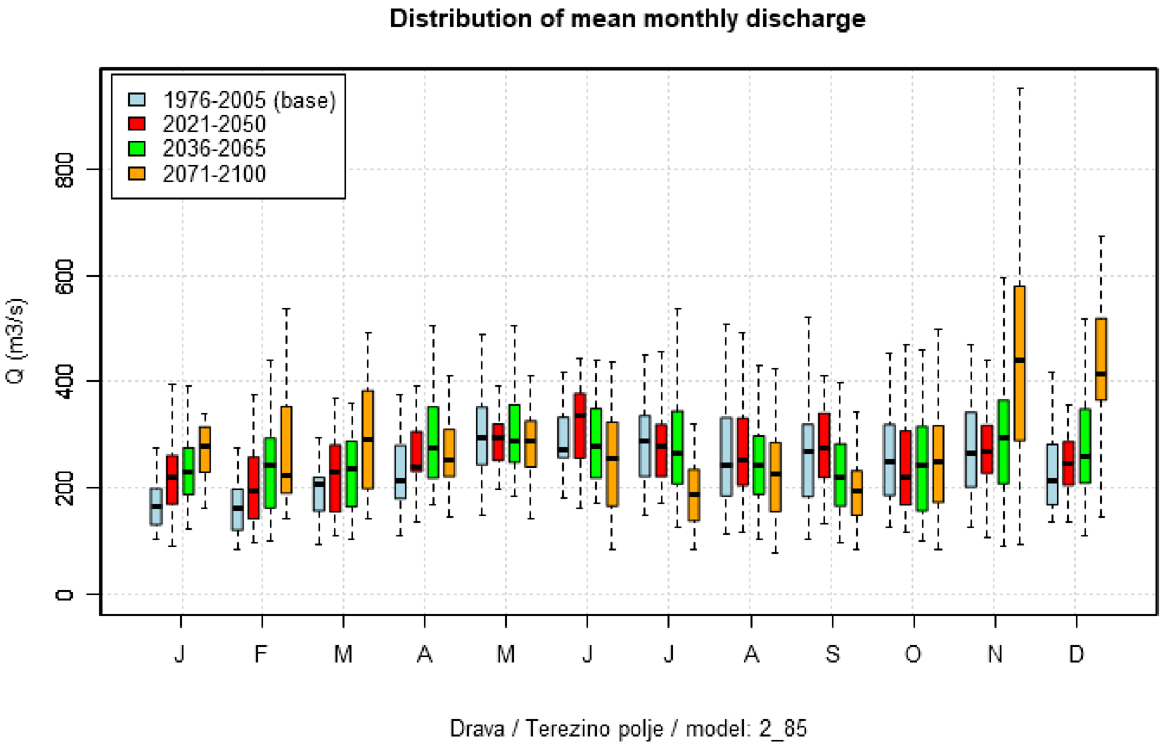
Distribution of mean monthly discharge
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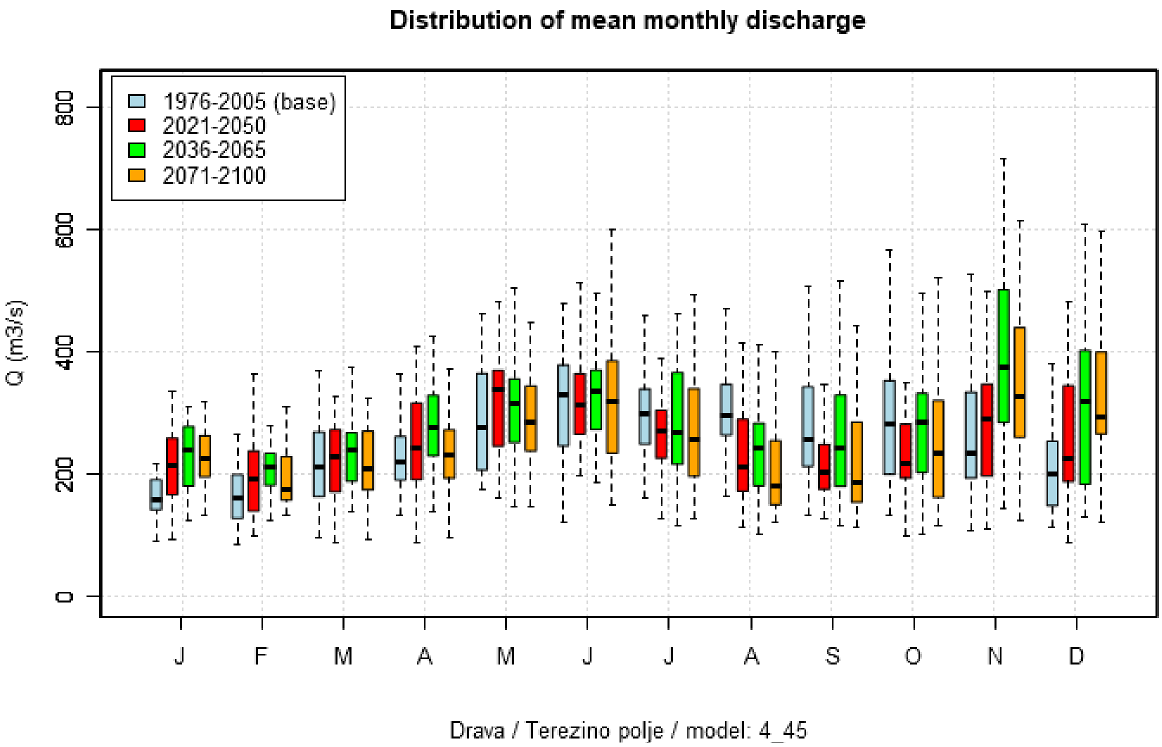
Distribution of mean monthly discharge
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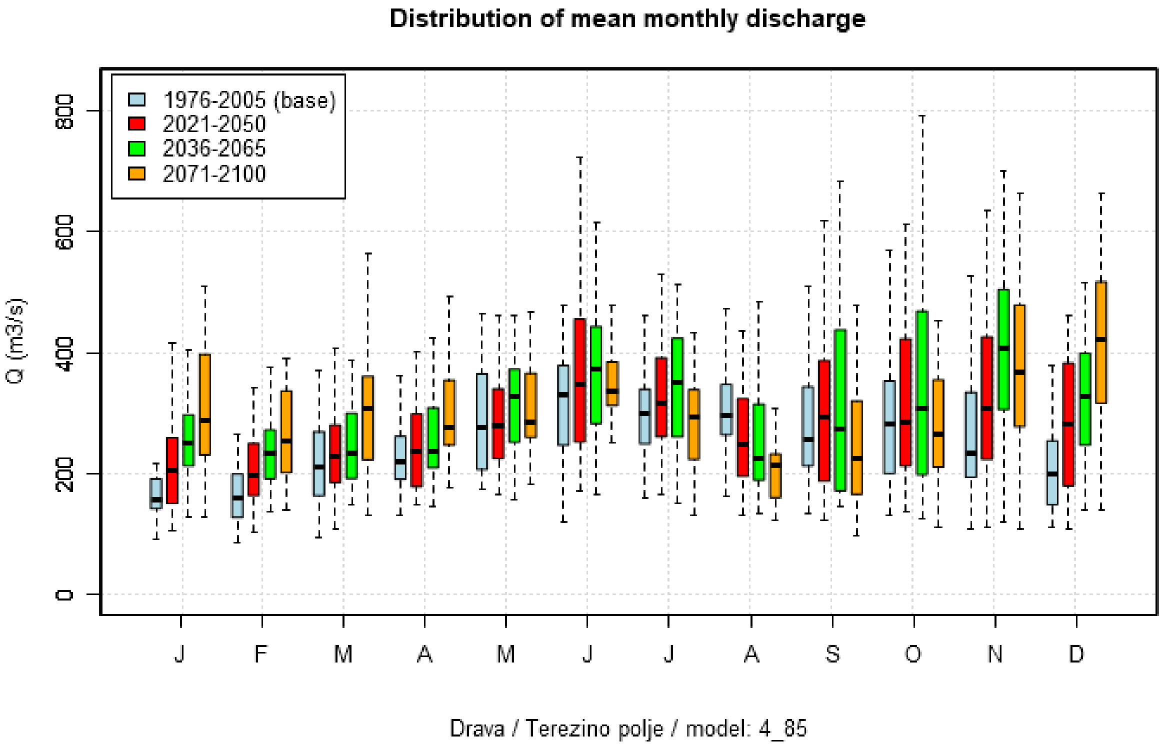
Distribution of mean monthly discharge
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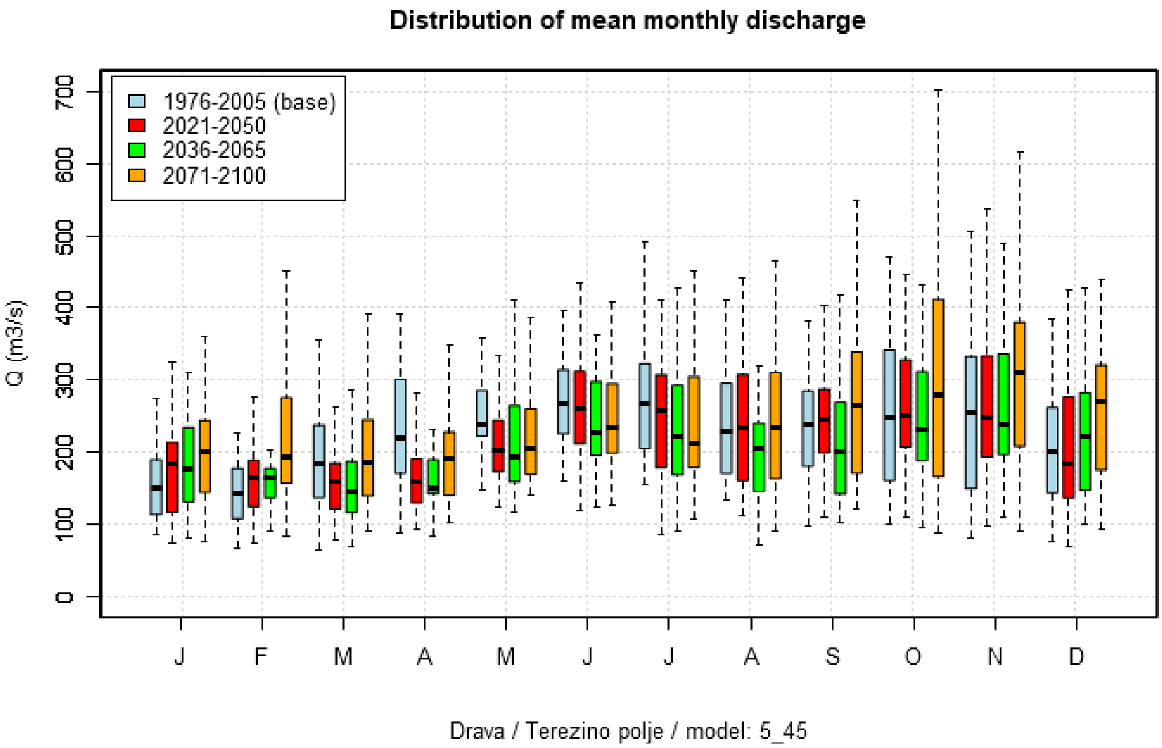
Distribution of mean monthly discharge
1976-2005 (base)
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2071-2100
Q (m3/s)
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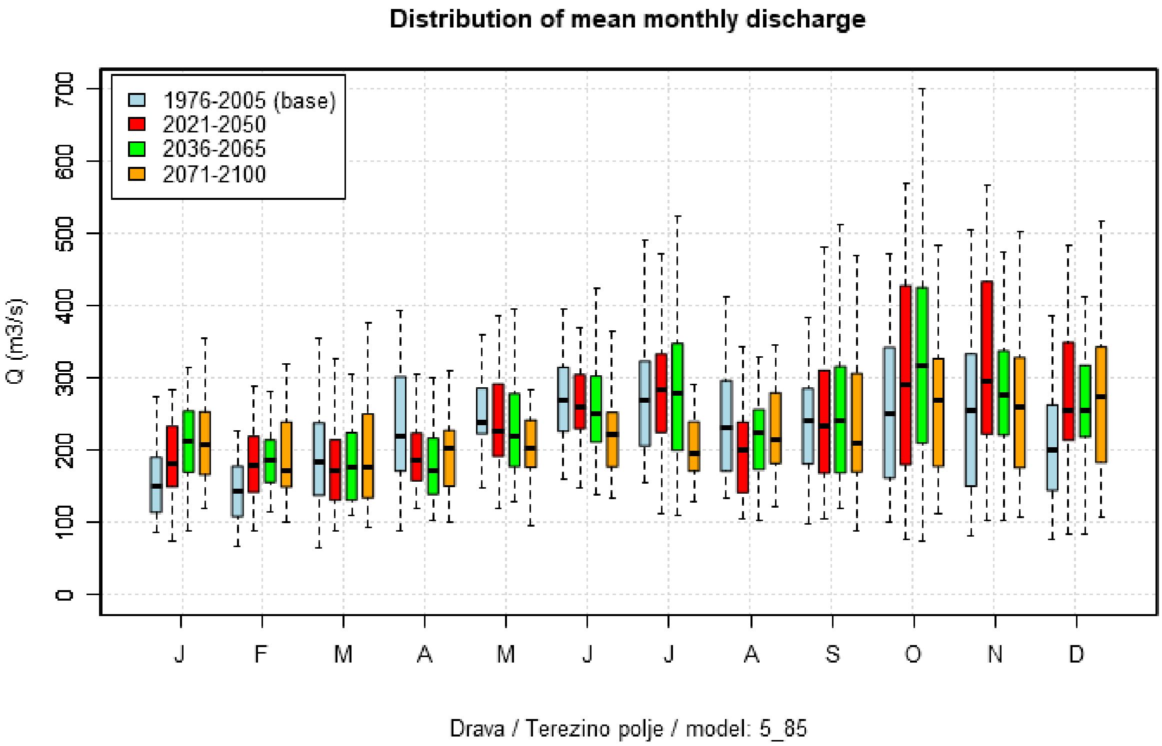
Drava / Terezino polje / model: 5_45


Distribution of mean monthly discharge
1976-2005 (base)
2021-2050
2036-2065
2071-2100
Q (m3/s)
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Drava / Terezino polje / model: 5_85