

Evaluating climate change effects on hydrological functionality and water-related ecosystem services

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Abstract

The paper investigates the effects of climate change on riverine ecosystems in the Upper Arno River basin, adopting a hybrid methodology relating the changes in streamflow to its related water ecosystem services. Twenty hydrological models were run using the Soil and Water Assessment Tool (SWAT), under their respective climate model and emission scenario. The streamflow variable obtained was analysed according to the method of Indicators of Hydrologic Alteration (IHA). The development of spatial maps of IHA allowed us to represent the spatial of the results according to the three river subbasins studied, with a focus on the presence of hotspots. Using IHA allowed to capture of the streamflow quantity and dynamics, through groups of magnitude, timing and rates, where the potential effect could be then linked to the concept of water ecosystem services. Finally, the results obtained were presented as a proxy that can be integrated into the existing Driver, Pressure, State, Impact, Response (DPSIR) management framework to eventually move towards an ecosystem-based management methodology. The main results, induced from the Mann–Kendall trend analysis of the IHA, suggested that provisioning and regulating services are to be affected by climate change where the quantity of flows shows a decreasing trend under several emission scenarios, in addition to an intensification of the extreme events. This shift is accompanied by a change in the dynamics of flow, which holds the potential of affecting habitat suitability. With the emergence of studies directed towards ecosystem-based management, the study refers to well-established hydrological modelling to evaluate climate change as a driver and provide screening results to ensure a proactive response planning that converges with the idea of ecosystems.

KEYWORDS

climate change, ecosystem services, hydrological modelling, Indicators of Hydrologic Alteration, river basin management

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1 | INTRODUCTION

Climate change is a direct driver for alterations in water-dependent ecosystems, affecting river systems from multiple perspectives, including hydrology and morphology (Ashmore & Church, 2001; Gelfan et al., 2017). Riverine ecosystem processes like evapotranspiration, infiltration, water quality preservation and the whole hydrologic system regulation are proven to be affected by the changes in precipitation and temperature induced by climate change (D'Oria et al., 2019; Nijssen et al., 2001; Nilawar & Waikar, 2019). Looking at stream flow in rivers as the main variable in the fluvial ecosystems (Arthington et al., 2006; Beechie et al., 2010), recent global changes in the magnitude and extremes of river flows are assigned to the effects of climate events (Lu et al., 2018; Tonkin et al., 2019). The change in stream flow holds its own consequence on the surrounding ecosystem, influencing river health and affecting multiple water-related ecosystem services (WES, Figure 1) from an allocation perspective, from an ecosystem management approach or from an ecological conservation point of view (Boltz et al., 2019; Däll & Zhang, 2010; Gudmundsson et al., 2021; Sofi et al., 2020). This direction is highlighted in the International Panel on Climate Change (henceforth, IPCC) report of 2021 (IPCC, 2021) where the evidence of weather becoming more extreme through heatwaves, floods and droughts implies the necessity to enhance nature's and people's ability to cope or adapt to changing climate conditions (Gerhard, 2004; Sherwood et al., 2020).

To address these challenges, spatial mapping and indicators are essential in planning for 'sustainable and healthy communities', a concept that extends to riverine ecosystems providing benefits for its surrounding users, which can be threatened under the stress of anthropogenic climate change (Lowe et al., 2015; Pletterbauer et al., 2018).

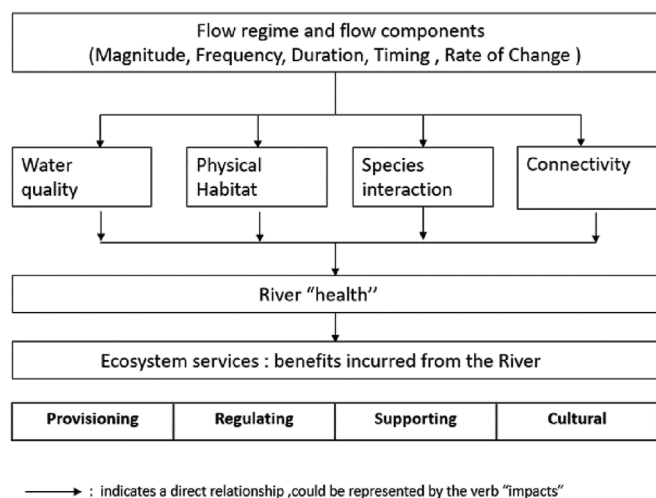


FIGURE 1 Adopting river flow as the main variable, connections with the surrounding ecosystem (developed based on Boltz et al., 2019).

Such application can be observed in the use of the Indicators of Hydrologic Alteration (IHA) as an extension for established hydrological models. Morid et al. (2019) investigated the Kikuchi river flow regime and its components, using the Soil and Water Assessment Tool (SWAT) under several climate change indicators. The IHA derived from the calculated stream flows, allowed to categorise through a set of indicators an imminent threat on habitat suitability, since major environmental components are encompassed by IHA. Similarly, Mittal et al. (2016) assessed the stream flow variability, under climate change and dam construction impact, with the IHA showing a stream flow reduction throughout the year that impacts those species sensitive to the low and high flow changes.

The usage of indicators to support ecohydrological understanding of the riverine systems is well documented in the implementation of the Water Framework Directive (WFD) (EU, 2000), specifically in the hydrological assessment methods. The use of IHA or similar indicators, depending on the country of application, is assigned to a first level of hydrological methodology, applicable for regional scale assessment, and serving as a mean for screening and analysis for information required for the higher second level of hydraulic habitat methodology. Hence, with the introduction of the IHA, the extension of hydrological models is possible and helps the promotion of information obtained to the river basin management applications (European Commission, 2016; Greco et al., 2021; Kiesel et al., 2019). Moreover, the use of IHA extends beyond statistical data simplification of hydrological behaviour and emphasises the ecohydrological functionality of rivers. With this application, hydrological models can be calibrated additionally, using IHA values, to encompass the ecohydrological component and better assess climate change and anthropogenic stressors (Cakir et al., 2019; Mylevaganam et al., 2015).

Hence, if the IHA form a link between the hydrological and the ecohydrological perspective, WES, defined as the benefits incurred from riverine ecosystems as water moves through the landscape (Böck et al., 2018; Brauman et al., 2007), could represent the end purpose of IHA in linking ecohydrology to the socio-economic dimension of watershed management. WES linked with the impact of stressors like climate change or land use allow the production of results facilitating evidence-based policy and management (Acuña et al., 2013; Grizzetti et al., 2016; Terrado et al., 2016). Aznarez et al. (2021) assessed the impact of climate change on WES through the development of a SWAT model coupled with an analysis of IHA results. The analysis performed in Laguna del Sauce (Uruguay) focused on IHA and the streamflow variable of SWAT as an indicator for the natural hazard protection of ecosystem services. The change in seasonality of floods under CanESM2 and HadGEM2-ES scenarios implied the amplification of extreme flow conditions under which species adaptation might not be attainable (Aznarez et al., 2021).

Scholes (2016) provided a systematic review of the impacts of climate change on certain ecosystem services. Looking at the 'drivers' represented by climate change, their effect on services is projected to be negative in most cases.

Given this background, this study aims at analysing the changes in stream flow in the Arno River hydrographic network (Tuscany,

Central Italy) according to multiple climate change scenarios and assessing their potential influence on WES production. We consider the 'function' of the hydrological system as the set of water-related ecosystem services provided. Hence, this functionality is mobilised through the assessment of changes in the provided ecosystem services. By accounting for the changes in precipitation and temperature under several climate models, representative indicators of hydrological alteration are analysed for exploring the consequences of existing water management challenges and the possible impact on the services provided by the riverine ecosystem. The results are presented through geographical information systems, highlighting the spatial distribution of the obtained results throughout the studied river basin, where concerned stakeholders can identify results of interest under several climate change scenarios.

2 | MATERIALS AND METHODS

The methodology adopted is based on investigating the hydrological functionality of the system, under different climate change scenarios, using the IHA. The results obtained are then linked to the available WES to provide a proxy for river basin management authorities by integrating the obtained modelling results into the existing management plan.

In particular, the analysis is organised into five steps (Figure 2):

- i. Hydrological modelling using the SWAT to characterise the hydrological regime: Using continuous hydrological data (30 years), the calibrated and validated hydrological model provides spatially distributed results of the variable of interest, i.e., stream flow.

- ii. Climate change scenarios analysis (evaluation of climate change effects on the hydrological regime): With the establishment of the calibrated and validated model, the next step consists of the investigation of several climate change scenarios by providing timeseries data of precipitation and temperature for the period ranging from 2021 to 2099.
- iii. IHA (as a summary of the hydrological regime) analysis: The results of the stream flow for each scenario are then analysed using the IHA to illustrate the quantity and the dynamics of the flow with respect to each assumed climate change scenario.
- iv. Linking IHA to WES (identification of WES potentially affected by hydrological regime changes): A qualitative link is made between the stream flow alterations and the services provided by the ecosystem, based on existing literature. This provides a useful insight into the relationship between the existing WES and the stream flow variable.
- v. Implications for water management definition: Within the adopted Driver, Pressure, Impact, State, Response (DPSIR) framework, the impacts of stream flow alterations driven by climate, can then be highlighted, and assigned to the corresponding ecosystem services. This screening procedure allows the allocation of potential preliminary future targets in the river basin management plan, with more detailed models developed.

2.1 | Study area

The Arno River basin is located almost entirely in the Tuscany region, Italy. With a main river length of about 241 km and a catchment area of about 8830 km², it forms the seventh longest river in Italy. The

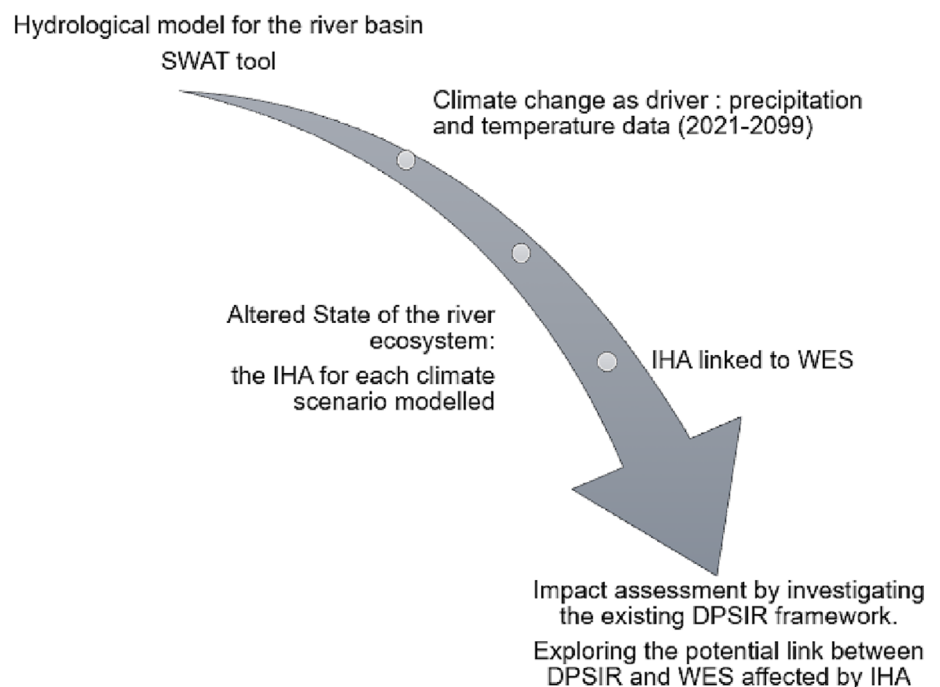


FIGURE 2 Study methodology adopted starting from the hydrological model and reaching the integration of results obtained with respect to the managerial framework. DPSIR, Driver, Pressure, State, Impact, Response; IHA, Indicators of Hydrologic Alteration; WES, water ecosystem services.

chosen study area is above an important reservoir, upstream of La Penna dam, and includes three subbasins: Casentino, Val di Chiana and Upper Valdarno at the outlet (Figure 3).

Its topography is characterised as Horst and Graben (or valley range) aligned in NW–SE direction, due to the tectonics extension, and dictates the physiography of the catchment through a series of intermontane river basins, separated by bedrock-controlled reaches (Caporali et al., 2005). In general, the soils in the river basin can be classified according to five major categories: Umbric Acrisols, Calcaric Cambisols, Dystric Endoskeletal Cambisols, Profundi Stagnic Luvisols and Gleys Cambisols. These categories comprise mainly clay and silty clay soils with different conditions of weathering and aging, suitable for the cultivation practiced in the area, but also holding the risk of erosivity and soil loss. The climate zone of the Arno river basin is described by a dry summer, during which a rainfall pattern shows a minimum in July and maximums in November and the end of Winter. The range of annual rainfall is between 800 and 1800 mm. The highest flow rates are generally recorded in January; on the other hand, the lowest rates are usually recorded in August (Monti & Rapetti, 2011).

The analysed river basin is managed by the Northern Apennines River Basin District Authority which collects, processes, stores and broadcasts data. The authority management plan introduced by the WFD later transposed into national legislation, is based on the DPSIR framework.

Following this logical model, the major drivers and pressure presented by the Northern Apennines River Basin District Authority, for the three sub-catchments, identify firstly the issues related to the ecological and chemical states of the three sub-catchments (Northern Apennines River Basin District, 2021). The Val di Chiana subbasin is

identified as having the worst state, with a ‘Poor’ ecological state and a ‘Bad’ chemical one. The Valdarno area presents a ‘Moderate’ ecological state, while the Casentino subbasin is considered as having the best state with a ‘sufficient’ ecological and a ‘good’ chemical state. The major drivers are agriculture and industry for the three subbasins (Table 1). This information is crucial because it allows the identification of the most critical WES in the area of study: the demand for provisioning services, with the pressures associated with the presence of industries and irrigation practices, and the lack of regulating services due to the presence of erosion, sedimentation and flood protection pressures (Mori et al., 2021; Pacetti et al., 2020).

2.2 | Hydrological model: SWAT

The hydrological component of the ecosystem is to be modelled following the scientific steps traditionally followed (Skop, 1996):

- Collection and analysis of data from meteorological stations
- Model development with respect to the question to be answered (in this study, the hydrological component of the river basin)
- Conception of a mathematical model to be calibrated and validated
- The usage of the model obtained as a predictive tool for inputted scenarios connected to climate change

The SWAT model is a semi-distributed non-point source hydrological model that can be used to estimate long-term management practices on runoff, sediment load and loss of nutrients at different scales. The model is a continuous time model, or long-term yield, making it

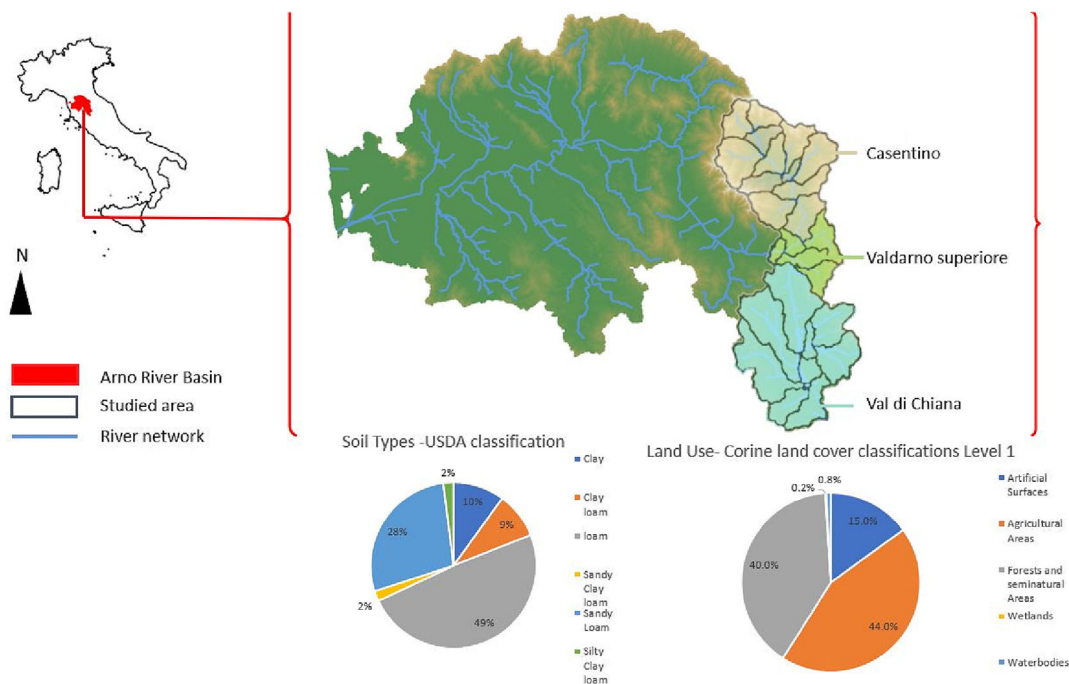


FIGURE 3 Study area: Upper Arno River basin with the soil types present according to the USDA classification criteria.

TABLE 1 Main drivers and pressures presented by the river basin management plan, x: pressure not identified. It is noteworthy to mention the absence of climate change consideration as a main driver with its corresponding pressures.

State	Casentino		Val di Chiana		Valdamo superiore	
	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
Ecological	Moderate		Poor		Moderate	
Chemical	Good		Bad		Bad	
Pressures						
Drivers						
Agriculture	Physical alteration of channel/bed/riparian/area	Physical alteration of channel/bed/riparian/area	Diffuse agriculture	-diffuse agriculture	Abstraction/flow diversion	
Climate change	x	x	x	x	x	
Energy-hydro	Dams/barriers	x	Dams/barriers	x	Dams/barriers	
Energy-nonhydro	x	x	x	x	x	
Fisheries	Aquaculture	x	Aquaculture	x	x	
Flood protection	Physical alteration of channel/bed/riparian/area	Physical alteration of channel/bed/riparian/area	-physical alteration of channel/bed/riparian/area	-physical alteration of channel/bed/riparian/area	x	
Forestry	x	x	x	x	x	
Industry	-contaminated sites	-contaminated sites	IED plants	-contaminated sites	Industrial wastewater	
	-urban runoff	-urban runoff	-contaminated sites	-urban runoff		
	-transport		-wastewater			
Tourism	x	x	x	x	x	
Transport	-physical alteration of channel/bed/riparian/area	Physical alteration of channel/bed/riparian/area	-diffuse transport	-abstraction flow	-diffuse transport	
	-diffuse transport		-abstraction flow	-diversion	-abstraction/flow diversion	
Urban development	-urban wastewater	x	-physical alteration of channel/bed/riparian/area	-physical alteration of channel/bed/riparian/area	-urban wastewater	
	-urban runoff		-urban wastewater	-urban wastewater	-abstraction/flow diversion	
Other	x	x	x	x	x	

suitable for the objective of the study presented, compared to single event flood routing. The physical processes simulated in a watershed through SWAT are dominated by the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^t (R_{\text{day}} - Q_{\text{surf}} - E_a - w_{\text{seep}} - Q_{\text{gw}}), \quad (1)$$

where

SW_t : final soil water content (mm H₂O) at time t (days)

SW_0 : initial soil water content (mm H₂O)

R_{day} : amount of precipitation per day (mm H₂O)

Q_{surf} : amount of surface runoff on day i (mm H₂O)

E_a : amount of evapotranspiration on day i (mm H₂O)

w_{seep} : amount entering the vadose zone from the soil profile on day i (mm H₂O)

Q_{gw} : amount of return flow on day i (mm H₂O)

SWAT enables to establish modelling units known as hydrological response units (henceforth, HRU). Such aggregation allows variability in scale when observing outputs, where for example, hotspots need to be identified (small scale), or where several HRUs can be grouped under one management or administrative area, for decision making purposes (large scale). The digital terrain model, along with the soils and land use, allows SWAT to create the corresponding HRUs (Table 2).

One hundred eight subtypes of soils are in the study region and are assigned in each HRU by updating the database of SWAT with the corresponding parameters (Table 3). The obtained river basin model, with elevation and soil properties, is after assigned the meteorological data according to the 16 weather gauge stations located within the river basin (Figure 4). The 16 meteorological gauge stations are used for daily values of rainfall, minimum and maximum temperature, wind speed, solar radiation and relative humidity. The use of daily values in climate change study is recommended, especially when dealing with long-term simulation and scenarios comparison (Tan et al., 2020).

TABLE 2 Input data for SWAT.

Data input	Source	Format
Digital terrain model	Tuscany Region ^a	10 m × 10 m grid
Soils	Tuscany Region ^a	Vector 1:10,000
Land use	Tuscany Region ^a	Vector 1:100,000
Meteorological data	Tuscany Region ^b	Daily datasets (2000–2020)

^aFrom regione.toscana.it/geoscopio

^bFrom sir.toscana.it

TABLE 3 Soils parameter input for SWAT model.

Soil parameter	Description
Hydrological group-HYDGRP	Infiltration rating criteria
Maximum rooting depth-SOL_ZMX	Development of roots in the soil profile
Bulk density-SOL_BD	mg/m ³
Available water capacity-SOL_AWC	mm H ₂ O/mm of soil
Saturated hydraulic conductivity-SOL_K	mm/h, relating flow rate to hydraulic gradient
Organic carbon content-SOL_CBN	% of soil weight
Clay, silt and sand percentage	% of soil weight
Soil erodibility factor K-USLE	According to the universal soil loss equation

After setting up the inputs required to establish the hydrological modelling, the next step adopted is to ensure that the results obtained are representative, accurate and efficient (Leta et al., 2015). The model evaluation suggested by Moriasi et al. (2015), accounts for a standardised root mean square error (RSR), an efficiency presented by the Nash–Sutcliffe efficiency (NSE) and a percent bias (PBIAS). The statistics calculated respectively evaluate the scaled error index that can be applied to different constituents, the magnitude of noise to information where the fit of the plot of observed and simulated discharges is assessed and finally the tendency of simulated data to differ from the observed ones.

The parameters calculated are as follows:

$$RSR = \sqrt{\frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^n (Y_i^{obs} - Y^{mean})^2}}, \quad (2)$$

$$NSE = 1 - \left(\frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^n (Y_i^{obs} - Y^{mean})^2} \right), \quad (3)$$

$$PBIAS = \left(\frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim}) \times 100}{\sum_{i=1}^n (Y_i^{obs})} \right). \quad (4)$$

The evaluation of the model ranges from unsatisfactory to a very good rating. Using SWAT-CUP software developed by Abbaspour (2015), 500 runs of several iterations are performed to obtain criteria allowing for correct analysis.

Firstly, a sensitivity analysis is performed to identify the parameters needed to start the calibration process. Using a developed software package in R that offers computational speed with the adopted R environment, 'SWATplusR', it is possible to identify the sensitivity of initial calibration parameters like the SCS-Curve Number, groundwater parameters and evapotranspiration factors (Table 4). The

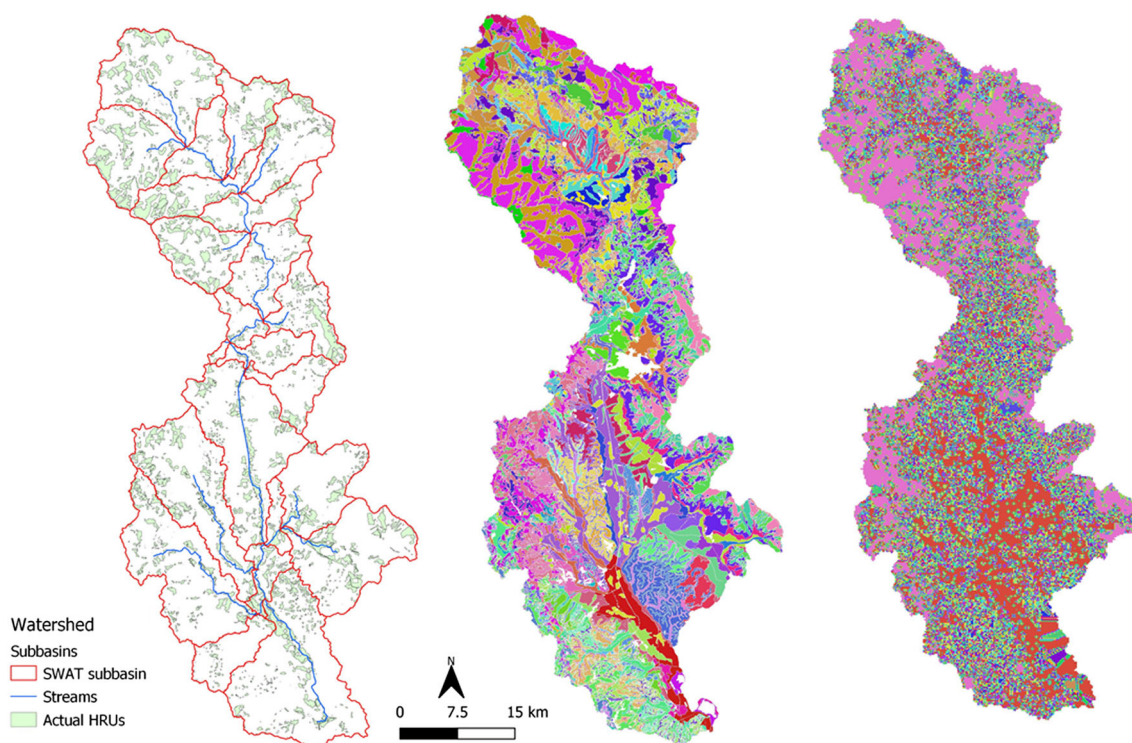


FIGURE 4 SWAT model, from left to right: obtained HRUs (watersheds), 108 soil types inputted and 36 land use classes inputted.

TABLE 4 Calibration parameters for SWAT models.

Parameter	Definition	Scale of input	Type of adjustment*
ALPHA_BF	Base-flow recession constant (days)	Watershed	Replace
GW_DELAY	Groundwater delay (days)	Watershed	Absolute
GWQMN	Threshold groundwater depth for return flow (mm water)	Watershed	Replace
GW_REVAP	Groundwater 'revap' coefficient	Watershed	Replace
REVAPMN	Reevaporating threshold (mm water)	Watershed	Replace
SOL_AWC	Available soil water capacity (mm water/mm soil)	HRU	Relative
SOL_K	Soil-saturated hydraulic conductivity (mm/h)	HRU	Relative
ESCO	Soil evaporation compensation factor	HRU	Replace
EPCO	Plant uptake compensation factor	HRU	Relative
CH_K2	Main channel hydraulic conductivity (mm/h)	Reach	Relative
OV_N	Manning's <i>N</i> value for overland flow	Reach	Relative
CN2	Curve number for moisture condition II	Reach	Relative

Abbreviation: HRU, hydrological response units.

plots obtained from the analysis allow us to identify critical parameters as initial inputs for SWAT-CUP runs (Schuerz, 2019).

2.3 | Climate change scenarios

Precipitation and temperature are important variables in studying the hydrological cycle impacted by climate change (Huang et al., 2015). While predicting climate change impact through future scenarios forms a future-oriented outlook on the river's health, the analysis of

past time series provides fundamental information on the hydrological behaviours and trends in the river basin. Understanding the current hydrological setting with reference to the climate allows for improved scenario-based analyses.

Using the projected temperature, precipitation and soil moisture, it is possible to characterise the future regime and seasonal behaviour of a river flow, through developed methods and indices (Bower et al., 2004; Kaiser et al., 2021) on a different spatial and temporal scale (Lu & Jiang, 2009). By doing so, the interaction of the river with the surrounding riverine ecosystem is assessed to study its potential

effects. Worldwide, the concept of using future climate variables, coupled with a hydrological model at the river basin scale, is proving to be more used and more effective (Chen et al., 2017). The models available to project the climate for the most likely future conditions are the global climate model (henceforth, GCM), regional climate model (henceforth, RCM) and their forcing scenarios. In this study, a selection of five climate models (Table 5) is chosen with their respective forcing scenarios or representative concentration pathway (henceforth, RCP). The intent is to explore five different general climate models supported by the inter-sectoral Impact Model Intercomparison Project (henceforth, ISI-MIP5). Each model holds its own methodology, assumptions and calculations to project according to the relevant forcing scenarios.

SWAT offers downscaled data for the basin studied through the climate change toolkit where data extraction and management, bias correction and downscaling are performed with an output of future of time series (Ashraf Vaghefi et al., 2017). The statistical downscaling performed through the provided tool reflects the approach developed by Muluneh et al. (2014), on the Upper Tiber basin close to the selected study area.

In total, 20 climate change scenarios were analysed. Using down-scaled temperature and rainfall data corresponding to the study area, and provided by SWAT, the stream flow variable output (Q_{out}) is obtained for each model, becoming the main variable to be investigated.

2.4 | Indicators of Hydrologic Alteration

The outputs of the 20 SWAT models are daily time series discharge at the HRU/subbasin scale for the studied period (2020–2099). The output is then analysed through the IHA, developed by the Nature Conservancy (The Nature Conservancy, 2009). The commonly used IHA indicate alterations in river regime through 33 parameters of magnitude, frequency, duration, timing and rate of change (Richter et al., 1996). Additional environmental flow components can be obtained for the changes in extreme, low, high, small and large floods (Neff et al., 2009). With the presence of over 170 hydrological indicators, Olden et. al presented through principal components analyses, the ability for non-redundant IHA parameters to characterise the flow regime (Olden & Poff, 2003). Following the approach proposed by Schneider et al. (2013) to address how climate change affects river flow regimes in Europe, 12 IHA were selected in this study (Table 6).

The values of IHA obtained for each time series and for the study period are then submitted to a Mann–Kendall trend analysis, a widely used test in the hydrological field (Fatichi & Caporali, 2009; Morbidelli et al., 2020).

2.5 | Linking IHA to water-related ecosystem services

The impacts of hydrological and hydro-morphological changes, with respect to the river flow variable, contribute to great pressure on the

TABLE 5 Climate change models used for temperature and rainfall projections with the corresponding emission scenarios.

Institutional models							
Code	Country	Related information	ESM 2 M	HadGEM	IPSL	MIROC	NoerESM
Forcing scenarios	Description		GFDL (US)	Met Office climate prediction (UK)	Institute Pierre-Simon Laplace (FR)	University of Tokyo (JA)	Norwegian meteorological institute (NO)
RCP 2.6	Most stringent scenario: CO ₂ should start declining by 2020		Biogeochemical cycles and anthropogenic factors	Most suitable for Mediterranean countries	Atmosphere-Land-Ocean-sea ice model	Flux coupling	Based on CESM2
RCP 4.5	Emissions peaking in 2040, ~2°C increase in temperature.						
RCP 6.0	Peaks in 2080						
RCP 8.5	Continuous growth until 2100, the basis for the worst-case climate scenario						

Abbreviation: RCP, representative concentration pathway.

TABLE 6 Indicators of Hydrologic Alteration (IHA) calculated from SWAT model discharges.

Parameter	Unit	Group
January mean river flow	$m^3.s^{-1}$	Group 1: Magnitude of monthly water conditions
April mean river flow	$m^3.s^{-1}$	
July mean river flow	$m^3.s^{-1}$	
October mean river flow	$m^3.s^{-1}$	
1-day minimum river flow	$m^3.s^{-1}$	Group 2: Magnitude of extreme water conditions
1-day maximum river flow	$m^3.s^{-1}$	
Day of 1-day minimum	Julian date	Group 3: Timing of extreme water conditions
Day of 1-day maximum	Julian date	
Number of high pulses	Number	Group 4: Frequency and duration of high and low pulses
Number of low pulses	Number	
Number of flow rises	Number	Group 5: Rate and frequency of water condition changes
Mean rise rate	m^3/s	

whole range of WES, especially the regulating and supporting categories. Focusing on the evaluation of the hydrological functionality of riverine ecosystems, the resulting river flow outputs are hence linked with their respective impacts on the WES (Grizzetti et al., 2016; Kagalou et al., 2012). Through this linkage and looking at the present WES in the three different subbasins, the qualitative assessment of the potential changes in the WES is performed as an extension to assist already existing management plans.

The hydrological alterations are classified into parameter groups. Each group of parameters is associated with a possible area of implication and eventually with corresponding ecosystem services in the studied river basin. According to established literature, the components of river flow are found to be directly affected by all categories of WES, meaning provisioning, regulating and cultural (Table 7). Despite the presence of redundancy where different IHA groups affect the same service, it is necessary to look at the difference in the manner each group affects the same service. For example, the magnitude of monthly water conditions clearly affects the quantity of water supply needed for urban, industry and irrigation services. Similarly, the magnitude and duration of annual extremes also affect the water supply but with a focus on discrete events that can impact the service rather than the continuous one represented by the magnitude of monthly water conditions. In addition, the flooding behaviour and protection can be attributed to the monthly condition, and the corresponding frequency and duration, in a way to portray floods not only as 'negative events', but detrimental to biodiversity and ecosystem sustainability. Such reasoning justifies the choice of using several groups of IHA for each service to encompass several aspects of each WES.

TABLE 7 Indicators of hydrologic alteration (IHA) groups linked with possible water ecosystem services from existing literature. Each group can be attributed to the WES through the possible area of implication. Different aspects of the same service can be investigated through the distinction between river flow components.

River flow changes and impacts	IHA group	I	II	III	IV	V
		Magnitude of monthly water conditions	Magnitude and duration of annual extreme weather conditions	Timing of annual extreme water conditions	Frequency and duration of water conditions	Rate and frequency of water conditions changes
Possible area of implication		Aquatic habitat suitability, water supply, fishing, activities, river regime	River productivity, biodiversity, water quality, sedimentation	Migration and reproductive behaviour of species, management of river activities	Agricultural practices, fitness of species	Agricultural practices, stranding behaviour of organisms,
Provisioning		Water supply, irrigation, biotic material, hydropower	Biotic material, aquaculture, water supply	Biotic material	Biotic material, aquaculture,	Biotic material, irrigation
Regulating		Flood protection, habitat suitability	Erosion prevention, flood protection, habitat suitability	Habitat suitability	Habitat suitability	Flood protection, habitat suitability
Cultural		Recreational, intellectual	Recreational, intellectual	Recreational, intellectual		
References		(Grantham et al., 2020), (Gao et al., 2018), (Vismara et al., 2001)	(Forner et al., 2018), (Choi et al., 2018), (Britton & Pegg, 2011)	(Peng et al., 2019), (Gao et al., 2018)	(Zhang et al., 2018) (Mallen-Cooper & Zampatti, 2020)	(Ponce-Campos et al., 2013), (Nilsson & Svedmark, 2002)

3 | RESULTS

3.1 | Calibration and validation

The sensitivity of seven initial parameters and nine parameters (Figure 5) shows that besides the obvious dependence of river flow estimation of curve number, chosen groundwater and soil parameters provide a sound basis to start the calibration in SWAT-CUP. Accounting for statistical similarity in the calibration and validation process, the time periods chosen for the process are from 2003 until 2010 for the calibration and 2011 until 2020 for the validation. The performance of the model (Table 8) is deemed satisfactory looking at the NSE and RSR and very good when looking at the PBIAS.

The simulated river flows obtained (Figure 6) are the result of 11 iterations of 500 runs each, with 14 adjusted parameters. The range of the curve number is imposed to a maximum of 20% to ensure the correct representation of land cover and land use compared with real scenarios. This process is performed for the model at one station near the outlet of the study area, where data are extended and verified for the study period.

3.2 | IHA result evaluation and trend analysis

The analysis performed on the obtained river flows resulted in spatial maps for the 12 IHA parameters for all the emission scenarios of the different climate change models considered. The models show an adequate consistency for the same scenario; hence the results (Table 9)

are explored with respect to the forcing emissions allowing the identification of the main environmental and management issue for the three subbasins (i.e., upper Casentino, the Southern Val di Chiana subbasins and the middle Valdarno subbasin).

3.2.1 | Group I: Magnitude of monthly water conditions

Looking at the magnitude of monthly water conditions (Group I), represented by January, April, July and October mean river flows, a negative trend dominates for the three subbasins and the several emission scenarios. More specifically, January, July and October are expected to exhibit a decrease in mean river flow in the Casentino and Val di Chiana subbasins, for the RCP 6.0 and RCP 8.5. However, the month of April exhibits a possible increase in the mean river flow for the three subbasins, regardless of the scenario modelled. From an impact perspective, it is possible to distinguish between the similarity in river flow changes between Casentino and Val di Chiana subbasins from one side and Valdarno Superiore subbasin from the other. More positive river flow trends are observed in the latter, especially for the April and October durations. The results hint at dry seasons become drier, while wet seasons become wetter. The current management scheme identifies a change of 20% in streamflow as an initial medium state of alteration, while a change starting from 40% is critical. Such criticalities are observed for the three subbasins with significant *p*-value test results with a possible 49% decrease in flow in the Valdarno region for RCP8.5.

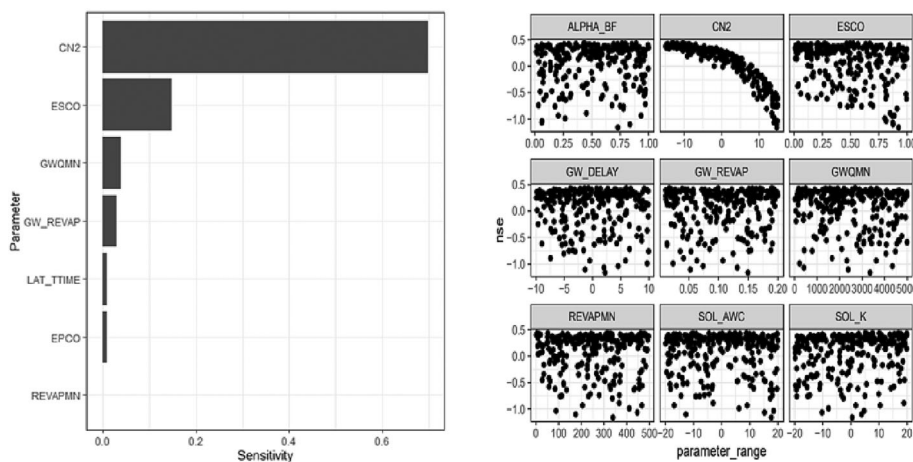


FIGURE 5 Sensitivity analysis results showing the prevalence of the curve number variable in affecting the hydrological SWAT model outputs.

TABLE 8 Model performance criteria for gauging stations of Casentino and Val di Chiana subbasins.

Statistical index	Calibration period		Validation period	
	Casentino Gauging Station	Val di Chiana Gauging Station	Casentino Gauging Station	Val di Chiana Gauging Station
NSE	0.60 (satisfactory)	0.64 (satisfactory)	0.63 (satisfactory)	0.52 (satisfactory)
RSR	0.63 (satisfactory)	0.67 (satisfactory)	0.62 (satisfactory)	0.59 (good)
PBIAS	7.7% (very good)	10.1% (good)	9.5% (very good)	12.1% (very good)

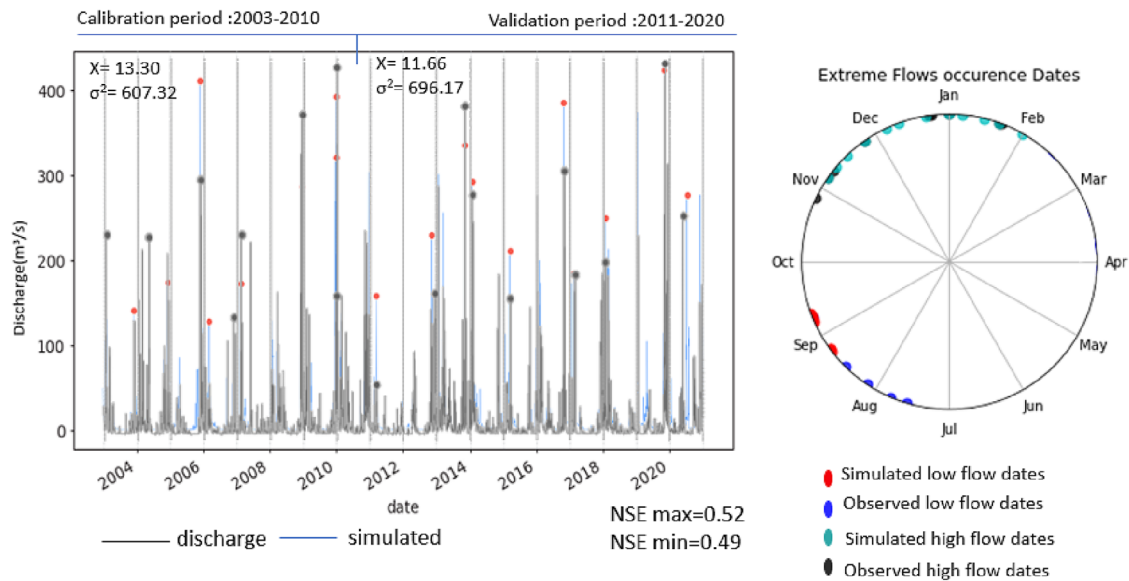


FIGURE 6 Calibration and validation results for the model for the gauging station in Casentino. NSE metrics are presented for the estimation of high and low flows. In addition, the dates of occurrence of low and high flows are shown, with low flows being the 7-day average flows that recur once in 3 and 10 years (7Q10 and 7Q3)s and high flows being all peak flows that are greater than the 95th percentile (POT95).

3.2.2 | Group II: Magnitude and duration of annual extreme weather conditions

This initial observation from the magnitude component of the river flow is complemented by the magnitude and duration of the extreme weather conditions (Group II). Throughout the whole river basin, the minimum and maximum river flow trends showed that extreme conditions reveal trends that suggest extremes are to become more severe with an increase in the maximum river flow values and a decrease in the minimum river flow values. Minimum flows present a range of decrease between 10% and 55% with Val di Chiana subbasin showing the most significant flow decrease. Similarly, the same subbasin presents increases in flood magnitude that can reach 66% but with a *p*-value bigger than the confidence interval of 95%. The highest significant increase is observed in Valdarno Superiore with a value of 38% and a *p*-value of 0.0282.

3.2.3 | Group III: Timing of extreme weather conditions

Moreover, the intensification of extremes is expected to be accompanied by a shift in the timing of extremes (Group III). Hydrological droughts, or minimum stream flows, are expected to occur later than usual with a positive trend of the Julian date of occurrence, while the date of flooding events or Julian date of maximum river flow occur earlier than usual. However, changes in terms of timing do not exceed the weekly timesteps. The highest delay of the 1-day minimum is observed in the Casentino subbasin (20 days), shifting from the beginning of January to the end of the month or the start of February. 1-day maximums present an earlier occurrence of a maximum of

15 days in the Casentino subbasin. The information obtained from the shifts in group III is not definitive to define a valid change in seasonality of occurrence.

3.2.4 | Group IV: Frequency and duration of water conditions

However, not all flooding events are catastrophic, small floods in fact are considered essential for the sustainability of the habitat. This is present in the concept of high and low pulses (Group IV), where the results are more heterogeneous than other groups. Similar results are obtained for the Casentino and Val di Chiana subbasin, where the RCP 4.5 and 6.0 scenarios lead to negative and positive trends in high and low pulses respectively. The difference lies in the most stringent scenario (RCP 8.5) where high and low pulses are expected to increase in the Val di Chiana subbasin. On another side, Valdarno superior shows a negative trend of low pulses for all scenarios, with the only positive trend observed at the RCP 4.5 scenario for the number of high pulses.

3.2.5 | Group V: Rate and frequency of water condition changes

The final characterisation of the changes in the river regime is represented by the rate and frequency of water change conditions (Group V). For the more stringent scenarios of RCP 6.0 and RCP 8.5, the negative trend of the number of river flow rises and mean rise rate dominate, suggesting an overall decreasing trend in the water-changing conditions.

TABLE 9 Mann–Kendall trends observed for the 12 indicators of hydrologic alteration studied. N, negative trend; P, positive trend; H, presence of hotspots with an opposite trend. The change range [] of the moving average for the modelled period (2021–2099) with respect to the ranges in observed data (2000–2020); a combined *p*-value is presented for each subbasin.

IHA parameter	Casentino subbasin			Val di Chiana subbasin			Valdarno Superiore subbasin		
	RCP 4.5	RCP 6.0	RCP 8.5	RCP 4.5	RCP 6.0	RCP 8.5	RCP 4.5	RCP 6.0	RCP 8.5
January mean river flow	N/H	N/H	N	N/H	N/H	N	P/H	N	N
Change range (%)	[−29;10]	[−35;2]	[−37; −0.5]	[−21;16]	[−34;3]	[−39; −12]	[−15;22]	[−34; −9]	[−41; −20]
MK merged <i>p</i> -value	0.0234	0.0495	0.0431	0.0124	0.0574	0.0425	0.0518	0.0235	0.0175
April mean river flow	P	P/H	P	P	P	P/H	P/H	P/H	P/H
Change range (%)	[5.7;19]	[−9;23]	[3; 38]	[3;15]	[1;29]	[−3; 42]	[−2;16]	[−3;27]	[−10;38]
MK merged <i>p</i> -value	0.0143	0.0381	0.0328	0.054	0.00916	0.026	0.0222	0.03281	0.0487
July mean river flow	N	N/H	N/H	N/H	N	N	N	N/H	N/H
Change range (%)	[−35; −20]	[−34;3]	[−47; 0.5]	[−16;10]	[−28; −8]	[−39; −7]	[−24; −2]	[−38;3]	[−45; 3]
MK merged <i>p</i> -value	0.00737	0.0225	0.0759	0.0327	0.0514	0.00496	0.02183	0.079	0.0439
October mean river flow	P	N/H	N/H	P	N/H	N/H	P/H	P	P/H
Change range (%)	[3;20]	[−15; 10]	[−25; 3]	[13; 25]	[−2; 32]	[−21; 17]	[−4;12]	[2;29]	[−10;38]
MK merged <i>p</i> -value	0.0253	0.0657	0.0689	0.0981	0.0387	0.0289	0.0195	0.0235	0.0587
1-day minimum river flow	N	N	N/H	N/H	N	N	N/H	N	N
Change range (%)	[−25; −2]	[−38; −10]	[−35;12]	[−12;5]	[−23; −5]	[−55; −10]	[−21;10]	[−35; −10]	[−44; −5]
MK merged <i>p</i> -value	0.0522	0.0498	0.0868	0.0495	0.0320	0.0137	0.0144	0.0112	0.0553
1-day maximum river flow	P	P	P	P	P	P	P/H	P	P
Change range (%)	[2;15]	[8;23]	[12;39]	[6;29]	[25;38]	[50;66]	[−10;25]	[2;28]	[25;38]
MK merged <i>p</i> -value	0.0282	0.0805	0.0141	0.0469	0.0605	0.0953	0.0910	0.0711	0.0282
Day of 1-day minimum	P/H	P/H	P	P/H	P/H	P/H	P	P/H	P/H
Change range (day)	[−2;8]	[−8;20]	[10;11]	[−3;7]	[−5;10]	[−8;15]	[2;9]	[−5;10]	[5;16]
MK merged <i>p</i> -value	0.0122	0.0685	0.0429	0.0532	0.0860	0.0323	0.0059	0.0266	0.0122
Day of 1-day maximum	N/H	N/H	N	P/H	N	N/H	N/H	N/H	N/H
Change range (day)	[−10;5]	[−15;3]	[−15; −10]	[−5;5]	[−10;−5]	[−15;5]	[−18;5]	[−12;2]	[−15;2]
MK merged <i>p</i> -value	0.0963	0.0514	0.0182	0.0335	0.0464	0.0332	0.0577	0.0255	0.0963
Number of high pulses	N	P/H	N/H	N	P/H	P/H	P/H	N	N
Change range (%)	[−10;−5]	[−5;5]	[−15;5]	[−25;−15]	[5;15]	[−8;20]	[−10;15]	[−18;−2]	[−25;−12]
MK merged <i>p</i> -value	0.0641	0.0463	0.0113	0.0298	0.0905	0.0085	0.0334	0.0826	0.0641
Number of low pulses	N/H	P	P/H	N/H	P/H	P/H	N/H	N/H	N/H
Change range (%)	[−12;8]	[8;12]	[−2;26]	[−10;5]	[−2;25]	[−7;35]	[−25;3]	[−30;14]	[−40;11]
MK merged <i>p</i> -value	0.0529	0.0370	0.0712	0.0765	0.0761	0.0807	0.0388	0.0332	0.0529
Number of flow rises	P	N/H	N	P/H	N	N	N/H	N/H	N/H
Change range (%)	[8;16]	[−20;5]	[−25;−2]	[−7;16]	[−19;−16]	[−25;−13]	[−20;3]	[−25;3]	[−32;2]
MK merged <i>p</i> -value	0.0763	0.0903	0.0599	0.0359	0.0681	0.0810	0.0148	0.0253	0.0763
Mean rise rate	P	N	N	P/H	N	N	P/H	N	N
Change range (%)	[10;18]	[−25;−12]	[−38;−27]	[−27;11]	[−27;−23]	[−35;−12]	[−10;15]	[−25;−12]	[−33;−10]
MK merged <i>p</i> -value	0.0934	0.0813	0.0109	0.0215	0.0289	0.0339	0.0668	0.0760	0.0934

3.3 | IHA trends and implications on water-related ecosystem services

Starting from the information provided by DSPiR analysis (Section 2.1) is possible to identify the critical WES potentially influenced by river flow variable changes in the river basin. Moreover, the IHA-WES correlation table (Table 7), allows the identification of those WES that can be negatively influenced by climate change effects on river flow regime (Figure 7).

The IHA trend results associated with the WES within the three subcatchments are presented for each group of parameters (Figure 8). Regarding the monthly water conditions (Group I), a negative trend in January and July dominates, for the 20 models, affecting the water supply used for industries, irrigation and urban purposes in the three subcatchments, and the hydropower generation present in the upstream of Valdarno superior. During April and October, the results show that Val di Chiana and Valdarno superiore subbasins could exhibit a positive trend in river flow quantities, while Casentino river basin is expected to have a negative trend in runoff.

This change in river flow quantities is completed by the magnitude, duration and timing of annual extremes (Groups II and III), where the 20 models show that hydrological droughts (or low flows) are expected to be lower and floods (high flows) to be higher. In addition to affecting the provisioning services of water supply and irrigation,

the regulating services of erosion prevention and flood protection are affected by this change of extremes. Adding the behaviour of pulses and rises (Groups IV and V), the stress on the habitat and the riparian zone ecosystem is presented by the prevalence of a lessening of high and low pulses and the mean rise rate, which threatens the habitat suitability. Given the cultural importance of the existing streams, especially during spring and summer, these changes in river flow also influence the existing recreational and cultural activities partaken. Hence, from a qualitative perspective, the trends in IHA are expected to affect the existing WES negatively, and through the implications identified (Table 10), a useful indication can be provided for the management authorities on adapting future management plans to climate change drivers.

4 | DISCUSSION

The changes observed in river flow hold great importance from an ecosystem services perspective (Armsworth et al., 2004). Habitat suitability, migration behaviour, irrigation water and flooding behaviour are highly affected by the results obtained (Choi et al., 2018; Gao et al., 2018; Zeiringer et al., 2018).

Despite the lack of expansive studies on ecological flow relationship in the studied river basin, looking at the results of each of the five

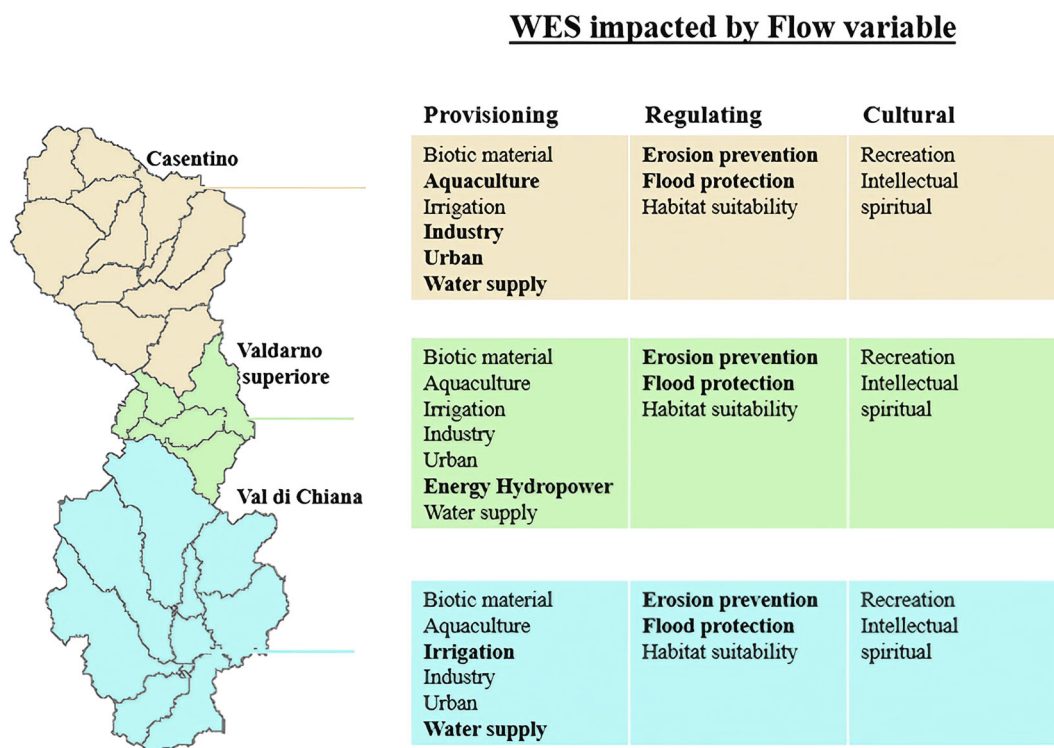


FIGURE 7 Major water ecosystem services (WES) assessed in the three subcatchments, with relation to the modelled stream flow variable; the terms in bold are the dominating WES in each subbasin given the existing management and practices. The relationship between the flow variable and WES is established from the Driver, Pressure, State, Impact, Response (DPSiR) model and existing literature (Grizzetti et al., 2016; Kagalou et al., 2012).

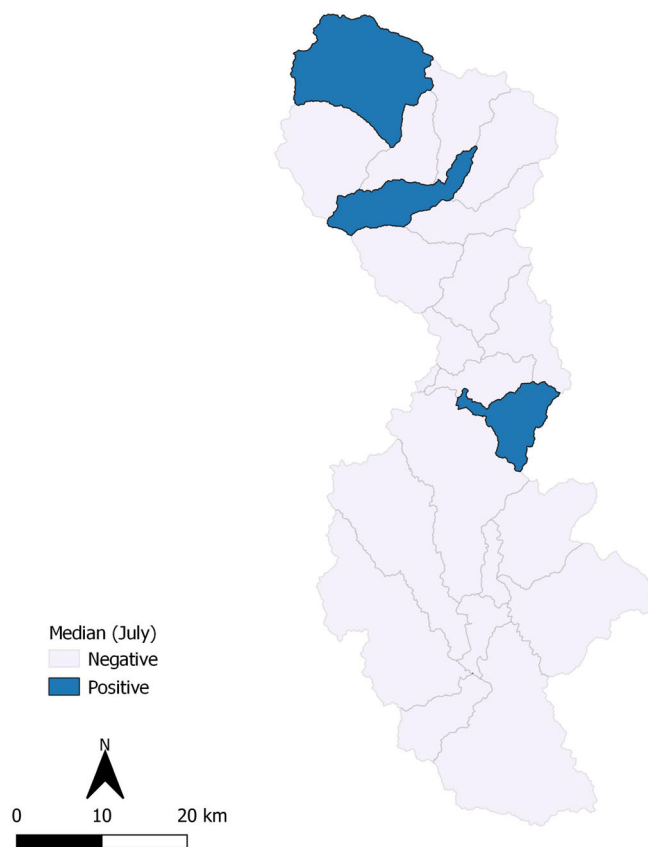


FIGURE 8 Example map output for the flow trends in July for RCP 6.0 and HadGEM model with identified hotspots.

groups of parameters aims at identifying the possible effects on the ecosystem and its services: The magnitude of water flow (L^3/T) is the first elementary indicator of water availability in the river basin. This indication can be extrapolated to look at changes within the seasons, years and eventually their corresponding outcomes. The decreasing trend in river flow, present throughout the year (except the spring season represented by April), hints at a potential future water scarcity caused by the changes in supply. From an ecological perspective, such a decrease in river flow affects important processes linked to the present biota. Along with the dominating agricultural nature of the river basin, extended cultivation, water-intensive crops and the pollutants load, the decrease in the runoff will create additional stress on the services and water yield provided by the freshwater ecosystem (Pacetti et al., 2021). Regarding the magnitude of monthly water conditions, a negative trend prevails mainly in July, showing summers with drier river flows in both subbasins. However, several hotspots appear where the trend is not in accordance with its surrounding (with a significant result test), suggesting special attention to it. Spring season (represented by the mean river flow of April) exhibits a notable positive trend in river flow for all emission scenarios. These changes in river flow values are accompanied by changes in the timings and durations with discrepancies between the two subbasins. In general, the Val di Chiana subbasin exhibits more hotspots with regard to its northern neighbour, especially with regard to the number of high and

low pulses. The shifts in occurrence of peak flow and their magnitude, are in accordance with the work suggested by Schneider et al. (2013), where earlier peaks are expected in the season. In the three subbasins, it is expected that the extreme conditions will intensify, with the Casentino subbasin showing a higher number of reaches affected. In addition, it is also possible to talk about a 'migration' of these extremes represented by the Julian Date of occurrence. The results show that the dry or low flow days occur later than usual, while high flows are to be observed earlier than foreseen. Such changes in magnitude and timing of floods, and potentially droughts, hold the ability to affect the riverine ecosystem through changes in water quality, sedimentation, erosions and aquatic community (Garner et al., 2015; Leigh et al., 2014; Talbot et al., 2018). One of the most adopted ecological theories in the river ecosystem is the flood pulse concept (Keizer et al., 2014), where floods are not seen as purely catastrophic, but as a connection within the aquatic/terrestrial transition zone. Dubbed as the 'central aspect for the integrity of river-floodplain system', both Val di Chiana and Casentino subbasins exhibit an increase in the number of pulses, with Casentino subbasin only showing a decrease in the pulses for the RCP8.5 scenario. This holds an effect on the inundation patterns for the surrounding habitat, and consequently on soil, aquatic organisms and plantations (Heiler et al., 1995; Sánchez-Andrés et al., 2010; Shivers et al., 2018). These effects are accompanied by changes in the benefits obtained from the river ecosystem, where a connection can be established between the trend observed and the service provided (Chang & Bonnette, 2016; Momblanch et al., 2020; Shaw et al., 2011).

This study also highlights the potential of integrating the WES concept within DPSIR-based management plans, by assessing how climate change can exacerbate the consequences of existing pressures and determine a potential reduction in the WES produced.

Kelble et al. (2013) suggested adding ecosystem services to the DPSIR model to promote the analysis of economic trade-offs and proactive measures, instead of a consequential and usually negative, implication output of the DPSIR model. The promotion can be done by looking at the categories of Impact and State of the model and linking them with the corresponding ecosystem services, since the benefits obtained from an ecosystem are directly linked to its state and impacts observed. It must be noticed that climate change as a driver is not only explicitly addressed in the existing DPSIR analysis, so the results obtained allow tackling this driver within the existing methodology provided, but also extending to the concept of WES, which allows setting targets and priorities. As an example, by looking at climate change as the driver and the hydrological models obtained characterised the pressures induced by hydrological alterations, the impacts of biodiversity loss and habitat alteration are then extended to the identified WES, which feeds in addition to the required response and action plan. In addition, looking at the results from a spatial point of view can help identify possible hotspots and areas of intervention. For example, the negative trend in river flow changes is dominating for the month of July for the RCP 6.0 scenarios. However, hotspots with positive trends appear in the Casentino and Valdarno Superiore subbasins (Figure 8). This draws attention to either a further

TABLE 10 The major effects of trends of each Indicator of Hydrologic Alteration (IHA) on the water ecosystem services (WES). x: identify the WES mainly impacted by each IHA.

IHA group	WES							
	Provisioning				Regulating			Cultural Recreation
	Water supply	Hydropower	Irrigation	Agriculture	Habitat suitability	Erosion	Flood	
I	x	x	x	x	x	x	x	x
II	x			x	x	x	x	x
III			x	x	x	x	x	x
IV			x	x	x	x	x	
V			x	x	x			

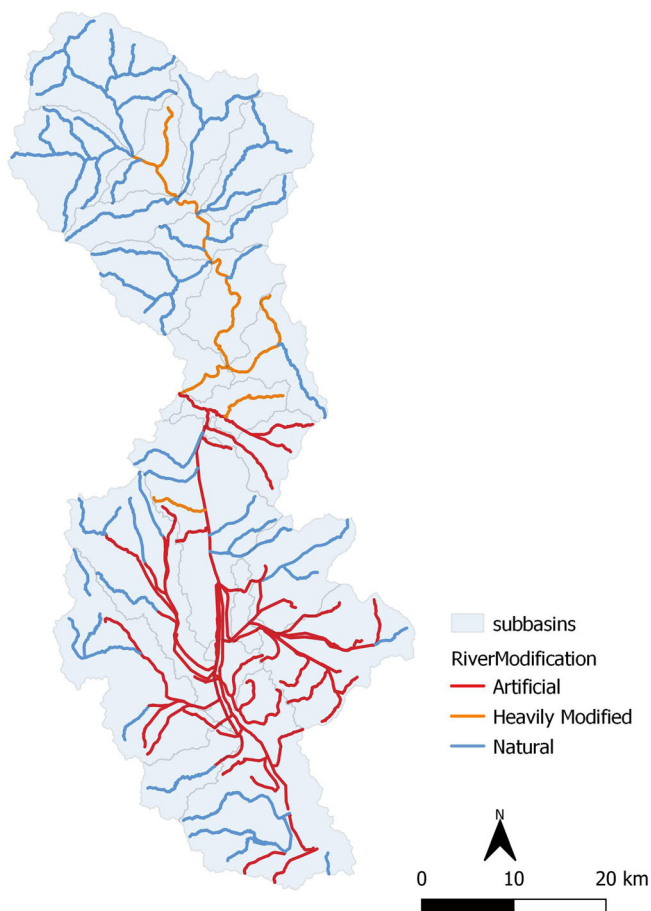


FIGURE 9 River reaches modifications where suggested hydrodynamic model holds the potential to help assess the current anthropogenic pressures due to river training performed.

analysis of the results obtained in these locations, accounting for a smaller scale, or the significance of the trends observed in these locations. Looking at the current management scheme, the river authority identifies anthropogenic pressures as key pressure to be further explored and integrated into the framework. In addition, the physical alteration of channels with the withdrawal canals is a subset with a high priority. Flood regime changes due to the river training (and

eventually anthropogenic intervention) performed at the reach scale are suggested to be performed using hydrodynamic models that allow to perform an assessment at the reach level (Hall et al., 2014). Figure 9 presents the reaches of the studied area where river training on river beds or banks has been performed. Such model is not part of the presented study and we suggest that this detailed assessment will allow us to compare the status quo with projected changes in the SWAT model.

The presented study can be advanced presented in terms of enhancing the hydrological process presented, especially evapotranspiration estimation. Zangiabadi et. al (2021) and Aouissi et. al (2016) highlighted the accuracy of three evapotranspiration in SWAT prediction of streamflow on basin scale with possible streamflow overestimation, while Jung et.al (2016) suggested that the use of the estimation methods requires an initial regional calibration of evapotranspiration data, which was addressed in the SWAT model presented with the use of actual available evapotranspiration data for the reference period.

5 | CONCLUSION

In conclusion, the study presented the hydrological models for the Upper Arno River basin under multiple climate change and emission scenarios. With respect to the Water Framework Directive methodologies, this analysis consists of the first level of screening and preliminary standard that serves eventual river basin management plans and a holistic approach. The results obtained from the use of IHA, related to WES, highlighted that agriculture and industries are to be affected under the modelled climate change scenarios, with the provisioning and supporting services showing negative trends for their corresponding IHAs. The habitat suitability was also found to be affected by the change in magnitude and dynamics of the river flow variable. Hence, the results obtained help assist the existing DPSIR management plan that undermines climate change as a driver. With the integration of the notion of water-related ecosystem services, the response and impact categories of the DPSIR plan can then be assessed more thoroughly to eventually plan the suitable way forward for action.

AUTHOR CONTRIBUTIONS

Jerome El Jeitany: Conceptualisation, Methodology, Data curation, formal analysis, software, development, Writing—original draft, visualisation. **Tommaso Pacetti:** Supervision, Methodology, Data curation, Writing—review and editing. **Enrica Caporali:** Supervision, Validation, Resources, Writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors have no relevant financial or non-financial interests to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, Jerome El Jeitany, upon reasonable request.

ETHICS STATEMENT

Not applicable.

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