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Climate service derived indicators to assess the impact of climate change on local river assimilative capacity

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ABSTRACT

Continental climate services provide information on essential climate variables and indicators, which can further be used to address challenges at the local scale. Climate impact indicators are the core data for evaluating the change of the assimilative capacity of the river systems under future projection scenarios. Here, the indicators from the Copernicus pan-European climate service are used to develop and showcase a water management information service for the Asopos River, Greece. River flow indicators are incorporated in the estimation of emission limit values which serve as environmental pressure indicators, for the reference and two future periods (early- and mid-century). Assimilative capacity is evaluated for six heavy metals, namely Cr, Cd, Cu, Pb, Ni and Zn. Socioeconomic indicators are also utilized to incorporate changes of economic activities in the assessment. Results from the large ensemble of 209 scenarios, consisting of different global circulation, regional climatic and impact model combinations as well as industrial activity evolution, indicate that a decrease (up to 33% of 209 scenarios) of assimilative capacity is more probable than an increase (up to 18% of the scenarios) in a future climate. Local industrial activity evolution also has an effect on the uncertainty of the results for the early-century period. We conclude that although climate impact indicators are free of the need for laborious processing, they cannot cover all requirements for local analyses. Consequently information from continental climate services and local data should be used for climate change impact investigations.

Practical implications

Water related challenges receive global interest particularly under a changing climate that has emerged as a major pressure to the water sector. Today a wealth of climatic information is available, produced and provided under various climate services. Water managers, stakeholders and various users are increasingly in need of these services to guide impact assessments and further to support policy- and decision-making. However, due to the complexity in model simulations and the variety of the climatic information available, service uptake is challenging for non-climate experts. In addition, the lack of regional tailoring of the available climatic information is a limitation since actual water-related challenges are often on the local scale. Moreover, uncertainty is inherent in climate projections and consequently propagated in impact assessments. Quantification and communication of uncertainty is not straightforward and this hinders the use of climate services by

consultants and water management experts who frequently deal with water challenges.

Here we put a practical implication of climate services for water and environmental consultants and managers by using a continental climate service to produce actionable information for climate impact analysis on the local scale. In particular, the use of the Copernicus Climate Change Service (C3S) through the application of post-processed, user-tailored climate indicators is presented. The work demonstrates, through a case study, that the combination of post-processed climatic information with local data can provide support for assessments of climate change impact on the environmental status of a river under various uses.

In addition, we demonstrate the uncertainty in the available climatic projections and assess their propagated impact on the impact indicators. We incorporate ready to use climate indicators derived from combinations of 3 Regional Climate Models, 4 Global Circulation Models and 4 Representative Concentration Pathways. Additionally, climate impact indicators are used from three hydrological models, providing in total an ensemble of 209 different

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scenarios (model combinations in Appendix, Table A1). The uncertainty can then be communicated to the users, in the present case an environmental regulatory authority, to support the decision-making process concerning the environmental policy for a river under climate change pressures. Consequently this effort can utilize uncertainty for better informed decision-making.

Another element highlighted here is the use of already available indicators as climate impact indicators for a specific analysis. This study utilizes Emission Limit Values (ELVs) for the industry which are already used for environmental regulation. They incorporate key stressors and factors which influence the water quality of a river; i.e. industry's effluent emissions, environmental regulations, and the river's hydrological regime. Climate change impacts on the values of ELVs reflect climate pressures on both water quality and industry environmental restrictions.

The present case study discusses issues related to the effective integration of climate services in the decision-making process. The use of climatic indicators relevant to the sector of interest, here the water sector, is highlighted under the necessity of bridging the gap between continental scale services and local scale challenges. Climate impact indicators are free of the need for laborious post-processing but cannot cover all aspects of local needs; however, combined with local information, they set added information for integrated, local-scale climate change impact investigations.

Introduction

Associated challenges driven by a warmer climate have put a major pressure on the water sector on the local, regional and large scales (IWA, 2016). However, for the benefit of the climate-sensitive sectors, the global awareness of systemic climate risks is steadily mainstreamed into decision- and policy-making (Hewitson et al., 2017). Access to usable climate information can help societies to better mitigate and adapt to the climate change risks, and therefore there has been a continuous effort on developing the climate service market and supporting its uptake (Bruno Soares et al., 2018; Perrels et al., 2020). Climatic information is available from a large ensemble of climate projections, nowadays operated at high spatial resolution (e.g. ENSEMBLES, NARCCAP, CORDEX experiments), based on various combinations of Global Circulation Models (GCMs), Regional Climate Models (RCMs) and hypotheses for the future evolution of anthropogenic emitted gasses (SRES and Representative Concentration Pathways) (Bruno Soares et al., 2018; Hewitson et al., 2017).

Nevertheless, climatic projections and information are prone to inherent uncertainties due to underlying hypotheses, including simplifications of physical processes and computing power limitations (e.g. spatiotemporal scalability of climate models) (Knutti and Sedláček, 2012). Although understanding of the climate and its numerical representation has improved (Knutti et al., 2013), the uncertainties which characterize the numerical models are further propagated when assessing climate change impacts on water related issues (Blöschl and Montanari, 2010; Chamorro et al., 2016; Clark et al., 2016). Multimodel ensembles with downscaled and bias-adjusted climatic information are commonly used to quantify the climate-related uncertainties (Christensen and Lettenmaier, 2007; Hewitt and Griggs, 2004; Lavers et al., 2020). Moreover, several studies explored the uncertainties related to impact modelling (Chamorro et al., 2016; Krysanova et al., 2017; Pechlivanidis et al., 2017; Samaniego et al., 2017), while effort has also been put on identifying representative subsets from the large ensemble and consequently constrain uncertainty (Kiesel et al., 2020; Pechlivanidis et al., 2018; Wilcke and Bärring, 2016).

Inherited and propagated uncertainty is nevertheless present in decision-making (Knutti and Sedláček, 2012). In spite of the overwhelming volume of information, the evaluation and effective implementation of climatic projections to various climate change impact

assessments usually requires significant expertise. The impact modelling process chain is very long; from selecting climate projections among the wealth of available information, choosing an adequate number (enough but avoid biasing the ensemble) of combinations of GCMs and RCMs that capture the desired range of uncertainty, bias-adjusting the climatic projections, to calibrating impact models (e.g. performance under wet, dry, cold or warmer conditions) and processing model output (e.g. statistical post-processing) in order to use it in an evaluation methodology for impact assessment. Consequently, selected or available climatic projections and their impacts are not easily incorporated in local scale impact studies (Hewitson et al., 2017; Hundercha et al., 2020). A usability gap among climate services and the users is lately, broader identified. The added value of service-dominant logic and the importance of strong engagement between the climate service providers and the users/stakeholders is now widely recognized (Alexander et al., 2019; Contreras et al., 2020; Hewitt et al., 2017; Tart et al., 2020; Vincent et al., 2018). The relationships between climate science/services and society are being investigated, not only under technical but also a substantive and structural prism (Webber, 2019). The need for producing actionable climate information that addresses user needs has been investigated throughout the development of various climate services prototypes (Buontempo et al., 2018; Visscher et al., 2020). Recently, there has been an effort on bridging the gap between climate experts and users through knowledge purveyors (i.e. consultants) by providing ready to use, user-tailored, climate change information in the form of climatic and climate impact indicators, bypassing the previously presented process chain from selecting climate projections to producing data which can be used for impact assessment (e.g. see among others C3S Sectoral Information Services) (Cortekar et al., 2020).

In the current study we investigate the application of user-tailored, climate impact indicators produced by continental climate services to address local scale water management problems. We pose the following scientific questions: 1) How can information from continental climate services be used in local scale investigations? 2) What is the impact of climate change on water management? 3) Which are the sources of uncertainty reflected on the modelling results? Focus is given on the investigation of the variation of the results, as a function of future time horizon. We debate about having managed to produce useful information and further, about having managed to actually solve the problem at hand.

The work presented is organized as follows. In Section 2, the region studied and local data which were incorporated in the analysis are introduced. The selected climate impact indicators and the combined environmental impact indicators used are presented in Section 3, with the experimental design which frames the methodology followed. Section 4 presents the climate change impact on river discharge and river's assimilative capacity, investigates uncertainty aspects regarding possible sources and its effect on modelling results, followed by a discussion on the potential of continental climate services and the uncertainty in impact assessments, in Section 5. Finally, Section 6 states the conclusions of the present work.

Study area and local data

The case study area

The Asopos River basin is located in central Greece (Fig. 1), belongs to the River Basin District of Eastern Sterea Ellada and covers an area of approximately 720 km². Its water bodies receive significant pressures, especially in terms of quality, mainly attributed to the significant industrial activity in the area. The proximity to the capital supported the development of the industrial activity in the Asopos River basin greater area, which rose to be approximately 20% of the total national industrial production (LIFE CHARM - LIFE 10 ENV /GR/00601, Final Report).

The river supports two, frequently opposing interests: 1) the well-being of the local population which is linked to the good environmental

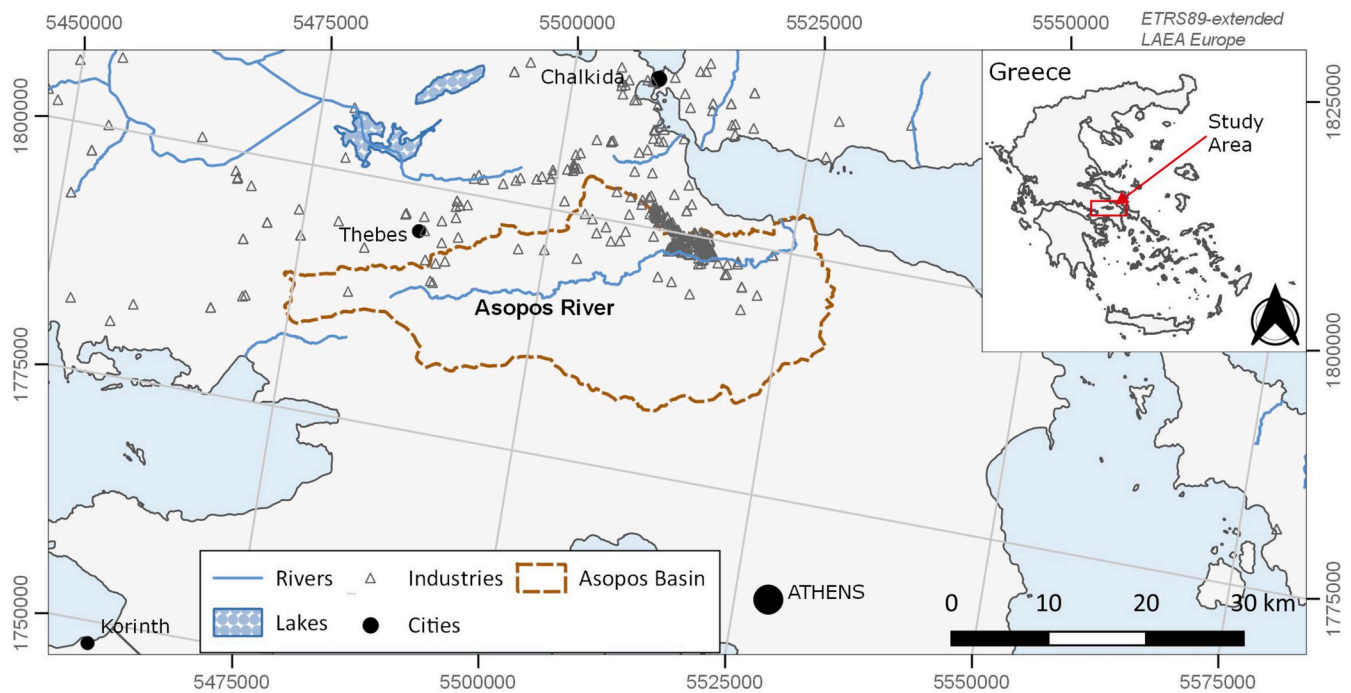


Fig. 1. The Asopos river basin, Greece.

status of the area, and 2) the development of the local and national economy, which is based on the significant industrial activity. While the environmental protection of the quality of Asopos River is an important priority, also following the Water Framework Directive implementation, likewise it is very important for the local economy that the significant industrial sector continues to be viable and not “strangled” by hard-to-comply-with regulations. The river’s capacity for assimilating treated industrial effluents, which supports a fragile balance between environmental status preservation and sustainable economy, is exposed to climatic pressures. There is a need for estimating probable climate change impacts on this capacity in order to ensure environmental sustainability along with economic growth of local industry, a key goal of national and European planning, closely depending on the ability to adapt to future climate conditions.

Local data

The industrial activity together with the characteristics of surface and groundwater bodies in the Asopos River Basin (e.g. [LIFE CHARM - LIFE 10 ENV /GR/00601](#), Deliverable 4.6) is monitored allowing the identification of major pressures and pollutants in the area for the reference period (1971–2000, see section 3.2) used in the present study; Almost 450 industries are located in the area, and the majority of the large facilities associated with the most significant pressures have been documented ([LIFE CHARM - LIFE 10 ENV /GR/00601](#), Deliverables 4.6, 10.1 and 10.2). In total 130 industries producing liquid waste were identified (Fig. 1). The present study only focuses on the 24 facilities that discharge their effluent directly in the Asopos River. The rest of the facilities associated with liquid waste are using other types of receivers (i.e. groundwater, soil) and therefore were excluded from the analysis. The presence of heavy metals in the soil, surface water and groundwater poses serious health risks to the Asopos region’s wider population, is considered the most serious environmental threat for the area and has been receiving increased attention and public concern in the last decades. The present study focuses on heavy metals pollution.

The 24 identified industries are categorized into 6 sectors: i) food production (7 industries), ii) drinks (beverage) production (2 ind.), iii) textile manufacturing (5 ind.), iv) manufacture of chemical products (2

ind.), v) manufacture of plastic (1 ind.), and vi) manufacture of basic metals (7 ind.). ELVs were estimated for 6 common heavy metals, namely Chromium (Cr), Cadmium (Cd), Copper (Cu), Lead (Pb), Nickel (Ni) and Zinc (Zn). The association of each heavy metal to the identified industries was based on available analyses conducted to wastewater samples from various industries ([LIFE CHARM - LIFE 10 ENV /GR/00601](#), Deliverable 4.6). If a heavy metal is detected in the effluent of a single industry of a specific industrial sector, then the whole sector is associated with the specific pollutant and all the related industries are taken into account in the calculations presented in the following (see sections 3.2 and 3.4). Cu, Zn, Ni, Cd and Cr were detected in at least one industry from the 6 sectors examined and therefore were associated with all 24 industries considered in the analysis. Pb was not detected in any industry belonging to the drinks (beverage) production sector and therefore it was only associated with the 22 industries belonging to the 5 remaining sectors.

Methodology

Socio-economic indicators and climate change

The socioeconomic trends and projections for the study area were assessed based on the Gross Domestic Product (GDP) and Land Use indicators. Two types of the GDP indicators were used; (i) The GDP SSP scenarios (the same used by the IPCC), consistent with the shared Socio-Economic Pathways (SSP, [O’Neill et al., 2014](#)) storylines and the OECD (Organization of Economic Cooperation and Development) developed national GDP scenarios, further combined with either a trend or convergence GDP scenario ([Hurth et al., 2017](#)). (ii) The GDP ECFIN (European Commission Directorate General for Economic and Financial Affairs) scenarios, which are based on the European Commission’s ECFIN 2015 trend and convergence scenarios ([Batista E Silva et al., 2016](#)). The trend scenarios assume a continuation of past GDP trends, whereas the convergence scenarios assume that the GDP levels of European regions will converge over time. The influence of the land use trajectories associated with the SSPs scenarios has been taken into account by using the GDP SSPs consistent scenarios. The Land Use datasets, based on outputs of the Land-Use based Integrated Sustainability

Assessment (LUISA) model v. 2014 developed by the European Commission's Joint Research Centre and they are available at an approximately 12 km grid (Lavalle, 2014), were incorporated in the evaluation as additional information.

RCPs scenarios were associated with GDP scenarios based on the major assumptions lying behind the scenarios about future human activity evolution (see Fig. 2a). RCP2.6 was associated with GDP SSP1 and ECFIN convergence scenarios, RCP4.5 was associated with DGP SSP4 and ECFIN trend scenarios, and RCP8.5 was associated with GDP SSP5 and Eurostat trend scenarios. These data show that the GDP projected change, relative to the reference period (1971–2000), follows positive trends for the study area. Additionally, the anticipated changes may reach up to significant increases, depending on the scenario examined. The gridded land use data were aggregated at the basin level. Only grid cells with their center located within the boundaries of Asopos River basin have been used. Land Use expected changes of the Asopos River Basin (Fig. 2b) show that industrial land use presents an increase during the period 2020–2050 (from 13.3% to 20.0%) while agricultural areas present a small decrease (from −9.6% to −9.9%).

We note that the GDP indicator reflects much more aspects of the economy than just the evolution of industry (even if the latter is an important economic sector for a specific area) and socio-economic policies may change more quickly and unexpected than climate change; consequently a more qualitative approach was followed in order to examine the impact of socio-economic changes, quantified through the impact of industry change, in the study area. GDP projections reveal an increasing economic trend (Fig. 2a), while land use projections show an industrial land use increase of 20% by 2050 (Fig. 2b). We consider as a reasonable, simplified approximation the hypothesis of an industry sector (and industry discharges), for the whole future period examined (2011–2070), uniformly increased by 20% in comparison to the baseline historical period. Additionally, taking into account the negative economic trends of the last decade as well as the environmental restrictions and a pan-European effort to reduce environmental pressures, we consider a hypothetical industry reduction scenario. Similarly, in the frame of a qualitative approach, an one-off reduction of the industry sector by 20% in comparison to the historical period was considered, assessing a reduction effect equal to that of the increase scenario used. Further, we incorporate in the analysis an intermediate scenario, according to which the industry remains constant through the whole future period examined (no change).

Climate impact indicators

We use the Emission Limit Values (ELVs) for industries as the main climate impact indicator for the river's assimilative capacity. The ELV for a specific pollutant is defined as the concentration of the pollutant in the industry's effluents, so that all industries can discharge simultaneously into the river without exceeding the Environmental Quality Standards (EQS) at any point along its course. The Environmental Quality Standards (EQS) are limit values which are defined and used for the environmental monitoring of the surface water bodies. They are defined on EU level through the Directive 2008/105/EC of the European

Parliament, as amended by Directive 2013/39/EC and have been incorporated in Greek legislation through the Common Ministerial Decision Num 51354/2641/E103, 08-12-2010. EQS for a specific pollutant is expressed as annual average concentration (AA-EQS), which accounts for the long-term effects of the pollutant in the water body, as well as maximum allowable concentrations (MAC-EQS) which account for short-term concentration peaks and protect against acute toxicity of certain pollutants. Due to the river's importance for the area, except from the national EQS regulations, EQS limits have been issued specifically for the Asopos River (Common Ministerial Decision Nr. 20488/31-5-2010, amended by C.M.D. Nr.100079/22-1-2015). Table 1 presents the EQS values for the heavy metals considered in the current analysis.

ELVs incorporate all the key stressors and factors which influence the water quality of a river, i.e. industry's effluent emissions, the official environmental regulations (EQS), and the river's hydrological regime (discharges), and for this reason they can be used as a climate change impact indicator. Climate change impacts on the values of ELVs reflect climate pressures on both water quality and industry environmental restrictions.

We calculate ELVs based on the average monthly effluent discharges of the relevant industries (see section 2.2), and the average monthly river discharge. The calculations are made through water quality modelling simulations, as presented in section 3.4. The model is forced with the monthly river flow discharges for the various scenarios examined in order to derive the ELV's for each heavy metal examined, taking into consideration both AA- and MAC-EQS (Table 1). Unfortunately there is no available information neither on the seasonal variation of the effluent discharge from the industries nor on their production that would allow estimation of an effluent discharge distribution for each month. Data were only available on an annual basis. Therefore, for the calculation of the ELVs, effluent discharge per industry is considered uniformly distributed in all months. Hence, for substances like Cr, Cd, Cu, where both AA- and MAC-EQS are defined, the critical EQS for ELV's determination is not known before-hand and depends on seasonal patterns of river discharges. Regarding MAC-EQS values, the low flows of August become critical. Moreover, a number of additional industries were not considered in the current study due to missing information regarding their activity, the quantity of effluent or the type of receiver. In order to cope with data deficiency, the EQS limits were reduced

Table 1

Environmental Quality Standards (EQS) values for the heavy metals considered in the assessment.

No	Name of substance	Unit	AA-EQS ⁽¹⁾	MAC-EQS ⁽²⁾
1	Chromium (Cr)	µg/l	50	110
2	Cadmium (Cd)	µg/l	0.25	1.5
3	Copper (Cu)	µg/l	26	37
4	Lead (Pb)	µg/l	7.2	n/a
5	Nickel (Ni)	µg/l	20	n/a
6	Zinc (Zn)	µg/l	125	n/a

¹ AA: annual average.

² MAC: maximum allowable concentration.

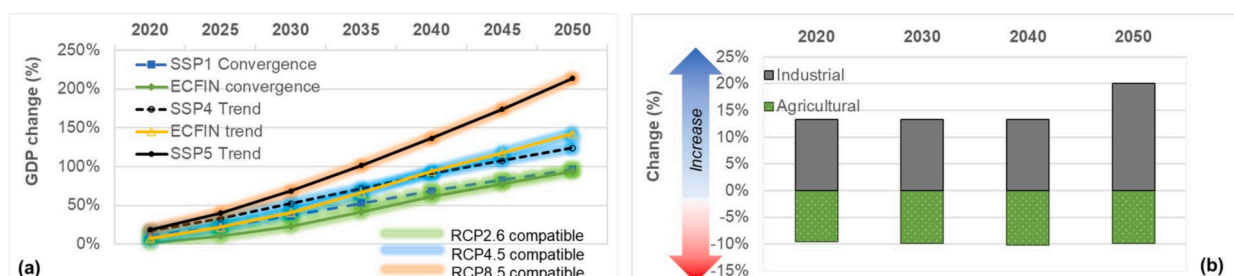


Fig. 2. Projections of socioeconomic indicators for the study area and future periods: (a) Gross Domestic Product (GDP), and (b) land use change.

during the calculation of the ELVs (see Section 3.4).

The climate indicator used for the ELVs calculation is the discharge of Asopos River. Multi-climate and impact projections are available for the study area from the Copernicus Climate Change Service (C3S). Monthly average values of river flow (archived as river discharge [m^3/s], providing mean values of all Januaries, Februaries etc. for each 30-year analysis period) were acquired from the C3S Climate Data Store (CDS, <https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-water-quantity-swicca?tab=doc,5/7/2021>), for the reference (1971–2000) and two future periods; early- (2011–2040) and mid- century (2041–2070), hereafter referred to as 2020s and 2050s, respectively. The river discharge (climate impact indicator) is based on hydrological impact modelling from three different impact models: E-HYPE (Hundecha et al., 2016), VIC (Roudier et al., 2016) and Lisflood (De Roo et al., 2000; Bates and de Roo, 2000; Van Der Knijff et al., 2010). We note that the E-HYPE hydrological model was tested over a verification framework and ensured its credibility for climate change impact assessments (Hundecha et al., 2020). However, since this investigation is driven by large-scale hydrological models and hence is subject to the large-scale modelling challenges, we make the hypothesis that a good overall historical performance (see Hundecha et al., 2016) implies a good performance in the Asopos system where discharge measurements are not available. The hydrological model was driven by an ensemble of bias-adjusted climate model data consisting of 3 RCPs, 4 GCMs and 4 RCMs (Table 2). The RCPs cover a range of policy scenarios for a mitigation scenario (RCP2.6), a stabilization scenario (RCP4.5) and a high greenhouse gas scenario (RCP8.5).

Experimental design

The methodology followed for the estimation of climate change impact on the assimilative capacity of the river is conceptualized in Fig. 3. Due to the importance of the heavy metal pollution for the Asopos River, the metals addressed in the present study are regulated through ELVs legislated specifically for the Asopos river (Common Ministerial Decision Nr. 20488/31-5-2010). However, within the present study we do not use absolute values of ELVs, rather the assessment of climate change impacts is based on the relative change of ELVs between the two future periods (2020s and 2050s) and the reference period. The aim of this approach is twofold.

Firstly, the discharge values used come from impact models, both for the future and reference periods. The hydrologic models were developed, calibrated and tested to provide for large scale applications and ungauged basins (Hundecha et al., 2016; Roudier et al., 2016; De Roo et al., 2000; Van Der Knijff et al., 2010; Bates and de Roo, 2000), but they have not been validated for the Asopos River Basin. This does not lessen the value of these data, on the contrary the hydrologic model results offer a considerable advantage in cases where local

measurements of river discharge are not available, as is the present case. We note that the relative change of ELVs incorporates directly the climatic signal, allowing to investigate the impact of climate change, unaffected by possible mismatches between actual and simulated river discharge.

Secondly, ELVs for the Asopos basin have been regulated and the assumptions behind the established values (C.M.D. Nr. 20488/31-5-2010) are not published. Consequently, differences between the calculated ELVs and their regulatory values may exist. If absolute values were to be presented, it can be assumed that they could possibly not be directly comparable to existing values. This could lead to misinterpretation of the produced results and the information they carry. However, possible differences could not affect the relative change of ELVs due to climate change impact, which is estimated in the current work. In order to avoid such misinterpretations, we use the relative changes of ELVs.

Water quality modelling scenarios

For the calculation of ELVs, the modelling engine of wPOLIS web application (<http://www.emvis.gr/index.php/wpolis>) was used. wPOLIS is an interactive, web-map tool that can be used for calculating the temporal and spatial variation of ELVs for specific pollutants in a river basin. wPOLIS uses a simple 1-dimensional water quality model to describe the fate of sediments and selected heavy metals in rivers and reservoirs. The biodegradation, volatilization and oxidation of heavy metals inside the water column is described through a lumped first order decay coefficient. The effect of sorption i.e., bonding of metals onto solid phases, which greatly affects their dissolved concentrations, is taken into consideration through a partition coefficient, allowing the model to calculate both dissolved and particulate metal concentrations. Water temperature is taken into consideration in these processes, however, the effect of the anticipated small water temperature changes in future periods was not considered critical. Therefore, climate projections of water temperatures were not used. wPOLIS is optimized for short runtimes and large-scale modelling and has been parameterized for the 14 River Basins Districts of Greece. For the calculation of ELVs, the list of point pollution sources of wPOLIS was populated with the identified industries in the Asopos area. Background concentrations have not been considered since such limits have not been established for the Asopos River and measurements in sampling campaigns (LIFE CHARM - LIFE 10 ENV /GR/00601) show low or less than the limit of detection concentrations of heavy metals in upstream points. The model was forced with the monthly river flow discharges (reference period and projections; see sections 3.3 and 3.4) in order to derive the ELV's for each substance taking into consideration both AA- and MAC-EQS values.

In the present study, a basic scenario assumption followed is that industry evolution in the Asopos basin area could follow different trends than the ones followed globally. In order to assess the effect of local economic perturbations, independently from general trends, the scenarios for the increase, decrease or no-change of local industry (see section 3.1) were investigated for all three RCPs included in the climate change scenarios (Table 2). To expand the analysis and further investigate uncertainty, scenarios incorporating a compatibility between the major assumptions lying behind the scenarios about future human activity (RCPs) and the economic projections (industry evolution) were taken into account. Under this analysis expansion approach, the scenario of a decreased industrial activity, compatible with decreased emissions and a greener economy, was combined to climate change data incorporating the RCP2.6. Accordingly, the scenario of an increased industrial activity, compatible with increasing industrial activity and increasing emissions, was combined to climate change data incorporating the RCP8.5. Consequently, the scenario of an unchanged local industrial activity was combined with the third RCP used, the 4.5 emission scenario.

The combination of the investigated time periods (3), the socio-economic scenarios (industrial activity, 3 scenarios), the climate change

Table 2
Available ensemble members for the climate impact indicators.

ID	Model input / forcing			Period	Service Provider / Institute
	RCP	GCM	RCM		
1	2.6	EC-EARTH	RCA4	1970–2100	SMHI
2		MPI-ESM-LR	REMO2009	1951–2100	CSC
3		EC-EARTH	RCA4	1970–2100	SMHI
4	4.5	EC-EARTH	RACMO22E	1951–2100	KNMI
5		HadGEM2-ES	RCA4	1970–2098	SMHI
6		MPI-ESM-LR	REMO2009	1951–2100	CSC
7	8.5	CM5A	WRF33	1971–2100	IPSL
8		EC-EARTH	RCA4	1970–2100	SMHI
9		EC-EARTH	RACMO22E	1951–2100	KNMI
10		HadGEM2-ES	RCA4	1970–2098	SMHI
11		MPI-ESM-LR	REMO2009	1951–2100	CSC

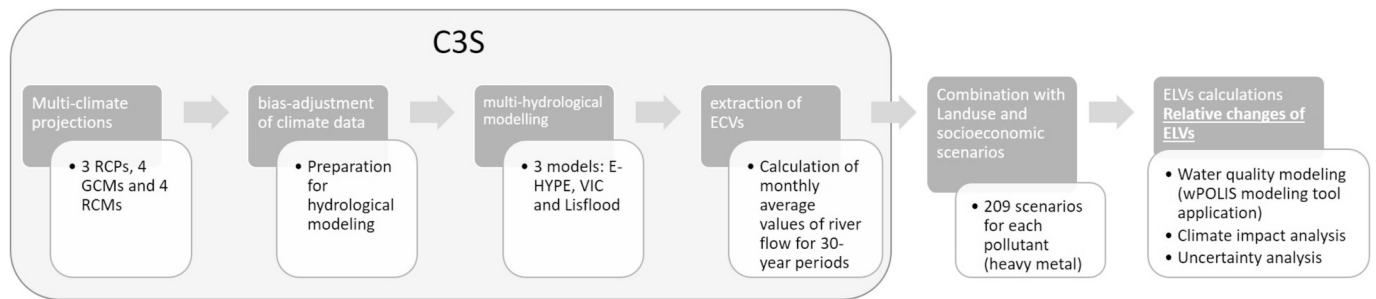


Fig. 3. Experimental design of the methodology followed, from multi-climate projections to the climate impact analysis for the river assimilative capacity.

scenarios (11 combinations, see Table 2), and the climate impact models (3 for each future period) leads to 209 modelling scenarios (model combinations in Appendix, Table A1), examined for each pollutant.

Results

Impact of climate change on discharge

The impact of climate change on the annual discharge for the Asopos River basin is not large, which is also an indication of potential changes in the assimilative capacity of the river. The summer months, especially July and August, present significantly lower discharges than the rest of the year (Fig. 4a), making them critical months for ELVs calculations (regarding MAC-EQS values, see section 3.2). Results show that the median and mean change in discharge is not significant taking also into account the low flows during these months (Fig. 4b and 4c). The median values show a marginal decrease which is getting even smaller in the mid-century (2050s) in comparison to the early century (2020s). Overall, future projections are characterized by large uncertainty, which also increases as a function of time.

Impact of climate change on ELVs

As presented in section 3.2, we base our analysis on relevant changes in the values of ELVs between the future periods and the reference period. Rise in ELVs indicates an increase of the river's assimilative capacity.

Results show that if only climate change is taken into account ("climate change scenarios" incorporating the assumption of no change in local industrial activity, see also section 3.1) the range of ELVs change in the 2020s period is small, and the mean and median is almost 0% (Fig. 5a). This outcome is also valid for the 2050s period; however results for the low/high extremes (1st, 5th, 95th and 99th percentiles) show a slightly larger range. Considering changes in the range of $\pm 10\%$ as marginal, then if local industrial activity will not change, climate change has a marginal effect on the ELVs change for the 2020s period, where 87% of scenarios examined (42% increase + 45% decrease) gave

changes less than $\pm 10\%$ (see Fig. 5b). Moreover, if local industry scenarios are taken into account, then results present a larger spread and the mean and median values show a slight decrease in the ELVs values. In total, 33% of the scenarios present a decrease larger than the marginal 10% (Fig. 5b), whilst 15% of the scenarios present an ELV increase more than 10% for the 2020s period. While similar results are computed for 2050s, it is evident that differences between considering or not local industry changes are smoothed out in comparison to the results from the 2020s period. This can be attributed to the fact that actual differences among the RCPs incorporated (2.6, 4.5 and 8.5) become significant only after the first half of the century. Thus, climate change scenarios are becoming more important for the period 2050s.

Changes of chromium ELVs are presented in Fig. 6. Results are presented for industry scenarios compatible with the global trends (RCPs compatible, 33 results per future period, see Appendix, Table A1). In general, the conclusions drawn are similar for all the metals examined and results for the rest of the metals are not shown here. The decrease of ELVs (indicating a similar effect to the decrease of the river's assimilative capacity) is mainly related to the model combinations under the RCP8.5 scenario (see Table 2 and Fig. 6). However, there are also some model combinations under RCP4.5 which lead to a marginal decrease of ELVs. It is also noted that the uncertainty in the results is larger under RCP8.5 than RCP2.6 and RCP4.5 during the 2020s period and decreases for the 2050s period. The uncertainty in ELV change under RCP2.6 and RCP4.5 increases with increased time.

Uncertainty driven by impact modelling

Here, we assess the impact of uncertainty driven by the impact model to the results. Differences between the results are expected because the models (E-HYPE, VIC and Lisflood) setups are different in terms of underlying datasets, spatial discretisation, parameter identification strategy, and model performance. In particular, Greuell et al. (2015) inter-compared the models showing that they compute evapotranspiration with different algorithms (hence requiring different meteorological variables), they differ in their treatment of surface runoff, soil and groundwater, and river routing and, in addition, they are calibrated

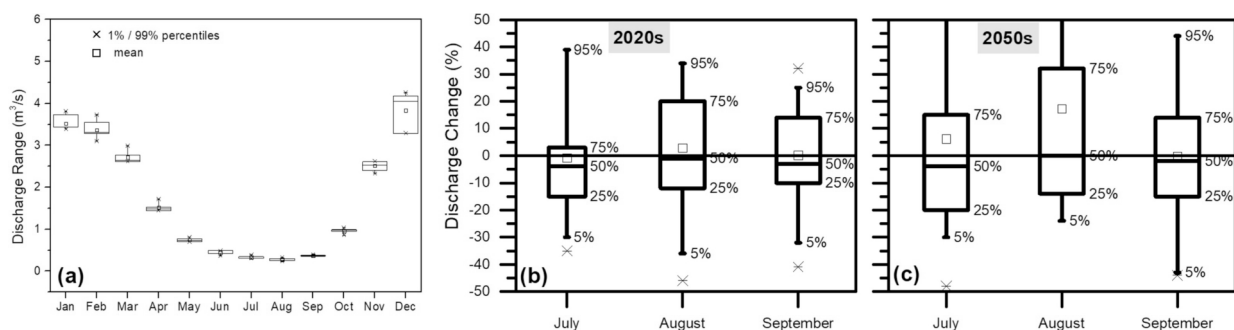


Fig. 4. Monthly average discharge in the Asopos River basin: (a) discharge distribution for the reference period 1971–2000, (b) relative change for the 2020s period, and (c) relative change for the 2050s period.

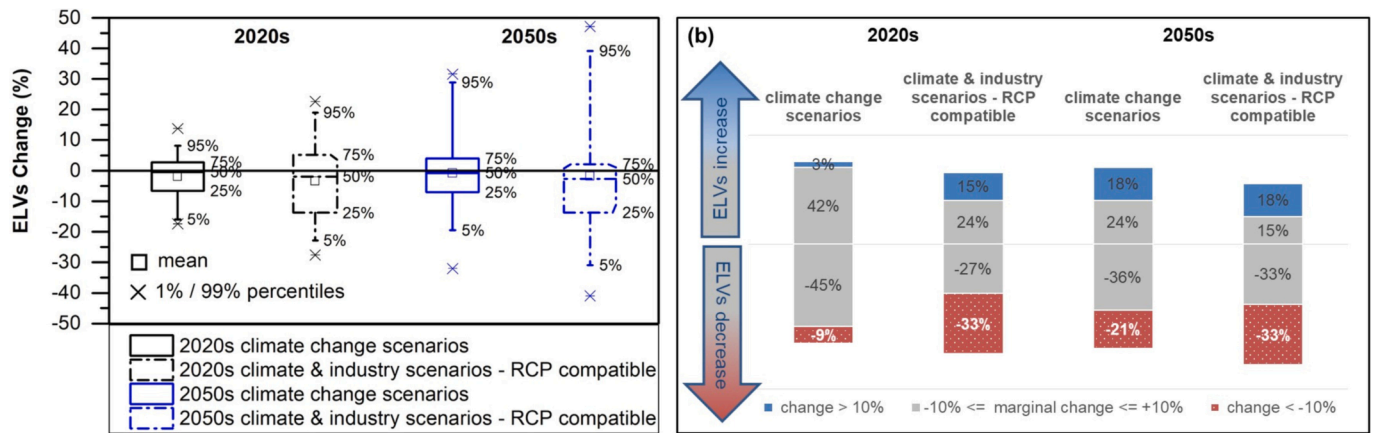


Fig. 5. Relative change of ELVs, for climate change and industry scenarios and for the time periods examined: (a) box chart and (b) % of scenarios examined per ELVs class-change. (“climate change scenarios”: no change in local industrial activity, “climate & industry scenarios”: changes in local industrial activity are considered).

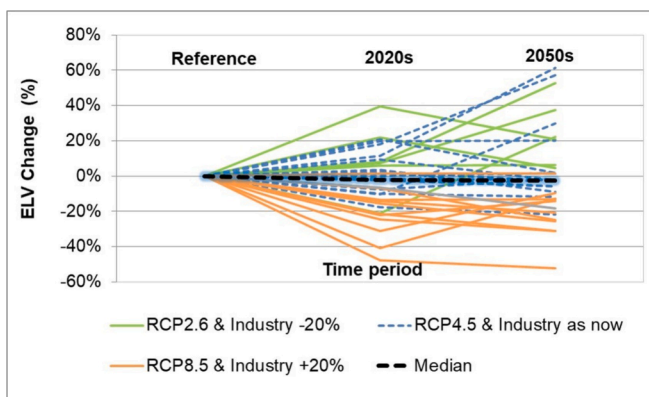


Fig. 6. Relative change of chromium ELVs for climate change and industry scenarios and time periods examined.

differently.

For the 2020s, only the E-HYPE results lead to 18% of the scenarios (209 in total) with decreased ELVs values, which are smaller than the marginal of -10% (Fig. 7). Results from the Lisflood and VIC models lead to a larger percentage of scenarios indicating an ELVs increase. The effect of impact model choice declines for the 2050s period, where the results are similar for all three models. This indicates that uncertainty from climate forcing is larger than uncertainty from hydrologic modelling for the mid-century.

The impact model uncertainty was investigated in comparison to the uncertainty due to climate forcing. For this comparison, the effect of

industry changes was not taken into account (combinations with industry as in the reference period used only). Here we use the standard deviation of the results (ELVs' relative change) to assess uncertainty. The climate forcing scenarios are the 11 combinations of GCMs, RCMs and RCPs presented in Table 2. For each future period, the standard deviation of the results for the 11 climate forcing scenarios, is calculated for each impact model used. These results represent the uncertainty due to climate forcing and for each model (see Fig. 8, grey dash for Lisflood, red triangle for E-HYPE, green circle for VIC). For each one of the 11 climate forcing scenarios, the standard deviation of the results for the different impact models used, represents the uncertainty due to the impact model. These are given in Fig. 8 as black dots (11 for each period). The comparison among these results shows that, for the early-century period (2020s), the uncertainty due to the hydrological model is, for most climate forcing scenarios, smaller than the uncertainty due to the climate forcing. For the mid-century period (2050s), the large uncertainty driven by climate projections is depicted also in the

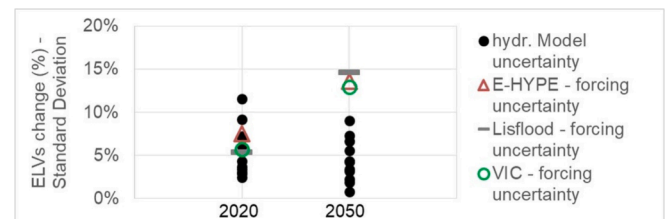


Fig. 8. Climate forcing and hydrological model uncertainty – Standard deviation of ELVs' relative change in comparison to the reference period, for the two periods examined.

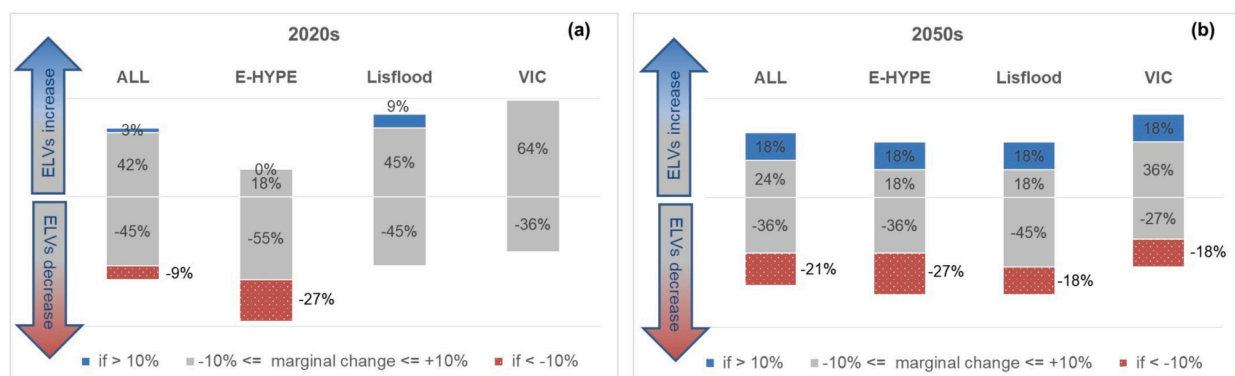


Fig. 7. Variation of all ELVs for climate change scenarios (industry scenarios not incorporated) and for the impact model used: (a) 2020s period and (b) 2050s period.

uncertainty of ELVs calculation, and is clearly larger than the one which is due to the hydrological model used.

Decomposition of uncertainty on the results

We next identify the sources of uncertainty which are depicted in the spread of the results, per impact model used, as well as for the ensemble of the three impact models. Again, the standard deviation of the results (ELVs' relative change) is used as a measure of uncertainty. We calculate the standard deviation for each future period examined and for three groups of model runs: (i) those where industrial activity is considered to be constant, as in the reference period. These are runs where only climate forcing changes and the resulting uncertainty is labeled in Fig. 9 as "CC"; (ii) those where industrial activity changes in a compatible manner with the assumptions behind RCPs. The resulting uncertainty is labeled in Fig. 9 as "CC+ industry"; (iii) those where local industrial activity changes independently of general trends (independent of RCP scenario). The resulting uncertainty is labeled in Fig. 9 as "all combinations".

Results presented in Fig. 9a show that for the 2020s period the prevailing source of uncertainty is the local industry scenarios. The standard deviation for the "CC" runs represents 33%-47% of the standard deviation for the results of the model runs where local industrial activity changes independently of general trends ("all combinations" group). The difference in the calculated standard deviation between the results of groups (ii) and (i) depicts the uncertainty added when industry scenarios, compatible to RCPs general trends, are taken into account. This added uncertainty is labeled as "industry additional uncertainty" in Fig. 9a and it is larger than that of climate change scenarios for the Lisflood and VIC models, and almost equal to CC scenarios, when all impact models are taken into account (Fig. 9a, Ensemble). Incorporating local industrial activity changes, independent of general trends, leads to additional uncertainty. For the 2050s period, the uncertainty due to climate change scenarios becomes prevailing. The standard deviation for the corresponding results ("CC" in Fig. 9b) represents 65%-70% of the standard deviation for the results of the "all combinations" group. Industrial activity still adds a level of uncertainty in the results but it is less than the uncertainty due to climate change, even if "all combinations" of industrial activity are considered.

Discussion

Potential of continental climate services for local water management

The need to address climate change challenges has led to the development of continental climate services, e.g. Copernicus C3S,

providing climate data and information at high spatiotemporal resolution. Nevertheless, most water-related challenges are still present at the local scale. Such challenges are often addressed by users who are not familiar with climate services, supported by consultants and water management experts who are, however, also not climate experts. This highlights the importance for climate services to produce actionable, post-processed, tailored information that addresses users' needs; this was also showcased in the present study.

Here, we used a climate impact indicator (ELVs) which incorporates the hydrological regime of the river (discharges) and the local environmental regulations (EQS) and its calculation requires projections of river discharge. Instead of following a procedure which would require the use of primary climate variables (e.g. temperature and precipitation), including downscaling and bias-adjustment for supporting regional approaches, in order to apply a hydrological model to produce river discharge, we directly used the river discharges offered by a large scale climate service. These are regionally tailored data since they have been produced on a catchment level (E-HYPE) or fine grid (VIC and Lisflood). These data are further tailored down to average monthly values of river discharges, which is the indicator used in the presented assessment. The use of the readily produced information (discharges) not only saves significant computational effort, since there is no need for the application of a hydrological model, but also does not require expert knowledge in hydrologic modeling.

The application of user-tailored, down the process line, information such as river discharges, presupposes that the assumptions, approaches and related uncertainty which accompany the production of this information, are accepted by the user and should be therefore made very clear and well documented. By using these data, these assumptions and uncertainties are transferred further and become part of the assessment. On the other hand, they offer a considerable advantage in cases of significant or complete lack of necessary data for local hydrologic applications, as it is the case for ungauged basins. Pan-European, large scale hydrological applications have been developed specifically to address such issues and provide a mean to assess local problems under sparse local data (Hundecha et al., 2020).

Moreover, we note that the number of downstream variables provided by a climate service is subject to limitations. Consequently, essential variables will need to be directly used by the local users for any further production of necessary downstream variables. Nevertheless, the selection of suitable combinations of GCMs, RCMs and RCPs for projections, is challenging and subjective to non-climate experts. A climate service can provide pre-selected combinations and brief information of what this selection means, saving time as well as expertise needed.

There is room for service evolution and supplement with commonly used or of significant importance, tailored indicators, while through the

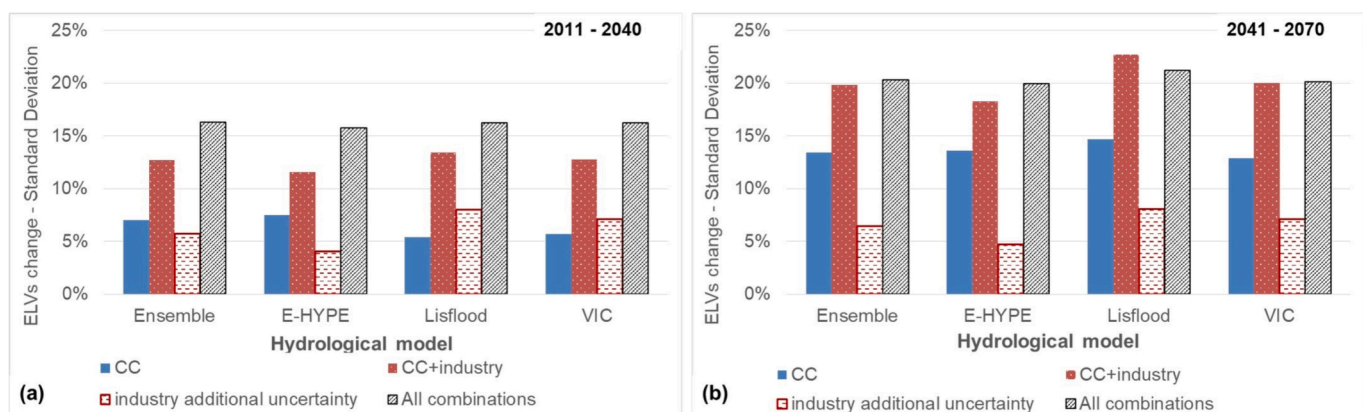


Fig. 9. Sources of uncertainty – Standard deviation of ELVs relative change for the (a) 2020s period and (b) 2050s period. ("CC" - climate change scenarios, no change in local industrial activity, "CC + industry" - changes in local industrial activity are considered, "All combinations" - local industrial activity changes independently of RCP scenario, "industry additional uncertainty" - difference in Standard Deviation between "CC + industry" and "CC" results).

spread of use of such services, other challenges will be addressed. This does not lessen the value of ready-to-use, further down the service process chain, variables or indicators. The use of climate impact indicators produced by continental climate services, free of the (direct) need for further post-processing and combined with local information, can support integrated, local-scale climate change impact investigations. Therefore, climate services uptake lies not only on the development of the services, but also on the users who can identify ways and means of making the most out of these services. This work could serve as a small example towards this direction.

Uncertainty in impact assessments

Uncertainty is present in all steps of the modelling chain in a climate service, and hence is inherently present in decision-making. It is therefore important that uncertainty is identified, quantified and further reduced in climate change impact assessments. As discussed above, a climate service may offer the advantage of preselected combinations to cover various ranges of uncertainty. In the present study, uncertainty was addressed by incorporating available climate data derived from combinations of 3 RCPs, 4 GCMs and 4 RCMs. Additionally, climate impact indicators were used from three hydrological models, which are proved to be suitable for making climate change impact projections of about similar quality (Greuell et al., 2015). Overall, the added value of exploiting available and ready to use climate impact indicators in order to address uncertainty issues is highlighted.

This work was based on climate projections and produced estimations for the early- and mid-century time period (2011–2040 and 2041–2070, respectively), which are valuable for long-term water and environmental management planning. Nevertheless, short-term planning is essential in a large number of water management applications. Improved decision-making can be accomplished when seasonal information is also available to users (Giuliani et al., 2020; Macian-Sorribes et al., 2020). Meeting these needs requires climate and indicator information covering seasonal (and depending on the user also sub-seasonal) time horizons (Pechlivanidis et al., 2020). Consequently, there is a growing need for climate services to incorporate seasonal time scales to further support local water management (Crochemore et al., 2020; Laviers et al., 2020).

Conclusions

Here, we demonstrate the usability of continental climate services data to address a water management problem at the local scale. Climate impact indicators were incorporated in the estimation of environmental pressure indicators (here the ELVs for local industry) for the early- and mid-century periods (2011–2040 and 2041–2070, respectively). The relative change of environmental pressure indicators (ELVs) was estimated and interpreted as an indicator for the assimilative capacity of the river. By investigating the ELVs from a large ensemble of multiple climate and impact projections, we found the following:

- A more than marginal ELVs decrease, translating to a decrease of the assimilative capacity of the river, is projected for a percentage of the scenarios examined ranging from 9% to 33%, depending on the group of the ensemble examined, for the two future periods (2020s and 2050s). A 3% to 18% of the ensemble shows a more than a marginal (+10%) increase of the assimilative capacity. The decrease of ELVs is mainly related to models under the extreme RCP8.5 scenario.
- The incorporation of local industry scenarios has an equal or even larger effect on ELVs than climate change in the early-century. This effect is not significant in terms of average values but it rather increases the spread of ELV values. In the mid-century period, the effect of RCPs becomes more important and the uncertainty of the results is mainly related to the ensemble members of the climate

impact indicators used and not the local industry scenarios. Industrial activity still adds a level of uncertainty but it is less than that due to climate change, even if industrial activity scenarios are independent of RCPs considered.

- Although, in terms of a more than marginal (more than 10%) change, a decrease of assimilative capacity is more probable than an increase, the trend differences are not large (decrease for 9–33% of scenarios versus increase for 3%–15% for 2020s, decrease for 21–33% of scenarios versus increase for 18% for 2050s). Even if all the results are considered, still the trend is not decisive. This means that the climate change signal is not decisively clear and it is likely that climate change impact in the river discharges will not be the factor which will trigger, if any, stricter environmental regulations to local industry.

Climate impact assessments could lead to results that may not decisively support actions towards a specific direction (e.g. mitigation). Climate change adaptation often depends on how each decision maker perceives uncertainties and associated risks and incorporates them to an adaptation/mitigation plan. This underlines the need for incorporating uncertainty into climate impact assessments at the local scale and communicating it to the decision makers. This can support managing the resources according to the risk-taking capabilities and priorities of the authorities responsible for mitigation and adaptation.

The results presented in this work support some of the aspects considered by an environmental regulatory authority in the decision making process concerning the environmental policy for the Asopos River as well as the effort for maintaining the fragile balance between environmental protection and economic viability and sustainability of the significant industrial activity in the area. Climate impact indicators are free of the need for laborious processing. They cannot cover all aspects of local analysis needs but, combined with local information, they can be key-data for integrated, local-scale climate change impact investigations.

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The climatic projections are freely accessible from the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu/#!/home>). The HYPE model code is available from the HYPEweb portal (<https://hypeweb.smhi.se/model-water/>). Hydro-climatic projections obtained through E-HYPE are openly available also on the HYPEweb portal (<https://hypeweb.smhi.se/explore-water/climate-change-data/europe-climate-change/>).

CRediT authorship contribution statement

Alexandros I. Ziogas: Methodology, Writing – original draft, Formal analysis, Visualization. Ilias G. Pechlivanidis: Conceptualization, Writing – review & editing, Resources. Evangelos D. Romas: Methodology, Software, Investigation. Apostolos M. Tzimas: Conceptualization, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cliser.2021.100250>.

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