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A Simplified Water Accounting Procedure to Assess Climate Change Impact on Water Resources for Agriculture across Different European River Basins

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Abstract: European agriculture and water policies require accurate information on climate change impacts on available water resources. Water accounting, that is a standardized documentation of data on water resources, is a useful tool to provide this information. Pan-European data on climate impacts do not recognize local anthropogenic interventions in the water cycle. Most European river basins have a specific toolset that is understood and used by local experts and stakeholders. However, these local tools are not versatile. Thus, there is a need for a common approach that can be understood by multi-fold users to quantify impact indicators based on local data and that can be used to synthesize information at the European level. Then, policies can be designed with the confidence that underlying data are backed-up by local context and expert knowledge. This work presents a simplified water accounting framework that allows for a standardized examination of climate impacts on water resource availability and use across multiple basins. The framework is applied to five different river basins across Europe. Several indicators are extracted that explicitly describe green water fluxes versus blue water fluxes and impacts on agriculture. The examples show that a simplified water accounting framework can be used to synthesize basin-level information on climate change impacts which can support policymaking on climate adaptation, water resources and agriculture.

Keywords: climate change impacts; water resources; agriculture; water accounting; hydrological data; water scarcity and drought

1. Introduction

In many regions in Europe, climate change impacts on water resources are threatening the sustainability of the agricultural systems [1,2]. The increased occurrence of drought and water scarcity is predicted in many regions throughout Europe [3–5], and recent events over the last ten years have demonstrated that drought episodes typically for Southern European countries are expanding to Eastern and Western Europe [6,7]. Thus, policies and legislation are needed to mitigate the related risks and to adapt to climate change impacts [8,9]. For this, European-level decision makers need information on how climate change impacts affect water resources for all sectors, particularly agriculture, especially in the most drought-prone and/or water scarce regions in Europe.

The European Union (EU), in coordination with its Member States, is committed to support the implementation of the United Nation's (UN) 2030 Agenda for Sustainable Development, and it strives towards improved water efficiencies and climate adaptation, among other targets, as are stated in the Sustainable Development Goals (SDGs). The European Water Framework Directive also requires solutions for water scarce conditions. One of the major goals of EU policy is to make agricultural water management across Europe more efficient [10,11], although it is not always clear how efficient water use shall be achieved. While some stakeholder groups think of solutions in terms of irrigation efficiencies, e.g., [12], others rather think of solutions in terms of crop water productivity, e.g., [13], reuse of drainage water, e.g., [14] or irrigation with wastewater, e.g., [15,16] for which legislation is currently being drafted by EU member states. Whatever the strategy is, there is an urgent need for information at the European level to feed into reports and monitoring efforts on past performance. Even more importantly, however, policy-relevant indicators on water availability, use, and water stress are needed for the future, under consideration of climate change [17,18].

To assess climate change impacts on water resources across Europe, several assessments have thus far been done using large-scale hydrological models [19–23]. These global models have the advantage that information is generated based on one single methodological approach, which makes it relatively easy to compare between different locations, e.g., [24]. On the other hand, they typically require lots of computational resources, have rather larger grid sizes (typically 10–50 km) and do not always converge, e.g., [25,26]. A more important limitation is that global approaches do not include local details in the water resources system [18] that can sometimes be crucial, including dams, diversions, groundwater abstractions, water harvesting schemes, spring water use, sub-surface drainage systems, and specific vulnerable water users with high priorities (wetlands, etc.), which often challenge drought monitoring and management [27,28]. On-farm irrigation and drainage systems are usually strongly simplified in these models or even entirely absent with no distinction between micro and flood irrigation systems. Additionally, these modelling systems, due to their global nature, do not consider local knowledge (from local experts and stakeholders) on the already occurring impacts or on the adoption and impact of national or EU regulations, such as the EU Water Framework Directive.

River basin-level climate change impact assessments are nowadays available for many regions in Europe [29–32]. Often, these studies are done or commissioned by the local water authorities to support the river basin management plan [33,34]. However, these studies are hardly useful for European-level decision making, simply because the outcomes of these studies are not reported to Brussels. Additionally, the chosen indicators are oriented towards the local decision-makers.

Accounting frameworks allow for a wide variety of data to be synthesized so that regular information and indicators are produced and can feed into decision-making processes. The underlying principle of these approaches recognizes that while there may be discrepancies between different data sources as well as data gaps, decisions need to be made based on the best-available standardized information. Eurostat has adopted the international standard for environmental accounting, which is the System of Environmental-Economic Accounting (SEEA). It was produced and released under the auspices of the United Nations Statistics Division and also includes accounts for water [35]. Several of the accounts in this framework (CO_2 emissions, energy flows, etc.) are already obligatory for EU countries. Eurostat has plans to develop water accounts, and some experiments are being done on the national level, e.g., [36]. On the other hand, the European Environmental Agency has also piloted several studies at the basin-level, which yielded accounts for several basins in Spain [37–41] and Italy [42]. Outside Europe, Australia has already successfully implemented a water accounting framework and uses it actively to support decision-making [43,44].

However, these efforts have thus far focused on reporting past water resources, yielding very comprehensive, detailed, and location-specific data-intensive studies. Only very few basin-level studies exist in which water accounting methodologies were applied for future conditions [45,46]. For describing future conditions and assessing local options to make water resources management more efficient and sustainable, water accounting has hardly been used. Given the uncertainties in future predictions, it is recommendable to use a simplified water accounting framework instead of an original one that relies on measurements and includes high levels of detail which are redundant in future studies. Additionally, a simplified framework will make the tool more accessible and interpretable by a large group of users.

The objective of this work is to demonstrate the application of a single water accounting framework to synthesize outcomes of climate change impact studies for five different European basins. The focus lies on future water resources for agriculture (green and blue) and the presentation of outcomes by means of a candidate set of impact indicators.

2. Materials and Methods

2.1. The Water Accounting Framework

A water accounting framework which is increasingly used and supported by the United Nations Food and Agriculture Organization and the Asian Development Bank is called Water Accounting Plus (WA+) [47–49]. This framework was largely inspired by the pioneering work of water accounting conducted by Molden [50], which used a water balance approach to classify inflows and outflows into various categories to provide information on the quantity of water depleted by various uses and the amount available for further use. The WA+ framework was designed to be mainly fed with the remote sensing of local water management and farming practices to assess water availability and water use by land use types. The inclusion of remote sensing data lowers the requirements on ground-based data and is a good example of standardized data collection and sharing. The active program of the European Space Agency (ESA) on agricultural water management is an essential asset (Goetz et al., 2017).

The simplified framework proposed here was based on the comprehensive WA+ framework, because of (1) the land-use and agriculture focus and (2) its emphasis on the distinction between green and blue water. The resource base sheet from Molden (1997) and WA+ was re-designed, simplified and finalized during a workshop in which all experts from included river basins participated to make sure that the framework was versatile and straightforward enough to be applied to the various case study basins. The modifications principally consisted of the aggregation of certain flow and stock components in order to limit the redundancies, based on the principal of parsimony.

The proposed water accounting framework makes uses of the increasingly used terminology green water and blue water, originally coined by [51] to distinguish, respectively, (1) soil water that is available for evapotranspiration and comes from direct rainfall and (2) water that is available for evapotranspiration and other consumptive uses by withdrawals from surface or groundwater sources. The main components of the resource base sheet are shown in Table 1. Appendix A provides a description of the components.

Table 1. The main components of the resource base sheet.

Inflows	Outflow	Others
Precipitation Interbasin transfer Upstream tributaries Lateral groundwater inflow Desalination	Green water evapotranspiration Blue water evapotranspiration Utilizable outflow Committed outflow Environmental outflow Non-utilizable outflow Interbasin transfer Lateral groundwater outflow	Total water withdrawal Agricultural water withdrawal Surface storage change Subsurface storage change

As in the WA+ framework, the evapotranspiration (ET) flows of the resource base sheet make distinctions between key land-uses types:

- Protected natural area (PNA)
- Non-protected natural area (NNA)
- Rainfed cropland (RC)
- Irrigated cropland (IC)
- Other managed water use (industry, services, households) (OMW)

More details on the water accounting framework can be found in Appendix A.

2.2. Case Study Approaches for Five River Basins

This work includes five river basin case studies in Europe (see Figure 1). A summary of the basins is given in Table 2. Four of the basins are in Southern Europe. Three of the basins have a Mediterranean climate and are water scarce. All case study basins have a relatively high share of land used for agriculture. In the Mediterranean basins, agriculture consumes most of the available water (green and blue). In the Lake Como basin, these values are relatively low, as the study area includes the wide Alpine catchment of the lake (about 4500 km^2) with the irrigation district located in the downstream part of the system and covering an area of about 700 km^2. In the Delta of the Rhine basin, most water is used to maintain water levels and flush the system, mainly in order to prevent peat dike breaches to reduce salinity intrusion. Green water is mostly used by rainfed cropland, as the largest part of the agricultural area is rainfed.

Figure 1. Location of the five river basins case study areas.

Each study basin has its own hydrological model and data sources. The simulations, analysis and synthesis into the water accounting framework for each study basin were performed by the local experts that managed the local toolset. For the historic period, the hydrological models were calibrated with 20–30-year meteorological data (rainfall and temperature) and corresponding streamflow observations. In the study basins where water resources are highly regulated, simulations from the hydrological model of river flow were then used as input into a water resources system model. For the climate change scenarios, the models were forced with future climate projections from climate models (details in next section).

Table 2. Summary table of the case study basins.

Abbreviation	Case Study Basin	Country	Climate (Köppen Classification)	Total Area (km^2)	Agricultural Area (%)
SEG	Segura	ES	Semi-arid (BSk)/ Mediterranean (Csa)	18,870	45
JUC	Jucar	ES	Semi-arid (BSk)/ Mediterranean (Csa)	22,187	35
LCO	Lake Como	IT	Humid continental (Dfb)	4500	31
MES	Messara	GR	Mediterranean (Csa)	400	63
RHI	Delta Rhine (only NL)	NL	Temperate oceanic (Cfb)	25,347	55

Details on the modelling and data sources per basin can be found in Appendix B. Here, only a summary is given for each river basin. For the Segura river basin, the Spain02 meteorological dataset was used to simulate the historic period using the hydrological model SPHY (Spatial Processes in Hydrology). The simulated stream flow from SPHY was used in the water resources system model WEAP (Water Resources and Evaluation Planning) to simulate water demands, supplies, storage, and releases from the reservoirs. More details can be found in Appendix B.1.

For the Jucar basin, data from the rainfall-runoff model PATRICAL [52] for the baseline period 1980–2012 were used: The same data that were used as for the Jucar River Basin Management Plan. The SIMGES module (Andreu et al., 2007) from the AQUATOOL Decision Support System Shell (DSSS) (Andreu et al., 1996; Andreu and Ferrer-Polo, 2009) was used to simulate supplies, demands, water allocation, and reservoir operations. More details can be found in Appendix B.2.

For the Messara basin, rainfall data from fourteen weather stations were used. The Sacramento hydrological model (SAC-SMA) was used to simulate the hydrological flows after Koutroulis et al. (2013) and Tsanis and Apostolaki, 2009. The water balance of the reference period was validated with observations provided by the Directorate of Water of the Decentralized Administration of Crete. Future projections affecting the water balance were based on the work of Koutroulis et al. (2016). More details can be found in Appendix B.3.

For the Lake Como basin, the water accounts were developed by using an integrated model (for details, see Giuliani et al., 2016) that included three main components: (1) The hydrological model Topkapi-ETH, a spatially distributed and physically based model for the watershed of Lake Como; (2) the Lake Como operational model describing the lake dynamics by a mass-balance equation; and (3) an agricultural district model which simulates the dynamic processes of the Muzza irrigation district including the water balance, crop growth and yield. More details can be found in Appendix B.4.

For the Delta of the Rhine river basin, the water accounts were developed using the Dutch National Hydrological Model (NHM), which contains four coupled models to assess changes in ground and surface water flows (for more information, see Lange et al., 2014). The results were validated with water accounting results of the Central Bureau of Statistics of The Netherlands (Graveland et al., 2017). More details can be found in Appendix B.5.

2.3. Future Horizons and Projections

The water accounts were made for an historic period and two future periods. The exact time-window for the three periods depended slightly on the case study but were within the following time windows:

- Historic baseline (BL): 1980–2015
- Near-future (NF): 2030–2060
- Far future (FF): 2080–2100

All case studies assessed the two "Representative Concentration Pathways" (RCPs) that are commonly used for climate impact assessments: (1) RCP4.5: Emissions peak around mid-century being approximately 50% higher than 2000 levels, then declining rapidly over 30 years, and then stabilizing at half of 2000 levels, associated with moderate population and economic growth; and (2) RCP8.5: Most pessimistic scenario in which emissions continue to increase rapidly through the early and mid-parts of the century. Population growth is high, reaching 12 billion by century's end. The scenarios assessed for all case study basins are summarized in Table 3.

Table 3. Summary table of the scenarios studied for the case study basins.

ID	Horizon	Emission Scenario [1]	Name [1]
1	Baseline		BL
2	Near Future	RCP4.5	NF45
3	Near Future	RCP8.5	NF85
4	Far Future	RCP4.5	FF45
5	Far Future	RCP8.5	FF85

[1] For Delta Rhine, only the Dutch Delta Scenario WARM2050 was available, which corresponds to near future RCP8.5.

Socio-economic development was considered by including the future demands and population growth, as indicated by the SSP2 (Shared Socioeconomic Pathway 2), also sometimes called the "middle of the road" scenario. Additionally, infrastructural developments that are currently considered in the respective river basin management plans were included in the simulation, as far as information was available.

2.4. Indicators

Based on the water account sheets, a wide range of indicators could be assessed. For this work, a selection was made focusing on indicators that characterize four key aspects of river basin water resources and agriculture:

- Green water availability and blue water availability: Relative change compared to the baseline period.
- Green water use for agriculture and blue water use for agriculture: Relative change compared to the baseline period.
- Blue water dependency-indicators, expressed as blue water availability and use compared to total availability and use
- Water stress-indicators expressed as green and blue water use compared to water resource availability.

Table 4 shows how these indicators were calculated based on the components of the water account resource base sheet (see Appendix A for a definition of the components).

Table 4. Definition of the indicators used.

Type	Name	Derived from
Water availability	Total Water Availability	Precipitation + Interbasin transfer + Upstream tributaries + Lateral groundwater inflow + Desalination
	Blue Water Availability	Total water availability − Green water evapotranspiration
Water use	Green Water Use Agriculture	Evapotranspiration from Rainfed Agriculture + Evapotranspiration (only green) from Irrigated Agriculture
	Blue Water Use Agriculture	Evapotranspiration (only blue, originating from field external supplies) for Irrigated Agriculture
Blue water dependency	Blue Water Available versus Total Water Available	Blue Water Available/Total Water Available
	Blue Water Use versus Total Water Use	Blue Water Use (all sectors)/Total Water Use (green and blue)
Water Stress	Green Water Use versus Total Water Available	Green Water Use (all land-uses)/Total Water Available
	Blue Water Use versus Blue Water Available	Blue Water Use (all sectors)/Blue Water Available

3. Results

The water accounts (resource base sheet) were developed for each river basin based on the data and toolset used in each basin. The resulting sheets can be found in Appendix C. Based on these accounts, the indicators listed in the previous section were assessed. These indicators are presented and discussed here to illustrate the potential of the water accounting framework to extract policy-relevant indicators from these multiple accounts. The results presented here focus on the relative change compared to the baseline period; for the absolute numbers per river basin, please refer to Appendix C.

3.1. Water Availability

Figure 2 shows how water availability is affected by climate change in the five river basin areas. The figure shows the percentage change of the indicator values for the future periods compared to the baseline (historic) period. The four climate change scenarios (two horizons, two RCPs) are shown.

As can be seen in Figure 2, green water availability will decrease for the three Mediterranean basins (Segura, SEG; Jucar, JUC; and Messara, MES). For the near future, decreases of a few percent are expected, although for the Messara basin, this trend is not clear. For the far future, expected decreases are substantial: Around −20% for the most pessimistic emission scenario RCP8.5. For Lake Como (LCO), no significant trend could be observed, and both positive as well as negative changes are predicted, depending on the scenario. These results mostly depend on the predicted dynamics of glaciers and snowpack, which are expected to melt in the near future, thus increasing water availability, and then disappear in the far future for the RCP8.5. For the Delta Rhine basin area (please note only NF85 was available for this case study), a slightly positive trend was observed related to increased annual rainfall.

Blue water availability is even more affected by climate change in the Mediterranean basins. For the near future, reductions between 10% and 20% are predicted. For the far future, decreases are predicted around −30%. Again, for the Lake Como basin, no negative or positive trend could be observed in this indicator. For the Delta Rhine basin, blue water availability is expected to increase slightly.

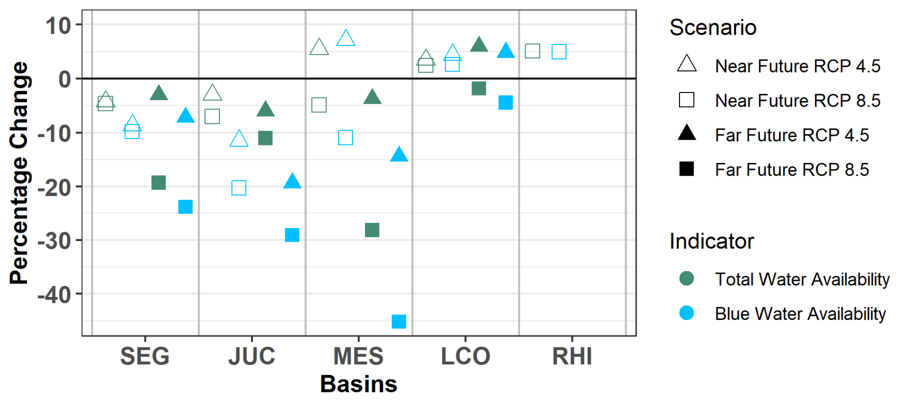

Figure 2. Percentage change of (1) total water availability (**green**) and (2) blue water availability (**blue**) for the five river basins for the climate change scenarios.

3.2. Water Use for Agriculture

Changes in water availability lead to changes in consumptive water use (evapotranspiration) and thus likely to changes in productivity. Hydrological simulations were done for all basins to assess water use across the main landcover classes, assuming no climate adaptation. Climate change impacts on water use in agriculture due to changes in water availability are shown Figure 3. The water accounting framework aggregated flows per main landcover class and distinguished between rainfed and irrigated agriculture. Green water is relevant for rainfed and irrigated agriculture, while blue water applies only to irrigated agriculture. Figure 3 shows the relative change compared to the baseline scenario.

For the near future, changes in green water use are in the order of a few percent, except for the Lake Como basin, where higher decreases are projected. For the far future, the RCP4.5 scenario shows similar decreases as in the near future, but the RCP8.5 scenario shows substantial decreases in water use, ranging from −10% to −20% (for the Delta Rhine basin, a far future scenario was not available).

Blue water use in (irrigated) agriculture decreases slightly more than green water Use. The trends across the river basins are similar to green water use. The reductions in consumptive water use shown here are caused by a reduction in the amount of water that is available to crops, considering the crop growth season and crop water demands. These reductions, if not counteracted with adaptation measures, are typically related to a reduction in productivity and thus imply an economic impact.

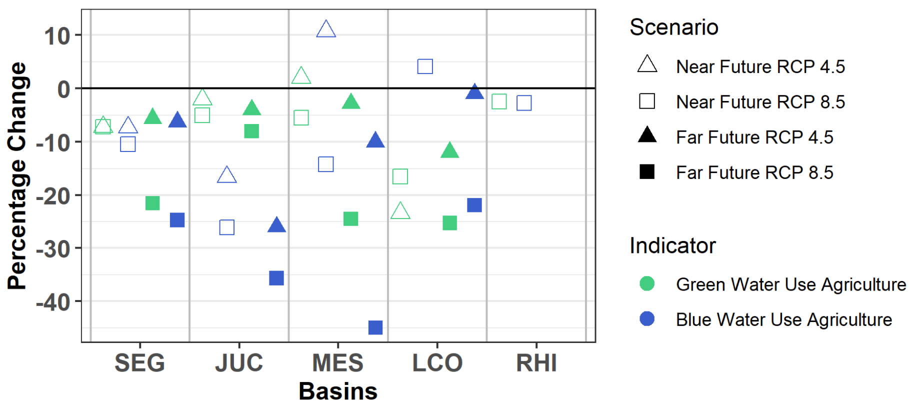

Figure 3. Percentage change of (**green**) green water use for rainfed and irrigated agriculture and (**blue**) blue water use for irrigated agriculture for the five river basins under the climate change scenarios.

3.3. Blue Water Dependency

Irrigated agriculture relies on blue water availability, which in turn relies on total water availability in the basin and upstream green water use by rainfed agriculture and natural land-uses. The fraction of blue water in the total water resources availability is informative for the vulnerability of irrigated agriculture to consequences of climate change. Figure 4 shows how blue water availability and blue water use compare to total water availability and water use for the baseline (historic) scenario and the four future climate scenarios. As an example, a value of 0.2 for the availability indicator would mean that 20% of the renewable water resources availability becomes available as blue water and could thus potentially be used for irrigation or other blue water uses (domestic, industrial, etc.). A value of 20% of the use indicator would mean that 80% of the water could be consumptively used as green water, and 20% could be used as blue water.

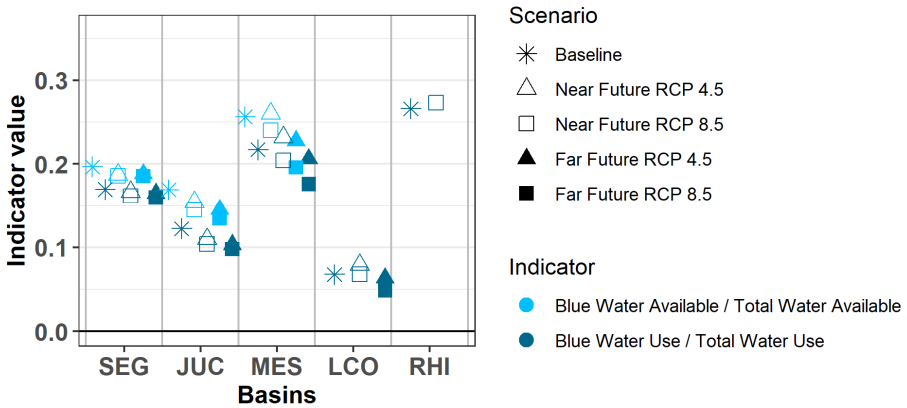

Figure 4. Blue water dependency indicators: (1) Blue water available versus total water available, and (2) blue water use versus total water use for the five river basins under the baseline and climate change scenarios.

Figure 4 shows that for most future scenarios and basins, the values of both indicators decrease slightly relative to the baseline. The availability indicator is only shown for the three semi-arid Mediterranean basins (SEG, JUC and MES): For the other two basin areas, blue water availability is very high (above 0.8), and, thus, changes in this indicator are less likely to affect the agricultural sector. For all three semi-arid basins, a smaller fraction of the total water available is expected to become available as blue water under the future scenarios.

Due to reduced availability, the fraction of total water use that is used as blue water also slightly reduces. For the LCO basin, green water use upstream is expected to increase slightly, causing blue water/total water use to decrease. Again, impacts are likely to be small because water is not a scarce resource. For the Delta Rhine basin area, blue water use is expected to increase because of additional withdrawals from surface and groundwater bodies to meet higher water demands, as well as an increase of blue water evapotranspiration in wetlands.

3.4. *Water Stress*

Figure 5 shows two indicators that relate water use with water availability. Use-to-availability indicators can be informative for the stress level of a basin and are often used in water resources planning as well as climate impact assessments, mostly for blue water (second indicator in the figure). The proposed framework also allows for the assessment of a similar indicator for green water (first indicator). For both indicators, higher values are indicative for a higher level of water stress in the basin.

Figure 5 shows only the values for the semi-arid Mediterranean basins. For the other basins, the water stress indicator values are relatively low and below the threshold (0.2) at which a basin is typically considered to be in a stress condition [53]. Thus, for the Como and Delta Rhine basin areas, this indicator is not informative on possible climate change impacts on water resources, and other stress indices that consider, e.g., seasonal variability, should be considered.

For the green water indicator, values for the three basins are around 80%, confirming the relatively high share of water consumed by rainfed agricultural systems and natural land-uses in basins in this climate zone. No clear trend could be observed in this indicator, some scenarios show a slight increase, and others show a slight decrease, possibly due to competing trends in evaporation and precipitation under future climate conditions. For the blue water indicator, there are large differences among the three case study basins. For the Segura river, this indicator shows a decrease in the near future, which results from the assumption that non-renewable groundwater abstraction will be eliminated, as required by the European Water Framework Directive. However, for far future scenarios, the stress indicator increases again. For the Jucar basin, a small downward trend could also be observed because of the same reason. For the Messara basin, this value monotonically increases in the future to values higher than 1, indicating water use rates exceeding renewable water availability and, thus, the use of non-renewable water sources.

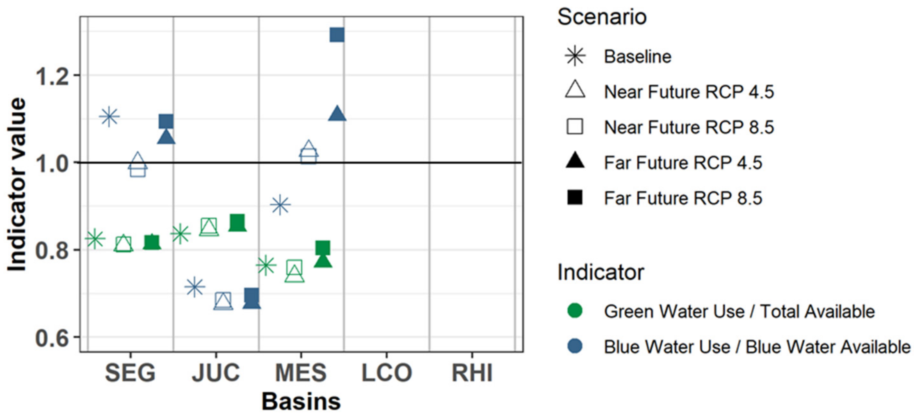

Figure 5. Water stress indicators: (1) Green water use versus total available and (2) blue water use versus blue water available for the five river basins under the baseline and climate change scenarios.

4. Discussion

A key question for designing policies related to climate change impacts on water resources is how the increased water deficits will partition between green water and blue water. This is important as it can determine, together with information on vulnerabilities, whether policies should focus more on natural areas and rainfed agriculture or on irrigated agriculture and other economic water-reliant economic sectors. The results presented here for the five river basins show that climate change impacts will decrease both green water as well as blue water availability and use for the Mediterranean basins. Decreases in blue water availability and use seem to be higher and more consistent. For the two non-Mediterranean basins, there are no clear trends. For Europe, Orth and Destouni [54] showed that droughts are likely to reduce blue water stronger and faster than they reduce green water; however, they found that this depends strongly on the climate zone, and that in drier climates, this effect is less clear. Other researchers have found similar outcomes [55–58], although it has appeared to be challenging to untangle the interdependent link with land-use change [59,60]. Water accounts by land use class solves this challenge.

The results for the Mediterranean river basins also show that blue water dependence will increase under climate change. Huang et al. [61] predicted that this will typically happen in semi-arid regions. At the same time, water stress may also increase in particular basins. Indicators extracted from accounts, such as the ones presented here, can be used to inform on targeting measures that are needed to increase the water productivity (WP) of agricultural systems and become more efficient while at the same time not compromising water used for environmental purposes [9,31,62,63]. Spain has dedicated substantial efforts to increase WP in basins like Jucar and Segura, although in some cases, these investments have ultimately led to an overall increase in water consumption [64]. Currently, Dutch aid policy is targeting a 25% increase in WP over the next decade, promoting adaptation measures that increase WP in various countries outside of the EU. A similar policy may be necessary at the EU level in order to mitigate the consequences of climate change on water resources available for agricultural production.

The water stress indicators extracted from the water accounts and presented here give an incomplete characterization of water stress, as water stress should typically be described by a variety of indicators that describe intensity, duration, vulnerability and other features. However, the blue water indicator presented here is often used (in a similar form) as a first approximation of water stress in basins and is one of the key SDG indicators (SDG Indicator 6.4.2). It is also used by the EU for reporting on water stress, referred to as the water exploitation index [65,66]. Vanham et al. [67] gave various recommendations for improving the monitoring of this type of indicators, which included a better recognition of the connection green–blue water and a clear distinction between net and gross abstractions. For future assessments of these indicators, the proposed framework allows for indicators that integrate these improvements.

The main purpose of the results presented here is exemplifying the use of a simplified water accounting framework to synthesize multiple individual climate change impact studies on water resources. Presenting indicators that aggregate several basins in a single figure or table allows for the comparison of trends and the detection of whether trends are consistent among different studies or similar basins. These indicators can also be used to identify hotspot regions that require specific attention. Such hotspot regions can be examined with the same framework, as water accounting is independent of scale. Future water accounts allow for a wide variety of data to be synthesized so that regular information and indicators can be produced and can feed into decision-making processes. At the same time, by definition, accounting recognizes that there may be discrepancies between different data sources as well as data gaps; however, experts that know the subject of study (i.e., river basin) can deal with that and extract the relevant features for decision-making.

Obviously, the indicators here are only a very small subset of what could potentially be presented and be useful for decision-making at the EU level. Even from the current information collected for this work, more indicators could be extracted, e.g., indicators that compare water uses among sectors and land-uses, indicators that compare gross versus net abstractions, and indicators on alternative water sources (basin transfer, desalination, etc.). Additionally, the indicators presented here were based on long-term averages, while climate change impacts on water resources are often felt most during dry spells: These can become more intense or longer, so they can be important to consider when looking at water scarcity [68,69]. Especially in (sub-)humid climates, annual trends can mask seasonal effects that can be very relevant. For example, in the Dutch part of the Rhine basin, annual precipitation is expected to increase in the future scenario, while summer precipitation is likely to decrease. These nuances have yet to be taken into account in the water accounting approach. However, the water accounting framework is flexible enough to select the time periods for aggregation in such a way that it accurately reflects the basin characteristics. It allows for the creation of extracting indicators based on inter-annual and intra-annual information, if relevant. Such indicators can be particularly relevant for determining maximum amounts for allocation to irrigation, not compromising other users and the environment.

Another venue for further extension and improvement is the use of a simplified water accounting framework, as presented here, for assessing the effectiveness of climate adaptation options across multiple basins. A harmonized set of indicators based on standardized water accounts needs to be agreed upon. Additionally, more information on productivity, biomass, and yield can be added to allow for the estimation of future water productivity and assess related interventions. Finally, it is recommended to compare the bottom-up approach presented here based on local tools, knowledge, and phenomena with the typical top-down approach for pan-European assessments using global hydrological and water resources models.

5. Conclusions

This work presents the application of a single simplified water accounting framework to assess the climate impacts on water resources availability and use across several European basins in a standardized way. Such a framework allows for the comparison of various independent and area-specific studies at the river basin scale and studies that integrate key local features and local knowledge that can be essential when assessing and synthesizing climate change impacts across various areas.

Water accounting methodologies are typically applied for reporting on statistical data about the availability of water resources and water use by sectors. This paper demonstrated a simplified framework harmonized across several river basins which used a bottom-up approach where local knowledge, modelling approaches, and datasets were incorporated with a focus on climate change impacts. Top-down approaches using global hydrological models can be ambiguous in decision making because they do not represent fully local key water-related and socio-economic issues and priorities. The framework proposed here can be used to assess future conditions and possible adaptation strategies across several basins, enabling the integration of local criteria and processes (biophysical, socio-economic, legal) that can be critical.

Using basin-specific information from various sources and for different areas also means that it becomes important to be transparent about the methods, datasets and models used. In order to improve on the interpretability and coherence among case studies, a large effort at the EU level is needed to distribute earth observation and climate model datasets. The current Copernicus program can support this and can improve the homogeneity among the individual basin-studies, as researchers and practitioners will increasingly use these sources to inform their analyses and modelling. This will lead to more standardized input data on land use, crop types, evapotranspiration and soil moisture, among others. The use of these EU-level or global datasets for regional and basin-level studies can benefit local decision-making, but we argue that there is a two-sided benefit, as it can also allow for a better integration of local knowledge on local phenomena in EU-level decision making.

Furthermore, the case studies presented in this paper show the importance of embedding green water use and availability in water accounts to fully represent the needs and future prospects of agricultural water use, water productivity and water allocation.

Understanding climate change impacts across blue and green-water fluxes throughout regions and sectors in Europe is essential for ensuring food and water security and for developing early-warning and adaptation systems in support of society and ecosystems. The proposed methodological framework can be useful to support European policies and decisions in this matter.

Author Contributions: Writing—original draft preparation, J.H.; conceptualization, J.H. and G.S.; methodology, data curation and analysis for Jucar case study, S.S.-A., A.S. and J.A.; methodology, data curation and analysis for Lake Como case study, M.G. (Matteo Giuliani) and P.Z.; methodology, data curation and analysis for Messara case study, M.G. (Manolis Grillakis), A.K. and I.T.; methodology, data curation and analysis for Delta Rhine case study, F.S.; methodology, data curation and analysis for Segura case study, S.C. and J.H.; visualization, E.E.; supervision, writing—review and editing, W.B.

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Appendix A Description of the Resource Base Sheet Components

Table A1 provides a description of the components of the resource base sheet, based on the resource base sheet in the Water Accounting Plus (WA+) framework [47–49].

Table A1. Resource base sheet components and description.

Class	Variable	Description
INFLOW	Precipitation	Comprises all forms of precipitation
INFLOW	Interbasin transfer	Artificial water transfers from other basins
INFLOW	Upstream tributaries	Only relevant if the area covers the downstream portion of a basin, thus having inflow from upstream
INFLOW	Lateral groundwater inflow	Inflow from an aquifer transcending the boundaries of the river basin/study area
INFLOW	Desalination	Inflow through desalinated water

Table A1. *Cont.*

Class	Variable	Description
WITHDRAWALS	Total water withdrawal	Total water withdrawal for all economic activities
WITHDRAWALS	Agricultural water withdrawal	Total water withdrawal for agriculture
STORAGE	Surface storage change	Artificial reservoirs, lakes and soil water. Positive values indicate a net extraction of water
STORAGE	Subsurface storage change	Groundwater. Positive values indicate a net extraction of water
OUTFLOW	Green water ET: PNA	Evapotranspiration of green water
OUTFLOW	Green water ET: NNA	Evapotranspiration of green water
OUTFLOW	Green water ET: RC	Evapotranspiration of green water
OUTFLOW	Green water ET: IC	Evapotranspiration of green water
OUTFLOW	Green water ET: OMW	Evapotranspiration of green water
OUTFLOW	Blue water ET: PNA	Evapotranspiration of blue water
OUTFLOW	Blue water ET: NNA	Evapotranspiration of blue water
OUTFLOW	Blue water ET: RC	Evapotranspiration of blue water
OUTFLOW	Blue water ET: IC	Evapotranspiration of blue water
OUTFLOW	Blue water consumption: OMW	Consumptive use of blue water in industry, services, households
OUTFLOW	Utilizable outflow	Water that is utilizable for economic activities in the basin
OUTFLOW	Committed outflow	Flow committed to specific uses downstream, such as in-stream use for navigation
OUTFLOW	Environmental outflow	Environmental flow requirements to preserve downstream ecosystems and/or prevent saline water intrusion
OUTFLOW	Non-utilizable outflow	Water that cannot be utilized (again) within the basin. Includes non-recoverable return flows from withdrawals
OUTFLOW	Interbasin transfer	Artificial water transfers to other basins
OUTFLOW	Lateral groundwater outflow	Outflow through an aquifer transcending the boundary of the river basin; can be natural or artificial (due to groundwater pumping)

Appendix B Model Approach and Data Sources for Each River Basin

This appendix provides more details on the modeling approach used and data sources for each of the river basin case studies.

Appendix B.1 Segura River Basin, Spain

Two modelling tools were employed for developing the water accounts in the Segura river basin:

(1) The hydrological model SPHY (Spatial Processes in Hydrology). The model was set-up for the baseline period 1981–2000 and was used for assessing evapotranspiration and runoff impacts. Results of these modeling efforts were summarized by Eekhout et al. [70].

(2) A water resources system model using the WEAP (Water Resources and Evaluation Planning) software that developed for the Segura river basin (Figure A1), based on and in collaboration with the River Basin Authority.

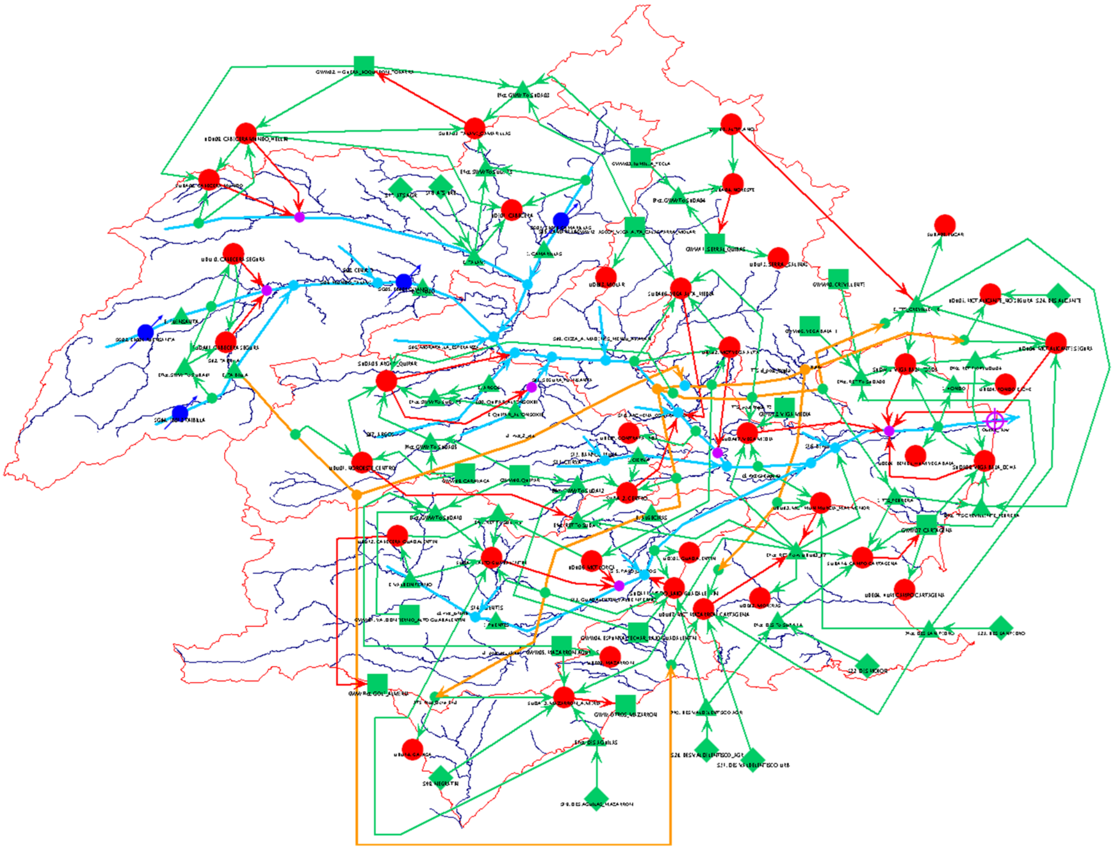

Figure A1. Water resources system model WEAP (Water Resources and Evaluation Planning) developed for the Segura river basin.

INFLOWS:

1 **Precipitation**: Based on the Spain02 dataset for baseline scenario, for future scenario based on nine Regional Climate Models (RCMs) for RCP4.5 and RCP8.5. Details in Eekhout et al. [70].

2 **Interbasin transfer**: Tajo–Segura water transfer: Baseline based on past data from water authority; future, based on percentage changes due to climate change as assessed by Pellicer-Martínez and Martínez-Paz [71].

3 **Upstream tributaries:** Not applicable.

4 **Lateral groundwater inflow:** Not applicable.

5 **Desalination**: Current: 158 hm^3 [72]. Future: 20% increase in NF, 50% increase in FF, interpreted from [73].

WITHDRAWALS:

6 **Total water withdrawal**: Simulated by the WEAP model that was developed for the Segura river basin.

7 **Agricultural water withdrawal**: Simulated by the WEAP model that was developed for the Segura river basin.

STORAGE:

8 **Surface storage change**: Storage change of soil water and surface water reservoirs, as simulated by the SPHY model and the WEAP model.

9 **Subsurface storage change**. Groundwater storage difference between start and end of the simulation period in WEAP. For the future periods, groundwater over-exploitation was assumed to be zero, as is required by the European Water Framework Directive.

OUTFLOWS:

10 **Green water ET: PNA**. Estimated by SPHY hydrological model.
11 **Green water ET: NNA**. Estimated by SPHY hydrological model.
12 **Green water ET: RC**. Estimated by SPHY hydrological model.
13 **Green water ET: IC**. Estimated by SPHY hydrological model.
14 **Green water ET: OMW**. Estimated by SPHY hydrological model.
15 **Blue water ET: PNA**. Estimated by the water resources system WEAP model.
16 **Blue water ET: NNA**. Estimated by the water resources system WEAP model.
17 **Blue water ET: RC**. Estimated by the water resources system WEAP model.
18 **Blue water ET: IC**. Estimated by the water resources system WEAP model.
19 **Blue water consumption: OMW**. Estimated by the water resources system WEAP model.
20 **Utilizable outflow**: Estimated by the water resources system WEAP model.
21 **Committed outflow**: Estimated by the water resources system WEAP model.
22 **Environmental outflow**: Extracted from Annex 1 of Drought Management Plan (PES) of the Segura river basin. During normal conditions: 1.0 m^3/s, during drought conditions: 0.5 m^3/s.
23 **Non-utilizable outflow**: Estimated by the water resources system WEAP model
24 **Interbasin transfer**: Estimated by the water resources system WEAP model
25 **Lateral groundwater outflow**: According to river basin management plan: 1.3 hm^3/year

Appendix B.2 Jucar River Basin, Spain

The modelling tools employed for developing the water accounts in the Jucar River Basin were:

(1) Data from the rainfall-runoff model PATRICAL [52] for the baseline period 1980–2012 are available in the Jucar River Basin Authority (CHJ) web (www.chj.es), coinciding with data used in the Jucar River Basin District Management Plan (JRBDMP) [74].
(2) SIMGES module from AQUATOOL Decision Support System Shell (DSSS) [75–77] see Figure A2. This module was used to build the water allocation or management model for all of Jucar District [78], a model which was calibrated using flows (in natural regime) from the CHJ for the period 1980–2012 and where all data referent to demands, operation rules, etc. coincide with those stated in the JRBDMP. Then, results from this model were filtered only for the Jucar River Basin in order to extract all data required in the water accounting sheets related to blue water, taking into account the relationships between this exploitation system and the others next to it.
(3) Future scenarios are based on the changes in precipitation, evapotranspiration and flows coming from 12 RCMs belonging to RCPs 4.5 and 8.5 of the Fifth Assessment Report (AR5) of the Intergovernmental Panel of Climate Change (IPCC) for periods between 2010 and 2100. These changes are available in the Technical Report on the Assessment of the Impact of Climate Change on Water Resources and Droughts in Spain for the Ministry of Agriculture and Fisheries, Food and the Environment [79].

INFLOWS:

1 Precipitation: Based on PATRICAL model data for the baseline scenario, which used data from Spain02 dataset. Future scenarios were based on 12 RCMs for RCPs 4.5 and 8.5 changes in precipitations [70].
2 Interbasin transfer. Not applicable.
3 Upstream tributaries. Not applicable.
4 Lateral groundwater inflow: Simulated by the SIMGES model.
5 Desalination. Not applicable.

WITHDRAWALS:

6 Total water withdrawal: Simulated by the SIMGES model.

7 Agricultural water withdrawal: Simulated by the SIMGES model.

STORAGE:

8 Surface storage change: Simulated by the SIMGES model.

9 Subsurface storage change: Simulated by the SIMGES model. For the future periods, the balance of surface and groundwater was assumed to be zero in order to avoid over-exploitation, as is required by the European Water Framework Directive.

OUTFLOWS:

10 Green water ET: PNA. Estimated by data from PATRICAL model.

11 Green water ET: NNA. Estimated by data from PATRICAL model.

12 Green water ET: RC. Estimated by data from PATRICAL model.

13 Green water ET: IC. Estimated by data from PATRICAL model.

14 Green water ET: OMW. Not applicable.

15 Blue water ET: PNA. Not applicable.

16 Blue water ET: NNA. Not applicable.

17 Blue water ET: RC. Not applicable.

18 Blue water ET: IC. Estimated by the water resources system SIMGES model.

19 Blue water consumption: OMW. Estimated by the water resources system SIMGES model.

20 Utilizable outflow: Estimated by the water resources system SIMGES model.

21 Committed outflow. Not applicable.

22 Environmental outflow. 18 hm^3/year, as stated in the JRBDMP.

23 Non-utilizable outflow. Not applicable.

24 Interbasin transfer. Not applicable in the baseline but considered for future periods in 20 hm^3/year as is predicted in the JRBDMP.

25 Lateral groundwater outflow. This was considered the groundwater flow to the sea that, according to the JRBDMP, is 27 hm^3/year.

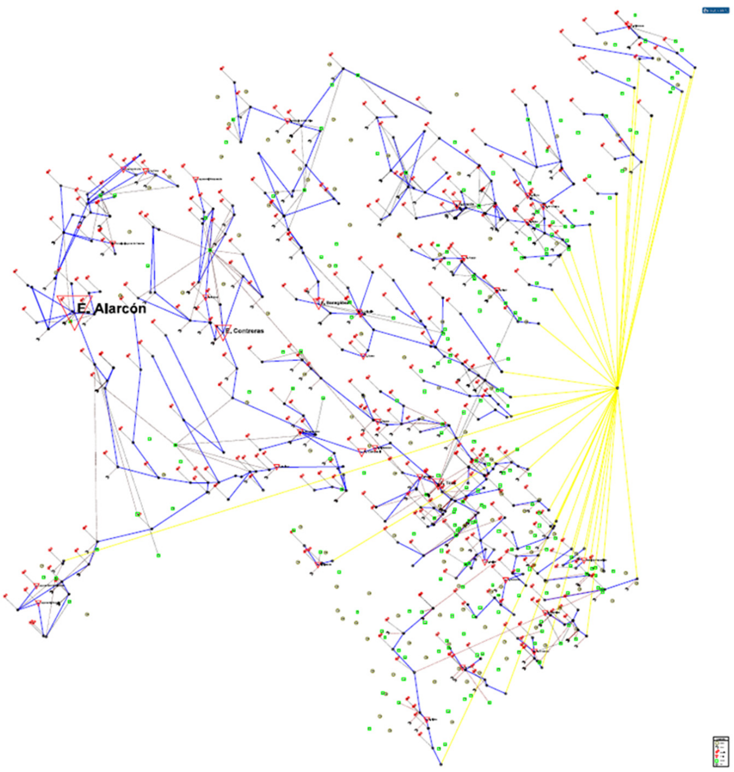

Figure A2. Jucar River Basin District Exploitation System in SIMGES module of AQUATOOL Decision Support System Shell (DSSS).

Appendix B.3 Messara River Basin, Greece

Water balance estimation for the Messara basin was based on the hydrologic modelling output the Sacramento (SAC-SMA) lumped continuous rainfall–runoff model after Koutroulis et al. (2013) and Tsanis and Apostolaki, 2009. The model was calibrated and validated with a genetic algorithm scheme. The water balance of the reference period (1981–2010) was derived from hydrological simulation driven by observations provided by the Directorate of Water of the Decentralized Administration of Crete. Projected hydro-climatologic and socioeconomic circumstances affecting future water balance were adopted by the study of Koutroulis et al. (2016); (Figure A3). Future supply and exploitation potential were estimated based on the future hydrologic regime and the feasibility (economic) of construction of planned water infrastructure. Projected water demand was based on a cross-sectorial approach accounting for changes in irrigation, tourism, domestic and industrial water needs, as well as changes in water use efficiency.

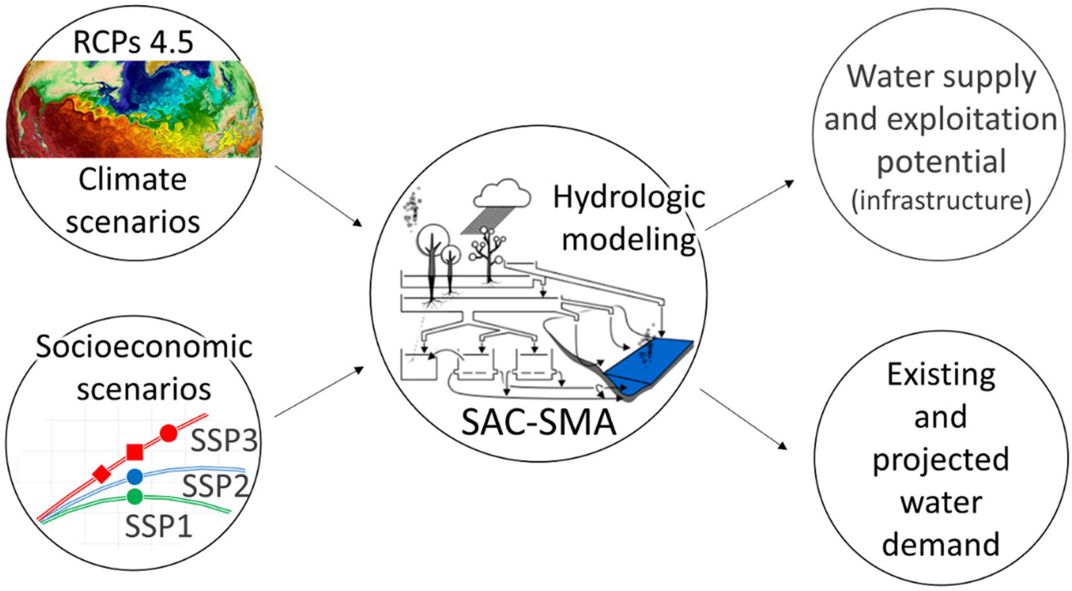

Figure A3. Framework for assessing the water resources balance of the Messara study site, adopted by Koutroulis et al. (2016).

INFLOWS:

(1) **Precipitation**: Estimated by from 14 ground stations, Thiessen weighted on the region. Projections of precipitation and temperature were obtained by the median future precipitation change signal model among five EURO CORDEX (Coordinated Downscaling Experiment - European Domain) models (RCP4.5 and RCP8.5). The data were downscaled and bias was corrected by using the observations to match the historical climatology of the area. Dry years were considered as the average of the lower 33rd percentile of years.

(2) **Interbasin transfers**: Currently, there are no interbasin transfers. However the Koutsoulidis dam is planned to be supplementary and filled with water transferred from the nearby Platis basin. The preliminary technical report of the transfer infrastructure construction refers to 20 Mm^3 per year, while a dry year the available transferable water will by approximately 10 Mm^3. For the far future scenario of RCP85 dry year, we used the assumption of 5 Mm^3 transfer availability.

(3) **Upstream tributaries**: The study domain that we considered includes the entire watershed, hence there are no upstream tributaries contributing to the surface water resources.

(4) **Lateral groundwater inflow**: According to the hydrogeological knowledge of the area, the watershed domain also roughly includes the hydrogeological domain.

(5) **Desalination**: Currently, there are no desalination plants in the area, nor any plans for such. The water resources will be expanded in the near future by the aforementioned interbasin transfer (with regard to the SSP2—most probable water infrastructure).

WITHDRAWALS:

(6) **Total water withdrawal**: Includes: Agricultural water use (95.3%), domestic water use (4.0%), livestock (0.5%) and industrial use (0.2%) (numbers in parentheses indicate the current average annual consumptions).

(7) **Agricultural water withdrawal**: Current agricultural water demand was estimated by the measurements of the local water management authorities that either own the water wells or manage the irrigation networks and dam water (local water infrastructure authorities, Local Organization of Land Reclamation and municipalities). For the future scenarios, an additional 5% increase in ET per degree of warming was considered. In the future scenario cases where the water does not meet the demand, we considered that the agricultural water was bounded to the water availability, considering availability priority to the other sectors.

STORAGE:

(8) Surface storage change: The currently available and the future Platis Dam consists of the available surface storage within the region of interest. In the average year, we considered no surface storage change to the water volume of those reservoirs. In the dry years, we considered an overexploitation equal to what these storages can hold as a backup in an average year.

(9) Subsurface storage change: No groundwater storage change was considered in the average years, while an overexploitation of the dry years was estimated equal to the excess replenishment of the wet years.

OUTFLOW:

(10) **Green water ET: PNA**: Estimated by Sacramento hydrological model (SAC-SMA).

(11) **Green water ET: NNA**: Estimated by Sacramento hydrological model (SAC-SMA).

(12) **Green water ET: RC**: Estimated by Sacramento hydrological model (SAC-SMA).

(13) **Green water ET: IC**: Estimated by Sacramento hydrological model (SAC-SMA).

(14) **Green water ET: OMW**: No green water for other managed water uses was considered.

(15) **Blue water ET: PNA**: No protected natural areas are irrigated in the study area.

(16) **Blue water ET: NNA**: No non-protected natural areas are irrigated in the study area.

(17) **Blue water ET: RC**: No rainfed areas are irrigated in the study area.

(18) **Blue water ET: IC**: Equal to Agricultural water withdrawal.

(19) **Blue water consumption: OMW**: Includes domestic, livestock and industrial water consumption. The baseline domestic water consumption was estimated from the measurements of the municipalities within the study region. An additional 10% increase in the domestic demand in the dry years was considered. In the future scenarios, a domestic demand increase of 20 Lt/day per °C warming was also added. Population projections for the future were considered according to the SSP2 scenario projections for Greece. Baseline industrial and livestock water use was estimated by measurements of the municipalities within the study region. Future livestock water use also considered the SSP2 development projections. Industrial water, mainly consumed in olive oil mills, is considered to be analog to the olives production which in turn is based on the irrigation water availability.

(20) **Utilizable outflow**: The simulated surface outflow of the hydrological model.

(21) **Committed outflow**: There is no commitment of flow downstream.

(22) **Environmental outflow**: The major river of the case study area is intermittent.

(23) **Non-utilizable outflow**: The simulated subsurface outflow of the hydrological model.

(24) **Interbasin transfer**: There is no interbasin outflow transfers or any related plans.

Appendix B.4 Lake Como River Basin, Italy

Lake Como is a sub-alpine lake in the Italian lake district in northern Italy. Its basin is a complex water system that can be divided in three parts (Denaro et al., 2018): An alpine lake catchment of around 4500 km, where numerous hydropower plants exploit the varied terrain for electricity production; a deep glacial regulated lake in the middle, with an active storage capacity of 250 Mm^3; and several water users, including four large irrigation districts, downstream.

The water accounts in the Lake Como basin were developed by using an integrated model (for details, see Giuliani et al., 2016) that includes three main components (Figure A4):

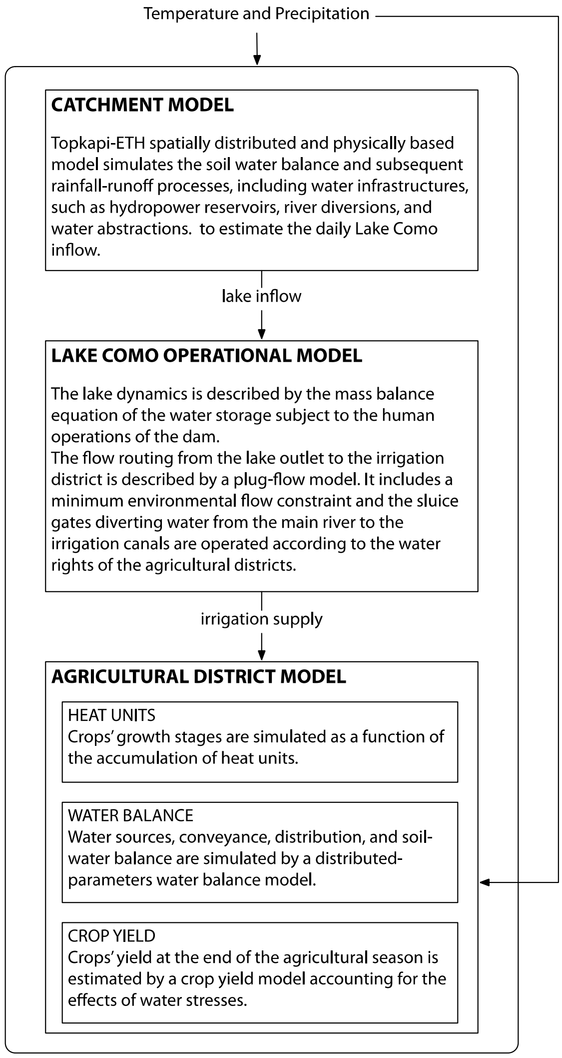

Figure A4. The Lake Como integrated model.

- Catchment model—the hydrological model used is Topkapi-ETH (TE), a spatially distributed and physically based model for the watershed of Lake Como. TE uses a regular grid to represent the topography and an advanced routing method to simulate flow accumulation. TE explicitly models water infrastructures, such as hydropower reservoirs, river diversions, and water abstractions. TE requires several inputs, including time series from geo-localized stations within the basin and spatial inputs for the entire basin (e.g., map such as land use, Digital Elevation Model, and soil type). In this analysis, we focused only on projecting the time series of precipitation (nine stations) and temperature (four stations), which are the most important drivers of the simulated hydrological processes, while the other spatial inputs were maintained equal to the historical observations. TE simulations were run with a daily time step over the control time horizon 1 January 1981–31 December 2004 and the future time horizon 1 January 2006–31 December 2100.

- Lake Como operational model—the lake dynamics is described by a mass-balance equation assuming a modelling and decision-making time step of 24 h, where the lake releases are determined by the lake operating policy. A minimum environmental flow (MEF) constraint on lake releases equal to 5 m^3/s is imposed to protect the aquatic ecosystems in the Adda River downstream from the lake. According to the daily time step, the Adda River can be described by a plug-flow model to simulate the routing of the lake releases from the lake outlet to the intake of the irrigation canals. This diversion of the water from the Adda River into the irrigation canal is regulated by the water rights of the agricultural districts.
- Agricultural district model—the dynamic processes internal to the Muzza irrigation district, which is the largest district served solely by Lake Como release, are described by three distinct modules devoted to specific tasks: (1) A distributed-parameter water balance module (Facchi et al., 2004) simulating water sources, conveyance, distribution, and soil-crop water balance over a regular mesh of cells with a side length of 250 m. Each individual cell identifies a soil volume which is subdivided into two layers, where the upper one (evaporative layer) represents the upper 15 cm of the soil and the bottom one (transpirative layer) represents the root zone and has a time-varying depth, with the water percolating out of the bottom layer that constitutes the recharge to the groundwater system; (2) a heat unit module (Neitsch, 2011) simulating the sequence of growth stages (e.g., root length, basal coefficient, and leaf area index), including the sowing and harvesting dates, as a function of the temperature in terms of cumulated heat units; (3) a crop yield module that first estimates the maximum yield achievable in optimal conditions and, then reduces it to take into account the stresses due to insufficient water supply from rainfall and irrigation happened during the agricultural season, where the yield response to water stresses is estimated according to the empirical function proposed in the AquaCrop model (Steduto et al., 2009) and based on the approach proposed by the Food and Agriculture Organization (Doorenbos et al., 1979). Finally, the yield of the cultivated crops is used to estimate the farmers net profit, which also depends on the crop price and cost along with the subsidies derived from the EU's Common Agricultural Policy (Gandolfi et al., 2014).

INFLOWS:

(1) **Precipitation**: Estimated by nine ground stations in the upper basin and from three ground stations in the irrigation districts. Projections of precipitation and temperature were obtained by the global model ICHEC-EC-EARTH and regional model RCA4 for the scenario RCP4.5 and RCP8.5, which were provided by the EURO CORDEX project. The data were downscaled and bias-corrected using a time-varying quantile-quantile mapping method. The total precipitation was composed of both liquid precipitation and solid precipitation. We considered the 1995–2004 as the historical period, 2030–3050 as the near future period, and 2080–2100 as the far period.

(2) **Interbasin transfer:** Not applicable.

(3) **Upstream tributaries:** Not applicable.

(4) **Lateral groundwater inflow:** Not applicable.

(5) **Desalination**: Not applicable.

WITHDRAWALS:

(6) **Total water withdrawal**: Simulated by the Lake Como operational model. Since the irrigation district only involves agricultural activities, agricultural withdrawal is the same as total withdrawal.

(7) **Agricultural water withdrawal in the Muzza district**: Simulated by the Lake Como operational model and the Agricultural District model.

    a. **Agricultural water withdrawal in the other districts**: Simulated by the Lake Como operational model and the Agricultural District model.

STORAGE:

(8) **Surface storage change**: Evaluated by TE as the annual storage variation of Lake Como and the alpine hydropower reservoirs.

(9) **Subsurface storage change**: Not applicable. There is limited water abstraction from grounder water source for the irrigation districts because of the soil type and the difficulty to reach the deep groundwater source.

OUTFLOWS:

(10) **Green water ET: PNA.** Not applicable.

(11) **Green water ET: NNA**. Estimated by TE accounting for the green water in the alpine basin that is composed only by natural area.

(12) **Green water ET: RC.** Not applicable.

(13) **Green water ET: IC**. Estimated by the Agricultural Model accounting for the green water in the cultivated area of the Muzza irrigation district.

(14) **Green water ET: OMW.** Not applicable.

(15) **Blue water ET: PNA.** Not applicable.

(16) **Blue water ET: NNA.** Not applicable.

(17) **Blue water ET: RC.** Not applicable.

(18) **Blue water ET: IC**. Estimated by the Lake Como operational model, accounting for the blue water diverted to the irrigation districts.

(19) **Blue water consumption: OMW.** Not applicable.

(20) **Utilizable outflow**: Estimated by the Lake Como operational model, representing the water that is not derived by the irrigation districts and that flows downstream.

(21) **Committed outflow**: Not applicable.

(22) **Environmental outflow**: It is generally equal to the MEF (5.0 m^3/s) or exceptionally to the Lake Como release if the lake inflow is lower than 5.0 m^3/s (the MEF constraint does not imply environmental flow augmentation)

(23) **Non-utilizable outflow**: Not applicable.

(24) **Interbasin transfer:** Not applicable.

(25) **Lateral groundwater outflow**: Not applicable.

Appendix B.5 Rhine River Basin, The Netherlands

The modelling tools employed for developing the water accounts in the delta of the Rhine Basin are part of the Dutch National Hydrological Model (NHM), which contains a range of models to assess changes in ground and surface water flows (for more information, see Lange et al., 2014).

(1) MOZART: The national regional surface water model

(2) MetaSWAP: Model for the unsaturated zone.

(3) DM: National water allocation model

(4) QWAST: Quick Scan Water Allocation Tool

The results were compared with water accounting results of the Central Bureau of Statistics of The Netherlands (Graveland et al., 2017) and, in some instances, adjusted accordingly (see the description of the different variables).

The Delta scenario warm has been used for the short future (2050) containing the Wh-scenario (rapid climate change, similar to RCP8.5) and slow socio-economic growth (Van der Hurk et al., 2014). The agricultural area is smaller in the slow socio-economic growth scenario, which affects the water demand of agriculture. The results of the low climate and socio-economic change scenario are similar to the current situation and are therefore not depicted.

INFLOWS:

(1) **Precipitation**: Precipitation in the current situation is based on water accounting estimates of National Bureu of Statistics (Graveland et al., 2017). The projections of precipitation were obtained from the KNMI scenarios (Van de Hurk et al., 2014), which are based on model projections with EC-Earth/RACMO. The precipitation estimates were derived from the MOZART model, a regional surface water model.

(2) **Interbasin transfer**: Flow from Meuse to Waal through the Meuse-Waal channel derived from DM, the national water allocation model.

(3) **Upstream tributaries**: Inflow from the Rhine at Lobith (main inflow from upstream tributaries) including other inflows from Germany.

(4) **Lateral groundwater inflow**: Not applicable.

(5) **Desalination**: Not applicable.

WITHDRAWALS:

(6) **Total water withdrawal**: Agriculture, drinking water and industrial water surface water withdrawals are derived from MOZART, the regional surface water model. Groundwater withdrawals for drinking water and industrial water were derived from CBS statistics and were added to obtain total water withdrawals.

STORAGE:

(7) **Surface storage change**: The annual storage variation in the Ijssel Lake. The water level is managed in such a way that storage will not change.

(8) **Subsurface storage change**: In very dry years, the subsurface storage is lower in the higher parts of The Netherlands. In normal years, subsurface storage does not change, as the subsurface storage is refilled every year. Therefore, on average, there are no subsurface storage changes.

OUTFLOWS:

(9) **Green water ET: PNA**. Approximately 600,000 hectares of land are assigned as protected natural area. Evaporation for nature is assessed with the MetaSWAP model, the national unsaturated soil model.

(10) **Green water ET: NNA**. No differentiation could be made between non-protected natural areas and other areas, e.g., urban area. Therefore, green water for non-protected natural areas is not separately reported.

(11) **Green water ET: RC**. Estimated by the MetaSWAP model for all farm land. Largest part of the farmland in The Netherlands is rainfed. Model results are multiplied by percentage of rainfed agricultural land.

(12) **Green water ET: IC**. Approximately 12% of the agricultural land uses surface water irrigation. The total evapotranspiration obtained from the MetaSWAP model has been multiplied by the percentage of surface water irrigated land.

(13) **Green water ET: OMW**. Total evapotranspiration minus total evapotranspiration from agricultural and protected natural area.

(14) **Blue water ET: PNA**. Open water evaporation from Lake Ijssel and other protected lakes estimated by MOZART.

(15) **Blue water ET: NNA**. Not applicable.

(16) **Blue water ET: RC**. Not applicable.

(17) **Blue water ET: IC**. Total evapotranspiration obtained from the MetaSWAP model multiplied by the surface area with groundwater irrigation.

(18) **Blue water consumption: OMW**. Water consumption within economy derived from CBS (Graveland et al., 2017)

(19) **Utilizable outflow**: Other flow than committed, environmental or non-utilizable outflow estimated with MOZART. Flows for inland water transport, flushing, the environment and water level management are hard to distinguish.

(20) **Committed outflow**: Flow committed for drinking water and industrial uses estimated with MOZART.
(21) **Environmental outflow**: Flow used for flushing the system in order to reduce salinity intrusion estimated with QWAST, the national quick scan water allocation tool.
(22) **Non-utilizable outflow**: Outflow Ijssel Lake estimated with QWAST.
(23) **Interbasin transfer**: Not applicable.
(24) **Lateral groundwater outflow**: Not applicable.

Appendix C Resource Base Sheets for Each River Basin

This appendix includes all the resource base sheets for the five river basins (see Tables A2–A6) included in this work.

Table A2. Resource base sheet for the Segura river basin, Spain.

Variable (Million m^3/Year)	BL	NF45	FF45	NF85	FF85
Precipitation	6620	6482	6583	6482	5463
Interbasin transfer	283	90	28	63	0
Upstream tributaries	0	0	0	0	0
Lateral groundwater inflow	0	0	0	0	0
Desalination	158	190	237	190	237
Total water withdrawal	1190	1203	1114	1200	994
Agricultural water withdrawal	1012	1026	940	1023	833
Surface storage change	−30	−16	11	−11	13
Subsurface storage change	185	0	0	0	0
Green water ET: PNA	1726	1646	1642	1619	1363
Green water ET: NNA	1661	1546	1567	1536	1313
Green water ET: RC	573	534	540	528	448
Green water ET: IC	1660	1538	1568	1544	1305
Green water ET: OMW	116	107	109	108	91
Blue water ET: PNA	20	19	17	19	14
Blue water ET: NNA	24	23	21	23	18
Blue water ET: RC	0	0	0	0	0
Blue water ET: IC	948	991	965	1041	810
Blue water consumption: OMW	128	123	106	122	97
Utilizable outflow	21	21	21	21	21
Committed outflow	0	0	0	0	0
Environmental outflow	32	32	32	32	32
Non-utilizable outflow	67	36	9	29	3
Interbasin transfer	0	0	0	0	0
Lateral groundwater outflow	1	1	1	1	1
Inflow−Outflow	0	0	0	0	0

Table A3. Resource base sheet of the Jucar river basin, Spain.

Variable (Million m^3/Year)	BL	NF45	FF45	NF85	FF85
Precipitation	10,626	10,307	9988	9882	9457
Interbasin transfer	0	0	0	0	0
Upstream tributaries	0	0	0	0	0
Lateral groundwater inflow	1	1	1	1	1
Desalination	0	0	0	0	0
Total water withdrawal	1446	1446	1316	1298	1140
Agricultural water withdrawal	1329	1329	1199	1181	1023
Surface storage change	−165	0	0	0	0
Subsurface storage change	335	0	0	0	0
Green water ET: PNA	84	82	81	80	77
Green water ET: NNA	5709	5606	5481	5424	5253
Green water ET: RC	1776	1741	1705	1687	1634
Green water ET: IC	1311	1285	1258	1245	1206
Green water ET: OMW	0	0	0	0	0

Table A3. *Cont.*

Variable (Million m^3/Year)	BL	NF45	FF45	NF85	FF85
Blue water ET: PNA	0	0	0	0	0
Blue water ET: NNA	0	0	0	0	0
Blue water ET: RC	0	0	0	0	0
Blue water ET: IC	1329	1329	1199	1181	1023
Blue water consumption: OMW	117	117	117	117	117
Utilizable outflow	342	0	0	0	0
Committed outflow	0	0	0	0	0
Environmental outflow	18	18	18	18	18
Non-utilizable outflow	0	0	0	0	0
Interbasin transfer	0	20	20	20	20
Lateral groundwater outflow	110	110	110	110	110
Inflow−Outflow	0	0	0	0	0

Table A4. Resource base sheet of the Messara river basin, Greece.

Variable (Million m^3/Year)	BL	NF45	FF45	NF85	FF85
Precipitation	441.5	445.7	405.1	399.9	297.1
Interbasin transfer	0.0	20.0	20.0	20.0	20.0
Upstream tributaries	0.0	0.0	0.0	0.0	0.0
Lateral groundwater inflow	0.0	0.0	0.0	0.0	0.0
Desalination	0.0	0.0	0.0	0.0	0.0
Total water withdrawal	93.7	103.9	85.2	81.9	54.4
Agricultural water withdrawal	89.5	99.0	80.5	76.8	49.3
Surface storage change	0.0	0.0	0.0	0.0	0.0
Subsurface storage change	9.4	0.0	0.0	0.0	0.0
Green water ET: PNA	29.4	29.9	28.5	27.7	22.2
Green water ET: NNA	60.4	61.7	58.7	57.1	45.6
Green water ET: RC	112.3	114.5	109.1	106.1	84.8
Green water ET: IC	135.6	138.3	131.8	128.2	102.4
Green water ET: OMW	0.0	0.0	0.0	0.0	0.0
Blue water ET: PNA	0.0	0.0	0.0	0.0	0.0
Blue water ET: NNA	0.0	0.0	0.0	0.0	0.0
Blue water ET: RC	0.0	0.0	0.0	0.0	0.0
Blue water ET: IC	89.5	99.0	80.5	76.8	49.3
Blue water consumption: OMW	4.3	4.9	4.7	5.2	5.1
Utilizable outflow	4.2	4.6	3.2	5.0	2.4
Committed outflow	0.0	0.0	0.0	0.0	0.0
Environmental outflow	0.0	0.0	0.0	0.0	0.0
Non-utilizable outflow	2.3	1.8	1.2	2.0	0.7
Interbasin transfer	0.0	0.0	0.0	0.0	0.0
Lateral groundwater outflow	0.0	0.0	0.0	0.0	0.0
Inflow−Outflow	0	0	0	0	0

Table A5. Resource base sheet of the Lake Como river basin, Italy.

Variable (Million m^3/Year)	BL	NF45	FF45	NF85	FF85
Precipitation	7480	7739	7926	7662	7344
Interbasin transfer	0	0	0	0	0
Upstream tributaries	0	0	0	0	0
Lateral groundwater inflow	0	0	0	0	0
Desalination	0	0	0	0	0
Total water withdrawal	5055	5255	5161	5159	4706
Agricultural water withdrawal	5055	5255	5161	5159	4706
Surface storage change	62	119	−5	91	40
Subsurface storage change	0	0	0	0	0
Green water ET: PNA	0	0	0	0	0
Green water ET: NNA	1031	1088	1110	1089	1182
Green water ET: RC	0	0	0	0	0
Green water ET: IC	96	74	85	81	72

Table A5. *Cont.*

Variable (Million m³/Year)	BL	NF45	FF45	NF85	FF85
Green water ET: OMW	0	0	0	0	0
Blue water ET: PNA	0	0	0	0	0
Blue water ET: NNA	0	0	0	0	0
Blue water ET: RC	0	0	0	0	0
Blue water ET: IC	82	100	81	85	64
Blue water consumption: OMW	0	0	0	0	0
Utilizable outflow	682	851	909	808	829
Committed outflow	0	0	0	0	0
Environmental outflow	158	158	158	158	158
Non-utilizable outflow	0	0	0	0	0
Interbasin transfer	0	0	0	0	0
Lateral groundwater outflow	3637	3843	3969	3800	3757
Inflow−Outflow	0	0	0	0	0

Table A6. Resource base sheet of the Delta Rhine river basin area, The Netherlands [1].

Variable (Million m³/Year)	BL	NF45	FF45	NF85	FF85
Precipitation	21,785			26,532	
Interbasin transfer	50			55	
Upstream tributaries	62,770			62,323	
Lateral groundwater inflow	0			0	
Desalination	0			0	
Total water withdrawal	1726			1834	
Agricultural water withdrawal	149			293	
Surface storage change	0			0	
Subsurface storage change	0			0	
Green water ET: PNA	2592			2961	
Green water ET: NNA	0			0	
Green water ET: RC	6567			6407	
Green water ET: IC	903			880	
Green water ET: OMW	3567			4075	
Blue water ET: PNA	3253			3716	
Blue water ET: NNA	0			0	
Blue water ET: RC	0			0	
Blue water ET: IC	58			55	
Blue water consumption: OMW	400			400	
Utilizable outflow	1170			1300	
Committed outflow	643			794	
Environmental outflow	50,745			53,614	
Non-utilizable outflow	14,708			14,708	
Interbasin transfer	0			0	
Lateral groundwater outflow	0			0	
Inflow−Outflow	0			0	

[1] For Rhine, only the Dutch Delta Scenario WARM2050 was available, which corresponds to near future RCP8.5.

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